U.S. Department of Energy Hydrogen and Fuel Cells Program:

2017 Annual Merit Review and Peer Evaluation Report

June 5–9, 2017
Washington, D.C.

U.S. DEPARTMENT OF
ENERGY

DOE/GO-102017-5043
October 2017

U.S. Department of Energy Hydrogen and Fuel Cells Program

2017 Annual Merit Review and Peer Evaluation Report

June 5–9, 2017
Washington, DC

October 2017 **DOE/GO-102017-5043**

NOTICE

Prologue

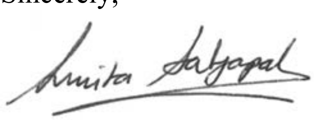
Dear Colleague:

This document summarizes the comments provided by peer reviewers on hydrogen and fuel cell projects presented at the fiscal year (FY) 2017 U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program Annual Merit Review and Peer Evaluation Meeting (AMR), held in conjunction with DOE's Vehicle Technologies Office Annual Merit Review, on June 5–9, 2017, Washington, DC. In response to direction from various stakeholders, including the National Academies, this review process provides evaluations of the DOE-funded projects in applied research, development, demonstration, and analysis of hydrogen and fuel cell technologies. Acting Assistant Secretary for the Office of Energy Efficiency and Renewable Energy (EERE) Daniel Simmons opened the joint plenary session with more than 1,000 attendees, followed by keynote addresses and a fireside chat hosted by Deputy Assistant Secretary Reuben Sarkar with Jon Lauckner (Chief Technical Officer, Vice President of Research & Development, and President, GM Ventures, General Motors) and Joseph Powell (Chief Scientist – Chemical Engineering, Shell). The joint plenary also included overview presentations from the Fuel Cell Technologies Office and the Vehicle Technologies Office.

DOE values the transparent public process of soliciting technical input on its projects and overall programs from relevant experts with depth and breadth of knowledge across a number of broad areas. The recommendations of the reviewers are taken into consideration by DOE technology managers in generating future work plans. The table in this report lists the projects presented at the review, evaluation scores, and the major reviewer recommendations to be considered during the upcoming fiscal year (October 1, 2017–September 30, 2018). The projects have been grouped according to sub-program and reviewed according to the appropriate evaluation criteria. To furnish principal investigators (PIs) with direct feedback, all of the evaluations and comments are provided to each presenter; however, the authors of the individual comments remain anonymous. The PIs are instructed by DOE to fully consider these summary evaluation comments, along with any other comments by DOE managers, in their FY 2018 plans. In addition, DOE managers contact each PI individually and discuss the comments and recommendations as future plans are developed.

In addition to thanking all participants of the AMR, I would like to express my sincere appreciation to the reviewers for your strong commitment, expertise, and dedication in advancing hydrogen and fuel cell technologies. You make this report possible, and we rely on your comments, along with other management processes, to help make project decisions for the new fiscal year. We look forward to your participation in the FY 2018 AMR, which is tentatively scheduled for June in Washington, DC. Thank you for participating in the FY 2017 AMR.

Sincerely,



Sunita Satyapal
Director
Hydrogen and Fuel Cells Program
U.S. Department of Energy

Hydrogen Production and Delivery

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
PD-014	Hydrogen Refueling Analysis of Heavy-Duty Fuel Cell Vehicle Fleet *Amgad Elgowainy; Argonne National Laboratory*	3.4	X			Reviewers were supportive of the project's approach and praised the accomplishments to date, particularly noting the importance of working on hydrogen heavy-duty vehicles. Reviewers suggested collaborating with industry on the analysis results and ensuring that European work is referenced and incorporated as appropriate.
PD-025	Fatigue Performance of High-Strength Pipeline Steels and Their Welds in Hydrogen Gas Service *Joe Ronevich; Sandia National Laboratories*	2.9	X			The overall approach and objectives of this project were commended by reviewers. However, the reviewers questioned the delays in the project schedule and expressed concern about how time will be made up. Reviewers were also interested in seeing additional information on the detailed input and contributions of collaborators, particularly NIST.
PD-031	Renewable Electrolysis Integrated System Development and Testing *Michael Peters; National Renewable Energy Laboratory*	3.2			X	Reviewers commended the project for the thoroughness of the approach, including analysis and validation of technologies from leading electrolyzer industry members. According to reviewers, the project enabled clear, open, and comprehensive interaction between the U.S. Department of Energy (DOE) and industry stakeholders. It was further noted by reviewers that this project provided robust data on electrolyzer performance and capabilities with a rigorous, independent assessment of electrolyzer technologies.
PD-038	Biomass to Hydrogen (B2H2) *Pin-Ching Maness; National Renewable Energy Laboratory*	3.7	X			Reviewers agreed that this project has been successful in identifying and addressing the barriers of biohydrogen production. Reviewers identified the progress made in the genetic engineering of the C. thermocellum enzyme to yield increased hydrogen production as a major success. The principal investigator (PI) was commended for successfully leveraging collaborations, given that the project tasks cover a wide range of areas, including chemistry, process engineering, and molecular biology. The reviewers mentioned that they would like to see how the progress more directly connects to the overall cost of hydrogen.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
PD-100	700 bar Hydrogen Dispenser Hose Reliability Improvement *Kevin Harrison; National Renewable Energy Laboratory*	3.4	X			Reviewers praised the project approach and overall accomplishments, although they noted that testing has been limited in cycles and numbers of hoses. Reviewers would like to see additional scenarios for fueling and hose pressurization covered in the testing to ensure laboratory results are representative of real-world operations.
PD-102	Hydrogen Production and Delivery Cost Analysis *Brian James; Strategic Analysis, Inc.*	3.4	X			There was broad reviewer consensus that the technoeconomic analyses performed in this project are extremely important to DOE objectives, particularly in identification of the long-term potential and bottlenecks of hydrogen production and delivery pathways. Reviewers noted that the project has exhibited strong collaboration with DOE, industry stakeholders, and technology providers. Reviewers recommended that the analyses should be more transparent in key assumptions and sensitivities used.
PD-108	Hydrogen Compression Application of the Linear Motor Reciprocating Compressor *Eugene Broerman; Southwest Research Institute*	3.1	X			Reviewers supported this project's approach and importance, but they would like to see additional detail on technology comparisons and how targets align with DOE goals. Reviewers praised existing collaborations and suggested collaborating with additional suppliers to avoid project delays in the future.
PD-110	Low-Cost Hydrogen Storage at 875 bar Using Steel Liner and Steel Wire Wrap *Amit Prakash; Wiretough Cylinders*	3.2	X			Reviewers were generally pleased by the project's progress, collaborations, and contributions to meeting DOE goals. Reviewers had a number of technical questions on details presented and expressed the need for additional technical information to enable a complete assessment of the approach's technical merits and potential.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
PD-111	Monolithic Piston-Type Reactor for Hydrogen Production through Rapid Swing of Reforming/Combustion Reactions *Kenneth Rappe; Pacific Northwest National Laboratory*	3.2		X		Reviewers praised this project for its straightforward approach and innovative design. They noted that despite missing scheduled project milestones, the project showed reasonable progress in increasing the hydrogen production rate through improvements in both sorbent and catalyst formulations. Reviewers suggested incorporating additional cost data to better evaluate the impact of system optimization on capital cost.
PD-113	High-Efficiency Solar Thermochemical Reactor for Hydrogen Production *Tony McDaniel; Sandia National Laboratories*	3.1			X	Reviewers commended the project for its innovative approach and its work on reactor design. However, they felt that the project's scope was too broad and not enough attention was paid to the material screening and development process. Overall, the reviewers were impressed with the project team's extensive collaborations.
PD-114	Flowing Particle Bed Solarthermal Reduction–Oxidation Process to Split Water *Al Weimer; University of Colorado Boulder*	3.1			X	The reviewers praised this project for its progress in the on-sun reactor demonstration and for meeting the hydrogen production targets. The project's excellent collaboration with partners was highlighted. However, reviewers felt that the project scope was too broad to meet all of its milestones and that the project would have benefitted from additional technoeconomic analysis.
PD-115	High-Efficiency Tandem Absorbers for Economical Solar Hydrogen Production *Todd Deutsch; National Renewable Energy Laboratory*	3.5			X	Reviewers commended the project's approach to improving efficiency, which yielded a new world record in solar-to-hydrogen conversion efficiency. The project was praised for its careful attention to benchmarking the device accurately. However, reviewers were concerned that the project was unlikely to meet its durability goals, specifically emphasizing key durability challenges for the device when exposed to 10x solar illumination, a future goal.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
PD-116	Wide-Bandgap Chalcopyrite Photoelectrodes for Direct Solar Water Splitting *Nicolas Gaillard; University of Hawaii*	3.2	X			Reviewers appreciated the significant progress being made toward the project goals with successful integration of synthesis, characterization, and theory. They highlighted the excellent collaboration with university and national lab partners that comprise a team well suited to achieve the project goals. However, the reviewers expressed concern over the project's ability to meet all final targets relating to open circuit voltage, durability, and solar-to-hydrogen efficiency.
PD-125	Tandem Particle-Slurry Batch Reactors for Solar Water Splitting *Shane Ardo; University of California, Irvine*	3.1	X			The reviewers commended the project for developing an innovative system for photoelectrochemical hydrogen production, highlighting the excellent synergy between theory and design. The PI was encouraged to place additional emphasis on photoactive materials discovery and development relative to the extensive work on reactor design. Reviewers agreed that meeting the DOE solar-to-hydrogen efficiency targets will be a key challenge to this approach.
PD-127	Sweet Hydrogen: High-Yield Production of Hydrogen from Biomass Sugars Catalyzed by in vitro Synthetic Biosystems *Y-H Percival Zhang; Virginia Tech*	3.2			X	Reviewers praised this project for its progress in increasing hydrogen production rates from enzyme engineering and for its unique approach to incorporating several parallel research thrusts. It was noted, however, that there was not sufficient cost analysis performed to gauge the practicality of this approach. Reviewers also emphasized that further attention should be given to scale-up efforts to determine the project approach's feasibility.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
PD-129	Novel Hybrid Microbial Electrochemical System for Efficient Hydrogen Generation from Biomass *Hong Liu; Oregon State University*	3.7	X			According to reviewers, the project has a strong and comprehensive approach, with a focus on evaluating both system and feedstock costs to provide critical guidance in the design of the bio-reactor. Reviewers praised the overall progress of the project toward meeting milestones and cost targets as well as the collaboration between partners. A specific project strength cited was the use of, and cost analysis on, wastewater as a money-saving feedstock. Reviewer recommendations emphasized that further work is needed to address the electrocatalyst stability.
PD-130	Improved Hydrogen Liquefaction through Heisenberg Vortex Separation of Para- and Orthohydrogen *Christopher Ainscough; National Renewable Energy Laboratory*	3.3	X			Reviewers praised the project's innovative approach, potential impact, and progress to date, while recognizing specific project delays resulting from the reported facility failure. Reviewers expressed confidence in the collaborative partnership's collective abilities, but would have liked additional information explicitly detailing the partner roles and contributions.
PD-131	Magnetocaloric Hydrogen Liquefaction *Jamie Holladay; Pacific Northwest National Laboratory*	3.2	X			Reviewers were supportive of this project's innovative approach to hydrogen liquefaction and novel implementation. They praised current collaborations but encouraged adding collaborators as the project and technology progress. Reviewers suggested that the project could be presented more clearly to better explain the project steps in developing this complex technology.
PD-133	Hydrogen Fueling Infrastructure Research and Station Technology (H2FIRST) – Consolidation *Christopher Ainscough; National Renewable Energy Laboratory*	3.7	X			Reviewers praised the relevance of this project, highlighting its importance to industry stakeholders. They also commended the excellent leveraging of the project's collaborative efforts in successful project execution. Reviewers were particularly supportive of the combination of analytical and experimental work implemented to achieve project targets in support of broader DOE goals.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
PD-135	Liquid Hydrogen Infrastructure Analysis *Guillaume Petitpas; Lawrence Livermore National Laboratory*	3.2	X			While this project has just started, reviewers provided positive feedback on the approach and scope of the project, as well as the collaborations. Reviewers emphasized the importance of this work, noting that liquid delivery may become critical to hydrogen infrastructure in the future.
PD-136	Electrochemical Compression *Monjid Hamdan; Giner, Inc.*	3.4	X			Reviewers praised the accomplishments made by the project team in the short time since the project started. They were also broadly supportive of the project approach, importance to DOE goals, and project partners.
PD-137	Hybrid Electrochemical–Metal Hydride Compression *Scott Greenway; Greenway Energy, Inc.*	3.3	X			Overall, reviewers were pleased with this project's approach, importance, goals, creativity, and accomplishments to date. Recommendations included increasing the focus on technoeconomic analysis of the hybrid approach to determine at an earlier stage whether the hybrid approach can be cost-competitive. Clarifying the collaborators' roles was also encouraged.
PD-138	Metal Hydride Compression *Terry Johnson; Sandia National Laboratories*	2.9	X			While reviewers praised the relevance of this work and its coordination with other compressor projects, they questioned whether additional work should go into metal hydride compression. They recommended development of a solid value proposition to justify this specific implementation of the technology. Reviewers also suggested the project add additional collaborations in this area, particularly to assist with cost projection analysis.
PD-139	Reference Station Design, Phase II *Ethan Hecht; Sandia National Laboratories*	3.3	X			Reviewers praised this project for its contributions to the understanding of station design and cost drivers. Also commended were the project's collaborations, potential impact, and future plans. Reviewers emphasized the critical importance of continuing to focus on market-relevant station advancements, given the rapidly changing context for station designs.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
PD-140	Dispenser Reliability *Christopher Ainscough; National Renewable Energy Laboratory*	3.2	X			Reviewers provided positive feedback on the accomplishments to date and the impact and relevance of this project to DOE objectives. However, reviewers expressed concern that the component-testing part of the project may not be the best or most cost-effective approach. They also encouraged partnership with component manufacturers.
PD-143	High-Temperature Alkaline Water Electrolysis *Hui Xu; Giner, Inc.*	3.2	X			Reviewers commended the project for its novel concept and progress, given its recent start. They also noted that this project has significant potential to reduce the cost of electrolytic hydrogen production. However, reviewers felt that the project will face daunting technical challenges as the project progresses, including electrolyte and interfacial stability, and suggested that it would benefit from enhanced collaboration. There was also concern that the project's efficiency and current density goals might be overly ambitious.
PD-144	Multiscale Ordered Cell Structure for Cost-Effective Production of Hydrogen by High-Temperature Water Splitting *Elango Elangovan; Ceramatec*	3.1	X			The reviewers noted that the project has a strong team with significant potential to reduce the cost of hydrogen production via high-temperature electrolysis. Reviewers were critical of the device architecture, noting that it will be very complex to assemble, given the constraints of the electrode fabrication methods and the seals with which it will interact. Reviewers were also critical of the lack of durability testing and power and efficiency targets.
PD-146	Advancing Hydrogen Dispenser Technology by Using Innovative Intelligent Networks *Darryl Pollica; Ivys Energy Solutions Inc.*	3.6	X			Reviewers were impressed by this project and praised its innovative approach, progress to date, and effective leveraging of collaborations. The potential impact and relevance to DOE goals were also commended. Reviewers suggested expanding collaborations in the future to include an automotive original equipment manufacturer.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
PD-147	Economical Production of Hydrogen through Development of Novel, High-Efficiency Electrocatalysts for Alkaline Membrane Electrolysis *Kathy Ayers; Proton Onsite*	3.5	X			The project was commended for its demonstrated progress toward lowering costs and expanding hydrogen production options. Reviewers praised the project approach, noting that improved alkaline exchange membranes (AEMs) are critical to hydrogen production from AEM-based water electrolysis. Reviewers noted that while replacing Ir with Rr will result in cost savings, this is a short-term solution, as Ru is also a platinum group metal. Suggestions included validating the initial durability testing on longer timescales and placing more emphasis on performing detailed technoeconomic analysis.

Hydrogen Storage

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
ST-001	System-Level Analysis of Hydrogen Storage Options *Rajesh Ahluwalia; Argonne National Laboratory*	3.1	X			According to the reviewers, the project approach is sound, and the independent assessment of hydrogen storage systems and materials is useful. The reviewers felt that the project effectively applies strong physical and chemical modeling and analysis while providing sensitivity studies to understand tradeoffs for hydrogen storage system materials and performance. The reviewers noted that the assessment of cryogenic-compressed hydrogen storage systems were of high technical quality, but questioned the focus of this year's effort on bus applications.
ST-008	Hydrogen Storage System Modeling: Public Access, Maintenance, and Enhancements *Matt Thornton; National Renewable Energy Laboratory*	2.9	X			The reviewers stated that the models the project is providing and improving are an important resource for the hydrogen storage community. They commended the makeup of the team and the approach. However, reviewers also added that there are additional metrics beyond gravimetric and volumetric capacities that should be addressed.
ST-063	Formation and Regeneration of Alane *Ragaiy Zidan; Savannah River National Laboratory*	2.8			X	This project was completed in fiscal year (FY) 2017. Reviewers stated that the impact coming from the project's progress on the production of alane will be relevant to non-automotive and portable power applications. The team's effort in scaling up the quantities of material was commended.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
ST-100	Hydrogen Storage Cost Analysis *Brian James; Strategic Analysis, Inc.*	3.4	X			The reviewers noted that the project team provides quality results to address the primary barrier of cost for hydrogen storage system technology development. The reviewers felt that the project team has very good collaboration with external researchers to provide increased technical background for more accurate cost analyses, and the transparency of assumptions and technical rigor was commended. The reviewers suggested that the project consider new hydrogen storage materials that are being commercialized for other applications, such as alane, and identify key cost drivers for new hydrogen storage materials where research and development could lead to cost reductions.
ST-113	Innovative Development, Selection, and Testing to Reduce Cost and Weight of Materials for Balance-of-Plant Components *Jon Zimmerman; Sandia National Laboratories*	3.0	X			The reviewers commented that the project's combination of computational and empirical activities to identify novel hydrogen-compatible materials is a good approach to providing lower-cost balance-of-plant material alternatives. It was noted that the project could benefit from more consideration of whether discovered materials are able to be manufactured into balance-of-plant components. The reviewers highlighted the project's interactions with industrial partners and recommended that the project team seek more collaboration with original equipment manufacturers (OEMs).
ST-116	Low-Cost α-Alane for Hydrogen Storage *Tibor Fabian; Ardica*	2.9			X	This project was completed in FY 2017. The reviewers stated that the project's cost model is strong and takes into account key areas relevant to the material's synthesis and recovery processes. However, the reviewers stated that the approach should have a greater focus on higher yield of adduct and on optimizing the regeneration process using spent AlH_3.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
ST-118	Improving the Kinetics and Thermodynamics of $Mg(BH_4)_2$ for Hydrogen Storage *Brandon Wood; Lawrence Livermore National Laboratory*	3.2			X	This project was completed in FY 2017. The reviewers stated the insights gained on the reaction pathways and properties of magnesium borohydride at the nanoscale level are valuable. Reviewers commended the team's ability to leverage collaborations to produce concrete results that benefit the hydrogen storage materials community. However, the reviewers stated that it is not clear how insights gained throughout the project could be translated into strategies to develop new and novel hydrogen storage materials.
ST-119	High-Capacity Hydrogen Storage Systems via Mechanochemistry *Vitalij Pecharsky; Ames Laboratory*	2.9		X		This project is planned to be discontinued after FY 2017. Reviewers commended the project's use of mechanochemistry as the means to gain a fundamental understanding of complex metal hydrides. However, the project's link between applying the fundamental understanding gained and identifying practical hydrogen storage materials with the potential to meet the targets was described as weak. Reviewers also stated the project has little to no collaboration with the Hydrogen Materials–Advanced Research Consortium (HyMARC).
ST-120	Design and Synthesis of Materials with High Capacities for Hydrogen Physisorption *Brent Fultz; California Institute of Technology*	3.2	X			The project was given high marks for its approach to determining how pore chemistry can control binding energies and its potential impact on the Hydrogen and Fuel Cells Program. The reviewers commended the upcoming collaborations with project partners to generate large-scale reproducible carbons. However, reviewers also commented that several aspects of the synthetic processes, both in the accomplishments to date and in the proposed future work, lacked sufficient detail.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
ST-122	Hydrogen Adsorbents with High Volumetric Density: New Materials and System Projections *Don Siegel; University of Michigan*	3.1	X			The reviewers were complimentary of the computational screening approach used in this project to direct synthetic targets. It was felt that the project has made excellent progress toward linking structural properties and capacities. Reviewers also noted that the project should place more emphasis on higher-temperature adsorption by addressing binding enthalpies, as well as potential volumetric capacity losses through low packing densities.
ST-126	Conformable Hydrogen Storage Coil Reservoir *Erik Bigelow; Center for Transportation and the Environment*	2.7	X			Reviewers noted that this project presents a promising concept for conformable hydrogen storage, with potential high impact if successfully demonstrated. It was also noted how progress was made in identifying a reinforcement fiber for burst requirements. However, the reviewers observed that the project's main challenge continues to be finding a suitable barrier liner material with low enough permeability to prevent hydrogen leakage. Recommendations for the project team included seeking out more collaborations with materials experts to assist in finding suitable liner materials to meet the permeability requirements.
ST-127	Hydrogen Materials–Advanced Research Consortium (HyMARC) – A Consortium for Advancing Solid-State Hydrogen Storage Materials *Mark Allendorf; Sandia National Laboratories*	3.4	X			The reviewers were impressed by the progress made in several aspects of the consortium's work, including the overall coordination of the effort, communication of and justification for its goals, engagement with the seedling projects, and integration of theory with experiments. According to reviewers, it will be important going forward to provide clarity as to how the foundational knowledge gained through model system studies will be applied to develop more complex, relevant systems.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
ST-128	Hydrogen Materials–Advanced Research Consortium (HyMARC) – Sandia National Laboratory's Technical Effort *Mark Allendorf; Sandia National Laboratories*	3.3	X			Reviewers commended the level of collaboration between all the HyMARC/ Hydrogen Storage Characterization and Optimization Research Effort (HySCORE) laboratories and the seedling projects. Much of the consortium's modeling work for both sorbents and hydrides was described as a significant success over the past year. Reviewers suggested that the topics of reaction kinetics and additives/catalysts be enhanced in future work.
ST-129	Hydrogen Materials–Advanced Research Consortium (HyMARC) – Lawrence Livermore National Laboratory's Technical Effort *Brandon Wood; Lawrence Livermore National Laboratory*	3.3	X			Reviewers were very complimentary of the many computational modeling accomplishments presented by the project. The reviewers were impressed by the quality of the team, the results, and the high level of collaboration with the seedling projects. However, reviewers were concerned that there is not enough experimental validation of the modeling work and hoped that this would be a focus in future work.
ST-130	Hydrogen Materials–Advanced Research Consortium (HyMARC) – Lawrence Berkeley National Laboratory's Technical Efforts *Jeffrey Urban; Lawrence Berkeley National Laboratory*	3.0	X			Reviewers were particularly satisfied with advancements on modeling of metal–organic frameworks in conjunction with other HyMARC partners and with the progress on the metal hydride encapsulation work. The reviewers indicated that the capabilities at the Advanced Light Source are unique and very important to the consortium's overall efforts. A few specific concerns were raised involving the integration of the encapsulation effort with the HyMARC computational work, as well as the nature of the graphene oxide coating in these composites.
ST-131	Hydrogen Storage Characterization and Optimization Research Effort (HySCORE) – National Renewable Energy Laboratory's Technical Efforts *Thomas Gennett; National Renewable Energy Laboratory*	3.4	X			The reviewers had a very positive view of the organization and coordination of the HySCORE group within HyMARC. They were extremely supportive of the interlab round-robin study and believe it is of great significance to the hydrogen storage community. The reviewers also commended many of the other characterization tools for sorbent investigations. Collaborations within HyMARC were noted, but some reviewers felt that these could be stronger or broader.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
ST-132	Hydrogen Storage Characterization and Optimization Research Effort (HySCORE) – Pacific Northwest National Laboratory's Technical Efforts *Tom Autrey; Pacific Northwest National Laboratory*	3.2	X			The project's in situ nuclear magnetic resonance (NMR) capabilities were noted by reviewers as being essential to the overall consortium and the Hydrogen Storage sub-program. Reviewers were complimentary of the project's collaboration on work related to magnesium borohydride with several other core consortium laboratories and seedling projects. However, some concerns were expressed about the liquid organic carrier component of the project. Reviewers noted this work was an outlier among the overall consortium efforts and that the goals of future work on these materials are unclear.
ST-133	Hydrogen Storage Characterization and Optimization Research Effort (HySCORE) – Lawrence Berkeley National Laboratory's Technical Efforts *Jeffrey Long; Lawrence Berkeley National Laboratory*	3.2	X			Reviewers commended progress made in several areas of the project, specifically the installation and utilization of the diffuse reflectance Fourier transform infrared spectroscopy (DRIFTS) instrument for hydrogen binding characterization, the technoeconomic analysis performed for metal–organic framework synthesis, and the continued experimental and computational work in pursuit of materials capable of binding several hydrogen molecules at a single open metal site. Some reviewers questioned the importance of the calcium oxalate work and recommended that it be either discontinued or more focused to align with the overall goals of the project.
ST-134	Investigation of Solid-State Hydrides for Autonomous Fuel Cell Vehicles *Joseph Teprovich; Savannah River National Laboratory*	3.3	X			The approach and achievements presented by the project were strongly praised by the reviewers, who were impressed by the innovative design of the unmanned underwater vehicle systems. They commended the collaboration between U.S. Department of Defense and U.S. Department of Energy (DOE) groups to demonstrate an important extension of fuel cell technology to a new type of mobile application. While some reviewers pointed out that the design choices were ideal for this application, others mentioned that this would ultimately require a scaled-up alane production process to lower material costs.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
ST-136	Hydrogen Materials–Advanced Research Consortium (HyMARC) Seedling: “Graphene-Wrapped” Complex Hydrides as High-Capacity, Regenerable Hydrogen Storage Materials *Di Jia Liu; Argonne National Laboratory*	3.0	X			The reviewers stated that the project is a novel and innovative approach to addressing the important kinetic barriers present in complex metal hydrides. They noted that advancements in material performance over what was reported in the original publication have not been that significant, but did acknowledge that the project is still at a very early stage. Some reviewers were troubled by what they viewed as disconcerting or confusing NMR results. With regard to future work, suggestions included expanding the scope of complex hydrides beyond sodium borohydride, as well as carrying out more mechanistic studies in conjunction with HyMARC.
ST-137	Hydrogen Materials–Advanced Research Consortium (HyMARC) Seedling: Electrolyte-Assisted Hydrogen Storage Reactions *Channing Ahn; Liox Power*	2.7	X			As this project had been underway for only a few months at the time of the presentation, the reviewers found it difficult to rate progress; however, they commended the novelty of the project’s approach and the strength of the team. Looking forward, the reviewers believed that the project may find solvents or electrolytes that will enhance kinetics, but were somewhat skeptical that any system would provide significant progress toward the storage targets. Multiple reviewers identified the ionic liquid and eutectic tasks as being the most promising future work.
ST-138	Hydrogen Materials–Advanced Research Consortium (HyMARC) Seedling: Development of Magnesium Boride Etherates as Hydrogen Storage Materials *Godwin Severa; University of Hawaii*	3.3	X			The reviewers all agreed that the project is addressing a very relevant problem in the storage materials field by focusing on improving the thermodynamics and kinetics of magnesium borohydride. They believe that the project has made good progress in its early stages and commended the level of integration it displays with the HyMARC and HySCORE laboratory teams. The reviewers were also supportive of the planned future efforts and tasks, but did state that going forward it will be important to utilize the computational capabilities of the core teams to assist with the elucidation of reaction mechanisms.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
ST-139	Hydrogen Materials–Advanced Research Consortium (HyMARC) Seedling: Fundamental Studies of Surface-Functionalized Mesoporous Carbons for Thermodynamic Stabilization and Reversibility of Metal Hydrides *Eric Majzoub; University of Missouri–St. Louis*	3.2	X			The reviewers found the project's approach to be a novel and innovative method of altering the thermodynamics of high-capacity hydrides. Reviewers commended the expertise of the project team and the amount of collaboration with the HyMARC core team at this early stage of the project. According to the reviewers, knowledge gained through this work may have impact on other efforts and projects. However, concerns were raised about whether the materials developed in this project could ultimately meet the DOE storage targets. There were also questions raised regarding alane as the best choice for the infiltration material.
ST-140	Hydrogen Materials–Advanced Research Consortium (HyMARC) Seedling: Developing a Novel Hydrogen Sponge with Ideal Binding Energy and High Surface Area for Practical Hydrogen Storage *Mike Chung; The Pennsylvania State University*	3.1	X			Reviewers commended the overall approach of the project and said that the targeted materials are promising. The project was seen as having the potential for high impact on the hydrogen storage field in terms of quantifying the effects of boron sites on adsorption behavior. However, the reviewers were somewhat concerned with the isotherms shown in the presentation and suggested that the project leverage the program's existing adsorption validation and characterization capabilities to accelerate the understanding of the material properties.
ST-141	Integrated Insulation System for Automotive Cryogenic Storage Tanks *Barry Meneghelli; Vencore*	3.0	X			The reviewers noted that the project's system-level approach is well suited to addressing key challenges associated with maintaining thermal vacuum insulation quality for cold/cryo-compressed hydrogen storage systems. The reviewers highlighted the project's structure of modeling and experimental activities for identifying heat leakage pathways and potential system improvements. Also highlighted were the project team's strong collaborations, but it was noted that the team could benefit from collaboration with OEMs.

Fuel Cells

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
FC-017	Fuel Cell System Modeling and Analysis *Rajesh Ahluwalia; Argonne National Laboratory*	3.5	X			Reviewers widely agreed that the approach to the analysis was sound and that the results would be useful to the fuel cell original equipment manufacturer (OEM) community-at-large. Reviewers also expressed approval of the results achieved since the last review and said that they will be key to the development of the U.S. Department of Energy's (DOE's) future objectives and targets for fuel cells. It was noted that future work could be better focused on validating durability of stack- or system-level models.
FC-021	Neutron Imaging Study of the Water Transport in Operating Fuel Cells *David Jacobson; National Institute of Standards and Technology*	3.1		X		Based on the fiscal year (FY) 2018 Budget, no further DOE funding is requested for this project at this time.
FC-052	Technical Assistance to Developers *Tommy Rockward; Los Alamos National Laboratory*	2.9			X	Based on the FY 2018 Budget Request's focus on early-stage applied energy research and development (R&D) activities, no further DOE funding is requested for this project at this time.
FC-081	Fuel Cell Technology Status: Degradation *Jennifer Kurtz; National Renewable Energy Laboratory*	3.0		X		Based on the FY 2018 Budget Request's focus on early-stage applied energy R&D activities, no further DOE funding is requested for this project at this time.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
FC-105	Novel Structured Metal Bipolar Plates for Low-Cost Manufacturing *C. H. Wang; TreadStone Technologies, Inc.*	3.2	X			Reviewers generally agreed that while the project was in its early stages, initial progress in modifying the deposition process was satisfactory. Reviewers also said that the approach was based on sound cost analysis and testing partnerships were well structured. There was some concern about whether spray-coating on pre-stamped plates is scalable. It was noted that the project's origins as a Small Business Innovation Research Program (SBIR) project has given it a clear understanding of challenges and goals related to bipolar plate R&D. Reviewers affirmed that future work should adjust primary targets and timelines, including scaled-up system analysis and characterization.
FC-110	Advanced Hybrid Membranes for Next-Generation Polymer Electrolyte Membrane Fuel Cell Automotive Applications *Andrew Herring; Colorado School of Mines*	3.2			X	Reviewers noted that recent progress has been promising. They agreed that, with further rigorous degradation testing and analysis, the new membrane has the potential to outperform others and to meet several critical DOE targets. However, they expressed mixed approval of the overall design of the project, noting that there is a need for proper balance between testing of membranes in fuel cells and fundamental understanding of the novel membranes. Additionally, questions were raised about the collaboration and proposed work with certain partners. Reviewers proposed more attention be paid to meeting cost and durability targets.
FC-128	Facilitated Direct Liquid Fuel Cells with High-Temperature Membrane Electrode Assemblies *Emory DeCastro; Advent Technologies, Inc.*	3.1	X			Reviewers viewed the project's approach as sound and remarked that it is addressing key barriers to commercialization. Reviewers widely noted that there was still a lack of demonstration of the focused catalyst, PtRuPd, and that the team remains short of stated targets. They urged greater collaboration on imaging techniques and agreed that the potential applications for liquid-fueled high-temperature direct dimethyl ether (DME) cells were generally beneficial to DOE's strategic goals.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
FC-130	Development of Platinum-Group-Metal-Free Catalysts for Hydrogen Oxidation Reaction in Alkaline Media *Alexey Serov; University of New Mexico*	3.3	X			Reviewers commended the project's approach to testing a platinum-group-metal (PGM)-free anode for alkaline membrane fuel cells (AMFCs). However, some reviewers noted a lack of clear rationale for some tested material combinations. They were clear that the project has met its stated goals but that the catalyst was still not performing highly. Reviewers were generally optimistic about potential future work and breakthroughs, but it was noted that the project was nearing completion and any additions to scope or future work may not be able to happen. Reviewers raised the possibility of a no-cost extension of the project while project partners continued to optimize carbon-supported NiCu.
FC-131	Highly Stable Anion-Exchange Membranes for High-Voltage Redox-Flow Batteries *Yushan Yan; University of Delaware*	3.0			X	Reviewers mostly agreed that the approach toward membrane fabrication is reasonable and well integrated into existing testing systems. According to reviewers, the project's switch to a polybenzimidazole (PBI) backbone demonstrated improvements in stability and progress toward the project targets, although further work is needed to improve overall membrane conductivity. Reviewers said it was difficult to assess the relevance to DOE goals and potential impact, given that the focus was on redox flow batteries, but the work could yield benefits in advancing hydroxide-exchange membrane technology. Finally, they suggested the future focus be on testing and making improvements at high temperatures to better assess performance in fuel cells.
FC-132	Innovative Non-Platinum-Group-Metal Catalysts for High-Temperature Polymer Electrolyte Membrane Fuel Cells *Sanjeev Mukerjee; Northeastern University*	3.5	X			Reviewers expressed wide approval for the approach in testing PGM-free catalysts, noting its innovative work in related durability studies and performance. Additionally, the strength of the wide collaboration between university and industry partners was noted. Reviewers agreed that future work should include longer durability testing periods with a focus toward commercialization of the catalyst.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
FC-135	FC-PAD: Fuel Cell Consortium for Performance and Durability *Rod Borup; Los Alamos National Laboratory*	3.0	X			Reviewers spoke highly of the consortia approach, which allows the project to collaborate with complementary projects. Reviewers pointed to this collaboration and facilitation of inter-laboratory work as a key strength of the project. They pointed to clear and measured progress in the 1.5 years the project has been underway, highlighting modeling and degradation analysis work. According to reviewers, the project is critical to meeting DOE targets. It was noted that one risk is an increased level of administration that gets in the way of progress. For future work, reviewers suggested an increased focus on model quantification and extrapolation of results leading to new stack designs.
FC-136	FC-PAD: Fuel Cell Consortium for Performance and Durability – Components and Characterization *Karren More; Oak Ridge National Laboratory*	3.4	X			Reviewers observed that the project has made significant progress in its role in supporting other work, such as the characterization and quantification of PtCo catalyst degradation through use of state-of-the-art techniques. There was strong agreement that the dissemination of this work is very beneficial for the fuel cell industry as well. One weakness identified was the lack of wider industry participation in the project's characterization efforts. Reviewers were supportive of the project's future work in developing new characterization methods and increasing understanding of fuel cell performance and durability issues.
FC-137	FC-PAD: Fuel Cell Consortium for Performance and Durability – Electrode Layers and Optimization *Adam Weber; Lawrence Berkeley National Laboratory*	3.3	X			Reviewers affirmed that significant progress has been made in characterization and diagnostic methods for optimization. Reviewers thought the project's relevance was dependent on achieving a better understanding of ionomer structure conditions, which will have a greater impact on DOE targets. Several reviewers also encouraged further collaboration with projects focused on studying novel structures for enhanced performance and durability.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
FC-140	Tailored High-Performance Low-Platinum-Group-Metal Alloy Cathode Catalysts *Vojislav Stamenkovic; Argonne National Laboratory*	3.3	X			Reviewers enthusiastically approved of the project's approach, design, state-of-the-art methods, and aggressive targets for low-PGM novel catalysts. They agreed, however, that progress has slowed since 2016 and that while more catalysts had been developed, performance remains low. They agreed that the project will align well with DOE goals if catalyst activity can be improved within the membrane electrode assembly (MEA), demonstrating potential for significant cost reductions for polymer electrolyte membrane fuel cells (PEMFCs). Finally, several reviewers noted that future work for the project remained unclear.
FC-141	Platinum Monolayer Electrocatalysts *Radoslav Adzic; Brookhaven National Laboratory*	3.1	X			Reviewers generally approved of the project's approach to addressing key barriers and including proper MEA testing. They specifically pointed to MEA testing of Pt/PdNiN/C systems as an important part of the project. These tests, in their view, are critical to meeting the goals of PEMFC cost reduction and could significantly improve Pt utilization in fuel cells; more effort is needed to understand limiting factors. However, reviewers noted that catalyst performance needs to be improved. They feel that the new catalyst synthesis and characterization shows potential but that it runs the risk of moving in too many directions. They believe that there may be advantages to focusing more on a single catalyst. Reviewers suggested future work should include scale-up of materials with collaboration with MEA OEMs and FC-PAD.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
FC-142	Extended-Surface Electrocatalyst Development *Bryan Pivovar; National Renewable Energy Laboratory*	3.0	X			Reviewers were in agreement that the approach to low-PGM nanowire was relevant and appropriate for the project. They noted that some moderate progress has been made in atomic layer deposition activities and in improving batch sizes. There was concern about remaining issues regarding durability, stability of the Ni core, and catalyst performance. Suggestions included focusing future work on improving the mechanical integrity of the catalyst and demonstrating scaled-up performance at MEA levels.
FC-143	Highly Active, Durable, and Ultra-Low-Platinum-Group-Metal Nanostructured Thin-Film Oxygen Reduction Reaction Catalysts and Supports *Andrew Steinbach; 3M*	3.0	X			For this project, reviewers expressed mixed support for the dual approach to thin-film catalysts, unitized thin film and nanoporous thin film, noting that performance of one was clearly superior to the other. Reviewers recognized that pursuing both does mitigate risk. They pointed to performance progress through extensive testing on nanostructured thin-film (NSTF) catalysts as important to meeting 2020 targets for catalyst mass activity. The reviewers affirmed that both approaches generally support DOE goals and that only one will meet final project goals, which should define future work. The focus of this future work should include an increased focus on optimizing the catalyst layer structure for improved performance.
FC-144	Highly Accessible Catalysts for Durable High-Power Performance *Anu Kongkanand; General Motors*	3.2	X			Reviewers thought the project's approach to addressing varying causes of performance degradation of PEMFCs was relevant and appropriate. They praised the work to develop high-performing PtCo catalysts on porous supports and investigate Pt-electrolyte interactions. This work was seen as having potential to significantly increase the understanding of degradation and make key improvements in durability, which could lead to new approaches in PEMFCs. The project was viewed as having a strong mix of technical expertise and avenues to achieve stated goals. Reviewers also felt that further work was needed to better understand the interactions of ionic liquids in the catalyst layer.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
FC-145	Corrosion-Resistant Non-Carbon Electrocatalyst Supports for Proton Exchange Fuel Cells *Vijay Ramani; Washington University in St. Louis*	2.5		X		Reviewers commended the results attained using density functional theory modeling. There was disagreement as to whether the approach is appropriate, specifically in regard to support stability of a platinum catalyst and whether a better understanding is required. Reviewers showed some doubts on the relevance of the project and suggested more clarity was needed around fuel cell testing. Reviewers felt that collaboration could focus on catalyst supplier and automotive OEM interactions to help meet requirements.
FC-146	Advanced Materials for Fully Integrated Membrane Electrode Assemblies in Anion-Exchange Membrane Fuel Cells *Yu Seung Kim; Los Alamos National Laboratory*	3.4	X			Reviewers agreed that the innovative approach to studying alkaline membranes will most effectively help determine stability and, by extension, practicality for commercial application. They also affirmed that the project has made solid progress in reaching milestones and in situ testing of membranes under basic conditions of the AMFC, with the exception of the milestone of a downselect ionomer. Collaborations were seen to be well structured. Reviewers thought that the work on alkaline membrane stability was aligned with DOE goals and that future work should focus on PGM-free rather than low-PGM catalysts.
FC-147	Advanced Ionomers and Membrane Electrode Assemblies for Alkaline Membrane Fuel Cells *Bryan Pivovar; National Renewable Energy Laboratory*	3.3	X			Reviewers were generally supportive of the project's approach to developing stable AMFCs, specifically in regard to eliminating sulfonamide linkage, which reviewers believe will result in a more stable membrane. They did, however, conclude that there could be more of a focus on cost and performance, in addition to stability. They recognized the project's potential to fulfill relevant DOE targets for an alkaline membrane for automotive applications, and to advance general understanding of new membranes. As a result, the reviewers felt that future work should focus on the limitations preventing the project from meeting the targets at a fuel-cell-system level.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
FC-154	Regenerative Fuel Cell System (Small Business Innovation Research Phase II) *Paul Matter; pH Matter LLC*	3.1	X			Reviewers stated that, while the benefits of a regenerative fuel cell were obvious, the approach was perhaps too broad and optimistic to reach certain targets. It was observed that certain cost and performance targets are already being met by other dedicated systems, but that the niche-application potential of the regenerative fuel cell makes the targets more reasonable. Reviewers thought future work should focus on the individual technology readiness levels of components and cost-effectiveness of the system to ensure market relevance and a clear business case, which would broadly help meet DOE goals.
FC-155	Novel Ionomers and Electrode Structures for Improved Polymer Electrolyte Membrane Fuel Cell Electrode Performance at Low-Platinum-Group-Metal Loadings *Andrew Haug; 3M*	3.4	X			Reviewers agreed that both the approach for ionomer characterization and the NSTF performance were well designed and have high potential for results. Additionally, they felt that good progress has been made in the short time the project has been active, particularly in catalyst layer and ionomer activities. It was clear to reviewers that the project was well leveraged within FC-PAD and that the team communicated well between project partners, with the dispersion capabilities being a particular strength of the effort. Reviewers stressed that the characterization work was relevant to both FC-PAD objectives and Multi-Year Research, Development, and Demonstration Plan targets and that the project should continue to focus on those aspects over developmental efforts.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
FC-156	Durable High-Power Membrane Electrode Assemblies with Low Platinum Loading *Swami Kumaraguru; General Motors*	3.2	X			Reviewers agreed that the project's initial approach to developing state-of-the-art (SOA) MEAs was comprehensive and followed DOE guidelines, which will help to integrate with FC-PAD activities. It was noted that this should produce results in line with targets in the project's first year. According to reviewers, the project partners' MEA expertise will ensure appropriate access to SOA materials and will contribute to the development of a durable, high-performance electrode. Reviewers suggested feedback from first-year results guide MEA optimization in the second project year.
FC-157	High-Performance Polymer Electrolyte Fuel Cell Electrode Structures *Mike Perry; United Technologies Research Center*	3.1	X			Reviewers agreed overall with the high-level focus and the experimental design to further understand transport losses in low-PGM electrodes. However, it was noted that project partners could have provided more clarity on metrics to validate results for mass transport losses. Early results, according to reviewers, showed satisfactory progress in the development of a model for getting insight on the catalyst at the rotating disk electrode (RDE) layer. They indicated that the challenge will be transferring those findings to useful results at the MEA level. Reviewers concurred that future work needs to aim toward ensuring SOA performance and to streamline thin-film catalyst activities by approaching project partners.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
FC-158	Fuel Cell Membrane Electrode Assemblies with Ultra-Low-Platinum Nanofiber Electrodes *Peter Pintauro; Vanderbilt University*	3.3	X			Reviewers widely commended the project's novel approach in using electrospun nanofibers to address key barriers to MEA commercialization. They indicated electrospun catalyst results showed good progress in catalyst performance and mass activity in a short amount of time, especially within the PtCo/C nanofiber cathode. Reviewers were confident that the approach and the diversified team of experts showed high potential for reaching DOE 2020 targets and that, as the project moves forward, FC-PAD laboratories will be able to collaborate further. Reviewers thought the project could do a better job of understanding the correlation between electrospun nanofiber MEAs and performance improvements. It was suggested that future efforts include work to increase characterization of electrospun electrode transport properties, with comparison to SOA MEAs.
FC-160	ElectroCat (Electrocatalysis Consortium) *Piotr Zelenay; Los Alamos National Laboratory*	3.1	X			Reviewers widely agreed that the approach to PGM-free catalysts was sound and comprehensive. Reviewers expressed approval of the electrode performance progress achieved thus far but indicated that further progress was needed to improve catalyst stability. They agreed that the laboratory collaboration structure worked well, especially with the consortium's strong technical team. Some reservations were expressed about the lack of any outside partners. Reviewers agreed future work should increasingly address catalyst stability and durability.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
FC-161	Advanced Electrocatalysts through Crystallographic Enhancement *Jacob Spendelow; Los Alamos National Laboratory*	3.2	X			Reviewers stated that the alloying approach to catalyst improvements in stability and activity was appropriate and will address major barriers to commercialization. The project was observed to have shown good initial results, particularly in the mass activity of the face-centered tetragonal (fct)-CoPt catalyst. Also praised were the level of collaboration and no-cost involvement of project partners. Reviewers agreed that the project is focused on all key catalyst target barriers identified by DOE, though some felt it was unclear whether they could reach such aggressive one-year targets. Reviewer recommendations for future work included additions of go/no-go decision points for catalyst activity and stability.
FC-162	Vapor Deposition Process for Engineering of Dispersed Polymer Electrolyte Membrane Fuel Cell Oxygen Reduction Reaction $Pt/NbO_x/C$ Catalysts *Jim Waldecker; Ford Motor Company*	3.0				Reviewers expressed skepticism in the project's methodology, pointing to poor RDE results and the choice of component materials. Reviewers observed that these issues were reflected in the lack of progress but understood that the project is new and further characterization and testing of Pt/C is needed. They maintain that the project will remain relevant if it can reach the performance targets for this component material, though it is not clear based on initial results whether the project will be able to. Reviewers recommended that the team better characterize Pt/C and develop risk mitigation strategies with go/no-go decision points in the event the material is not able to meet targets.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
FC-163	Fuel Cell Systems Analysis *Brian James; Strategic Analysis, Inc.*	3.4	X			Reviewers widely agreed that the design for manufacture and assembly approach in cost estimation is sound and will be extremely helpful in setting realistic cost targets at DOE in the future. Reviewers pointed to the work in high-power-density automotive applications as particularly good progress. It was also noted that the project accurately captured cost benefits of recent catalyst developments in other DOE projects. It was clear to reviewers that collaboration was strong, making good use of a wide range of supplier sources for analysis. Suggestions for future work included using OEM data for model validation.
FC-164	Development of Corrosion-Resistant Carbon Support for Ultra-Low-Platinum-Group-Metal Catalysts (Small Business Innovation Research Phase I) *Prabhu Ganesan; Greenway Energy, LLC*	3.2	X			Reviewers agreed that the use of corrosion-resistant carbon support is logical and builds soundly upon previous work, if perhaps lacking a little detail. They remarked that encouraging progress has been made so far in carbon scale-up and that this work demonstrated satisfactory stability. Reviewers approved of the integration of project partners to enhance capabilities of resistant carbon supports, which are highly relevant to DOE goals. It was felt that future work should focus on expanding this work, along with fundamental analysis on impacts of pore size, durability, and stability.
FC-165	Mesoporous Non-Carbon Catalyst Supports of Polymer Electrolyte Membrane Fuel Cells (Small Business Innovation Research Phase I) *Jacob Coppage-Gross; Certaintech, Inc.*	2.9	X			Reviewers agreed that the project is relevant to DOE goals and on track to reach the first set of targets. Reviewers expressed some doubt about the project's approach. They felt that, while novel, the approach presented concerns about selecting and investigating metal carbides and made them question whether the work would result in lower Pt loadings or higher catalyst stability. Reviewers also noted that meeting performance and durability targets will be challenging. For future work, they thought the project should focus more on substrates in Phase I, with clear and measurable goals or milestones before Phase II and MEA testing.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
FC-166	Development of Durable Active Supports for Low-Platinum-Group-Metal Catalysts (Small Business Innovation Research Phase I) *Barr Halevi; Pajarito Powder*	3.3	X			Reviewers stated that early progress in durability testing has been noteworthy. However, they expressed some skepticism of the techniques, normally used for PGM-free catalyst supports, to create low-PGM catalysts. Reviewers stated that there is a need for further work regarding catalyst support stability to justify these techniques. There was also agreement that the project's durability testing addresses DOE's goals to reduce Pt loading and PEMFC durability. Reviewers identified improvement of support stability as potential future work and agreed that the project is on the right path for MEA development.
FC-167	Multi-Functional Catalyst Support (Small Business Innovation Research Phase I) *Minette Ocampo; pH Matter LLC*	2.9	X			Reviewers generally agreed that using PGM-free carbon catalysts as supports for low-Pt electrodes was appropriate and will address cost and performance targets, but questions were raised about overall impact on durability. Reviewers largely thought it was too early in the project to judge progress, but early accomplishments in RDE performance with Pt deposits were viewed as encouraging. Reviewers did note the apparent lack of collaboration but said that it may be due to the nature of the SBIR project. Reviewers stressed the need to validate RDE data with MEA fabrication and fuel cell tests.
FC-168	Highly Robust Low-Platinum-Group-Metal Membrane Electrode Assemblies Based upon Composite Supports *Arrelaine Dameron; Forge Nano*	3.0	X			Reviewers expressed approval of the project's novel, durability-focused approach in using an overcoat on the catalyst. They were less clear on how the project would ensure a carbon-only coating. Reviewers also agreed that the project is a sound translation of demonstrated gas-phase catalysis to electrocatalysis technology that will address key DOE durability targets. It was thought that future work could include clearer targets for each project phase, including conductivity of the overcoat material, activity, and durability.

Manufacturing R&D

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
MN-001	Fuel Cell Membrane Electrode Assembly Manufacturing Research and Development *Michael Ulsh; National Renewable Energy Laboratory*	3.3	NA			Based on the fiscal year 2018 Budget Request's focus on early-stage applied energy research and development activities, no further U.S. Department of Energy (DOE) funding is requested for this project at this time.
MN-012	Clean Energy Supply Chain and Manufacturing Competitiveness Analysis for Hydrogen and Fuel Cell Technologies *Pat Valente; Ohio Fuel Cell Coalition*	2.9			X	Reviewers approved of the project's approach to developing technical exchange centers and leveraging other relevant DOE projects, which also received positive feedback from attendees at the exchange centers. However, reviewers expressed that further metrics are needed to determine the actual efficacy and impacts of matchmaking events. Several reviewers shared concerns about the industry brochure deliverable timetable and its apparent decrease in scope, which has not been reflected in the project in the budget. Reviewers suggested that future exchanges focus on more specific themes, such as standardization of specific components, as the supply chain is not yet mature. They also highlighted the continued need for increased industry and trade group collaboration. This project was funded through prior year funds and will continue to completion.
MN-013	Fuel Cell and Hydrogen Opportunity Center *Alleyn Harned; Virginia Clean Cities at James Madison University*	3.1			X	Reviewers commented favorably on the project's approach and effective presentation of industry participants via the Hydrogen Fuel Cell (HFC) Nexus website. Several reviewers raised questions about the extent of collaboration with outside groups and the international community, which is viewed as critical. Additionally, some doubts were expressed about project sustainability, specifically maintenance. Reviewers urged that a plan be put in place to address this concern. This project was funded through prior year funds and will continue to completion.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
MN-014	U.S. Clean Energy Hydrogen and Fuel Cell Technologies: A Competiveness Analysis *Patrick Fullenkamp; GLWN – Westside Industrial Retention & Expansion Network*	3.3			X	Reviewers provided positive comments on the project approach, noting the quality of the team and clear and concise analysis. It was agreed that clear conclusions could be drawn from the strength of the competitive analysis on the manufacturing sector. Reviewers remarked that most of the work has been completed and that the remainder of the project should focus on reporting activities to overcome regional and global barriers to competitiveness. Lastly, several reviewers suggested future work could target a broader scope internationally or target specific fuel cell components for analysis. This project was funded through prior year funds and will continue to completion.
MN-015	Continuous Fiber Composite Electrofusion Coupler *Brett Kimball; Automated Dynamics*	3.2			X	Reviewers commended the project for its approach to component materials adjustment and simple and elegant engineering, and for meeting the project's testing targets. It was agreed that the project will help achieve DOE's goals of increasing pipeline safety and integrity. Reviewers expressed the importance of more clearly communicating cost factors and impacts. They said that future work is straightforward and that the project is properly focused on fatigue testing and finishing the prototype. This project was funded through prior year funds and will continue to completion.
MN-016	In-Line Quality Control of Polymer Electrolyte Membrane Materials *Paul Yelvington; Mainstream Engineering*	3.2			X	Reviewers largely agreed that the project's approach in optical inspection is appropriate and expected. They concluded that progress was evident and significant for targeted inspection methods. Furthermore, reviewers concluded the project was relevant to DOE's goals for roll-to-roll processing and cost/ performance targets. It was suggested that future work be focused on real-world detection and increased collaboration with parallel projects at the National Renewable Energy Laboratory. This project was funded through prior year funds and will continue to completion.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
MN-017	Manufacturing Competitiveness Analysis for Hydrogen Refueling Stations *Margaret Mann; National Renewable Energy Laboratory*	2.9			X	Reviewers had mixed reactions to the project approach, specifically in the clarity of methodologies and the lack of specificity in quantitative metrics. Reviewers also commented on the appearance of incomplete data in some areas such as hydrogen refueling station rollout and intra-country trade. Recommendations included completing more detailed and complete analysis of trade flows. Citing a lack of actionable results and clarity, reviewers said that future work should focus on expanding collaborations, standardization of refueling station components, and electrolyzers.

Technology Validation

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
TV-001	Fuel Cell Electric Vehicle Evaluation *Jennifer Kurtz; National Renewable Energy Laboratory*	3.4	NA			Based on the fiscal year (FY) 2018 Budget Request's focus on early-stage applied energy research and development (R&D) activities, no further U.S. Department of Energy (DOE) funding is requested for this project at this time.
TV-008	Fuel Cell Bus Evaluations *Leslie Eudy; National Renewable Energy Laboratory*	3.7	NA			Based on the FY 2018 Budget Request's focus on early-stage applied energy R&D activities, no further DOE funding is requested for this project at this time.
TV-017	Hydrogen Station Data Collection and Analysis *Sam Sprik; National Renewable Energy Laboratory*	3.6	NA			Based on the FY 2018 Budget Request's focus on early-stage applied energy R&D activities, no further DOE funding is requested for this project at this time.
TV-019	Hydrogen Component Validation *Daniel Terlip; National Renewable Energy Laboratory*	3.0	NA			Based on the FY 2018 Budget Request's focus on early-stage applied energy R&D activities, no further DOE funding is requested for this project at this time.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
TV-025	Performance Evaluation of Delivered Hydrogen Fueling Stations *Ted Barnes; Gas Technology Institute (GTI)*	3.5	X			Reviewers said that data collection at hydrogen stations is an important part of measuring station maturity and progress toward goals, and that data gathered will be useful in estimating hydrogen fuel demand. While reviewers acknowledged that progress has been made in installing and collecting data of value on two stations, concern was expressed over permitting challenges and having adequate time for data collection on the remaining three stations. The experience and capabilities of the project team and collaboration between project partners were commended. Because of concerns about severely curtailing data, reviewers proposed having at least four quarters of data provided for each of the five stations via a no-cost extension of the project. Moreover, reviewers suggested that alternative approaches to dealing with delays in permitting new stations be cited, and that a specific plan to communicate lessons learned on subjects such as system development, network communications, and commissioning be outlined. This project was funded through prior year funds and will continue to completion.
TV-029	Performance and Durability Testing of Volumetrically Efficient Cryogenic Vessels and High-Pressure Liquid Hydrogen Pump *Salvador Aceves; Lawrence Livermore National Laboratory*	3.2	NA			Based on the FY 2018 Budget Request's focus on early-stage applied energy R&D activities, no further DOE funding is requested for this project at this time.
TV-031	Dynamic Modeling and Validation of Electrolyzers in Real-Time Grid Simulation *Robert Hovsapian; Idaho National Laboratory*	3.6	NA			Based on the FY 2018 Budget Request's focus on early-stage applied energy R&D activities, no further DOE funding is requested for this project at this time.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
TV-034	Fuel Cell Hybrid Electric Delivery Van Project *Jason Hanlin; Center for Transportation and the Environment*	3.2	X			Reviewers saw potential in the findings of this project, stating that it addresses a critical need in the medium- and heavy-duty vehicle space and has the potential to show that the technology is competitive. The project team was praised for a well-designed truck platform and detailed simulations of actual routes and fuel requirements. However, reviewers expressed concern over the project's delayed start and uncertainty regarding remaining cost share, which could result in fewer metrics or less progress. Developing a risk mitigation strategy for the potential of such a case was suggested. It was also stressed that fueling tests should be scheduled, since California retail hydrogen stations may respond differently to the different configuration and capacity of hydrogen tanks found on medium-duty delivery trucks (compared to light-duty fuel cell electric vehicles); reviewers cautioned against assuming that these delivery trucks can be fueled without any challenges. A suggestion for future consideration was to involve more hydrogen tank suppliers to provide a new "off-the-shelf" tank choice or to look at a new design that could be shared among multiple customers. This project was funded through prior year funds and will continue to completion.
TV-037	Hydrogen Meter Benchmark Testing *Michael Peters; National Renewable Energy Laboratory*	3.6	NA			Based on the FY 2018 Budget Request's focus on early-stage applied energy R&D activities, no further DOE funding is requested for this project at this time.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
TV-039	Innovative Advanced Hydrogen Mobile Fueler *Sara Odom; Electricore*	3.6	X			Reviewers saw the mobile fueler developed by this project as filling infrastructure gaps and increasing the understanding of local authorities having jurisdiction. The use of existing design and equipment was praised by reviewers, and design features were considered to be well-thought-out. The reviewers thought that the next steps were going to be the most difficult for the project because of risks related to hardware and safety testing. Therefore, reviewers suggested that project partners continue to maintain their close and strong collaboration to ensure success. Reviewers suggested that remaining uncertainties regarding siting, permitting, and transporting the fueler be considered and resolved. Suggestions for future enhancements included using an alternative source for on-board power, investigating whether 24/7 fueling would be possible with the fueler not connected to onsite power, performing Hydrogen Station Equipment Performance (HyStEP) testing to prove fueling performance per SAE J2601 requirements, engaging Northeastern Weights and Measures Association officials with their counterparts in California, adopting California regulations on retail sale (metering) of hydrogen for the fueler, and improving the user interface for the dispenser to support unattended fueling. This project was funded through prior year funds and will continue to completion.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
TV-041	Modular Solid Oxide Electrolyzer Cell System for Efficient Hydrogen Production at High Current Density *Hossein Ghezel-Ayagh; FuelCell Energy*	3.3	X			This project was regarded as well managed, as having the potential to advance understanding of high-temperature electrolysis, and as a significant step change in the ability to meet hydrogen needs for the medium and long terms. Reviewers praised the progressive approach, such as cell-level testing and exploration of operation range with multiple parameters. Reviewers highlighted that progress has been steady and the initial results have built confidence, but advised that cell degradation and project economics issues be moved to the forefront of focus. Concern was expressed over validation and/or deployment being at the end of the project and being poorly defined. Reviewers liked that the technology leverages previous work, but they noted that the role of partners was confusing and that there was limited outreach to appropriate end users or low-cost electricity providers. A third-party validation of system performance was suggested. Reviewers also suggested investigating the comparative advantage of the current work and accounting for the impact of integration with intermittent renewable power on system performance and cost. This project was funded through prior year funds and will continue to completion.
TV-042	Optimal Stationary Fuel Cell Integration and Control (Energy Dispatch Controller) *Genevieve Saur; National Renewable Energy Laboratory*	3.3	NA			Based on the FY 2018 Budget Request's focus on early-stage applied energy R&D activities, no further DOE funding is requested for this project at this time.
TV-043	Integrated Systems Modeling of the Interactions Between Stationary Hydrogen, Vehicle, and Grid Resources *Samveg Saxena; Lawrence Berkeley National Laboratory*	3.0	NA			Based on the FY 2018 Budget Request's focus on early-stage applied energy R&D activities, no further DOE funding is requested for this project at this time.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
TV-045	H2@ Scale Analysis *Mark Ruth; National Renewable Energy Laboratory*	3.6	X			This analysis was seen as an important and valuable effort in understanding the challenges and potential impacts of large-scale deployment of hydrogen technologies. Reviewers appreciated the comprehensive evaluation and analysis methodology, while praising the use of well-established models by a team with strong analytic capabilities. Concern was raised that the market potential was overstated as a result of double counting hydrogen needs in some sectors, as well as assuming that there would be high growth in hydrogen demand. Reviewers also expressed concern that this analysis may be too internally focused and thus encouraged the project team to seek additional collaborations with industry to look for synergies between supply and demand. Additional suggestions for enhancement were to consider transmission build-out, include a range of policy decisions as input, add uncertainty/variability to the hydrogen market potential numbers, and analyze nearer-term projects.

Safety, Codes and Standards

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
SCS-001	National Codes and Standards Deployment and Outreach *Carl Rivkin; National Renewable Energy Laboratory*	3.3	X			Reviewers were supportive of the approach, scope, collaborations, and design of this project and noted the excellent accomplishments achieved in outreach. However, reviewers would like to see clearer accomplishments and progress related to codes and standards development. Overall, reviewers were supportive of the importance of this work and praised the outreach portion in particular.
SCS-005	Research and Development for Safety, Codes and Standards: Materials and Component Compatibility *Chris San Marchi; Sandia National Laboratories*	3.7	X			Reviewers praised the project's approach, impact, collaborations, and progress toward goals. In particular, the focus on performance-based methods for materials compatibility was deemed useful for fuel cell electric vehicles. Reviewers suggested that additional public documentation of results through the code development and standard development organizations would be beneficial.
SCS-007	Fuel Quality Assurance Research and Development and Impurity Testing in Support of Codes and Standards *Tommy Rockward; Los Alamos National Laboratory*	3.3	X			Reviewers had positive feedback overall, particularly on the importance of developing an in-line fuel quality analyzer and on the progress made so far. They recognized that the membrane hydration challenge is a significant barrier to overcome and encouraged additional collaborations to expand the impact of the project. Suggestions included adding deliverables to ensure that the product is moving toward being commercially available to station developers.
SCS-010	Research and Development for Safety, Codes and Standards: Hydrogen Behavior *Ethan Hecht; Sandia National Laboratories*	3.6	X			Reviewers praised the interconnections between, and importance of, this project and others run by Sandia National Laboratories to advance hydrogen safety. A suggestion was made to consider integrating more tests at the same time to improve project results. Overall, extremely positive feedback was given on the progress and accomplishments of this project.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
SCS-011	Hydrogen Quantitative Risk Assessment *Katrina Groth; Sandia National Laboratories*	3.4	X			Reviewers praised the cross-cutting and unique nature of this project, as well as the many collaborations behind it. There was interest in providing additional details on how the Hydrogen Risk Assessment Model (HyRAM) has affected codes and standards development. Reviewers would like to see future plans include incorporating liquid hydrogen models into the tool.
SCS-019	Hydrogen Safety Panel, Safety Knowledge Tools, and First Responder Training Resources *Nick Barilo; Pacific Northwest National Laboratory*	3.9	NA			Based on the fiscal year (FY) 2018 Budget Request's focus on early-stage applied energy research and development (R&D) activities, no further U.S. Department of Energy (DOE) funding is requested for this project at this time.
SCS-021	National Renewable Energy Laboratory Hydrogen Sensor Testing Laboratory *Bill Buttner; National Renewable Energy Laboratory*	3.4	NA			Based on the FY 2018 Budget Request's focus on early-stage applied energy R&D activities, no further DOE funding is requested for this project at this time.
SCS-022	Fuel Cell & Hydrogen Energy Association Codes and Standards Support *Karen Quackenbush; Fuel Cell & Hydrogen Energy Association*	3.6	NA			Based on the FY 2018 Budget Request's focus on early-stage applied energy R&D activities, no further DOE funding is requested for this project at this time.
SCS-025	Enabling Hydrogen Infrastructure through Science-Based Codes and Standards *Chris LaFleur; Sandia National Laboratories*	3.5	X			Reviewers were supportive of this project's approach, collaborations, and accomplishments, although they recognized a lack of progress made in real-world testing due to factors outside of the project team's control. Reviewers suggested pursuing additional collaborations to help move this forward and to increase overall impact.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
SCS-026	Compatibility of Polymeric Materials Used in the Hydrogen Infrastructure *Kevin Simmons; Pacific Northwest National Laboratory*	3.5	X			Reviewers stressed the importance of this work and praised the planned future work. However, there were some concerns over a lack of explanation for the parameters selected for testing, as well as which stakeholders have been engaged. Reviewers indicated that collaborations should be more clearly presented in the future.
SCS-028	Diode Laser Sensor for Contaminants in Hydrogen Fuel *Mark Paige; Southwest Sciences*	3.4	X			This project was commended for its importance, progress made to date, and focused approach. The reviewers' primary concern was the development of a cost-effective/practical technology for wide-scale adoption. Reviewers also highlighted that additional collaborations with industry will be critical as the project moves forward. This project was funded through prior year funds and will continue to completion.
SCS-029	Electrochemical Hydrogen Contaminant Detection *Trent Molter; Sustainable Innovations*	3.5	X			Reviewers stressed that the project is impressive, both in approach and in progress so far, given that the project commenced this year. This project's significance to the industry's success was also praised. Reviewers suggested that additional collaborators be added as the project progresses and that adding targets for false detection could be beneficial. This project was funded through prior year funds and will continue to completion.
SCS-030	Advancing Fuel Cell Electric Vehicles in San Francisco and Beyond *Jessie Denver; City and County of San Francisco*	3.5	X			Reviewers were highly supportive of the importance of outreach in general and of the approach of this project. They noted that they would like to see results presented at a national conference. Reviewers are also eager for the project to consider additional interaction and collaboration with technical experts, others doing outreach in hydrogen and fuel cells, and industry stakeholders. This project was funded through prior year funds and will continue to completion.

Market Transformation

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
MT-008	Hydrogen Energy Systems as a Grid Management Tool *Mitch Ewan; Hawaii Natural Energy Institute*	3.4	X			Reviewers stated that the strategy for integration of motive power with grid management was excellent. However, they identified some areas that need attention: utility involvement for controller operation and integration with grid operations, and technical and economic investigation for design and/or selection of energy storage with battery, capacitor, or hydrogen production and storage. This project was funded through prior year funds and will continue to completion.
MT-011	Fuel-Cell-Powered Airport Ground Support Equipment Deployment *Jim Petrecky; Plug Power*	3.5	X			Reviewers commented that progress from the bench to prototype and advanced testing is adequate. According to reviewers, the emphasis on drop-in-place technology resolves many of the system design requirements. A strong emphasis on safety was seen as demonstrating recognition of moving emerging technology to the marketplace. Reviewers noted that the length of this project points to a continuing need to reduce the implementation time for this technology's deployment, adding that five years into the project, there should be a complete data collection set and determination of the value proposition. This project was funded through prior year funds and will continue to completion.
MT-013	Maritime Fuel Cell Generator Project *Joe Pratt; Sandia National Laboratories*	2.8	NA			Based on the fiscal year (FY) 2018 Budget Request's focus on early-stage applied energy research and development (R&D) activities, no further U.S. Department of Energy (DOE) funding is requested for this project at this time.
MT-014	Demonstration of Fuel Cell Auxiliary Power Unit to Power Truck Refrigeration Units in Refrigerated Trucks *Kriston Brooks; Pacific Northwest National Laboratory*	3.1	NA			Based on the FY 2018 Budget Request's focus on early-stage applied energy R&D activities, no further DOE funding is requested for this project at this time.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
MT-017	FedEx Express Hydrogen Fuel Cell Extended-Range Battery Electric Vehicles *Imran Ahmed; FedEx Express*	3.3	X			Reviewers stated that this project has realistic operational requirements for daily range, operation duration, and annual performance. One reviewer concern was that the ability to meet safety barriers and challenges is unclear, adding that a safety plan for the project needs to be completed. This project was funded through prior year funds and will continue to completion.
MT-021	Northeast Demonstration and Deployment of FCRx200 *Abas Goodarzi; US Hybrid Corporation*	2.9	X			Reviewers suggested that an economic assessment of this application and establishment of a duty cycle should both happen early in the project. Another comment was that safety planning and a hazard assessment need to be completed with all partners participating before the demonstration phase starts. This project was funded through prior year funds and will continue to completion.

Systems Analysis

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
SA-035	Employment Impacts of Hydrogen and Fuel Cell Technologies *Marianne Mintz; Argonne National Laboratory*	3.5	NA			Based on the fiscal year (FY) 2018 Budget Request's focus on early-stage applied energy research and development (R&D) activities, no further U.S. Department of Energy (DOE) funding is requested for this project at this time.
SA-039	Regional Water Stress Analysis with Hydrogen Production at Scale *Amgad Elgowainy; Argonne National Laboratory*	3.4	X			Reviewers agreed that the project has established a good fundamental understanding of water consumption associated with hydrogen pathways, which is essential for comparing multiple vehicle platforms, fuel pathways, and resource analysis. The work was commended for expanding the capabilities of existing modeling tools and for including county- and regional-level analysis of water consumption and potential for water stress. Suggestions include quantifying the net water impacts of fuel substitution or displacement, providing more context on water usage overall, considering the impacts of varying regional policies or economics affecting water use/cost, and increasing collaboration with/peer review by western state water authorities. Reviewers agreed with continuing the emphasis on completing and expanding regional analysis, especially in areas of the country where water limitations may be an issue.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
SA-044	Cost–Benefit Analysis of Technology Improvement in Light-Duty Fuel Cell Vehicles *Aymeric Rousseau; Argonne National Laboratory*	3.6	X			Reviewers generally agreed that this project is extremely relevant in that it evaluates the value of future early-stage R&D for fuel cell and hydrogen storage technology improvements to consumers, which will help support R&D target-setting and strategic planning. Reviewers praised the use of an established and well-respected modeling tool, and assumptions that enable comparisons across component sizing options and vehicle platforms. Suggestions included adding an industry partner or gathering more outside feedback from industry and conducting analysis to evaluate the impacts of reaching various performance goals on total cost of ownership (e.g., fuel cell efficiency, platinum loading, etc.). Reviewers supported plans to conduct sensitivity analysis on hydrogen cost and to evaluate possible tradeoffs between cost and efficiency.
SA-055	Hydrogen Analysis with the Sandia ParaChoice Model *Rebecca Levinson; Sandia National Laboratories*	3.2	NA			Based on the FY 2018 Budget Request's focus on early-stage applied energy R&D activities, no further DOE funding is requested for this project at this time.
SA-059	Sustainability Analysis: Hydrogen Regional Sustainability *Marc Melaina; National Renewable Energy Laboratory*	3.4	X			Reviewers emphasized the importance of a sustainability analysis tool to support technology evaluation and program decision-making and the broader stakeholder community, including technology developers and end users. The reviewers appreciated the project's efforts to integrate existing datasets and models, noting that this increases the utility and capabilities of models already developed. Recommendations included eliminating duplicative work being done by other projects (e.g., water use analysis and regional hydrogen supply analysis), providing additional clarification of input and output metrics, and engaging a broader audience (through increased industry collaboration and education/outreach). There were also some specific suggestions about the model's assumptions regarding technology selections and hydrogen cost. This work is aligned with H2@ Scale efforts.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
SA-062	Hydrogen Financial Analysis Scenario Tool (H2FAST) Updates with Analysis of 101st Station *Marc Melaina; National Renewable Energy Laboratory*	3.5	NA			Based on the FY 2018 Budget Request's focus on early-stage applied energy R&D activities, no further DOE funding is requested for this project at this time.
SA-063	Regional Supply of Hydrogen *Marc Melaina; National Renewable Energy Laboratory*	3.3	NA			Based on the FY 2018 Budget Request's focus on early-stage applied energy R&D activities, no further DOE funding is requested for this project at this time.
SA-064	Greenhouse Gas Emissions and Petroleum Use Reduction of Medium- and Heavy-Duty Trucks *Amgad Elgowainy; Argonne National Laboratory*	3.5	NA			Based on the FY 2018 Budget Request's focus on early-stage applied energy R&D activities, no further DOE funding is requested for this project at this time.
SA-065	Agent-Based Modeling of Consumer Behavior *Marianne Mintz; Argonne National Laboratory*	3.2	NA			Based on the FY 2018 Budget Request's focus on early-stage applied energy R&D activities, no further DOE funding is requested for this project at this time.
SA-066	Life-Cycle Analysis of Air Pollutant Emissions for Refinery and Hydrogen Production from Steam Methane Reforming *Amgad Elgowainy; Argonne National Laboratory*	3.5	NA			Based on the FY 2018 Budget Request's focus on early-stage applied energy R&D activities, no further DOE funding is requested for this project at this time.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
SA-067	Resource Availability for Hydrogen Production *Marc Melaina; National Renewable Energy Laboratory*	3.4	X			Reviewers noted that the project's approach is technically strong and thorough and properly integrates new efforts with existing models and data. There was consensus that updated estimates of regional hydrogen production potential are needed, given the availability of new resource data and technology improvements. Reviewers commended the plans to integrate the results into tools such as the Hydrogen Demand and Resource Analysis tool (HyDRA) and the Scenario Evaluation, Regionalization and Analysis model (SERA), which can be used to understand how supply chains may develop in different regions. Suggestions included adding uncertainty analysis for resource potential and production efficiencies; conducting analysis of relative cost, land use, and carbon dioxide emissions of various options; and increasing industry collaboration to vet key assumptions (such as hydrogen production efficiencies and ranges) and increase industry uptake and use of the results.
SA-068	Benefit Analysis of Multi-Fuel/Vehicle Platforms with a Focus on Hydrogen Fuel Cell Electric Vehicles *Tom Stephens; Argonne National Laboratory*	3.1	X			Reviewers observed that the project's approach is good and uses well-regarded, industry-vetted models to generate results. They recognized the importance of estimating the benefits of DOE R&D but questioned the attribution of benefits to federal programs vs. industry (and others). Reviewers suggested that the model use an estimated market price of hydrogen, as opposed to the Hydrogen Analysis model (H2A)-calculated production cost, and criticized the five-year ownership period as being too short. Other suggestions included quantifying air pollutant reductions; adding medium- and heavy-duty trucks; conducting sensitivity analysis around vehicle ownership, vehicle resale value, and discount rate; evaluating the effects of different policy drivers; and increasing industry review and vetting of the work, possibly by adding an industry advisory or steering committee.

Table of Contents

Introduction

The fiscal year (FY) 2017 U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program (the Program) Annual Merit Review and Peer Evaluation Meeting (AMR), in conjunction with DOE's Vehicle Technologies Office Annual Merit Review, was held June 5–9, 2017, at the Washington Marriott Wardman Park Hotel in Washington, DC. This report is a summary of comments by AMR peer reviewers about the hydrogen and fuel cell projects funded by DOE's Office of Energy Efficiency and Renewable Energy (EERE). Projects supported by other DOE offices (including the Office of Science [Basic Energy Sciences] and Advanced Research Projects Agency – Energy [ARPA-E]) in areas relevant to hydrogen and fuel cells were also presented at the FY 2017 AMR. DOE uses the results of this merit review and peer evaluation, along with additional review processes, to make funding decisions for upcoming fiscal years and help guide ongoing performance improvements to existing projects.

The objectives of this meeting include the following:

- Review and evaluate FY 2017 accomplishments and FY 2018 plans for DOE laboratory programs; industry/university cooperative agreements; and related research, development, and demonstration (RD&D) efforts.
- Provide an opportunity for stakeholders and participants (e.g., fuel cell and hydrogen system manufacturers, component developers, and others) to provide input to help shape the DOE-sponsored RD&D program in order to address the highest-priority technical barriers and facilitate technology transfer.
- Foster interactions among the national laboratories, industry, and universities conducting RD&D.

The peer review process followed the guidelines in the *Peer Review Guide* developed by EERE. The peer review panel members, listed in Table 1, provided comments about the projects presented. Panel members included experts from a variety of backgrounds related to hydrogen and fuel cells, and they represented national laboratories; universities; various government agencies; and manufacturers of hydrogen production, storage, delivery, and fuel cell technologies. Each reviewer was screened for conflicts of interest as prescribed by the *Peer Review Guide*. A complete list of the meeting participants is presented as Appendix A.

Table 1: Peer Review Panel Members

No.	Name	Organization
1	Abdel-Baset, Tarek	Fiat Chrysler Automobiles
2	Aceves, Salvador	Lawrence Livermore National Laboratory
3	Advani, Suresh	University of Delaware
4	Adzic, Radoslav	Brookhaven National Laboratory
5	Afzal, Kareem	PDC Machines, Inc.
6	Ahluwalia, Rajesh	Argonne National Laboratory
7	Ahn, Channing	California Institute of Technology
8	Albertus, Paul	ARPA-E
9	Allendorf, Mark	Sandia National Laboratories
10	Anton, Donald	Savannah River National Laboratory
11	Antoni, Laurent	Commissariat à l'énergie atomique et aux énergies alternatives (CEA)
12	Ardo, Shane	University of California, Irvine
13	Atanasiu, Mirela	Fuel Cells and Hydrogen Joint Undertaking (FCH JU)
14	Autrey, Tom	Pacific Northwest National Laboratory
15	Ayers, Katherine	Proton OnSite
16	Balbuena, Perla	Texas A&M University
17	Balema, Viktor	NASA Ames
18	Barilo, Nick	Pacific Northwest National Laboratory
19	Baronas, Jean	California Energy Commission
20	Baturina, Olga	U.S. Navy, Naval Research Laboratory
21	Benjamin, Thomas	Argonne National Laboratory
22	Biebuyck, Bart	Fuel Cells and Hydrogen Joint Undertaking (FCH JU)
23	Borup, Rodney	Los Alamos National Laboratory

No.	Name	Organization
24	Botta Reis, Livia Silva	Ergostech Renewal Energy Solutions
25	Bouwkamp, Nico	California Fuel Cell Partnership
26	Bouwman, Peter	Nedstack
27	Bouza, Antonio	U.S. Department of Energy
28	Bowden, Mark	Pacific Northwest National Laboratory
29	Bowman, Robert	Oak Ridge National Laboratory (Retired)
30	Boyd, Robert	Boyd Hydrogen LLC
31	Brinkman, Kyle	Clemson University
32	Brooks, Kriston	Pacific Northwest National Laboratory
33	Brouwer, Jack	University of California, Irvine
34	Brown, Craig	National Institute of Standards and Technology
35	Burgunder, Albert	Praxair, Inc.
36	Butsch, Hanno	NOW GmbH
37	Calabrese Barton, Scott	Michigan State University
38	Camiloti, Priscilla Rosseto	Ergostech Renewal Energy Solutions
39	Chapman, Bryan	Exxon Mobil Corporation
40	Chen, Shuo	University of Houston
41	Choudhury, Biswajit	DuPont
42	Collins, William	Consultant
43	Cornelius, Chris	University of Nebraska
44	Creager, Stephen	Clemson University
45	Cullen, David	Oak Ridge National Laboratory
46	Curry-Nkansah, Maria	Argonne National Laboratory
47	Danilovic, Nemanja	Lawrence Berkeley National Laboratory
48	Daum, Johannes	NOW GmBH
49	De Castro, Emory	Advent Technologies, Inc.
50	DeSantis, Daniel	Strategic Analysis, Inc.
51	Dillich, Sara	U.S. Department of Energy
52	Dobbins, Tabbetha	Rowan University
53	Dornheim, Martin	Helmholtz-Zentrum Geesthacht
54	Edwards, David	Air Liquide
55	Elrick, William	California Fuel Cell Partnership
56	Esposito, Dan	Columbia University
57	Farese, David	Air Products and Chemicals, Inc.
58	Funk, Stuart	LMI
59	Ganesan, Prabhu	Savannah River Consulting, LLC
60	Gardiner, Monterey	BMW Group
61	Garzon, Fernando	University of New Mexico
62	Ge, Qingfeng	Southern Illinois University
63	Gennett, Thomas	National Renewable Energy Laboratory
64	Gervasio, Don	University of Arizona
65	Graetz, Jason	HRL Laboratories
66	Grassilli, Leo	Consultant
67	Gross, Tom	Energy Planning and Solutions
68	Grot, Stephen	Ion Power
69	Hamdan, Monjid	Giner, Inc.
70	Hamilton, Jennifer	California Fuel Cell Partnership
71	Hanlin, Jason	Center for Transportation and the Environment (CTE)
72	Harris, Aaron	Air Liquide
73	Harrison, Kevin	National Renewable Energy Laboratory
74	Hartman, Brent	CSA Group
75	Hatzell, Kelsey	Vanderbilt University

No.	Name	Organization
76	Haug, Andrew	3M
77	Hays, Charles	Texas A&M University
78	Hennessey, Barbara	U.S. Department of Transportation
79	Herring, Andy	Colorado School of Mines
80	Hirano, Shinichi	Ford Motor Company
81	Holladay, Jamie	Pacific Northwest National Laboratory
82	Hovanski, Yuri	Brigham Young University
83	Hurst, Katherine	National Renewable Energy Laboratory
84	Ilevbare, Gabriel	Idaho National Laboratory
85	Irwin, Levi	U.S. Department of Energy
86	Jakupca, Ian J.	NASA
87	James, Brian	Strategic Analysis, Inc.
88	Jensen, Craig	University of Hawaii, Honolulu
89	Jerram, Lisa	Navigant
90	Kasab, John	AVL Powertrain Engineering, Inc.
91	Keller, Jay	Consultant
92	Kent, Ron	Southern California Gas Company
93	Kim, Sangil	University of Illinois, Chicago
94	Kim, Yu Seung	Los Alamos National Laboratory
95	Knights, Shanna	Ballard Power Systems
96	Kocha, Shyam	National Renewable Energy Laboratory
97	Kongkanand, Anusorn	General Motors
98	Kopasz, John	Argonne National Laboratory
99	Kraigsley, Alison	National Institutes of Health
100	Kuppa, Shashi	U.S. Department of Transportation
101	Lakshmanan, Balasubrumanian	General Motors
102	Linkous, Clovis	Youngstown State University
103	Lipp, Ludwig	eT2M
104	Liu, Di-Jia	Argonne National Laboratory
105	Maes, Miguel	NASA
106	Marenco, Claudia	Fuel Cells and Hydrogen Joint Undertaking (FCH JU)
107	Maric, Radenka	University of Connecticut
108	Markovic, Nenad	Argonne National Laboratory
109	Martinez, Andrew	California Air Resources Board
110	Marxen, Sara	CSA Group
111	Masten, David	General Motors
112	Matter, Paul	PH Matter
113	McKeown, Kyle	Linde
114	McWhorter, Scott	Savannah River National Laboratory
115	Meeks, Noah	Southern Company
116	Melaina, Marc	National Renewable Energy Laboratory
117	Minh, Nguyen	University of California, San Diego
118	Mittelsteadt, Cortney	Giner, Inc.
119	Moretto, Pietro	European Commission, Joint Research Centre
120	Motyka, Ted	Greenway Energy
121	Moulthrop, Larry	H2@LMDesk (dba name)
122	Mukerjee, Sanjeev	Northeastern University
123	Mukundan, Rangachary	Los Alamos National Laboratory
124	Myers, Deborah	Argonne National Laboratory
125	Nguyen, Nha	U.S. Department of Transportation
126	Nguyen, Tien	Independent
127	Oesterreich, Bob	Air Liquide

No.	Name	Organization
128	Ohma, Atsushi	Nissan Motor Co., Ltd.
129	Olson, Gregory	Consultant
130	Ott, Kevin	Los Alamos National Laboratory
131	Paczkowski, Benjamin	U.S. Army Tank Automotive Research Development and Engineering Center (TARDEC)
132	Parilla, Phil	National Renewable Energy Laboratory
133	Parks, George	FuelScience, LLC
134	Patel, Pinakin	Fuel Cell Energy, Inc.
135	Penev, Michael	National Renewable Energy Laboratory
136	Perry, Mike	United Technologies Research Center
137	Petitpas, Guillaume	Lawrence Livermore National Laboratory
138	Petri, Randy	Fuel Cell Energy, Inc.
139	Pintauro, Peter	Vanderbilt University
140	Pivovar, Bryan	National Renewable Energy Laboratory
141	Prasad, Ajay	University of Delaware
142	Quackenbush, Karen	Fuel Cell & Hydrogen Energy Association (FCHEA)
143	Ramsden, Todd	National Renewable Energy Laboratory
144	Renner, Julie	Case Western Reserve University
145	Rice, Brian	University of Dayton Research Institute
146	Rinebold, Joel	Connecticut Center for Advanced Technology, Inc.
147	Rohatgi, Aashish	Pacific Northwest National Laboratory
148	Rufael, Tecle	Chevron Corporation
149	Semelsberger, Troy	Los Alamos National Laboratory
150	Serre-Combe, Pierre	Commissariat à l'énergie atomique et aux énergies alternatives (CEA)
151	Siegel, Donald	University of Michigan, Ann Arbor
152	Simmons, Kevin	Pacific Northwest National Laboratory
153	Smart, John	Idaho National Laboratory
154	Snyder, Joshua	Drexel University
155	Sofronis, Petros	University of Illinois, Urbana-Champaign
156	Soto, Herie	Shell Oil Company
157	Spendelow, Jacob	Los Alamos National Laboratory
158	Stamenkovic, Vojislav	Argonne National Laboratory
159	Stavila, Vitalie	Sandia National Laboratories
160	Steinbach, Andy	3M
161	Steiner, Nadia	Université de Franche-Comté
162	Stottler, Gary	General Motors
163	Studer, Sarah	U.S. Department of Energy
164	Sutherland, Ian	General Motors
165	Swartz, Scott	NexTech Materials LTD
166	Swider-Lyons, Karen	U.S. Navy, Naval Research Laboratory
167	Tchouvelev, Andrei	A.V. Tchouvelev & Associates Inc.
168	Tisack, Monica	University of Southern Mississippi
169	Tong, Jianhua (Joshua)	Clemson University
170	Toughiry, Mark	U.S. Department of Transportation
171	Trocciola, John	SRA International, Inc.
172	Udovic, Terry	National Institute of Standards and Technology
173	Ulsh, Michael	National Renewable Energy Laboratory
174	Vacin, Gia Brazil	California Governor's Office of Business and Economic Development
175	Vanderborgh, Nicholas	Los Alamos National Laboratory
176	Veenstra, Mike	Ford Motor Company

No.	Name	Organization
177	Verduzco, Laura	Chevron Corporation
178	Wachsman, Eric	University of Maryland
179	Wagner, Frederick T.	Retired
180	Walchuk, George	Exxon Mobil Corporation
181	Waldecker, James	Ford Motor Company
182	Warren, C. David	Oak Ridge National Laboratory
183	Weber, Adam	Lawrence Berkeley National Laboratory
184	Wheeler, Douglas	DJW Technology, LLC
185	Williams, Mark	National Energy Technology Laboratory
186	Woods, Stephen	NASA
187	Xie, Jian	Indiana University–Purdue University Indianapolis
188	Xu, Hui	Giner, Inc.
189	Xu, Ye	Louisiana State University
190	Xue, Jisan	National Highway Traffic Safety Administration/ U.S. Department of Transportation
191	Yan, Yushan	University of Delaware
192	Yandrasits, Michael	3M
193	Zelenay, Piotr	Los Alamos National Laboratory

Summary of Peer Review Panel's Crosscutting Comments and Recommendations

AMR panel members provided comments and recommendations regarding selected DOE hydrogen and fuel cell projects, overall management of the Hydrogen and Fuel Cells Program, and the AMR peer evaluation process. The project comments, recommendations, and scores are provided in the following sections of this report, grouped by sub-program. Comments about sub-program management are provided in Appendix B.

Analysis Methodology

A total of **141** Fuel Cell Technologies Office (FCTO) projects were reviewed at the meeting. As shown in Table 1, **193** review panel members participated in the AMR process, providing a total of **848** project evaluations. These reviewers were asked to provide numeric scores (on a scale of 1–4, including half-point intervals, with 4 being the highest) for five aspects of the work presented. Sample evaluation forms are provided in Appendix C. Scores and comments were submitted using laptops (provided on-site) to a private online database, allowing for real-time tracking of the review process. A list of projects that were presented at the AMR but not reviewed is provided in Appendix D.

For the Hydrogen Production and Delivery; Hydrogen Storage; Fuel Cells; Manufacturing R&D; Safety, Codes and Standards; and Systems Analysis sub-programs, scores were based on the following five criteria and weights:

Score 1: Approach to performing the work (20%)
Score 2: Accomplishments and progress toward overall project and DOE goals (45%)
Score 3: Collaboration and coordination with other institutions (10%)
Score 4: Relevance/potential impact on DOE Program goals and RD&D objectives (15%)
Score 5: Proposed future work (10%)

For each project, individual reviewer scores for each of the five criteria were weighted using the formula in the box below to create a final score for each reviewer for that project. The average score for each project was then calculated by averaging the final scores for individual reviewers. The individual reviewer scores for each question were also averaged to provide information on the project's question-by-question scoring. In this manner, a project's final overall score can be meaningfully compared to that of another project.

Final Overall Score = [Score 1 x 0.20] + [Score 2 x 0.45] + [Score 3 x 0.10] + [Score 4 x 0.15] + [Score 5 x 0.10]

A perfect overall score of "4" indicates that a project satisfied the five criteria to the fullest possible extent; the lowest possible overall score of "1" indicates that a project did not satisfactorily meet any of the requirements of the five criteria.

For the Market Transformation and Technology Validation sub-programs, scores were based on the following five criteria and weights:

Score 1: Relevance/potential impact on DOE Program goals and RD&D objectives (15%)
Score 2: Strategy for technical validation and/or deployment (20%)
Score 3: Accomplishments and progress toward overall project and DOE goals (45%)
Score 4: Collaboration and coordination with other institutions (10%)
Score 5: Proposed future work (10%)

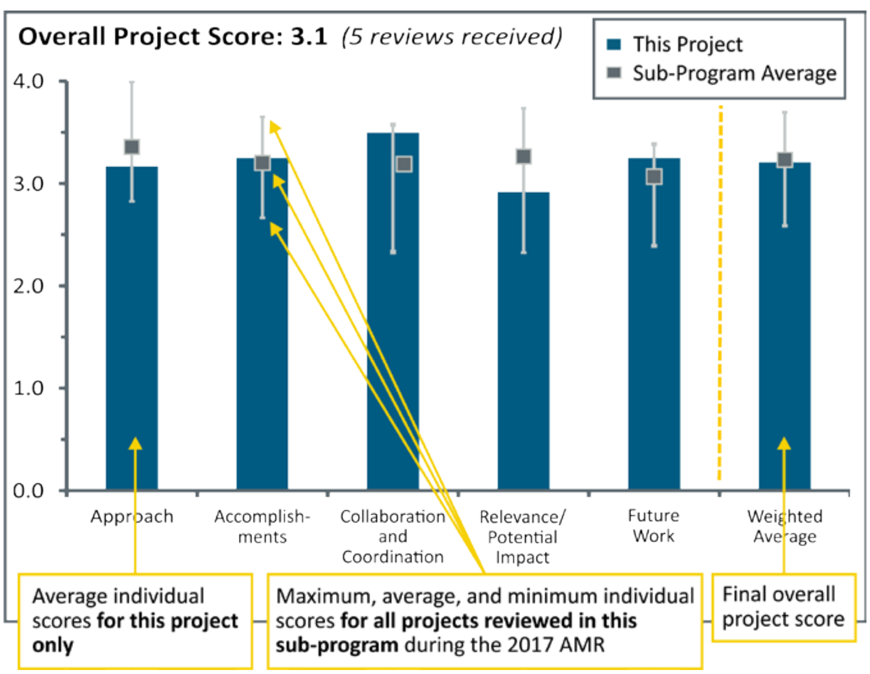
For all sub-programs, reviewers were also asked to provide qualitative comments regarding the five criteria, specific strengths and weaknesses of the project, and any recommendations relating to the work scope. These comments were also entered into the private online database for easy retrieval and analysis.

Organization of the Report

The project comments and scores are grouped by sub-program (Hydrogen Production and Delivery; Hydrogen Storage; Fuel Cells; Manufacturing R&D; Technology Validation; Safety, Codes and Standards; Market Transformation; and Systems Analysis) in order to align with FCTO's planning scheme. Each of these sections begins with a brief description of the general type of research and development or other activity being conducted. Next are the results of the reviews of each project presented at the 2017 AMR. The report also includes a summary of the qualitative comments for each project, as well as a graph showing the overall project score and a comparison of how each project aligns with all of the other projects in its sub-program. A sample graph is provided in Figure 1.

Projects are compared based on a consistent set of criteria. Each project report includes a chart with bars representing that project's average scores for each of the five designated criteria. The gray vertical hash marks that overlay the blue bars represent the corresponding maximum, average, and minimum scores for all of the projects in the same sub-program.

Figure 1: Sample Project Score Graph with Explanation



For clarification, consider a hypothetical review in which only five projects were presented and reviewed in a sub-program. Table 2 displays the average scores for each project according to the five rated criteria.

Table 2: Sample Project Scores

	Approach (20%)	Accomplishments (45%)	Collaboration and Coordination (10%)	Relevance/ Potential Impact (15%)	Future Work (10%)
Project A	3.4	3.3	3.3	3.2	3.1
Project B	3.1	2.8	2.7	2.7	2.9
Project C	3.0	2.6	2.7	2.8	2.9
Project D	3.4	3.5	3.4	3.2	3.3
Project E	3.6	3.7	3.5	3.4	3.4
Maximum	3.6	3.7	3.5	3.4	3.4
Average	3.3	3.2	3.1	3.0	3.1
Minimum	3.0	2.6	2.7	2.7	2.9

Using this data, the chart for Project A would contain five bars representing the values listed for that project in Table 2. A gray hash mark indicating the related maximum, average, and minimum values for all of the projects in Project A's sub-program (the last three lines in Table 2) would overlay each corresponding bar to facilitate comparison. In addition, each project's criteria scores would be weighted and combined to produce a final, overall project score that would permit meaningful comparisons to other projects. Below is a sample calculation for the Project A weighted score.

Final Score for Project A = [3.4 x 0.20] + [3.3 x 0.45] + [3.3 x 0.10] + [3.2 x 0.15] + [3.1 x 0.10] = 3.3

2017 – Hydrogen Production and Delivery
Summary of Annual Merit Review of the Hydrogen Production and Delivery Sub-Program

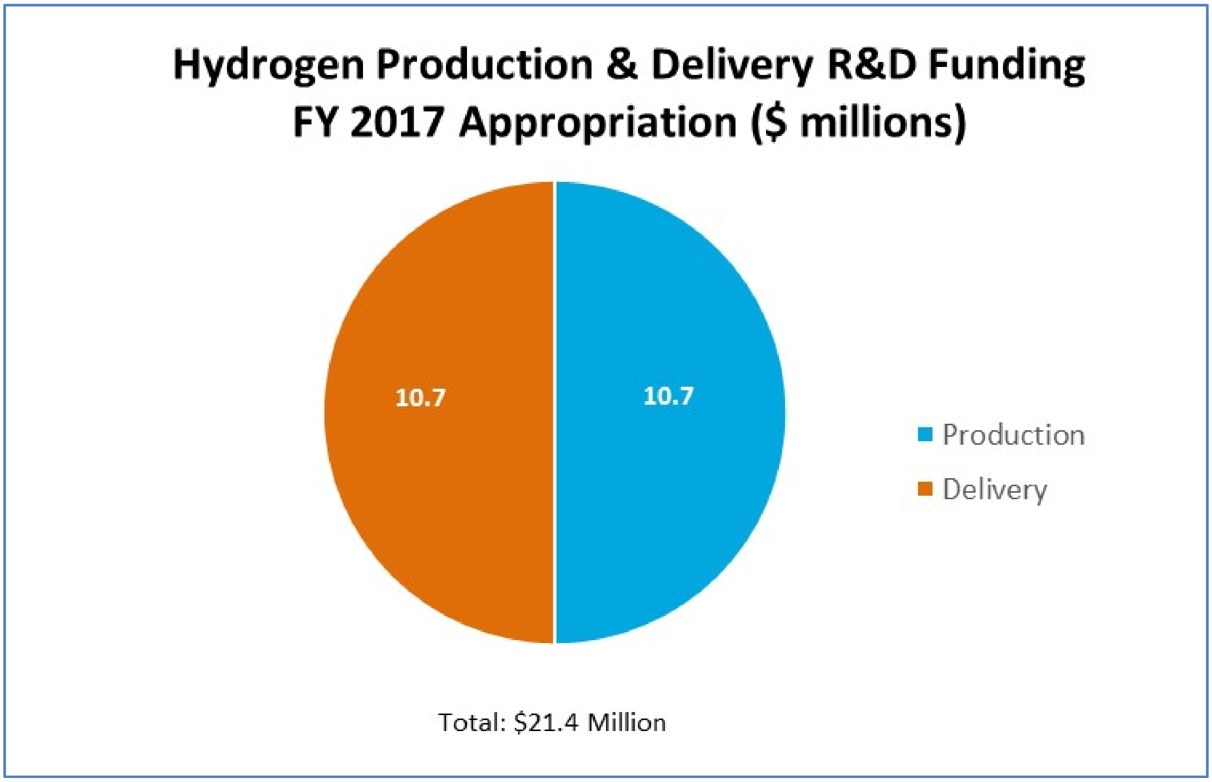
Summary of Reviewer Comments on the Hydrogen Production and Delivery Sub-Program:

The Hydrogen Production and Delivery sub-program includes a broad portfolio of technologies to produce and deliver hydrogen from diverse domestic energy resources. Production project sub-categories in 2017 included thermal and bio-fermentative conversion of hydrocarbon-based feedstocks, advanced high- and low-temperature electrochemical water splitting, direct solar thermochemical (STCH) and photoelectrochemical (PEC) water splitting, and hydrogen production pathway analysis. Hydrogen delivery projects focused on research and development (R&D) to lower the cost and enhance the reliability of technologies that deliver hydrogen to end users (liquefaction, pipelines, and tube trailers), technologies at hydrogen fueling stations (compression, storage, and dispensing) for vehicles, and technoeconomic analyses of delivery pathways.

The reviewers recognized the Hydrogen Production and Delivery sub-program as comprehensive, well balanced, effective, and well managed, with a clear strategy to achieve DOE goals and objectives. Reviewers commented positively on the relevance of the foundational research portfolio to the broader H2@ Scale initiative, and on the overarching technoeconomic framework guiding R&D priorities. They also were impressed with specific project highlights and accomplishments. The reviewers commended the sub-program's effective leveraging of cross-office and cross-agency resources (e.g., synergistic research with the DOE Office of Science and with the National Science Foundation) and strongly recommended continued expansion of such activities. The sub-program was encouraged to maintain a robust foundational research portfolio supporting important hydrogen delivery and dispensing needs to encourage early markets, as well as the needs for developing a sustainable portfolio of hydrogen production options leveraging diverse domestic resources.

Hydrogen Production and Delivery Funding:

The fiscal year 2017 appropriation for the Hydrogen Production and Delivery sub-program totaled $21.4 million. This funding was used to support foundational R&D needs identified through the H2@ Scale initiative, including early-stage R&D through the HydroGEN Advanced Water Splitting Materials Consortium and R&D to utilize advanced materials in lowering the costs of hydrogen delivery and dispensing (e.g., non-mechanical liquefaction using magnetocaloric materials, non-mechanical compression using metal hydride materials, and enhanced durability of steels using novel microstructures). The sub-program continues to emphasize leveraging of cross-program, cross-office, and cross-agency R&D opportunities and resources. The total active Hydrogen Production and Delivery R&D portfolio, including funding opportunities and laboratory call projects and joint projects with the National Science Foundation and Small Business Innovation Research program, comprises technoeconomic analysis, hydrogen materials compatibility, advanced water splitting, novel hydrocarbon reforming, non-mechanical compression, novel liquefaction, and next-generation station design. Future work is expected to continue focusing on foundational, early-stage research needs identified through the H2@ Scale initiative and the hydrogen production and delivery stakeholder communities.



Reviewer Comments and Recommendations:

Twenty-nine projects were reviewed, receiving scores ranging from 2.9 to 3.7, with an average score of 3.3. The scores indicate technical progress made over the past year across the hydrogen production and delivery R&D portfolio.

Production Projects

Hydrogen Production Pathway Analysis: One project was reviewed in the area of hydrogen production pathway analysis. The project received a score of 3.4. There was reviewer consensus that the technoeconomic analyses performed are important to DOE objectives, particularly the identification of the long-term potential and bottlenecks of production and delivery pathways. Reviewers noted that the project has exhibited strong collaboration with DOE, industry stakeholders, and technology providers. Reviewers recommended that the key assumptions and sensitivities used in the analyses should be more transparent.

Advanced Electrochemical Water Splitting: Four projects in the area of hydrogen production from advanced electrochemical water splitting were reviewed, receiving an average score of 3.3. Projects included efforts to integrate and test renewable electrolysis systems, develop new high-temperature alkaline electrolysis, decrease the platinum group metal (PGM) loading in alkaline exchange membrane electrolysis cells, and develop solid oxide electrolyzers with a novel cell architecture. Reviewers were supportive of the projects' innovation and progress overall. In particular, integrating renewable electrolysis was praised for its enablement of clear, open, and comprehensive interaction between DOE and industry stakeholders. Reviewers commented that success in these projects offers the potential to achieve significant reduction in the capital cost of electrolyzers, as well as the cost of hydrogen production via high-temperature electrolysis and alkaline-exchange-membrane-based water electrolysis, which is critical for technology introduction on a larger scale. Reviewers suggested that enhanced collaboration would benefit the technical challenges faced by these projects and encouraged a strong emphasis on technoeconomic analyses.

Bio-Derived Feedstock Conversion: One project was reviewed in the area of bio-feedstock conversion, with a score of 3.2. Reviewers commended this project for its straightforward approach and innovative design. They noted that the project had missed scheduled project milestones but stated that the project showed reasonable progress in increasing the hydrogen production rate through improvements in both sorbent and catalyst formulations. Reviewers suggested incorporating additional cost data to better evaluate the impact of system optimization on capital cost.

Biological Hydrogen Production: Three projects were reviewed in the area of biological hydrogen production and these received an average score of 3.5. One project is focused on developing direct fermentation technologies to convert renewable lignocellulosic biomass to hydrogen, another on developing cost-efficient advanced synthetic biological generation technologies to produce hydrogen, and the third on developing a hybrid fermentation and microbial electrochemical cell (FMEC) system for hydrogen production using low-cost feedstocks. Reviewers commended all three projects on their accomplishments, progress toward goals, and significance, but they expressed some concern over practicality and ability to meet cost targets. For the direct fermentation and synthetic biosystem projects, reviewers would like to see additional cost analysis and connections to overall cost of hydrogen to better judge feasibility. Reviewers considered the cost analysis a strength for the FMEC project, and they encouraged additional work to address the electrocatalyst stability.

PEC Hydrogen Production: Three PEC projects were reviewed, receiving an average score of 3.3. The projects are investigating new materials and/or reactor designs that can operate at high solar concentration and achieve DOE efficiency goals for hydrogen production via PEC water splitting. Reviewers commended all three projects for their alignment with DOE objectives, innovation, and progress made so far. Specifically, reviewers praised the world record for solar-to-hydrogen conversion efficiency set by one project and highlighted excellent collaborations and synergies in the other two projects. The primary concern reviewers had with these three projects was that the projects might not meet all of their final targets for durability and performance.

STCH Hydrogen Production: Two projects were reviewed in the area of STCH hydrogen production, with an average score of 3.1. Both projects propose using concentrated solar power in a two-step metal oxide cycle for hydrogen production using unique reactor designs. Both projects were praised for their innovative approaches, work accomplished on the reactor designs, and progress toward meeting hydrogen production targets. For both projects, reviewers praised the collaborations, but they felt that the scope was too broad to meet all of the milestones.

Delivery Projects

Hydrogen Delivery Technoeconomic Analyses: Two projects were reviewed in this area, with an average score of 3.3. These projects included an analysis of cost drivers for fueling heavy-duty fuel cell vehicle fleets and a recently started thermodynamic analysis of liquid hydrogen infrastructure, including boil-off losses in liquid delivery infrastructure. Reviewers praised the projects for their approach, scope, accomplishments, and relevance. Recommendations included collaborating more closely with industry partners and similar international efforts, as appropriate.

Hydrogen Delivery Technologies: Two projects were reviewed in the area of hydrogen liquefaction, receiving an average score of 3.3, and one project was reviewed in the area of hydrogen pipelines, receiving a score of 2.9. The pipeline project was praised for its team composition and approach. However, reviewers questioned the delays in project schedule and ability to meet project goals. They recommended more exploration of the fundamental causes of behavior seen in experiments, leveraging industry work and collaborations to ensure relevance, and providing more information on input and contributions of collaborators, particularly the National Institute of Science and Technology. Reviewers praised the liquefaction projects for their innovative approach and progress. Suggestions to both projects included increasing industry collaboration and presenting work in a way that clearly highlights each technology's merits, potential benefits to industry, and roles of partners.

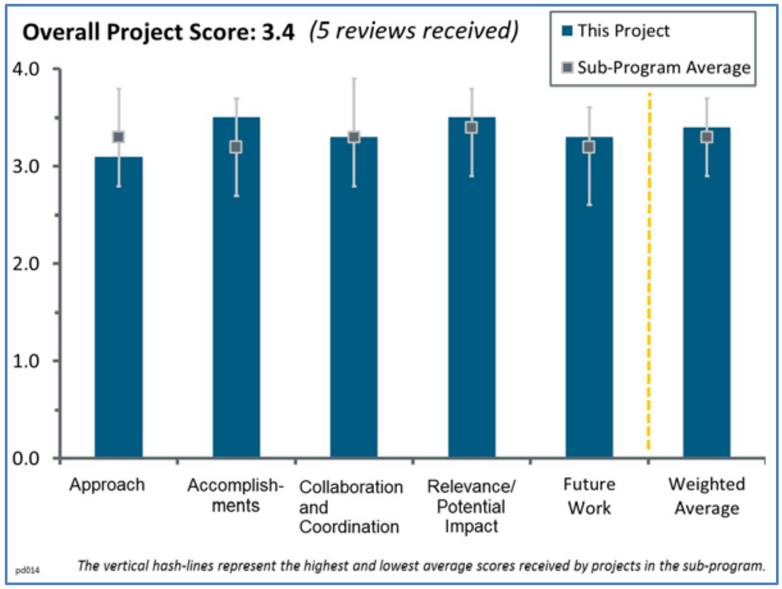
Hydrogen Fueling Station Technologies: Ten projects focused on hydrogen dispensers, compression, storage, and station operation were reviewed. They received an average score of 3.3. The three projects on dispensing hoses were praised for their technical approach, relevance, and accomplishments to date. Reviewers would like to see additional incorporation of real-world variables (such as human interaction with fueling hoses or conditions at fueling stations), exploration of the fundamental causes of material failures, partnering with additional component and/or automotive manufacturers, and collaboration with other researchers doing related research domestically and abroad. Reviewers would also like the projects to communicate results to the stakeholder community (e.g., local governments, code communities). The four compression technology projects were praised for their progress to date, responsiveness to reviewer comments from prior years, and potential to lower station costs and improve reliability. Reviewers suggested technoeconomic analyses to accurately assess potential cost competitiveness of technologies being developed, and better leveraging of prior and ongoing R&D in each area. They also recommended that system-level modeling be conducted to help determine focus areas and that closer attention be paid to the specific points of failure within each technology. The project on composite vessels was praised for its progress and accomplishments. Reviewers questioned the rationale for certain design features and experimentation and recommended validation of the prototype's performance in relevant operating conditions. The two station operation projects included one on station design and one on tube trailer consolidation. Projects were highly commended for relevance to industry stakeholders, potential for lowering station costs, and strong and appropriate collaborations. Reviewers recommended that the projects share results with industry and stakeholders.

Project #PD-014: Hydrogen Refueling Analysis of Heavy-Duty Fuel Cell Vehicle Fleet

Amgad Elgowainy; Argonne National Laboratory

Brief Summary of Project:

This project will assess impacts of delivery and refueling options on the cost of dispensed hydrogen by (1) modeling refueling costs in early fuel cell electric vehicle markets, (2) evaluating the impact of design and economic parameters, (3) identifying cost drivers of current technologies, and (4) developing estimates of delivery and refueling cost reduction with market penetration. The project aims to support existing U.S. Department of Energy-sponsored tools and assist with Fuel Cell Technologies Office (FCTO) planning.



Question 1: Approach to performing the work

This project was rated **3.1** for its approach.

- Given that there are currently no models for medium- and high-duty fuel cell vehicles, it is reasonable to start by building a technoeconomic model from the ground up to figure out the technical/market/economic parameters that influence the industry.
- The model seems to be a very interesting model to address the lack-of-analysis barrier for hydrogen refueling stations (HRSs) to meet large hydrogen consumption requirements, such as those that serve buses. In the model, the hydrogen production cost should be included, as onsite hydrogen production using electrolysis might be cheaper than the transport of a huge volume. If this is not considered, it might lead to conclusions that are not correct, and wrong judgments might be made in terms of what infrastructure governments should support in the future.
- The task appears to have been to generate a cost model for bus-fueling scenarios. The approach is sound.
- The projects aims at the right questions and deals with important issues for hydrogen in heavy-duty fleets and the needed infrastructure. However, further activities regarding bus fleets in Europe, as well as continuous feedback from fleet owners on critical parameters, should be taken into account.
- The Hydrogen Station Cost Optimization and Performance Evaluation (H2SCOPE) model is based on passenger vehicle fuel tanks; the project appears to assume that the transition to heavy-duty bus-size tanks will show the same temperature behavior in-tank.
    - There is very limited data available from heavy-duty bus fueling. This effort should include an effort to retrieve benchmark data from operational bus fleets and verify H2SCOPE applicability.
    - Staggered fueling has an impact on the logistics of transit agencies, dependent on the transit agency. Staggered fueling may require a significant change in transit logistics similar to the change required for charging battery electric buses.
    - The project should consider including the station footprint as a parameter/variable—in most cases, this is even more of an issue than with passenger hydrogen fueling stations integrated at existing gasoline stations.
    - Fill strategy should include a "fill window," which could be an added layer on top of a back-to-back strategy and is likely to define the number of dispensers.
    - For fleets larger than 10 buses (in the context of the next size of bus fleet being 30 buses), tube trailers are less likely to be an option, owing to logistics.
    - The larger the fleet, the narrower the fueling time window for all the buses.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.5** for its accomplishments and progress.

- Using liquid for precooling is cost-effective. Having a tap point partially through the evaporator and a second at the end of the evaporator, with both feeding a mixing valve controlled by the process temperature at the flow meter, should allow uniform precooling through the process, regardless of outside ambient temperature. This is the first modeling of multiple dispensers that the reviewer has seen—a laudable effort. Perhaps optimized multiple dispenser systems will be next.
- The team is well informed of existing refueling guidance and has talked to bus fleet owners to figure out common refueling modes, fleet sizes, and constraints. The current pathways developed seem appropriate. Much has been accomplished since the project started.
- Results are good.
    - The project should consider simulating three to four transit agencies' bus fleet operations, based on when buses return to the bus yard, to add a "one-to-one replacement of diesel/[compressed natural gas] bus fleet logistics with hydrogen" option, which will make this effort much more valuable. The staggered option can be considered only a modeling concept; otherwise, it will affect transit fleet logistics—unless it is staggered in the sense of what would happen if fuel cell buses were used as part of a larger fleet (for example, 30 buses of 100-bus fleet are fuel cell buses).
    - Fill strategy is indicative of station design.
    - Change of transit logistics equals "issues with transit unions." It is unclear how to quantify this (which does not indicate a change in approach, but it may be worth considering what the barriers are).
- In the future, heavy-duty usage of hydrogen will become very important. This study shows the refueling cost differences between various technologies. This understanding is very important for advising FCTO on what kind of infrastructure is needed and requires focus. Also, this study is very important for industry knowledge. In the presentation, the DOE targets were not shown, but DOE has some; in the future, it would be good to integrate those targets in the presentation.
- The project has a good approach to identify critical parameters for future heavy-duty vehicle station design.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.3** for its collaboration and coordination.

- At this point, collaborations seem appropriate. As the models are further developed, these could be shared with fuel cell bus fleet managers such as AC Transit.
- Collaboration with fleet operators exists and should be extended throughout the project run time.
- Collaboration is appropriate for this small task.
- During the presentations, it was mentioned that there are no other studies available in the literature. This is not correct, as a big study in Europe looked at exactly the same thing and finished in March. It would have been logical for the project to examine the European Union project and use the results, if useful. Also, a question was asked about whether the tentative results from the model were cross-checked with the industry, and the answer was very unclear. The industry is not yet deeply involved in this project, and that involvement would be crucial to verifying results.
- The project needs direct involvement of a transit agency as well as a bus manufacturer and/or a company that has designed a compressed hydrogen storage system (CHSS) for buses.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.5** for its relevance/potential impact.

- Medium- and heavy-duty vehicles represent an important segment of the market that is forecasted to grow even larger in terms of contributions to overall greenhouse gas emissions and criteria pollutants. In some cases, because management of these fleets is centralized, it may be feasible to have a dedicated HRS that can serve a number of buses either staggered or back to back. Understanding the economics of this proposition and the technical barriers is key to building a business case.
- The project showed some first results on estimated costs for the various technologies, a great value in reaching DOE targets.
- Understanding the critical parameters in hydrogen supply for heavy-duty vehicles helps to improve this issue and contributes to acceptance and future deployment of infrastructure.
- This appears to be the only directly heavy-duty fueling-infrastructure-related project supported by DOE and state agencies, and while transit buses are fueled every day in the United States, DOE normally funds only medium- and heavy-duty fuel cell vehicle (non-bus) projects.
- This modeling—and more importantly, starting to look at more realistic options based on commercial volumes—is refreshing.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- Proposed future work items are highly appreciated. However, further parameters (e.g., on-site hydrogen production) might be interesting to consider, as would further feedback from operators to better understand critical parameters from an operator perspective.
- Future work involves the cost of liquefied hydrogen (generation, transport and road damage, pollution, and storage) versus gaseous hydrogen from on-site generation (reforming, electrolyzing). This is industrial-gas-supplied versus public-utility-supplied.
- Future work is appropriate, but there are a few more pathways/alternatives that could be incorporated in the assessment, namely:
    - Explore forecourt hydrogen production.
    - Compare results with liquefied natural gas (LNG) switching.
    - Expand assessment to other types of medium and heavy vehicles.
- Consider the non-existence of 70 MPa fast fueling (comparable to 7.2 kg/min for 35 MPa)—45-minute fueling times will not work. Liquid hydrogen boil-off losses should be addressed by industry, not by a DOE-funded project. The project should consider working with Ricardo on a fueling station cost model; Ricardo and team have a well-developed model for hydrogen bus fueling based on industry interaction.
- There was no Gantt chart available, and it seems there are no in-between confirmation points planned, such as cross-checking the results with industry. It is strongly recommended that the project make a clear plan with clear output objectives at certain times and build in some go/no-go judgment points in the planning.

Project strengths:

- This is a very important study for understanding the economics of big HRSs for buses, which is crucial for future rollout of fuel cell and hydrogen technologies. The project looks at various transport technologies and made a model to simulate each technology and change the outcome quickly when market prices are changing for a certain technology.
- The project enters into unexplored territory and makes information available for public review. This is urgently needed for understanding fueling infrastructure requirements for truck applications, and it may contribute to standardization of SAE J2601/2 fueling protocols beyond Technical Information Report levels. J2601/2 does not need to be developed in the same manner as J2601 (for cars), which is prescriptive.

- Strengths include contribution to future station design for the deployment of heavy-duty fuel cell vehicles. Identification of critical parameters for station design can contribute to decision-making for operators.
- Strengths include the start toward high-volume, multiple-nozzle dispensing and the willingness to start to look into Pandora's Box.
- Strengths include strong knowledge of the industry, strong modeling capabilities, and a good business case.

Project weaknesses:

- The project is not checking hydrogen production cost, and this is a serious weakness. For example, on-site hydrogen production by electrolysis could be more interesting economically than transporting the hydrogen on site, as bigger volumes are required. This should be addressed in the model.
- The benchmark of bus CHSS fueling temperature data is missing. There is no direct involvement of a bus manufacturer or bus CHSS supplier such as Agilent, Worthington, or Lincoln.
- Further data sets and results from other bus projects, as well as on-site electrolysis, should be considered.
- Pathways explored are limited.

Recommendations for additions/deletions to project scope:

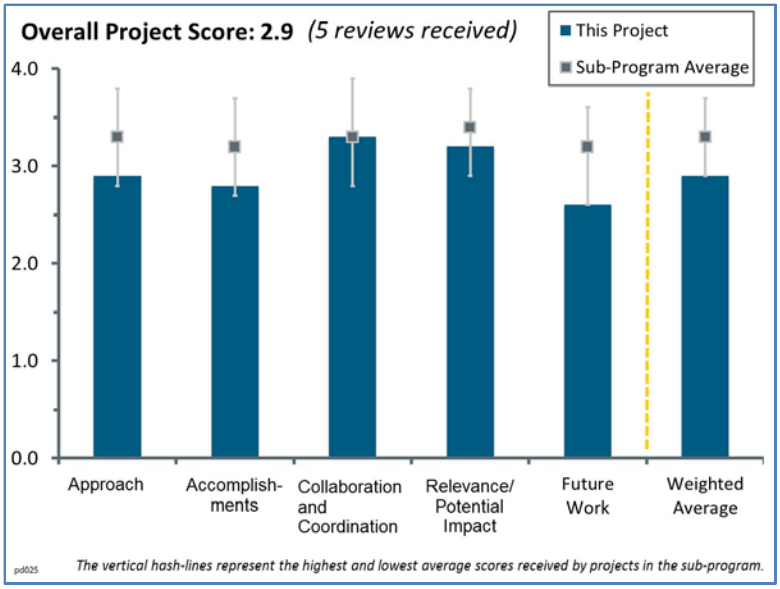
- Further feedback from fleet and station operators is crucial for relevance of parameter weighting.
  Two dispensers for 100 buses is not realistic, not even for diesel or compressed natural gas bus fleets. Take that factor out of the calculations and inquire as to what the number of dispensers is for a 100-bus fleet (conventional fuels). (For context: To fill 100 buses in 8–10 minutes with one dispenser is 800–1000 minutes, or 13–17 hours per day, which would become 6.5–8.5 hours with two dispensers—not considering the impact on logistics.) The project should include 200 bus fleet calculations to increase the value of transferability of project accomplishments to other heavy-duty vehicle applications.
- The project should:
  - Study the European project (www.newbusfuel.eu), which was published in March 2017.
  - Include hydrogen production in the model.
  - Crosscheck the results with industry and determine whether industry agrees with the findings.
- The project should explore forecourt hydrogen production and compare results with LNG switching, and the assessment should be expanded to other types of medium and heavy vehicles.
- Results should be applied to light-duty fleet vehicles.

Project #PD-025: Fatigue Performance of High-Strength Pipeline Steels and Their Welds in Hydrogen Gas Service

Joe Ronevich; Sandia National Laboratories

Brief Summary of Project:

The primary objective of this project is to evaluate the potential for modern, high-strength steels to facilitate reductions in the cost of hydrogen pipelines. Specific goals are to (1) characterize fatigue performance of high-strength girth welds in hydrogen gas and compare performance to low-strength pipe welds, and (2) establish models that predict pipeline behavior as a function of microstructure in hydrogen to inform future development.



Question 1: Approach to performing the work

This project was rated **2.9** for its approach.

- The project determined the fatigue behavior of high-strength pipeline steels in a hydrogen environment and found that the effect of residual stress needs to be considered. This aspect seems important when comparing welds and base metal and is a useful finding of this project. Reference was made to the development of "alternative consumable" filler metal for high-strength steel, but the background, rationale, and approach to developing this alternative filler was unclear. It is surprising that the manufacturer of the pipeline steel is not shouldering the cost of fatigue testing and weld/filler development, as it is the manufacturer's product.
- The approach to performing the work is generally good. Objectives are clear and well-thought-out, and they address a specific challenge. The test(s) chosen will yield results to address the issue, although modifications could be made to these tests to improve them.
- The objectives of the project are to determine whether high-strength girth welds are resistant to hydrogen embrittlement and develop microstructure-based predictive models of hydrogen-accelerated fatigue crack growth. High-strength gird welds are considered for cost reduction. The approach involves (1) use of the Gleeble® approach at Oak Ridge National Laboratory (ORNL) to predict/control weld microstructure, (2) fatigue testing at Sandia National Laboratories (SNL), and (3) model development at the National Institute of Standards and Technology (NIST). The overall goal is to assess the hydrogen embrittlement of X100 microstructure.
- The presentation was well defined and provided relevant testing and results to proof.
- The project timeline shows the project should be half-completed; however, nearly every task is behind in overall completion. This includes the go/no-go gate, which has passed and is projected to be completed more than six months late. The team presented no proposal for getting back on schedule so that the information developed herein can be used to inform future work.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **2.8** for its accomplishments and progress.

- The project has described the importance of residual stresses in influencing the fatigue life. This aspect may have applicability to other lower-strength steels. If so, perhaps the past data on pipeline steel welds need to be re-evaluated.

- The project seems to be currently on track to achieve all the goals set.
- There is no progress at all on the development of controlled microstructure. In fact, the project has not presented any microstructure that the investigators think is going to be hydrogen-resistant (see slide 8). Fatigue testing at SNL, as described in slides 9 through 11, has revealed that X100 base metal performs similarly to the low-strength base metal (a result that was also reported by the investigators last year), but the X100 weld exhibits higher crack growth rates (CGRs). However, the presentation did not clarify the specific aspects of the microstructure that are responsible for fatigue acceleration by hydrogen. For instance, there was no justification as to why the W4 weld, a low-temperature transformation weld (LTTW), is hydrogen-resistant. As for the model development at NIST, slides 16 and 17 present no progress whatsoever. For instance, the investigators did not even discuss how the polygonal or acicular ferrite features are related to embrittlement, which is a very important ingredient in a microstructure-based model, as the project promises on slide 5.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.3** for its collaboration and coordination.

- The project has a good mix of partners, including two national laboratories, a university, and an institute. These are all organizations of high repute. Work seems to have been well coordinated between these partners.
- The presenter from SNL provided evidence of collaboration with NIST and Argonne National Laboratory, which further strengthens the research work.
- The ORNL contributions to the identification of the weld microstructures can be significant. On the other hand, the project did not demonstrate what the NIST contributions are. Looking at the 2016 presentation, one cannot identify what progress has been made on model development in the last two years.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.2** for its relevance/potential impact.

- The usage of higher-strength steel will have a significant impact on the energy cost of storing and transporting hydrogen and other energy products such as compressed natural gas.
- Reducing weld and pipeline cost is an important DOE goal, so the project's objectives are worth pursuing.
- The project goals aligns well with the transportation of hydrogen.
- While the fatigue data on X100 was presented, the presenter did not clarify whether one could conclude whether the X100 pipeline steel (at least from a fatigue perspective) was suitable material for a hydrogen pipeline. Although the project aims to reduce the as-installed cost of pipelines, it is impossible to predict the steel/pipeline industry's pricing models. For example, the industry may decide to charge a premium for X100 steel that may negate lower material cost associated with using less X100 material (i.e., thinner sections). Thus, in that case, DOE's investment in "validating" this steel for hydrogen pipelines will not have the desired impact of lowering the installation cost of pipelines.

Question 5: Proposed future work

This project was rated **2.6** for its proposed future work.

- The presenter provided a clear strategy and short-/long-term planning for this project.
- Proposed future work is reasonable and will assist in meeting additional objectives.
- Regarding the Proposed Future Work slide, second bullet (Fabricate friction stir weld....), friction stir welding (FSW) is already well established as a means to generally produce better welds than fusion welds and, hence, better fatigue life. It would make sense for industry (instead of DOE) to be responsible for development of an FSW process of their products. Regarding Proposed Future Work, third bullet (Develop lab-scale high-strength steel...), there are numerous varieties of commercial high-strength steels with an

equally large variety of microstructures. Thus, the need to develop yet another steel is not clear, and it may be more cost-effective to have the industry pursue it.
- As in the 2016 presentation, it is not yet clear what the significance of the incorporation of the Gleeble approach in the project is. No significant results have been reported on the relationship of the weld microstructure to hydrogen embrittlement. The proposed future work on slide 19 is unfocused; it is designed as if the project has just started. One cannot see a systematic continuation of progress building upon the accomplishments from the last two years.
- The project failed to mention the influence of post-weld heat treatments, which are of much greater importance in high-strength pipeline steels.

Project strengths:

- The team composition is very good. The organization of the work increases the chance of success and places this team in a position to succeed. Goals are clear.
- There are very nice collaborative efforts with project partners. The relationships are clear and provide strength to the overall team.
- The project team has the capabilities to perform the proposed work and has also previously tested a variety of pipeline steels in hydrogen.
- The involvement of SNL and ORNL is a strength.
- This project is very promising in terms of solving the issues related to high-pressure hydrogen storage and transport.

Project weaknesses:

- Lack of prototypical testing is a weakness, as a better understanding of component behavior is usually achieved with well-thought-out prototypical testing. Prototypical testing is usually complicated and subject to misinterpretation if not carefully executed, but these tests yield very powerful results when carefully executed, though they are very expensive to carry out. Perhaps sponsors could consider this for future investigations. Workers may well find that predicted lifetime may change, maybe even improve, with prototypical testing. It is not certain that Gleeble-generated microstructural gradient specimens will be of much use. It might be difficult to correlate microstructure with the growth rates, especially as there may be no clear boundaries between microstructural variations. However, the thinking merits applause. It would be more useful if results could be tied to particular microstructural features such as precipitates or different phases (if they occur). It seems possible that the information already exists in literature. Investigators are encouraged not to dial out the effect of residual stresses in all instances. An attempt should be made to understand the relationship between microstructure, residual stresses, and CGRs. Residual stresses are a fact of life and can usually be linked to microstructure and then to CGR. Besides, pipes in the field will not be perfect; they will have different levels of residual stress and microstructural deformation, which will affect lifetime predictions. It is important to contribute to knowledge in this area.
- Microstructure work at ORNL and testing at SNL are not coordinated yet in a systematic way to reveal potential weld microstructures that are hydrogen-resistant. NIST contributions are not identified.
- The project needs to focus on more collaboration with the steel cylinder manufacturers and the U.S. Department of Transportation to prevent repetition of testing and evaluation.
- The project is behind schedule and is projecting a go/no-go decision six months late. Such gates are meant to be deterministic to evaluate whether the project should move forward; this should not simply be a task that can be pushed back based on changing circumstances.
- The project budget is excessive when compared to other DOE projects of similar scope.

Recommendations for additions/deletions to project scope:

- There is no explanation as to why the X100 base metal behaves similarly to low-strength steel and why the X100 weld does not. The project needs to investigate these features if it aims to develop predictions accounting for microstructural features. It is not clear how nano-indentation will produce any results useful to the J2 theory of plasticity. J2 theory is a homogenized theory with no relationship whatsoever to nanoscale. It is a collective representation of the dislocation and the broader microstructural response.

Lastly, the participation of NIST in the project should be reconsidered, as there are no tangible contributions over the past two years.

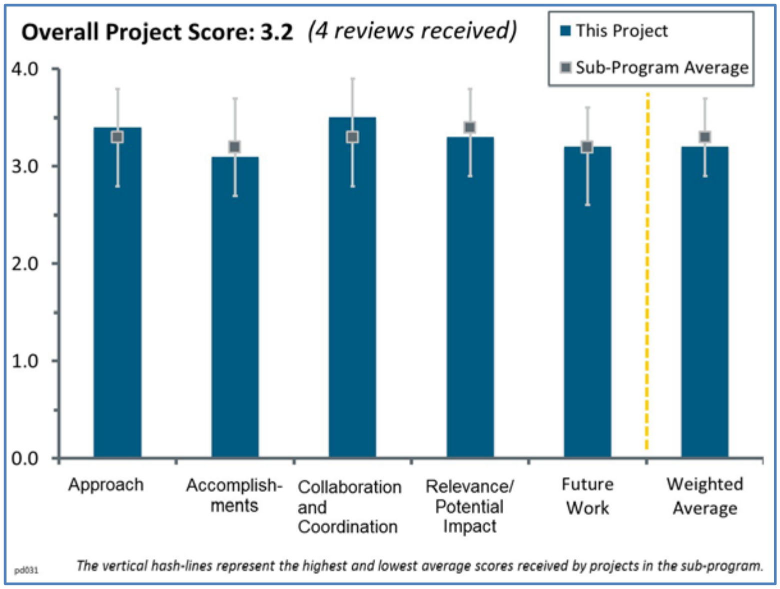
- Regarding model validation, many models fall apart when an attempt is made to use them to interpret data not used in their development. Validation of any predictive model is just as important as generating the model. The project should verify that cracks are compliant in the heat-affected zone (HAZ) measurements. HAZs are very thin, and cracks usually wander outside the zone. Investigators need to verify that what they say they are measuring is what they are actually measuring.
- This project should proceed with direct collaboration with the standards development organization, International Organization for Standardization Technical Committee (ISO/TC) 197, and ISO/TC 58 to get informed about the tremendous amount of work that has been achieved in this area.
- The team should be addressing the influence of post-weld heat treatments on microstructure. This can be addressed both in the weldments produced by ORNL and the Gleeble specimens used to evaluate the microstructure gradients.
- Development of new steel seems unnecessary, considering the large variety of steels commercially available.
- FSW development should be performed by the steel pipeline industry rather than DOE.

Project #PD-031: Renewable Electrolysis Integrated System Development and Testing

Michael Peters; National Renewable Energy Laboratory

Brief Summary of Project:

The objectives of this project are to (1) validate cell, stack, and system electrolyzer performance; (2) explore and optimize electrolyzer system efficiency and performance under varying power operation as well as integration with hydrogen infrastructure components; and (3) track the progress over long-duration testing. These objectives support the goals of integrating electrolyzers with intermittent renewable power sources and increasing the durability of electrolyzer stacks operating under variable loads while maintaining high system efficiency.



Question 1: Approach to performing the work

This project was rated **3.4** for its approach.

- The approach of sustained research on low-temperature electrolyzer deployment issues is commendable. Implementation of real-world systems, at increasing scale, provides much-needed public data sets on hardware performance that should help the community address technical barriers.
- The project is taking an excellent approach by assessing capital costs and improving system efficiencies and renewable system integration, which are essential areas for making renewable electrolysis a pathway for future large-scale hydrogen production.
- This is a well-designed project that addresses and validates U.S. Department of Energy goals and targets related to electrolyzer cost, efficiency, and integration into renewable energy sources. The project encompasses new technology developments in electrolysis stacks and systems over a 14-year period.
- Conducting actual testing of electrolyzer stacks is the highest-confidence pathway to full understanding and verification. The long-term nature of the project (14 years) creates complications, as the technology is constantly advancing and thus the performance of new tech stacks needs to be differentiated from older tech stacks. Investigation of separate research topics/focus areas each year is a good approach.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.1** for its accomplishments and progress.

- As this project is wrapping up, the team highlighted the accomplishments throughout the 14 years of the project duration. These have been excellent, as the team has shown continuous progress against DOE electrolyzer goals. The project has done excellent work by validating small units of 10 kW all the way to the most recent ones of 250 kW, plus looking into improving system efficiencies.
- There has been substantial and commendable progress over the years on a variety of specific performance questions: maximum power point tracking vs. direct coupling, frequency response, and decay rate assessment.
- It is not clear what accomplishments have been made since the last DOE Hydrogen and Fuel Cells Program Annual Merit Review. The score is based primarily on that. However, over its lifetime, the project clearly

has made important contributions in areas of low-temperature electrolysis efficiency, durability, and operational capabilities. Also, the project has supported development of National Renewable Energy Laboratory (NREL) infrastructure and expertise that should pay dividends for years to come.
- The project investigates and reports on the major aspects of electrolysis, including the hydrogen dryer, stack performance degradation/duration, and system efficiency.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.5** for its collaboration and coordination.

- Interactions with U.S. electrolyzer manufacturers (Giner, Proton) and power providers (Xcel, SoCal Gas) have been very worthwhile. Also, involvement in the Hydrogen Fueling Infrastructure Research and Station Technology (H2FIRST) initiative is important to DOE goals. As a final push on the "collaboration with others" front—particularly since the project is ending—a dedicated effort to make as much data available to the public as possible is strongly encouraged. Transfer of knowledge cannot stop at NREL doors. A good example is the best practices and lessons learned regarding balance-of-plant (BOP) maintenance, given the potential for significant adverse impacts on electrolyzer performance.
- The project seems to be linked/collaborating with numerous other DOE-funded efforts. This is commendable. Collaboration with leading electrolyzer industry members through cooperative research and development agreements and technical services agreements is a key enabling arrangement to foster clear, open, and comprehensive interaction.
- Successful collaborations with multiple stack and system manufacturers were key to validation, modeling studies, and suggested improvements to the technology.
- Working along with two excellent electrolyzer providers, Giner and Proton, clearly brings significant value to the success of this project.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.3** for its relevance/potential impact.

- Investigation to discern reality vs. manufacturers' claims is highly relevant. This project directly increases understanding of system operation and performance in real-world environments.
- As more renewable electricity becomes available, there is larger potential for large-scale hydrogen production via electrolysis. This project's relevance clearly supports this pathway.
- Project tasks are aligned with DOE goals, and the data collected enable electrolysis manufacturers to understand where further improvements are needed and can be implemented.
- Relevance of this work is conditional on providing unbiased, unfiltered data to the electrolyzer community. This is because the project is mostly a demonstration, problem-solving, and data-acquisition exercise. Root cause and fundamental analysis are needed to fully exploit the hard work—and that relies on publication of the data in their gory detail.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- The project is ending this year, so there is not much future work left, although the expertise, knowledge, and assets involved on this work will be very valuable for the initiatives around H2@ Scale.
- Technoeconomic analysis of concentrator photovoltaic/polymer electrolyte membrane (CPV/PEM) electrolysis is a good addition to the project. A final project report will be an important contribution.
- The project is nearing the suggested end date. Remaining tasks focus on technoeconomic analysis of CPV and PEM electrolyzers and continued validation of cell voltage monitoring systems developed at NREL.

Project strengths:

- Rigorous, independent assessment of technologies is a project strength. Examination of large format cells is a plus. The project is used as an assessment of technologies, and the results can influence DOE in selection of research and development investments.
- This is a sustained effort, focused on providing robust data on electrolyzer performance and capabilities. Collaboration with equipment providers and potential users is also a project strength.
- The project has good collaboration with electrolyzer manufacturers Giner and Proton. NREL's testbed provides stack and system manufacturers with a means of validating their commercial stacks and BOP components.
- The project has strong technical expertise at NREL, plus the collaboration with top electrolyzer providers.

Project weaknesses:

- There were no specific weaknesses.
- The project should assess sources of power consumption, not just report overall system efficiency/ consumption.
- There is an apparent lack of collaboration with other national laboratories, e.g., for data analysis and modeling.

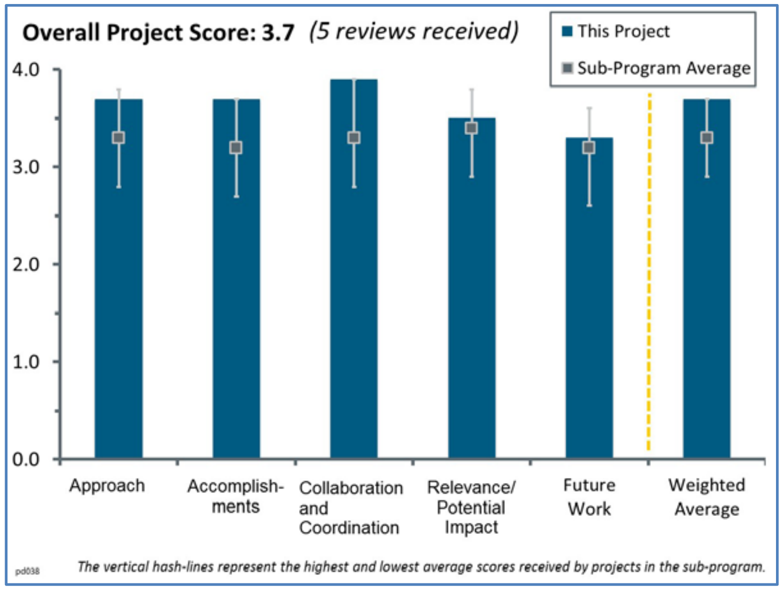
Recommendations for additions/deletions to project scope:

- Continuing this work as part of H2@ Scale is strongly recommended.
- While the project assesses various stacks, etc., it should go one step further and make recommendations as to what combination of technologies forms a pathway to achieving DOE system efficiency goals. A distinction should be made between drier hydrogen losses and drier energy inputs. Both are important. Additionally, the impact of gas pressure on hydrogen losses and drier energy should be explored.
- NREL should plan on the development of new testbeds that address emerging electrolyzer technologies such as anion-exchange membrane, high-temperature alkaline, and solid-oxide. In addition to providing operating and capital expense comparisons, the data would provide insight into the best use or selection of electrolyzer technology in various real-world scenarios.
- The project should publish learnings and make key data available.

Project #PD-038: Biomass to Hydrogen (B2H2)

Pin-Ching Maness; National Renewable Energy Laboratory

Brief Summary of Project:



The objective of this project is to develop direct fermentation technologies to convert renewable lignocellulosic biomass resources to hydrogen. The project addresses technoeconomic feasibility of hydrogen production via biomass fermentation in three tasks. Task 1 optimizes bioreactor performance, focusing on de-acetylated and mechanically refined (DMR) biomass to lower feedstock costs. Task 2 focuses on using ionic liquid pretreatment for biomass processing. Task 3 develops and applies genetic tools to modify metabolic pathways aimed at improving hydrogen molar yield. Task 4 integrates a microbial electrolysis cell (MEC) reactor into the system, producing hydrogen while cleaning the fermentation effluent to improve the overall hydrogen molar yield.

Question 1: Approach to performing the work

This project was rated **3.7** for its approach.

- The approach was direct to overcome the barriers of this project. First of all, the final feedstock cost was reduced by the replacement of expensive ingredients with industrial byproducts as sources of crucial nutrients for bacterial fitness, and the DMR corn stover pretreatment, a less intensive pretreatment, was efficient in releasing fermentable sugars. Second, the study of operational parameters, such as hydraulic retention time and liquid volume replacement, led to the definition of optimal conditions for higher hydrogen yield. In addition, the hydrogen yield was increased by the use of engineered *C. thermocellum*, capable of fermenting C5 and C6 sugars available in the feedstock. Third, the sequential MEC system ensures the overall conversion of biomass feedstock to hydrogen, leading to higher hydrogen yield.
- The project developed by the group is quite complete and well designed. The project contemplates some important points, such as genetic improvement and use of residues. In the case of biohydrogen production, there was concern regarding treatment of the fermentation effluent, which is rich in organic acids and was used for hydrogen production by means of MECs. The group is composed of a team of experts, and they are making progress on the stated goals while also addressing potential barriers and challenges.
- The investigators have a strong approach to addressing their proposed work. It is a good combination of innovative and sequential work. They are showing strong progress in all aspects of the work, including the logical termination of work that is not hitting go/no-go targets. This shows that their approach is actionable.
- The project has identified key barriers including hydrogen rate, final molar yield, feedstock costs, system engineering, and reactor performance, and the project uses multiple approaches to address these issues. Some aspects, such as biomass cost, are outside the scope of the project, but others are being addressed.
- The project approach seems to be well designed for maximizing hydrogen molar yield via genetic engineering. A clear example is the development of a mutant that successfully shut off two of the three competing pathways. Also, the decision to stop the fermentation of pretreated biomass using ionic liquid demonstrated serious discipline. Further progress related to eliminating costly process ingredients appears to be advancing cost reductions, although it is hard to understand how helpful those reductions are to reaching the hydrogen cost target. For next year's review, a more detailed discussion on reducing the cost

barrier would be useful. Further, it would be nice to see the conversion performance of a fully integrated system in which all of the individual components are brought together for process and cost optimization.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.7** for its accomplishments and progress.

- The project has made accomplishments and is progressing in the bioreactor, genetic engineering, and MEC tasks. The ionic liquid task will not be continued, which is reasonable because the poor growth demonstrated would be a significant barrier to progress in that area. All tasks except for the ionic liquid task appear to be meeting their milestones. A particularly interesting accomplishment is the demonstration that an engineered *C. thermocellum* strain can co-utilize both xylose and glucose, and even seems to have a slight preference for xylose. This is unexpected, as bacteria will often preferentially use glucose, in which case long batch periods could be needed to allow the strains to first consume all glucose and then switch to other compounds. The balanced co-utilization will likely make fermentation of the mixed substrates more straightforward and allow for more bioreactor options, while increasing the portion of the biomass feedstock that can be converted to hydrogen.
- The experiments were carried out in a way to directly overcome the barriers and challenges regarding this project, which was hydrogen molar yield, feedstock cost, and system engineering.
    - Hydrogen molar yield: This barrier has been overcome by means of applying a cheap and efficient pretreatment to the lignocellulosic biomass with an increased hydrogen production rate and yield; via genetic engineering of high-rate cellulose degrader *C. thermocellum*, which led to successful hydrogen production results; and by integration with an MEC, with increased hydrogen yield.
    - Feedstock cost: This barrier has been overcome by achieving high-rate hydrogen production from a byproduct, lignocellulosic biomass; cheap and efficient feedstock pretreatment (DMR) with increased DMR loadings; and successful hydrogen production using industrial waste or industrial byproducts as a source of supplementation, replacing expensive ingredients and leading to a growth medium cost reduction of 49%.
    - System engineering: The use of a combined electrochemically assisted microbial fermentation to convert the fermentation byproducts to hydrogen gas greatly increases the overall hydrogen yield from lignocellulosic feedstocks. Achieving a high rate of hydrogen production with a non-Pt-based cathode—stainless steel wool, a cheaper material—is a great milestone for the system engineering performance.
- The principal investigator (PI) presented accomplishments for four task areas and noted good progress in all areas. The research team has produced a high-impact publication in *Proceedings of the National Academy of Sciences*. The PI noted that Task 2 was not hitting the stated milestones, and therefore, Task 2 was terminated. This was a logical action, and it was good to see resources redirected when a project is not hitting project goals. The overall progress on the project is outstanding. Each individual task has made meaningful steps forward, and all of the tasks are synergistic.
- The project seems to be making progress and is meeting milestones. The group has reached the hydrogen production rate target using DMR. The pre-treatment is an important step for project progress. However, the tests with ionic liquid did not see progress owing to the cost of the methodology. Perhaps it would be possible to test other methods of treatment.
- There were not enough data given to determine whether the cost targets can be met.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.9** for its collaboration and coordination.

- The project has multiple collaborators that leverage expertise in different areas, including a long-term partnership with Pennsylvania State University (Penn State) to develop MECs to run on fermentation effluent, recent collaborations with Lawrence Berkeley National Laboratory (LBNL) and Sandia National Laboratories (SNL) to evaluate a different biomass treatment method, and a no-cost collaborator at University of California, Los Angeles (UCLA) involved in the pathway engineering work.

- This project included different approaches to achieve the goals of reducing feedstock cost, optimizing system design and operation, and increasing hydrogen yield. These approaches involved different areas, such as chemistry, process engineering, and molecular biology. Therefore, a high degree of interaction among institutions and researchers was necessary and successfully done. Each laboratory (institution) worked on its specialty to achieve the goals together.
- Collaboration appears to be excellent and includes major research groups. There is great cooperation between the partners, who have a good deal of expertise on this subject.
- The National Renewable Energy Laboratory (NREL) has a number of symbiotic collaborations including those with Penn State, UCLA, and SNL, as well as the attempt to work with LBNL.
- The PI is doing an excellent job of leveraging collaborations and other resources to maximize the impact of this project.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.5** for its relevance/potential impact.

- The PI has presented a logical project to improve and operationalize hydrogen production and MECs. The PI has consistently produced strong results. The relevance of the work to supporting a diverse Hydrogen and Fuel Cells Program is high. This work will likely have a moderate to high impact on the field.
- This project covers the main steps to sustainable hydrogen production from wastes. In addition to hydrogen production from wastes, the project includes steps such as genetic engineering to improve waste utilization by microorganisms and effluent reactor use. The effluent of dark fermentation, which is rich in organic acids, could be used for biogas production or, as in this case, to produce hydrogen using MECs. The design project includes cost reduction in each step, addressing the Multi-Year Research, Development, and Demonstration Plan (MYRDDP).
- Although it will be difficult for the project to meet the 2020 hydrogen cost target, the innovative genetic technology approaches will certainly help to inform other bioreactor projects using lignocellulose. For instance, the elimination of expensive enzyme cocktails and replacement of extract with industrial corn steep liquor are useful discoveries to advancing bioreactor processing in general.
- The project was carried out outstandingly. However, one of the main goals of MYRDDP is to reduce the cost of hydrogen to <$2/gge. Despite the great performance of the *C. thermocellum* mutants for producing hydrogen from hydrolysate, the use of pure culture of bacteria or pure culture of engineered bacteria systems may not be a low-cost process for practical-scale hydrogen production because of contamination issues. Therefore, this approach to increasing hydrogen production may not be the best possibility. The use of sequential fermentation–MEC systems with mixed microbial culture might be preferable for achieving low-cost hydrogen production.
- The project is making progress toward the identified goals and objectives for biological hydrogen production work and has identified additional objectives needed to support the overall goals, such as increasing feedstock loading. To understand the degree of progress, it would be useful to include information about comparable results from past years or the start of the project. For example, the bioreactor performance milestone was clearly met (and slightly exceeded the target), but the progress over past years was not entirely clear.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- The proposed future work goes toward achieving new milestones in increasing hydrogen production yield and efficiency, using complex substrates, and reducing the overall cost of the hydrogen production process. Tasks involve examining new alternative materials and catalysts for the cathode and increasing MEC performance.
- The proposed future work is highly relevant and will provide useful results.
    - Task 1: The optimization of hydrogen production seems reasonable.

  - Task 4: The further improvement and the tests with others materials seem reasonable. Showing the biohydrogen production long-term stability is interesting.
- The work proposed for the next steps will continue to build on the progress of the different tasks. There are several separate lines of ongoing work, and it is not clear when these improvements will be combined and tested or whether there are plans to do so at a certain point in the development process. For example, for fermentation, there are separate lines of work on bioreactor performance optimization, xylose and glucose co-utilization, media cost reductions, and the enzyme mutations; and it is not certain how the different changes will interact—for example, how the mutant hydrogen production will be affected when the strain can utilize xylose and is growing in the lower-cost media. The new proposed life-cycle analysis work with Argonne National Laboratory will provide useful information about the impacts and potential benefits of this pathway, which will help in understanding the relevance and potential impact on the overall DOE goals for hydrogen production.
- The proposed future work is logical and will make progress toward the stated project goals. It would be good to see some additional work to address the long-term stability of the engineering strains. Additionally, it would have been good to see a plan for how funds from Task 2 would be redirected (if applicable).
- In general, the next steps are logical progressions in a particular mutant that can block all three competing pathways. It would have been helpful to have Bruce Logan present to answer questions related to progress with alternative cathode materials along with next steps. It is not clear whether the stainless steel wool is a good enough replacement for Pt/C. The expected stability limitations are also unclear.

Project strengths:

- The NREL work on genetic engineering of *C. thermocellum* has resulted in strong progress in the area of metabolic engineering to improve hydrogen production. The project team is applying this to multiple areas, from addressing sugar metabolism by engineering xylose utilization to addressing redox pathways with the ferredoxin work. The decision to end the work on ionic-liquid-treated biomass in Task 2, based on the poor growth of the *C. thermocellum* in the ionic liquids, will allow the project to focus on more promising directions.
- Covering the main steps for the biohydrogen production, the project has as its main strengths:
  - The search for alternative methods for the pre-treatment of lignocellulosic biomass
  - Cost reduction using wastes
  - Redirection of the metabolic pathways, removing those that compete in hydrogen production
  - Reduction in the amount of precious metals needed
  - Utilization of organic-acid-rich effluent from the fermentative reactor to produce more hydrogen
- This is a strong project with an overall goal of improving direct fermentation technology. The PI consistently produces high-quality work. The four tasks are interrelated but not interdependent, which is an asset. Each task has a measurable goal and specific milestones. Overall, this is an exciting project, and future work is pleasantly anticipated.
- Some of the project strengths are integration among institutions and research groups to achieve the best result for each task, the complete study of main barriers for biological hydrogen production from biomass (biomass pretreatment, system design and operation, and microorganism performance) for low-cost hydrogen production, and the planning to achieve the milestones and targets.
- All of the collaborators seem to be making significant advancements toward the collective whole.

Project weaknesses:

- No significant weaknesses were noted. Additional analysis of engineered strains would strengthen the work.
- Though there has been progress in the bioreactor performance, the noted high variability of performance during use could be a problem when scaling up, both in volume and in feedstock concentration, and make it difficult to identify what issues are due to actual poor performance and what are due to variation. The source of this variation is not clear. For the work on reducing culture media costs, it would be useful to have a comparison of what existing large-scale fermentation systems use.
- The project is well designed, attending to the DOE goals. However, one of the steps of the project is cost reduction of the feedstock, which relies on the use of waste. What is not very clear is how the hydrogen

will be produced by the mutant *C. thermocellum* using wastes. Contamination probably will occur, and the production period will be reduced by the contamination. In this way, a sterilization step probably will be considered, increasing the production costs.

- The only project weakness, but an important feature, is the use of bacteria pure culture to produce hydrogen. Pure culture systems demand higher operational steps and costs in order to prevent system contamination.
- The lack of details related to overall costs of hydrogen is an apparent weakness.

Recommendations for additions/deletions to project scope:

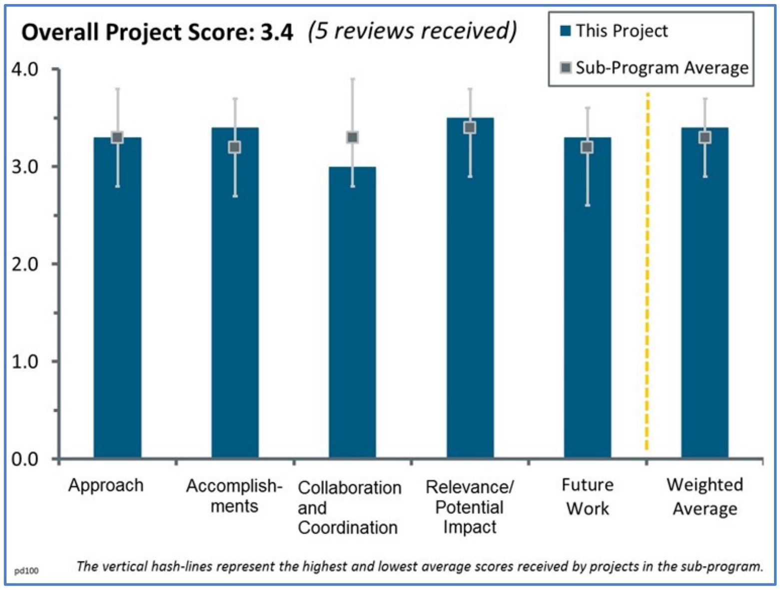
- A strong recommendation for addition to the project scope is to consider the possibility of system contamination by microorganisms present in the feedstock. The project should carry out tests without previous sterilization of the culture growth medium and feedstock to see whether there is any effect on the process performance. Another recommended addition to the project scope is to consider the use of methanogens inhibitors or shock pretreatment to the microbial mixed culture used in MECs to avoid methane production in long-term fermentation.
- Using the fermentation effluent in at least some future MEC experiments would strengthen the connection between the fermentation tasks and the MEC improvement task and provide information on how well the MEC improvements work with actual effluent. While this has been demonstrated in the past, there have been significant changes to both systems, such as the development of a xylose-utilizing strain. Though this was not listed in the slides as future work, it was mentioned in the question-and-answer session.
- Other methodologies of biomass pre-treatment should be included in the project design.
- Cost details should be included in next year’s presentation.

Project #PD-100: 700 bar Hydrogen Dispenser Hose Reliability Improvement

Kevin Harrison; National Renewable Energy Laboratory

Brief Summary of Project:

The objective of this project is to characterize and improve 700 bar refueling hose reliability under fueling conditions expected at heavily utilized hydrogen fueling stations. The National Renewable Energy Laboratory (NREL) designed a test system that subjects refueling hose assemblies to pressure, temperature, mechanical, and time stresses. The high-cycling test reveals the compounding impacts of high-volume 700 bar fuel cell electric vehicle refueling, which has yet to be experienced in today's low-volume market.



Question 1: Approach to performing the work

This project was rated **3.3** for its approach.

- The approach is excellent, with comprehensive validation.
- The approach and amount of funding ($633,500) are commensurate with the importance of this work. The project has been ongoing from 2013 to the present. It would have been preferable for this project to be shared with state and local governments active with hydrogen refueling stations and the proposed metrics with the end-user community (station developers, both large and small and established and new). The approach included metrics to determine leak evaluation and leak locations on the hose. Risk mitigation based on comments from the 2016 Hydrogen and Fuel Cells Program Annual Merit Review looks good. The issue is that the hose passes leak checks, but upon further inspection, leaks were found. Temperature's impact on leaks was evaluated, but it is not apparent that the impacts of novice users (real people) were evaluated. (The speaker explained that for safety reasons, robots were used instead of people.) The project looked at material choices on leaks and permeation. Although 700 bar is used, 350 bar is not, and no reason was given. The approach of using graphics to communicate is very good. Perhaps the user community can be told about the issue of the leaks occurring near the crimp on the hose. Efforts are underway to share results with all of the California station operators, but it is not clear who can assist with this information-sharing process. Hose replacements are expensive if one includes the station downtime. An Energy Systems Integration Facility (ESIF) portal is mentioned, but the portal is not well-known; the project team should get the word out. Note: valve leakage is noted as important, and more information may be needed here. If the valve leakage information could also be disseminated, it would be appreciated. Some writing can be improved: "Hose consumption larger than planned with new heat exchanger." Perhaps this means "Replacing hoses can be more expensive than replacing the heat exchanger."
- This is the fourth year of this project. During this project, three hoses have been tested for reliability under conditions that would be representative of a hydrogen dispensing station. Over the past year, one hose has undergone testing. The conditions tested were pressure cycling, range of temperatures of inlet hydrogen, and mechanical stressing of the hose using a robotic actuator. The project test protocols include checking for leaks using a hydrogen sensor, leak detector (tape), pressure loss measurements, and mass flux calculations using a permeability equation. Previous tests have included mechanical testing (torsion), scanning electron microscope (SEM) analysis, and other materials characterization. Overall, the work seems to be methodical and the objectives appear to have been met. However, some questions could be raised, as this large investment in equipment and personnel costs has resulted in the testing of just three

hoses, and all from one single vendor. It is not clear why more samples were not tested. It was not stated if this is the only vendor for this type of product.

- The approach is well-thought-out. One comment would be that the fueling profile, while meeting SAE J2601, does not cover all the possible scenarios of the pressurization of the hose. It would be good to test in "most severe" situations, which might include "rapid" pressurization to full pressure in both cold and warm conditions.
- Testing evaluates pressure, temperature, time, and mechanical stresses on a refueling hose and measures the leak rate of the hose. The real learning will come with the analysis of the material post-failure. The problem is the inability to test a variety of dissimilar materials and to vary parameters. The fact that the test-stand tube has continued to operate after 4700 cycles with consistent small leakages and with California station operators revealing that tubes in service failed after 1700 and 1000 cycles indicates that, despite the effort to reproduce all these effects in the laboratory, other key influences are not included.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.4** for its accomplishments and progress.

- Overall, the work is quite solid, and the objectives appear to have been met. The principal outcome seems to be that the hoses are actually quite good. Although they all display some level of leaks, none of them can be classified as "failed." In that sense, the lessons that could be learned from this study are probably lessened; had the hoses undergone actual failure, it might have led to clear directions for improvements. The permeability measurements and calculations clearly indicate that the rate of leakage from the crimp region is much too high to be accounted for purely by dissolution of hydrogen into, and diffusion through, the polymer. It has been convincingly shown that mechanical degradation of the hose material has led to the formation of cracks or other mechanical defects through which hydrogen has found a pathway to leak instead of diffusing through the polymer material itself. This could be confirmed by conducting SEM measurements of the hose sample adjacent to the crimped end. Cross-sections of the hose could be examined at, say, one-inch intervals, away from the crimp. The samples nearest to the crimp might be expected to display the greatest density of cracks or other mechanical defects.
- A DOE goal is to make progress on performance indicators, and the speaker mentioned that the set-up "passes all [National Fire Protection Association] (NFPA) leak checks."
- Project results contribute to safety of hydrogen refueling and therefore to the acceptance of the technology.
- Progress is good, but maybe some thought is needed as to how to expedite the testing to get more cycles in a shorter period. Testing has been limited in terms of number of hoses and number of cycles.
- It is not clear what the overall project and DOE technical requirements are for the number of cycles. It appears that the cold cycle results in higher hose permeability. Operating at or near the glass transition temperature also results in high hose permeability. This should be investigated further.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- Overall, the most intensive collaboration has been with the Colorado School of Mines for SEM imaging and torsion rheology benchmark testing. However, this collaboration was completed in an earlier period. Other collaborations are all minor in nature.
- The project should continue to work with the NFPA, International Organization for Standardization, and Canadian Standards Association code committees to address limitations of codes for hydrogen leakage. This project could help drive these committees to develop a limit for hydrogen leakage.
- Perhaps the California governmental agencies can be integrated/included in this study/project. There are 27 retail hydrogen refueling stations in California, and the user community is disparate; users' care and handling of hoses varies, and maybe best practices could help to lower the operation and maintenance of this expensive part of a hydrogen refueling station.
- Interaction with station operators is good, although other hose producers should be included in tests.
- It would be helpful to test some other hoses, although the supplier base is limited.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.5** for its relevance/potential impact.

- This project does address the goals and objectives of the Multi-Year Research, Development, and Demonstration Plan. This testing also provides the opportunity to evaluate valves, O-rings, connections, and break-away devices. Any failure of these components should also be analyzed to determine failure mode. Such an analysis should be done not just on the hose since these other components are also costly to replace and result in refueling station downtime.
- The goal of this project is to improve the reliability and thus reduce the cost of 700 bar hydrogen refueling hose assemblies by identifying points of failure. The goal is consistent with DOE's Hydrogen and Fuel Cells Program (the Program) goals and objectives.
- This work supports and advances progress toward Program goals and objectives in that it addresses the impact refueling station hose leakage and care and handling can have on the operations and maintenance of stations. Perhaps best practices are needed here.
- The project contributes to the safety of hydrogen refueling and therefore to the success of hydrogen as a market-ready fuel.
- Hose reliability is an issue, and this testing is important to improving safe operation of dispensers.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- The future work is explained, and this includes sharing the data with station developers. The future work includes the ESIF portal to get the word out. Note: valve leakage is noted as important, but this aspect is not developed in this study/paper. Including valve leakage would be appreciated. The presenters discussed the permeability experiment, which is not being run, as well as how repetitive bending causes cracks in hoses. Perhaps these can be included in future work.
- The project should evaluate the failed hoses provided by industry with the same suite of analytical methods as planned for the hose being stressed on site. The project also needs to investigate further why hoses fail significantly more frequently in actual operation as compared to the laboratory setting.
- The project should put more severe cycles on hoses to accelerate testing and/or simulate worst-case scenarios in the field. Maybe the project could work out a system to test multiple hoses at once.
- Plans to include further hose producers for testing samples are highly appreciated.
- Proposed future work seems reasonable.

Project strengths:

- The strength of this project is that the work is needed since hose replacement is an expensive part of a station's operation and maintenance. Standards compliance is key, and when the speaker was asked about the potential for leakage causing a lack of compliance with SAE J2601 (fueling protocols), the speaker commented that this effect occurs prior to a leak, causing lack of compliance with SAE J2601.
    - Another strength is that the project evaluated the hose from the station operator's point of view; the project evaluated the pin pricks required by standards (this is good).
    - Three-year-old hoses were tested, and no changes were observed. This is a practical side of this work. Some hose failures are due to internal dust, and the speaker explained how this work eliminates this as a factor.
    - The project will work with standards groups to explain the impact on standards, which is very much needed.
    - Preventative maintenance can identify hoses for early replacement, and this leads the way to providing information about the need for preventative maintenance for hoses.

    - When asked why people are not used for the testing, the speaker commented that the robot is highly accurate and measurable and that this is part of this analysis. Additionally, robots are used to protect people from accidents.
    - The speaker was asked whether the project could do some work on developing a harness to hold the hose so the fuel cell electric vehicle driver who uses the station will not have the propensity to drop this expensive part and possibly break the nozzle (and cause more cracks in the hose). The speaker agreed that would be a good future part of the project.
- A comprehensive evaluation protocol has been created to test the reliability of hoses for dispensing hydrogen. The protocol consists of pressure testing under different temperatures, mechanical stressing using a robotic arm, checking for leaks using a hydrogen sensor and leak detector tape, pressure loss measurements, mass flux calculations using a permeability equation, mechanical testing (torsion), SEM analysis, and other materials characterization. The work has been done with reasonable care and has paid good attention to the scientific method.
- There are great benefits to repetitively evaluating hoses with simultaneous pressure, temperature, and mechanical stresses mimicking real-world operations, following SAE J2601.
- The project has a great test set-up and ability to test a critical component of hydrogen fueling.
- Results of this project can ensure the safety of the refueling process for users. Therefore, the project contributes to the acceptance and success of hydrogen as a fuel.

Project weaknesses:

- In the context of operation and maintenance, preventative maintenance can be accomplished, and a hose can be replaced prior to wear and tear of the hose. The presenter touched on this, but more information here would have strengthened the presentation. The presentation does not explain how the user interface with the nozzle is important to the user interface of the hose (the speaker explicitly mentioned this is not included).
    - Some writing can be improved: "Hose consumption larger than planned with new heat exchanger." Perhaps this means, "Replacing hoses can be more expensive than replacing the heat exchanger."
    - The speaker did not mention the location of the station until asked; the speaker mentioned that the station is at NREL in Golden, Colorado.
    - The speaker did not explain how this project works with anticipatory changes to the standards; it would be appreciated it if more mention were made here.
    - The speaker mentioned that SAE J2601 contains no leak criteria, but it is not clear whether the speaker wants SAE J2601 to contain leak criteria.
    - The speaker did not dwell on how leaks can be mitigated for applications when people actually use the hose, e.g., whether people change the number or location of leaks.
- Only three hoses have been tested overall, and all from the same vendor. This is a rather small payoff from a large investment in personnel and equipment.
- Until now, only one sample was tested, so the relevance and reproducibility of tests for other hoses cannot be assessed.
- The experiment needs to be able to isolate and mimic the conditions in the field to better understand the failure modes that the laboratory experiment is not addressing.
- The project needs to test faster and under more severe conditions to better replicate some of the failures seen in the field.

Recommendations for additions/deletions to project scope:

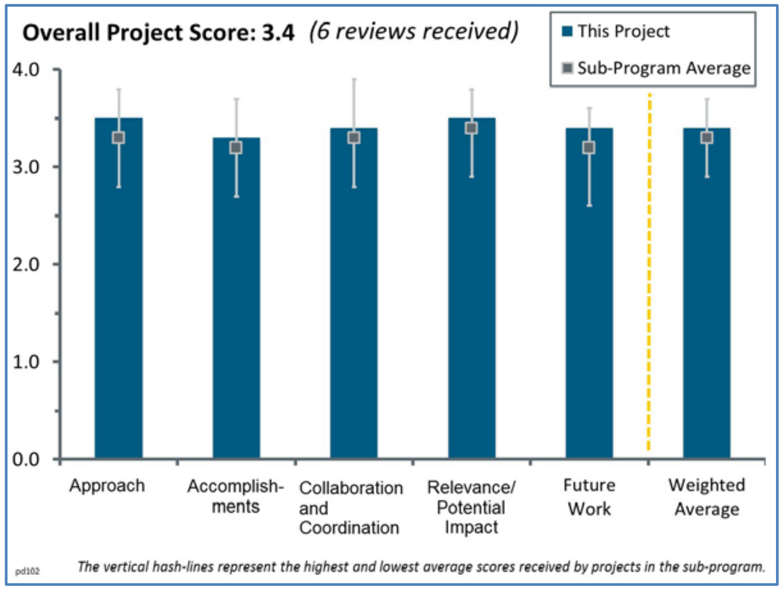
- Work is underway at other national laboratories to evaluate material permeation as a function of temperature, pressure, and frictional effects for polyoxymethylene in hydrogen. Efforts should be coordinated. A full suite of testing should be performed on the hoses that failed in the field. It appears that failure data are slow in coming for the hose testing in the laboratory. The failed hoses in the field could provide the information the project is trying to obtain in the laboratory.

- The project should broaden/widen the dissemination of this work as it continues. Hoses are expensive, and the user community needs some best practices to protect hoses that undergo wear and tear. Perhaps this work can be used to predict when the hose can be proactively replaced.
- The project should test under more rapid pressurization at both warm and cold temperatures and seek hoses that have failed in the field and apply analytical techniques to look at failure modes.
- Testing other hose samples from other producers to confirm results would be interesting. Recommendations for future design as well as testing standards should be developed from the results of the project.
- Detailed SEM analysis might provide critical evidence about the cause of leakage (mechanical damage) near the crimps.

Project #PD-102: Hydrogen Production and Delivery Cost Analysis

Brian James; Strategic Analysis, Inc.

Brief Summary of Project:



The objectives of this project are to (1) analyze hydrogen production and delivery (P&D) pathways to determine economical, environmentally benign, and societally feasible paths for the P&D of hydrogen fuel for fuel cell electric vehicles; (2) identify key bottlenecks to the success of these pathways, primary cost drivers, and remaining research and development (R&D) challenges; (3) assess technical progress, benefits and limitations, levelized hydrogen costs, and potential to meet U.S. Department of Energy (DOE) P&D cost goals of <$4 per kg H_2 by 2020; (4) provide analyses that assist DOE in setting research priorities; and (5) apply the Hydrogen Analysis (H2A) model as the primary tool for projection of levelized hydrogen costs and cost sensitivities.

Question 1: Approach to performing the work

This project was rated **3.5** for its approach.

- Technoeconomic analyses (TEAs) provide critical information to DOE and the broader community. Application of a consistent TEA methodology across the quite diverse set of pathways in the portfolio, such as that utilized by Strategic Analysis, Inc. (SA) for this project, is exactly what is needed. The next step—publishing those results, such as in DOE records, SA reports, and H2A model cases—is equally important, and SA does a good job. One area for improvement for SA is helping the community understand how scale-up affects the cost—not just the equations, exponents, etc. but key assumptions and sensitivities; this is the aspect of the TEA that usually draws the most questions/doubt.
- This type of work has been ongoing for many years in the Fuel Cell Technologies Office (FCTO) Hydrogen and Fuel Cells Program (the Program), and SA is the leader. While it would be nice to diversify the DOE portfolio for TEA, if the leaders can perform the work, then there is no reason to look any further. The project scope seems well defined and of interest to FCTO, and therefore, inherently it is integrated with other efforts in the FCTO portfolio. It is also nice to see TEAs of completely new designs (e.g., the REP work).
- The approach to this work is excellent: combining well-established DOE models together with SA internal models to provide a cost indication for hydrogen pathways that have been shown to be technically feasible (such as reformer–electrolyzer–purifier [REP] and WireTough's storage vessels) and that may have a direct impact on total hydrogen cost reduction.
- The approach for the cost analysis for the Hydrogen Production and Delivery sub-program is a very standardized, systematic process that is unbiased, using principles of Design for Manufacture and Assembly (DFMA) in conjunction with expert input.
- The approach is well conceived. There are no major suggestions for improvement.
- Technology readiness levels (TRLs) are part of a very good approach; new steps are an improvement for low TRLs.
    - Regarding dark fermentation, there is excellent linkage between laboratory and analysis work.
    - Regarding REP, it is not clear why a company's system is being endorsed. This is commercial technology, the data is not transparent, and there is no uncertainty analysis.

  - Regarding WireTough, this does not seem to be pre-competitive technology either. It is not clear why the company is not testing the cylinders themselves and doing TEA.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.3** for its accomplishments and progress.

- The accomplishment with regard to completing the REP analysis is excellent. It is also really interesting to see the progress being made on WireTough's storage technology. This looks like a forecourt storage technology that could be a cost-effective option. It would be interesting to see whether scaled-up designs could be assessed.
- This incarnation of the project was ongoing for only around six months prior to the due date for the Program Annual Merit Review (AMR) talk, although it does seem somewhat like a continuation from the 2016 work. Notwithstanding, the progress is strong and sufficient. This team's proven success in this work for DOE suggests the team will succeed at a high level on this project, too.
- There has been good progress in analyzing the methods suggested by DOE. There are no major concerns, although of course there are always questions about the detailed numbers that go into these types of analyses. SA is well aware of this and has a good approach to do as well as possible.
- The project investigators accomplished what DOE asked to have analyzed, which may not reflect the most high-priority technologies within the Program. The investigators updated a TRL determination methodology that should be applied across the sub-program portfolio to help prioritize costing and funding to help accelerate success of late-stage R&D.
- Regarding TRL levels, there is good progress. Results produced for dark fermentation are interesting. More needs to be done but mostly at the laboratory level. REP results are already available, but uncertainty analysis is needed. The cost assessment for WireTough seems to have already been completed.
- SA continued to do good job of fleshing out relative economics—and key R&D needs—of hydrogen production pathways by finalizing another two cases. The third case, related to compression, storage, and dispensing, is important because distribution and station costs can be on par with production costs, so it is good for SA to assess novel compression, storage, and dispensing strategies. However, the lack of transparency for the REP case was disappointing. It is difficult to discern key bottlenecks, R&D needs, and limitations; perhaps the full report will be more informative. If the lack of transparency is because the key information is proprietary, that probably means DOE should not have been involved.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.4** for its collaboration and coordination.

- There appears to be excellent communication with DOE. SA clearly reaches out to stakeholders, technology providers, and industry contacts to understand technology and get the best possible input. It would be good to see direct connections made with national laboratory modeling efforts where there is overlap, for example, Argonne National Laboratory (ANL) modeling and National Renewable Energy Laboratory (NREL) analysis. This would probably need to be facilitated by DOE.
- The project is primarily a collaboration between SA (prime), NREL, and ANL to provide technical expertise on different technologies. The investigators also interact with various technology investigators to provide input on their technologies and processes.
- While SA collaborates with appropriate groups, the number of groups is small, so there may be considerable bias. Therefore, it is nice to learn that SA sends questionnaires to many experts, although indicating an average +/- standard deviation per technology would be helpful for each high-TRL and low-TRL case.
- Good collaboration has been demonstrated with both NREL and ANL. It would be good to see what the contribution has been from the industry collaborators such as FuelCell Energy (FCE) and WireTough.
- Coordination is good. There is no reason for concerns.
- Collaboration has been adequate, but it would be good to have additional feedback from industry on the REP and pressure vessel analyses to ensure that this type of analysis is not favoring just two companies.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.5** for its relevance/potential impact.

- The analysis performed on this project is important, as it provides a cost indication for technologies that have been demonstrated to be technically feasible. This will provide DOE with an indication as to which R&D areas could be given increased focus to have a larger impact in progressing the Program goals and objectives.
- TEA is very important to DOE objectives, as it helps in identifying long-term potential (especially relative to other options) and pinch points where R&D is needed. SA does a thorough and trustworthy job of it. Transparency about key data and assumptions (where key data is measured by those with the largest impact on final results) is of tremendous value to the greater community. SA mostly meets the mark here, too. When SA cannot, DOE should be questioning its involvement in that particular technology.
- TEA is completely critical to the Program as well as any work funded by the DOE Office of Energy Efficiency & Renewable Energy or the Advanced Research Projects Agency-Energy (ARPA-E). Irrespective, if SA analyzed cases for FCTO in the past that have been around long enough now to approach future case scenarios, it would be good to know whether those technologies have been able to meet their long-term goals. The reason is that the long-term goals often seem slightly far-fetched, driven solely by DOE targets, and likely unattainable in practice.
- This project brings a level of practical assessment to the portfolio and demonstrates the potential for these technologies to meet DOE cost targets.
- Analyses provided by SA are extremely helpful for assessing various approaches and planning what areas to work on next. This clearly advances Program goals.
- A TEA of the technologies presented was needed to understand their status and feasibility, particularly for the dark fermentation technology, since it is at such a low TRL. The REP and WireTough technologies are also important to understand, but the companies should be conducting their own analyses and providing FCTO with data if they are looking to collaborate in government programs. It is not appropriate for a government-funded program to pay for all the analyses.

Question 5: Proposed future work

This project was rated **3.4** for its proposed future work.

- It is a very good idea to take a second look at steam methane reforming plus carbon capture and sequestration. This is an absolutely critical baseline. The project should consider adding the byproduct hydrogen (e.g., from ethane steam cracking) and other novel compression, storage, and dispensing technologies to the list for prioritization.
- The continuation of the proposed work on WireTough's storage technology seems appropriate as a complement to the existing analysis. It is good to see that carbon capture and sequestration advances will be implemented in future analyses.
- The proposed future work is reasonable and will advance our knowledge of the status of emerging technologies.
- A good scope of ideas and critical barriers is presented. However, it is noted that a new pathway for PEC hydrogen will be conducted, yet several have already been conducted in great detail and shown that the pathway to commercialization would require several miracles. There is no mention of milestones and targets, but this project may not have them, and presumably SA will perform sufficient analyses, as they have in the past.
- Future work was well explained. There are no concerns.
- It seems as though there has been an extreme amount of effort into costing various aspects of compressed storage technologies not completely different from what is being used today. More emphasis could be placed on P&D pathway technologies that show potential for large-scale renewable production. While photoelectrochemical (PEC) is a developing technology, it is still too immature to focus on costs currently,

and there are other P&D technologies that are closer to being demonstration-ready, such as the thermochemical cycles, that could benefit from a rigorous cost analysis.

Project strengths:

- Strengths include the sustained development and application of TEA methodology, resulting in cases that can be meaningfully compared and that are published in detail to promote transparency.
- SA is carrying out important analyses using an informed approach and provides critical information on various approaches and technologies relevant for the Program.
- The team has strong knowledge of the industry and good analytical/engineering capabilities.
- Investigators and collaborators have a strong understanding of costing principles and P&D technologies.
- SA has a great track record of performing TEA for FCTO, and their current output is representative of that.
- The cost analysis process is very comprehensive.

Project weaknesses:

- There are no major concerns. A challenge with these analyses is getting enough information, especially when some of it is proprietary, as in the FCE case. For REP, as an example, getting information on the stack life when it is operated as an electrolyzer/purifier would be helpful, but that may not be available or may not be something that FCE is willing to disclose.
- There is a lack of clarity around technology prioritization by DOE for SA evaluation. There should be better identification of "so what" implications/direct recommendations by SA on R&D needs.
- A focus is needed on technologies that are more commercially viable on a large scale.
- Use of confidential data is a weakness, and there is no uncertainty analysis in the REP work.
- More transparency in milestones and the number of experts polled per technology is desired.

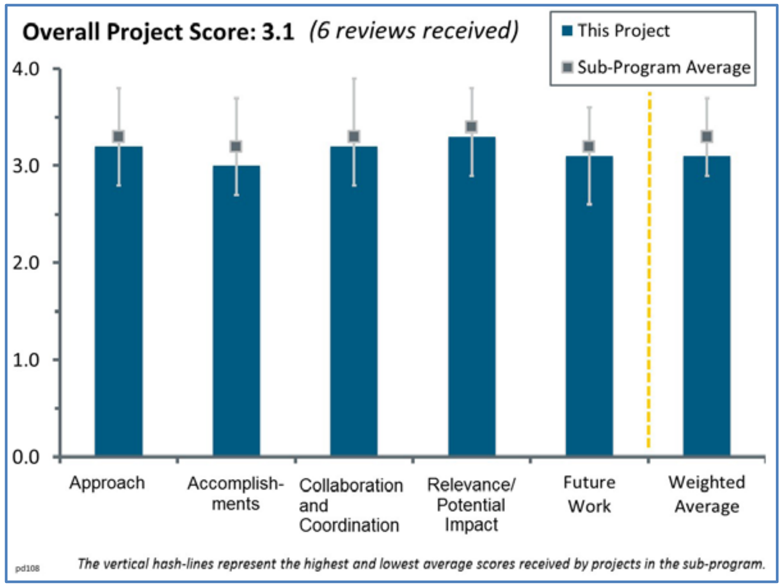
Recommendations for additions/deletions to project scope:

- A solar thermochemical hydrogen re-analysis would be preferred prior to a PEC analysis, based on the promising results from this year's AMR using cheap metal–oxide materials. An in-depth analysis of photovoltaics plus electrolyzer reactors and/or alkaline electrolysis alone could be conducted in place of another PEC TEA.
- The project should get uncertainty curves from FCE and have WireTough and FCE co-sponsor projects. Correlations between pentose conversion, broth concentration, and fermentation times should be investigated.
- The project team has reported that the methodology has been validated on fuel cells; another validation exercise should be considered. TRLs of technologies being evaluated should be clearly stated.

Project #PD-108: Hydrogen Compression Application of the Linear Motor Reciprocating Compressor

Eugene Broerman; Southwest Research Institute

Brief Summary of Project:



The objectives of this project are to (1) improve isentropic efficiency of high-pressure hydrogen compression above 95% by minimizing aerodynamic losses, (2) reduce capital costs to half those of conventional reciprocating compressors by minimizing part count, and (3) reduce required maintenance by simplifying the compressor design to eliminate common wear items.

Question 1: Approach to performing the work

This project was rated **3.2** for its approach.

- The approach seems reasonable and innovative in terms of electric drive: improves isentropic efficiency above 95%, splits into Budget Period 1 for design and build, and conducts testing in Period 2. The testing was delayed and pushed into fiscal year (FY) 2017. Isentropic efficiency should be clearly related to current target efficiency in the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan (MYRDDP).
- The technical approach to this project has been sound from the beginning. Project-management-wise, it seems to have tracked well, with the exception being the part delay/remake that occurred this funded year and that set the entire project back six months. This point should be of concern; given the tolerances involved on the high-pressure pistons and sealing rings, this is a very difficult part to make, and it is very easy to make it poorly and damage it during assembly, resulting in repeated setbacks.
- The combination of modeling and laboratory development work is very appropriate.
- Reducing capital cost and maintenance of hydrogen compressors is perfectly aligned with U.S. Department of Energy goals. It is not clear how the isentropic efficiency, however, aids in those goals; the team should draw easy-to-understand analogies to help show how they are tied together. The 2016 presentation presented a comparison with another compressor technology and how the linear motor reciprocating compressor (LMRC) would be greatly improved. It would be nice to read, in the 2017 report, about how this compressor will actually accomplish those improvements.
- The project is aiming for high isentropic efficiency, which apparently can also be achieved by a slow-speed mechanical compressor. It would be useful to clarify at what "speeds" the current design is able to achieve the high isentropic efficiency. Perhaps a fairer comparison with a mechanical compressor would be to state the respective isentropic efficiency at similar hydrogen flow rates and compression ratios. Since reducing the compressor cost relative to a conventional mechanical compressor is a key objective, it would be nice to compare a cost-breakdown pie chart of the proposed electromechanical compressor and a conventional reciprocating compressor (e.g., at the same hydrogen flow rate and compression ratio).
- Southwest Research Institute's (SwRI's) approach appears to be to follow a bulleted list. A description followed by a Gantt chart would be customary. The work itself appears to be close to schedule.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.0** for its accomplishments and progress.

- It seems from the material presented that the main accomplishments within this funding year are production of the core LMRC, dead load testing of the linear motor, and some initial gas testing of Stage 1 of the compressor. The predicted vs. actual production load of the solenoid coils is an impressive accomplishment, given that it seems to track well in a static test on a load cell. The ability to throttle the piston speed of the linear motor to minimize check valve losses during the compression stroke is a big potential benefit of the LMRC, and if it performs as the data shows it could, it is possible to realize the isentropic efficiencies noted. Other data and accomplishments from previous years (included in this year's work, backup slides) still do not clearly state how the seal design for the 1500-pounds-per-square-inch-gauge (psig) Stage 1 piston will translate to the larger challenge, which will be the Stage 3 14500 psig piston. The use of packing would not be possible at those pressures, and the leakage rate would be compounded. Progress of the project is good and methodical, and from the previous fiscal year, the LMRCs being built and ready for testing are good—and well on the way to the testing phase.
- The design appears to work. The target appears to be to generate a 3.6-times pressure raise with each stage. It is unclear whether the device meets the target efficiency levels. It would also be interesting to know the mean time between failure (MTBF) for the gaskets and seats. It would also be interesting to know if there is a preferred install origination—vertical versus horizontal. Site footprint size is always a station developer's concern.
- FY 2016 progress was shown up to some point last year owing to fabrication delays. The test stand is built, and the test article is also complete. Initial tests of the motor follow predicted performance (response of linear motor to current). The project is set for pressurization testing through the next budget period.
- This project experienced a delay and a hardware failure that put it back one year. It did not appear to result in increased project cost.
- One of the key objectives is to increase the isentropic efficiency. The team talked about reduced efficiency due to external mounting of the coils (for reduced risk). Slide 16 states "possible means to improve overall efficiency... have been evaluated." The overall presentation does not seem to lay out clearly the analysis of efficiency calculations/claims, so it is hard to know what the current status of efficiency value is. Another project objective is to reduce the capital cost—the team had to redesign the power controller; therefore, it seems to be a custom-built item (thus potentially expensive because it is not an off-the-shelf product). Further, in last year's presentation, the team realized that they needed an expensive casting material for one of the key parts. Thus, it is unclear whether the team will be able to meet the project cost objective—or at least, it would be useful for the team to lay out the cost breakdown that demonstrates that the custom controller, material costs, etc. will stay under control to meet the cost objective.
- Benchmarking against diaphragm and piston compressors (kilowatt-hours per kilogram compressed from 20 to 875 bar) would be helpful for understanding how this approach improves capital cost and/or reliability. Neither the 2016 nor 2017 slides mentioned how much energy it would take to compress a kilogram of hydrogen to fueling levels at 875 bar.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.2** for its collaboration and coordination.

- The project has established a collaboration team that covers topical areas needed to improve chances of success. The team is very good.
- Collaboration appears to be appropriate. It might be helpful for SwRI to interface with International Organization for Standardization (ISO) Technical Committee (TC) 197 and the Canadian Standards Association (CSA) Group. The current product safety document is in draft form. It is expected that this device will at some time require a product listing. Here is an opportunity to address these documents prior to public review and publishing. The point of contact at ISO is Karen Quackenbush. The point of contact at the CSA Group is Sara Marxen.

- The use of ACI Services, Inc., for the detailed check valve and piston design is adequate, and the proof of good collaboration will be within this coming year's testing results and adjustments to the testing and mechanical design as leakage data and compressor performance results come in. Beyond this, there is no change from the previous year. It is suggested that the team collaborate with multiple vendors to ensure that six-month delays due to vendors scrapping parts do not occur in the future—having a sole-source part would be a big inhibitor for a commercialized product.
- The team works well with multiple collaborators and suppliers. Parts are built to specification. The project has had issues with one supplier and delays going on one year. It is too late to pivot, but the team should consider the lessons learned.
- The team appears to have in place the resources and collaborations necessary to complete the work.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.3** for its relevance/potential impact.

- The key expectation of this project is to deliver a compressor at the stated cost target ($240,000) and with isentropic efficiency better than conventional reciprocating compressors. If such cost and efficiency targets can be met, this would be significant progress toward DOE goals.
- The second (now) most unreliable component in the dispensing of hydrogen is compression technologies. Improving reliability and reducing costs are critically important to the success of deploying hydrogen fueling technologies.
- This is relevant and may reduce compression costs and lower MTBFs for current compression systems.
- Improving the reliability, costs, and efficiency of hydrogen compression is well aligned with DOE goals and the needs of the industry. Expected performance should be compared with the project's preliminary data and commercially available data to show expected improvement in cost and energy intensity (kWh/kg).
- This project is relevant in the sense that a reduced-part-count compressor could reduce compressor capital expenses. The challenge for this team—and one for which they have provided targets without backup data—is that compressor performance projections are wildly optimistic without any high-pressure testing being completed. In this presentation, the team presented compressed power consumption value reductions of 9.2 kWh/kg (current) to 1.4 kWh/kg without having tested Stage 1 of the compressor. This is a broad assertion without technical backup. If this is truly possible, the team should present their calculations to back up this claim. Further to this point, the relevance of reduced maintenance cost is of course omnipresent; however, the presented claim says that the LMRC can reach values of 48 months without maintenance based on a 1/4 day duty cycle. When asked about exactly what this meant, the team was unable to quantify if this meant 100% run time for six hours or start–stop for some period of time. In compression equipment, this information is critical to making these assertions. After gathering one year of data, it will be good for the team to put running data to these claims to determine whether they can be backed up. This is a very important part to confirming this project's relevance.
- If efficiency can be improved through redesign, then the impact can be huge. This should be transferred to an industrial partner to do.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- The future work is appropriate. It is a pleasure to see that a focus on quantifying and improving first-law efficiencies has been included in this work.
- Testing is the balance of the work and must be completed. It would be good to see maintenance data to back up the operating expenses claim as well as detailed information and data sets on the kilowatt-hours-per-kilogram compressor claims made within this year's work.
- Future work comprises testing the compressor, which is highly encouraged.
- Proposed future work is appropriate.

- It seems that the current plan is to make a more efficient Stage 1, then to build Stage 2/3. The team should re-evaluate their cost and performance targets once the Stage 1 testing is complete so as to determine how close they are to their isentropic efficiency and cost targets.
- More care should be taken to improve the test facility and controls cabinet. Based on the pictures, it seems like the safety of the testing could be compromised by a lack of general housekeeping and good installation practices.

Project strengths:

- There is a possibility of a reduced-part-count compressor that achieves very high levels of efficiency and reliability. The build phase of the project—taking out the six-month delay due to a scrapped part—has gone well and is on track. The testing plan is well-thought-out. The project went through the national safety panel.
- The project claims that it will lower the capital cost of the compressor to $240,000. Presumably this cost is relative to a conventional mechanical hydrogen compressor for similar compression ratio and throughput. If this objective can be achieved, it would be a significant achievement.
- This project is flexible enough to respond to previous comments. It is good to see that the team has modified the overall project to address the efficiency point previously presented. The project has a good team and good execution and is resilient to unexpected delays.
- This project is focused on improving the cost and reliability of hydrogen compressors, which is aligned with DOE and industry goals. The LMRC approach may provide improved control of compression cycles.
- This is novel compression technology with high isentropic efficiency and potential cost and efficiency benefits.
- Novelty and potential to reduce cost are project strengths.

Project weaknesses:

- No real weaknesses are identified.
- Weaknesses include the following:
    - The project makes claims about maintenance and kilowatt-hours per kilogram, but there are no data, calculations, or evidence (even basic science) to substantiate these claims.
    - There is a lack of electrical data and surface temperature information on the linear motor. As this is pumping hydrogen, being in compliance with UL and other electrical codes and standards for explosion-proof equipment is a very big wild card for making the LMRC viable. The team must give great detail about having the coils of the linear motor (coils) rated or a possible path to UL or Nationally Recognized Testing Laboratory (NRTL) certification. It is strongly recommended that the team begin such a process. The testing matrix has a comment about the lack of seal performance, mentioning that there was a seal loss of 2% at 100 bar outlet pressure. This would be a very large red flag at this pressure and should be cause for concern about seal performance at lower pressures. It would be an exponential problem of seal losses on the higher-pressure stages.
    - While the team mentioned that 97% efficiency of the compression process was the target in the funding opportunity announcement (FOA), power put into the compression has a direct effect on overall compressor efficiency; thus, the team did not give an appropriate response to last year's comments.
- Benchmarking this compressor with commercial systems in terms of cost, energy efficiency, and reliability will help DOE understand whether this LMRC will ultimately achieve the goals of improving hydrogen compression systems. Such benchmarks are not just saying it will be better but are showing why/how the team believes these improvements will be realized—in other words, why the team believes that the seal life will last two to three times longer than the competing technology. The controls cabinet and test facility housekeeping and installation practices could be improved to reduce the chance of a mistake.
- Data on seal wear and the MTBF are weaknesses. The wear could have been independently tested. The MTBF is further down the pipeline. The four years pitched at the review is not realistic. There was no mention of field trials.
- The analysis of various efficiency numbers and cost breakdown are not clearly described. Assumptions of ceramic seal life (four years) requires experimental data to back up the life estimates.

- Weaknesses including lack of attention to system efficiency (kg/kwh); this seems to have been accounted for at the beginning of the project, possibly within the FOA. System efficiency should be looked at regardless since it is in the MYRDDP and is one of the issues with mechanical compression.

Recommendations for additions/deletions to project scope:

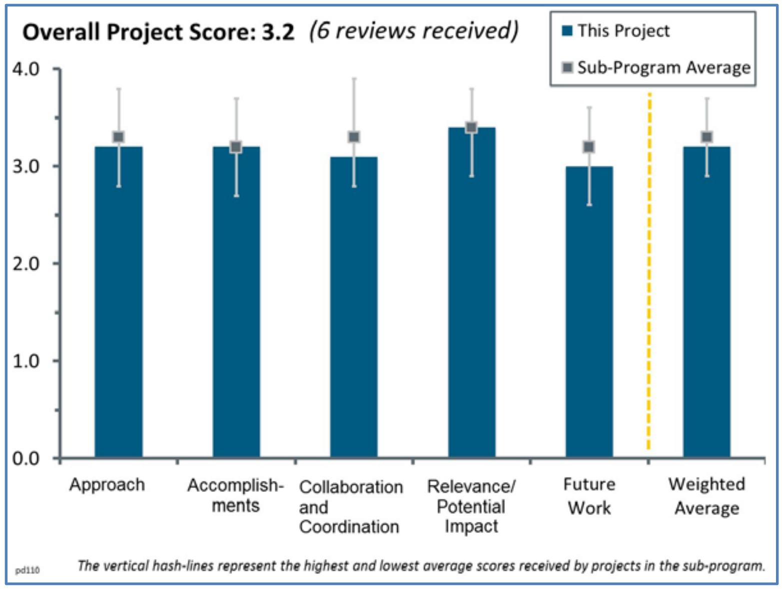
- The following additions are recommended:
    - Providing backup data and calculations for maintenance projections and kilowatt-hour-per-kilogram compressor targets
    - Ramping up the high-pressure stage seal testing, as this will be the larger project challenge
    - Finding a path to NRTL certification for explosive environments of the linear motor, without which there would be no path for the invention
- When determining the compressor's isentropic efficiency and costs, it would be useful to evaluate these aspects during both continuous and intermittent operation.
- The project should include field trials. The laboratory testing is fine. Field testing is the acid test.
- The team should consider an independent safety review of the test facility and controls cabinet to reduce the chances of an accident.
- Assessing or modeling system efficiency is recommended if project targets are met.

Project #PD-110: Low-Cost Hydrogen Storage at 875 bar Using Steel Liner and Steel Wire Wrap

Amit Prakash; WireTough Cylinders

Brief Summary of Project:

The overall objective of this project is to utilize innovative manufacturing technologies to develop a pressure vessel with a capacity of 765 liters that safely stores hydrogen at 875 bar while meeting the U.S. Department of Energy storage tank cost target of <$1,000/kg hydrogen. The vessel must have a lifetime that exceeds 30 years/10,000 pressure cycles, have a safety factor of 3 (burst pressure to operating pressure), deliver hydrogen that meets SAE J2719 hydrogen purity requirements, and have a design consistent with relevant ASME codes.



Question 1: Approach to performing the work

This project was rated **3.2** for its approach.

- The approach to performing the work is very good and will undoubtedly result in the completion of the task and achievement of most if not all objectives.
- The approach involves wrapping commercially available Type I cylinders with ultra-high-steel wires for safe storage of hydrogen at 87.5 MPa. In addition, autofrettage is used to induce compressive residual stresses in the liner. Fatigue crack growth is investigated, and the results are compared with results obtained at Sandia National Laboratories with tension–compression fatigue crack specimens. The KD-10 protocol is used to assess the life of the liner under the design specifications listed on slide 9. In summary, the approach is sound and state-of-the-art. A question investigators are asked to address is why they are concerned with negative R ratios as far as life prediction is concerned. In addition, it is not clear what the contribution of the autofrettage to the fatigue life is.
- The project has performed extremely well in the short duration and is highly impactful. It is not clear how the free ends of the steel wire wrap are terminated, for example, if they are welded to the tank. If so, perhaps the weld location needs to be tested for fatigue life similar to the analysis for the rest of the steel tank. It is also not clear whether, after the hydrotest, there is any check to ensure there is no residual water left behind in the tank to avoid any potential corrosion.
- The approach employed by this project is appropriate.
- The presentation was lacking the basic testing and confirmation for the claim.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.2** for its accomplishments and progress.

- Excellent progress has been made in all areas of work execution and in addressing the challenges laid out at the beginning of the project. Cost targets have been met, and the durability target has been largely met, albeit with a 20% shortfall from target (24 vs. >30 years) in the most conservative estimation. The project will be declared a success.
- The project has made good progress toward DOE goals. The cost target of <$1,000 per kilogram of hydrogen storage was achieved, as the presenter stated that the cost was $600–$800 per kilogram. The

project has performed fatigue life calculations that show an estimated life of 24 years, which is getting close to DOE's 30-year-life goal.
- Slide 12 reports the projected life of the liner to be 24 years for pressures alternating from 89 to 90 MPa (this is a vague piece of information that the presentation did not clarify). This is a significant accomplishment, although it is not clear what the pressure variation with time is. In addition, it is not clear what the relevance of the result is to real-life application, as it was obtained for R=0.5. It is not clear what the relevance of this ratio is to the negative ratios the investigators discussed in their introductory slides. It is interesting that slide 11 reports stresses vs "distance," but no explanation is given as to what length "distance" denotes or from where "distance" is measured. In their presentation, project investigators did not elaborate what information they are gleaning from the results of this slide for life prediction methodology.
- This project is making very good progress and is on schedule.
- The project team missed their completion date by more than eight months, and the project schedule slipped from 2016 to 2017. While this can happen for a myriad of reasons, the team provided no feedback as to why this delay was required, nor did they present a clear picture of how the new date would be attained.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.1** for its collaboration and coordination.

- This project has four partners, including WireTough Cylinders. This is a diverse and capable group with two national laboratories.
- Using external partners that are familiar with the code case was clearly demonstrated as an efficient and intelligent use of project resources.
- The collaborations established for this project are very good. The project might seriously consider contacting HyTrec in Fukuoka, Japan. This facility has the capability of cycle-testing cylinders this long.
- This type of work was successfully applied by the National Institute of Standards and Technology in 1970–1980, and the company shall use the results.
- The collaborations reported on slide 14 are deemed appropriate.
- The budget indicates recipient share of only $500,000 of the total project budget of ~$2.5 million. It was not clear how the remaining $2.0 million was distributed among the team so as to judge their respective contributions vs. cost to the project.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.4** for its relevance/potential impact.

- This project should produce inexpensive high-pressure cylinders for hydrogen transport. There is one point of curiosity, however: the lower bound on the pressure cycle is ~70 MPa, which presupposes that these cylinders will be used to top off local storage. The first thing that one will do is to empty these cylinders below 70 MPa. The cylinder should still be in compression (except the dome region). It would be good to know what the crack behavior will be at a high cycle rate (~10 cycles/day) when cycled to a lower lower bound pressure—for example, 30 MPa. This needs to be addressed.
- The project aligns well with the objectives of the Hydrogen and Fuel Cells Program in the area of hydrogen storage.
- The project meets the DOE targets with regard to both safety and cost.
- The overwhelming weight of this type of pressure vessel is impractical. Much better alternatives, such as carbon-overwrapped pressure vessels, can be used that are much lighter and not so much more expensive.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The remaining scope is clear and appropriate, but no timeline was tied to the remaining tasks to determine whether the scope was achievable. With project slip already being predicted, defining the timeline of the future work is critical to a successful evaluation.
- It would be good to see cycle data to a lower pressure than the ~70 MPa design lower pressure. This cylinder design will probably be fine, but the domes are not wrapped and are not under compression, so it begs the question as to whether this region will be more susceptible to higher-frequency lower lower pressure bounds.
- The rationale for testing wires (external to the tank) in hydrogen is not clear. Even if one argues the presence of "some hydrogen" in the local environment, it is unlikely that this hydrogen will be at pressures influencing fatigue life. The team should consider evaluating the design space for further cost reduction via using alternate steel cylinders, autofrettage pressures, wire strength, etc. Such effort will move the project toward DOE's long-term cost targets for hydrogen storage containers.
- On slide 13, it is proposed that a protocol be developed on ensuring that adequate compressive stresses be developed during autofrettage. There is not enough information to assess how the project addresses the effect of the compressive stresses on the life of the liner. This is not a well-analyzed part of the project, and the investigators' presentation did not clarify it.
- The future work described will close the project out with some unanswered questions. However, given the time and resources remaining through the end of the project, not much more may be achieved in the time left.

Project strengths:

- Project strengths include the collaborative team that performed the work, the technology brought to bear in solving the challenge being addressed at a fairly low cost, and the fact that the goals and milestones reached in the work are largely consistent with what was promised at the beginning of the project.
- This project is well executed, making timely progress from last year. It looks like this will be successful in producing a low-cost, high-pressure system for hydrogen transport.
- A strength is the data-analysis-driven solution to the cost challenge of fabricating long-term hydrogen storage containers.
- Dr. Saxena's scientific stature is a project strength.
- Cost targets were clearly demonstrated to be achievable.

Project weaknesses:

- No real weaknesses are identified.
- There is a lack of prototypical testing. A better understanding of component behavior is usually achieved with well-thought-out prototypical testing. Tests are usually complicated and subject to misinterpretation if not carefully executed, but they yield very powerful results if they are carefully executed. They are also very expensive to carry out. Perhaps sponsors could consider this for future investigations. Workers may well find that predicted lifetime may change, maybe even improve, with prototypical testing. The technology highlighted depends solely on the ability to maintain the compressive stresses imposed by the wire wrap on the storage tank. If wires relax or fail, the benefit of the technology is lost (until re-wrapping is carried out). Very little testing seems to have been focused on the durability of the wire wraps when exposed to various types of service environments the tanks are likely to be in, especially as they are expected to be in service for decades. The issues of stress relaxation over long periods of time are not addressed in this presentation either. Other presentations may have addressed these issues, but this one certainly did not.
- It is not clear by how much the autofrettage affects fatigue crack growth. In fact, the elaboration on negative R ratios seems to be out of place because fatigue crack growth under hydrogen pressure takes place under positive hoop stresses and hence positive R. There is no information on what pressure profile the investigators used in their life analysis and whether the profile is relevant to real-life applications. An

overall comment is that the presentation at the 2017 Annual Merit Review lacked clarity with regard to essential ingredients of the project.

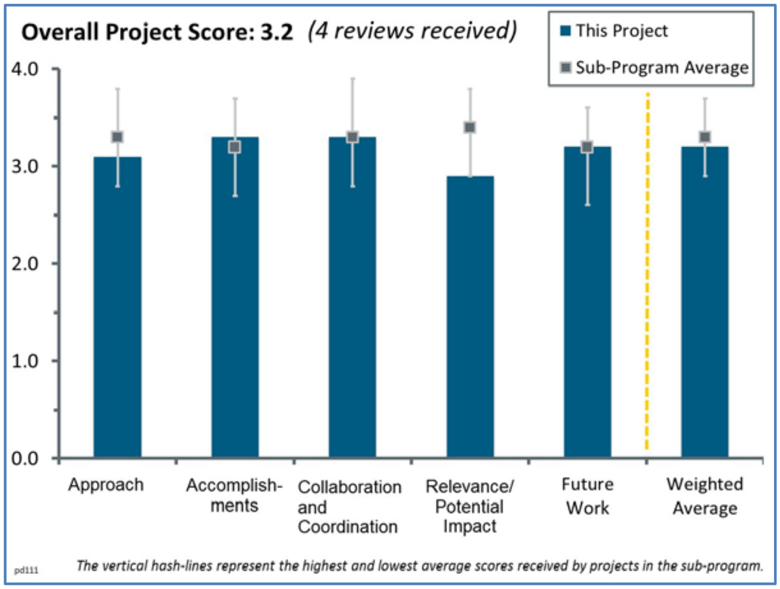
- The presentation has numerous typographical errors. In the da/din vs. delta K graph on page 7, the reasons for different trends shown by the green line, black line, and dotted black line are not clear, i.e., whether the differences are due to differences in pressure, R value, frequency, etc.
- While the project team was working to evaluate the lifecycle of the cylinders (they believed they were doing well), they still are falling short of the target 30-year design life.

Recommendations for additions/deletions to project scope:

- The wire testing task seems unnecessary. Perhaps it is possible to determine whether the design space—combinations of cylinder material, autofrettage pressure, and wire strength—can be played with to further bring down the cost of hydrogen storage.
- A test facility that can cycle test these tanks under anticipated real-life duty cycles should be sought; the project should look into HyTrec in Fukuoka, Japan.
- No additions are recommended. The project is in the final stages, and any additions to project scope based on project weaknesses will require additional funds and time to complete. The project will provide useful data as planned to completion.
- Presentation slides should be numbered. The autofrettage protocol must be presented in relation to real-life pressure variations with time. The project has not demonstrated why autofrettage is needed.

Project #PD-111: Monolithic Piston-Type Reactor for Hydrogen Production through Rapid Swing of Reforming/Combustion Reactions

Kenneth Rappe; Pacific Northwest National Laboratory



Brief Summary of Project:

Bio-oil reforming technology advancements are being pursued in this project. Pacific Northwest National Laboratory (PNNL) is working to (1) reduce the capital cost of hydrogen production from bio-oil through minimized unit operations, smaller pressure swing adsorption, and process simplification; (2) increase energy conversion efficiency through in situ CO_2 capture and in situ heat exchange between reaction and regeneration; and (3) increase operating flexibility and durability through reduced operations and maintenance requirements.

Question 1: Approach to performing the work

This project was rated **3.1** for its approach.

- The rapid swing reforming/combustion process demonstrated in this project appears to be a novel, potentially low-cost approach to producing hydrogen from bio-oil. The identified barriers are (1) plant capital costs and efficiency (unit scale of economy) and (2) operations and maintenance (O&M). To reduce capital costs, the project team minimized unit operations and simplified the process. To increase energy conversion efficiency, the team used in situ heat exchange between reaction and regeneration to minimize heat loss, and in situ CO_2 capture to push thermodynamics of reforming to higher conversion. To reduce O&M costs, the project team attempted to improve operating flexibility and durability by minimizing coking and catalyst deactivation. There are likely to be several more points of system vulnerability that could have an impact on efficiency and durability over time. The impacts of pH, temperature, and pressure cycling on vessels, pumps, valves, and sensors were not mentioned. Also, control strategies should be discussed.
- The project team has successfully addressed and made improvements to the barrier targeting hydrogen production at less than $2/gallon of gas equivalent (gge). The work shows good progress in improving the production rate of hydrogen through improved sorbent formulation and loading as well as catalyst formulation and loading. Further, the work demonstrates limited degradation of the primary components over multiple cycles, though any future work should include extended cycles in which the degradation is measured over hundreds or thousands of cycles. While optimization will also lower system costs, it does not specifically lower capital cost of the equipment, which was a targeted barrier of the work. Perhaps work was done to lower these costs, but no values were presented for estimates on the capital equipment, the catalysts, or the monolith used in the project.
- The system approach takes advantage of two sets of reactions cyclically to synergistically improve hydrogen production from a biomass-derived liquid (bio-oil), including taking advantage of coking, which is often an obstacle to performance. This is aimed at addressing multiple barriers, including improving conversion efficiently, reducing capital costs, and improving operational requirements. The approach combines development of system components such as catalysts with an integrated pilot demonstration. The demonstration step is important to evaluating the integrated impact of the developments.
- The investigators have done a reasonable job but have tested very few catalysts for this reaction. In a commercial laboratory, over a hundred different catalysts might be tested in a year. Material balances seem

to have been ignored. Analysis of coke yields and compositions, accurate analysis of light gases produced, etc. would allow the investigators to optimize the process to perhaps convert methane and other light hydrocarbons formed, or at least to get a good estimate of theoretical yield of hydrogen. The incorporation of a CO_2 adsorbent was a good addition, probably shifting water–gas shift equilibrium to give higher yields of hydrogen.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.3** for its accomplishments and progress.

- This is good work. The team reports that the addition of K and La to the reforming catalyst reduced selectivity to methane and coke formation and increased reform rates by increased metal–oxide dispersion. The sorbent was successfully optimized for scaled synthesis and stability by optimizing eutectic weight percent in sorbent, and by a method of synthesis that includes direct impregnation of Li, Na, and K carbonate eutectics on dolomite; synthesis time was reduced by 75%. The team also reports that the source of deactivation in the integrated system was identified and stable operation has been achieved. Ultimately, stable bio-oil reforming with integrated CO_2 capture was demonstrated. CO_2 capture was shown to significantly improve hydrogen yield (up to 5x). The team should consider manufacturing in further developing its design to gain efficiencies of mass production. Refined design could minimize the cost and amounts of materials used in both the primary reactors and the balance of plant, as well as thermal efficiency, durability, and long-term costs incurred in replacing components.
- The project has shown significant improvement from previous work. The work innovatively deals with the production of CO_2 and creatively uses the coke created during hydrogen production for heat generation. The work utilizes bio-oil in the form of pyrolysis oil, which is useful and in keeping with DOE goals. The group showed clear performance in hydrogen production capability and method for improving catalyst and sorbent performance.
- There has been progress in the project tasks, including accomplishments in improving the catalysts and demonstrating an integrated pilot system. The fiscal year 2016 milestone of demonstrating extended operation of the system integrated with CO_2 capture has been significantly delayed. The project identified a production target of 10% kilograms of H_2/kilogram of bio-oil. The highest status presented was around 6%, though it was noted that it was expected to increase if further optimization was done.
- The investigators have shown conversion to hydrogen, but no good heat and material balances were presented. Limited catalyst optimization has been attempted. Also, since conversion is less than 100%, the reactor would need to operate in recycle mode. The unreacted bio-oil is probably less reactive, so problems in converting this material would need to be addressed.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.3** for its collaboration and coordination.

- The project has multiple partners, leveraging expertise in catalysts (Washington State University [WSU]), monoliths (Cormetech), and testing apparatus (Dason). In addition to extending the types of experiments that could be performed, collaboration was demonstrated by the troubleshooting described to identify and address the root causes of problems with the testing system, such as thermal management and opening the reactor for maintenance.
- Collaboration and coordination appear to be quite good. Team problem-solving in selecting, testing, and optimizing the catalyst is evidence of excellent coordination and collaboration. It is difficult to gauge coordination and collaboration in much detail based on the simple organization chart.
- Collaboration efforts are obvious. There appear to be some small gaps in understanding of what various groups are doing and have done, specifically regarding work done at WSU for catalyst formation. Some improved communication is advised.
- Collaborations appear to be limited to one university, a monolith supplier, and a reactor supplier. There was no attempt to work with catalyst manufacturers, bio-oil suppliers, or companies engaged in upgrading bio-oil. All of these entities could probably have made significant contributions to the success of the project.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **2.9** for its relevance/potential impact.

- The project directly relates to the DOE Hydrogen Production and Delivery sub-program goals and even utilizes use of a renewable feedstock in the form of bio-oil.
- The project identifies barriers that it is addressing, but the objectives listed (reduce capital costs, increase efficiency, increase operation flexibility and durability) do not have clear targets for progress identified. These may be built into the cost analysis, but without identifying those, it is difficult to evaluate the impact of each on the overall listed target of producing hydrogen at <$2/gge. The investigators estimate that if the project meets its technical targets, the cost for hydrogen production would be reduced to just under $4/gge, with potential for further reductions. However, the estimate with further optimization is above the $2/gge identified as the target, and there is no indication of how or whether further reductions could be made, or how much of the reduction is due to using a future pyrolysis oil cost of $6 per gigajoule (compared to a $14.1-per-gigajoule bio-oil cost in the other cases).
- Among the options for using bio-oil, upgrading for mixing with hydrocarbon fuels for internal combustion engines is a much more likely option. Given the low yields of hydrogen, upgrading to hydrocarbons is a more likely option. This technology might be utilized in small-scale remote operations to provide hydrogen for bio-oil upgrading/stabilization.
- Assuming a robust hydrogen market develops, the potential significance of bio-oil as a feedstock and this technology is unclear. Likely bio-feedstock will come from municipal solid waste, biosolids, and waste wood. It is not clear how this technology will address the energy conversion needs of those markets or what portion of the hydrogen market this technology can meet.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- The presenter stated that in the time since the slides were submitted, the decision was made to end the project for funding reasons, and therefore the future work is to prepare information for report-out. As the project work is ending, this is important work to ensure that the results and lessons learned can be shared.
- It is understood that the remaining time for the project will be spent on data reporting.
- The proposed final tasks are clear and appropriate.

Project strengths:

- Project strengths include the novel approach and simple design execution, as well as team problem-solving in selecting, testing, and optimizing the catalyst. The technology does not include exotic materials or extreme operating conditions, and there is a line of sight to commercial viability.
- Project strengths include use of bio-oil as a feedstock, use of CO_2 sorbent to purify hydrogen during the process, high-level collaborative partners, and a significant improvement in optimization.
- The partners were able to work together to identify real-world process issues such as opening reactor temperature control issues. In addition to allowing for the demonstrations to continue, this also will be useful information for developing designs and plans for scaling up.
- Use of CO_2 sorbent in the reactor is a strength.

Project weaknesses:

- There are not enough cost data presented to confirm the impact of optimization on capital cost. The poster presentation would be better as a poster, not a series of PowerPoint slides. The presenter seemed to have trouble presenting work in a fluid, coherent manner.

- Weaknesses include the lack of materials balance and light gas analysis of off-gas. There has been no consideration of recycle issues. The project failed to achieve targeted hydrogen yields.
- The impact of the technical accomplishments on the modeled cost is not clear. The numbers have been updated from last year, but the source of the changes is not described.
- Assuming that this technology becomes commercial, its potential impact on the supply of renewable hydrogen is unclear.

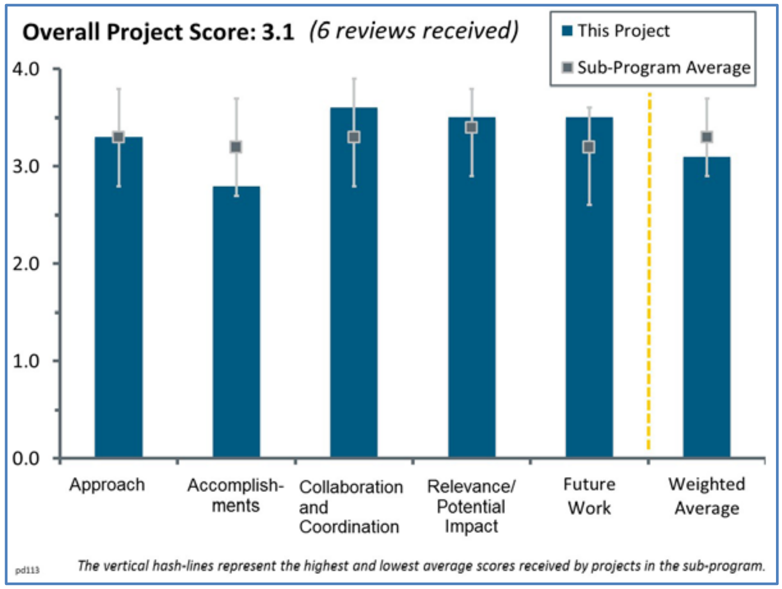
Recommendations for additions/deletions to project scope:

- Manufacturing strategies and design could be pursued to help minimize system costs. Future work could also include the development of advanced pathways for limiting CO_2 emissions. One common example might be methanol co-production. Other approaches might involve using some of the solid carbon produced by this process to make high-value materials such as carbon-based structural fiber and coatings.
- It would be useful to expand on the experimental work, specifically increasing the tests for degradation of the catalyst. Some information on capital cost and the impact of optimization on performance cost would assist in directly addressing the barriers for capital cost.

Project #PD-113: High-Efficiency Solar Thermochemical Reactor for Hydrogen Production

Tony McDaniel; Sandia National Laboratories

Brief Summary of Project:



The objective of this project is to develop and validate a particle bed reactor for producing hydrogen via a thermochemical water-splitting cycle using a non-volatile metal oxide as the working fluid. Sandia National Laboratories (SNL) will demonstrate eight continuous hours of "on-sun" operation, producing more than three liters of hydrogen by the end of the project. Fiscal year 2016–2017 objectives are to (1) discover and characterize suitable materials for two-step, non-volatile metal oxide thermochemical water-splitting cycles, (2) construct and demonstrate a particle receiver–reactor capable of continuous operation at 3 kW thermal input, and (3) conduct full technoeconomic, sensitivity, and trade-off analyses of a large-scale hydrogen production facility using a plant-specific predictor model coupled to the Hydrogen Analysis (H2A) model.

Question 1: Approach to performing the work

This project was rated **3.3** for its approach.

- From the onset, the team took an aggressive approach to innovating not only a complex reactor design but also novel materials. While making significant progress, choices of how to prioritize and arrange research efforts between these objectives have resulted in no clear success for either. Research is like that sometimes—big bets do not always pan out. However, the strategy of parallel materials, reactor, and analysis thrusts is commendable. Not to be endorsed is the idea of waiting until the end of a three-year project to publish all the results.
- SNL set a very ambitious and focused project scope and schedule to meet the U.S. Department of Energy (DOE) objectives, to develop materials discovery approaches for improved reaction materials for water splitting, and to design and construct a particle receiver–reactor capable of continuous operation. The approach made the most of a relatively modest amount of funding over less than three years, and the approach was high-risk and innovative. While not all barriers were anticipated or overcome, significant gains in knowledge were achieved that will allow future efforts to be even more focused and successful. This project was well integrated with the interests of the DOE Materials Genome Initiative.
- Solar thermochemical hydrogen production (STCH) is a unique process for solar water splitting that is different from photoelectrochemical (which is very similar to photovoltaics [PV] + electrolysis). The uniqueness of the reactor means that the scaling and cost-learning curves from historical technologies could be very different, and thus it has the chance to be a game-changing technology in the field of solar water splitting. However, to further support this, it should be clarified how the technoeconomics of STCH compare to solar thermal PV + electrolysis. This project is well designed and nicely complements the STCH efforts at University of Colorado Boulder.
- The investigators have combined theory, high-volume material screening, and testing to advance the science. The "small"-scale reactor work is very useful and necessary for this type of work to progress.
- With an experimental campaign that surveyed up to 200 perovskites, it seems that, using the principled approach the principal investigator (PI) describes (these experiments were not Edisonian in nature), one

ought to have validated the scientific principles the researchers set out to prove. Given the number of samples, this has the opportunity to occur to such an extent that we might argue the materials space has been "covered," in the mathematically complete sense of the word, assuming a properly executed statistical design of experiments occurred. Unfortunately, it seems we do not yet have this confidence in the materials space. It is not clear that the part of the project validating the principles set forth in the materials design was properly structured. Interesting discoveries are still happening (a new dual perovskite—right at the end of the project). While, as argued by the PI, we might not know enough design rules at the start of a project, we may certainly design an experiment to thoughtfully and efficiently cover a space, especially if the investigators bring their extensive understanding of how thermodynamic stability brackets interesting materials combinations as "possibility." Tradeoffs always happen; it is not clear that the project has been managed with such tradeoffs in mind.

- Given STCH's low technology readiness level (TRL) and long-shot prospect, the project's scope and breadth is way too broad for the project duration and funding level. The team focus and capability appear to be on reactor design and construction (which should be the primary effort) rather than on materials discovery.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **2.8** for its accomplishments and progress.

- The demonstration of the operating system was very good. It is to be hoped that the investigators can get it fixed so they can complete their run. The discovery that other design considerations need to be included is important, and the team should document it well for other developers. Unless the steam requirements can be lowered, this technology will be expensive. The project should see what the H2A model costs are when the large amounts of steam are included in the system. The high-temperature "waste heat" is of extremely high value and should not be wasted. It is surprising that the waste heat cannot be used on the material and steam preheating. If it is not heated in material preheating, then it should definitely be used for other value-added product production such as electricity generation. The investigators have an impressive number of papers being written (13). In the future, they should try to publish more often to avoid having so many at one time. They identified only a handful of materials that could be used and only one or two that were better than their baseline, after screening hundreds. They need to improve the screening process.
- The primary demonstrable accomplishment was the design/build of a (mostly) operational STCH reactor. The team nearly accomplished the hydrogen production goal. It is unclear whether the failure exposed a fatal design flaw or if the team will repair and repeat the attempt. The ultimate payoff of this substantial project will be judged in the impact of the many planned publications, including use of the material design rules claimed to have been developed, and future research enabled by a functioning STCH reactor. The project also highlighted the potential for hydrogen–electricity co-generation as a significant potential advantage. This should be explored further by DOE.
- The work on cerium oxide (CeO_2) and the demonstration reactor is superb and exciting. The results and predictive capabilities from the entropy engineering have been less successful, but that is of lesser concern. Interestingly, the concept of co-generation of hydrogen and electricity is mentioned, but the global minimum for ultimate cost based on the fraction of heat going to STCH vs. concentrated solar power (CSP) electricity (followed by hydrogen via electrolysis, for example) was not mentioned. This is an important comparison that should be performed to identify the benefits of co-generation or determine whether solar thermal PV + electrolysis is projected to be less expensive.
- In collaboration with partners, SNL was able to design, construct, and test a solar simulator, reaction chambers, and the Cascading Pressure Receiver–Reactor (CPR2). Although the project demonstrated hydrogen production with this reactor, it was not able to demonstrate eight hours of continuous operation and production. The reason was not adequately explained, nor was a possible fix to the system to allow for longer-term operation discussed. It would seem that this would have to be done if the CPR2 is to be a valuable resource for future research by SNL and others and contribute to technology transfer efforts. Materials discovery work to date has not identified the optimum water-splitting material or materials, but good progress has been made in identifying design rules and protocols. This will allow future materials work to continue to make progress in this area.

- The project goals do not appear to be well defined or were too ambitious from the outset. For example, the stated goal to "develop a viable integrated solar-driven high-temperature thermochemical water-splitting process" can be subjective. It is difficult to measure the success of the stated milestones, such as "Formulate and synthesize [reduction–oxidation reaction] active oxides from $LaAlO_3$," without mention of size, properties, or performance of the synthesized material.
- The project has not achieved three liters of hydrogen in an eight-hour period. The thermally induced mechanical failure in the system is a harbinger of things to come.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.6** for its collaboration and coordination.

- This project has demonstrated excellent collaboration, cooperation, and coordination between multiple partners, including several universities and a European laboratory. Participation in the newly formed HydroGEN Advanced Water Splitting Materials Consortium will provide another opportunity for SNL to shape the future of this technology.
- This project has a large number of national and international collaborators that seem dedicated to the work and the project. This project nicely complements the STCH efforts at University of Colorado Boulder.
- Most seem to have made meaningful contributions, and SNL actively engaged its partners.
- This is a very impressive national and international team. The team inputs to the project need to be better defined.
- The project appears to have key academic and international (German Aerospace Center–DLR) collaboration.
- This was done well.
- The list of collaborators is long—possibly too long, possibly resulting in high coordination/management overhead.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.5** for its relevance/potential impact.

- The reactor system designed and built under this project should provide a valuable resource to future work by SNL or others, especially if it can be fixed to run continuously for eight hours or more. This project group has been an early leader in materials discovery research and development of metal oxides and perovskites for water-splitting applications, and their experience and results to date will serve as a springboard for further studies in this area.
- STCH needs proof-of-principle projects like this one to jump-start serious evaluation of the concept. A more conventional technoeconomic analysis (TEA) is encouraged, consistent with those done for other hydrogen production pathways. The detailed plant model developed for the project offers an excellent starting point.
- This group essentially hit their final project metric of three standard liters of hydrogen in eight hours before a catastrophic materials failure. DOE deemed this an appropriate target at this stage of development of the project and the field, and therefore this result should be commended.
- The project goals and scope are in alignment with the DOE Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan.
- STCH production is a long-range technology. It seems much of the development is low-TRL, perhaps even TRL 1. DOE Basic Energy Sciences funding should be sought for this area.
- This project cited CSP with thermal storage for heat and electricity as enabling. This has not been well appended, and claims need further vetting.

Question 5: Proposed future work

This project was rated **3.5** for its proposed future work.

- The project will be ending this year, and it is not clear at this time what resources will be available to continue the investigations under HydroGEN. The investigators have identified remaining challenges and possible future work. The suggestion to combine hydrogen production with cogeneration of electricity into a hybrid system appears to be a reasonable one, and it is very important that the project team continue to make the economic argument for this route versus competing technologies, perhaps through an updated case study with DOE. Demonstration of the value proposition to gas and electricity providers is a good idea, as these may be potential partners in a higher-TRL stage of development for this technology. TEA studies of the STCH technologies would benefit from up-to-date estimates of the cost of heliostats. Perhaps in the future, the investigators or the Fuel Cell Technologies Office could obtain periodic updates on this from the Solar Energy Technologies Office. Future work in development and scale-up of the CPR2 should address design and components, which were outside the scope of this project. For example, perhaps another heat exchanger will be needed, as was suggested in the 2016 annual report, or perhaps further pressure cascade to higher vacuum than ~ 10 Pa will be required.
- In light of the fact that the project is ending in September of this year, the two stated tasks for future plans seem reasonable. Making the CPR2 available for other projects through HydroGEN to test new materials makes sense. However, considering the limited remaining resources and time, it is not clear how the project team plans to accomplish the preparation, submission, and responses to peer reviews of all 13 papers in such a short time.
- The remaining barriers for additional study are reported as being addressed by the Energy Materials Network's (EMN's) HydroGEN or are motivated by making the demonstration reactor a user-facility-based instrument for testing materials for others in the community. This seems like a very logical progression for a national laboratory. The PI mentioned a new double-perovskite materials discovery that sounds like it should be followed up on by someone in the EMN.
- The project should come to its natural, time-based end. In the PI's slides, the project's period of performance was always qualified with an asterisk. The asterisk read, "End contingent upon meeting [funding opportunity announcement] metrics," suggesting the project never ends if it keeps missing its success metrics. Sometimes it is best to wrap up, regroup and reorganize, and come again with a new, thoughtful proposal.
- This project is ending.

Project strengths:

- The reactor demonstration was fantastic. The cost analysis in the backup slides is promising, given the current state of the art (although the lifetime of materials in practice is very low), and the projected costs do not seem to constitute unreasonable advances.
- The primary strengths of the project were the excellent project team, innovation in research and design, leadership in investigations into new materials of reaction, and coordination between materials discovery work and reactor design.
- This is an ambitious, well-funded effort to demonstrate STCH—a good DOE investment with a learn-by-doing objective. The project has a strong, motivated team.
- The project has a great PI, a great team, and great resources for executing, as well as a good experimental campaign. There is a fair level of clarity in scientific conclusions.
- The project has a very strong team and is very well supported by DOE. Facilities and tools are very good.
- High-temperature reactor design and fabrication capability are project strengths.

Project weaknesses:

- It is not clear how reactor design learnings will be socialized within the STCH community. It is not clear whether this is a one-off or whether there are ways other/future designs can benefit. A large amount of "high-quality waste heat" is usually a sign that you need to go back to the drawing board. Perhaps integration with electricity generation, or integration with high-temperature electrolysis, is the answer; or perhaps it is a serious flaw of the entire STCH concept, making the technology useful only when solar towers are commoditized. It is not clear from project analysis where on that spectrum we are sitting. We have not addressed water—quantity and quality, or how much pre-treatment is needed. These topics should be in future TEAs. The presentation, which should be to assist the broader audience, made excessive use of undefined acronyms.

- The project inadequately conveys when materials formulation is (ever) complete. Continued materials exploration has diminishing returns, barring a "Eureka" discovery moment, the pursuit of which is less investment and more like a gamble. There are concerns about mechanical robust operation of the system and how the risk register for these is established, updated, and conveyed to DOE.
- The project identified only a handful of materials that could be used and only one or two that were better than the project baseline, after screening hundreds. The project team needs to improve the screening process.
- The scope of high-temperature materials discovery should not have been part of this project. Given the early stage of STCH development, materials discovery and characterization should have been given separate and full attention by other researchers.
- The inability to achieve funding opportunity announcement goals for this project was the primary weakness. It is to be hoped that this will be addressed within the remaining months of the project.
- The entropy engineering efforts were admittedly not that informative.

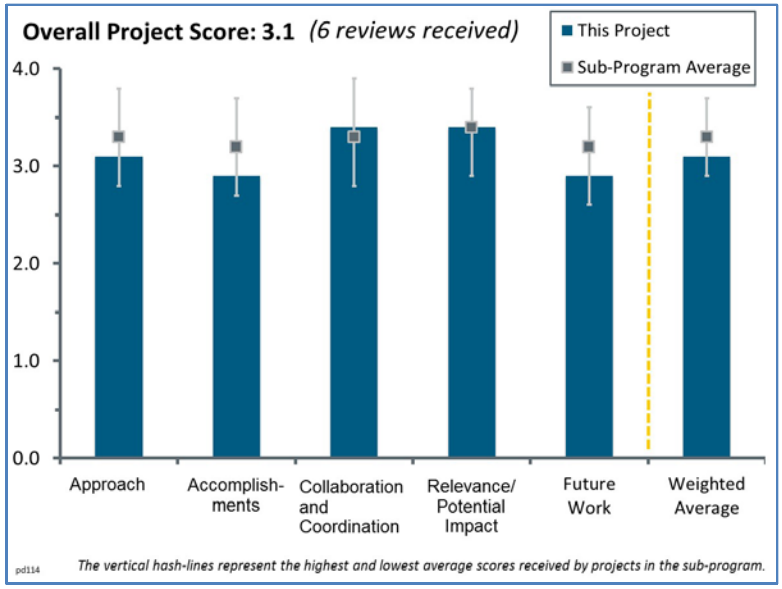
Recommendations for additions/deletions to project scope:

- As the project concludes, the investigators should:
  - Compare results of their "high-fidelity" process model to H2A's. This is the community standard and a valuable reference point.
  - Provide context for the HydroGEN effort on STCH materials. It would be good to know how and by how much materials would need to improve to move the needle on STCH capital expenditure (capex), operating expenses, and the cost of hydrogen. Perhaps other levers are more important. The water-splitting community should be helped in applying limited resources to areas with the highest impact potential.
  - The idea that each STCH plant requires a multi-billion-dollar capex investment should be concerning to the community. A roadmap should be laid out—there just may be many other lower-risk technologies to try first.
- The project has too broad a scope that demands a whole range of skill sets and expertise to expect coherent and meaningful achievements, given the resources and timeframe. High-temperature materials discovery, characterization, and testing; reactor design, construction and operation; solar field design and optimization; and TEA can be too much for one project team to do well. Given its low TRL, it may be more effective to break the tasks into separate projects, perhaps under different sub-programs. Moreover, the TEA results, assumptions, and uncertainties may need to be strengthened. This is a low-TRL technology that will demand long-term and sustained commitment.
- The project should be allowed to come to its time-based conclusion and then allowed to re-submit an application for merit review.
- The project is ending this fiscal year.

Project #PD-114: Flowing Particle Bed Solarthermal Reduction–Oxidation Process to Split Water

Al Weimer; University of Colorado Boulder

Brief Summary of Project:



The overall objective of this project is to design and test the individual components of a novel flowing particle solar thermal water-splitting system and show a pathway to a system capable of producing 50,000 kg of hydrogen per day at a cost of less than $2/kg. Further objectives include (1) identifying and developing high-performance active material formations; (2) synthesizing flowable, attrition-resistant, long-use spherical particles from low-cost precursors; (3) demonstrating high-temperature-tolerant, refractory, non-reactive containment materials; (4) constructing a flowing particle redox test system and testing components of the system; and (5) monitoring progress toward cost targets by incorporating experimental results into frequently updated and detailed process models.

Question 1: Approach to performing the work

This project was rated **3.1** for its approach.

- It seems this project has increased its focus on reactor design, materials, and critical components, while leaving active materials developments to a sister U.S. Department of Energy (DOE)/National Science Foundation (NSF) project. If so, this is a wise move and entirely appropriate. The team has demonstrated creative thinking in terms of reactor design options, such as integrating recuperated heat to extend operational time and exploring both fluidized bed (near-isothermal) and moving bed (temperature-swing) processes. However, the project resourcing and timeline were not built to carry along two radically different designs—there should have been alignment with DOE earlier on which one to execute. (The fluidized bed approach would have been the better choice.) The project would benefit from engaging a seasoned expert in high-temperature fluidized beds. The presenter gave a run-down of key differences between this project team's implementation of the solar thermochemical hydrogen (STCH) concept and that of Sandia National Laboratories (SNL), which was appreciated.
- STCH is a unique process for solar water splitting that is different from photoelectrochemical (which is very similar to photovoltaics [PV] + electrolysis). The uniqueness of the reactor means that the scaling and cost-learning curves from historical technologies could be very different, and thus it has the chance to be a game-changing technology in the field of solar water splitting. However, to further support this, it should be clarified how the technoeconomics of STCH compare to solar thermal PV + electrolysis. This project is well designed and nicely complements the STCH efforts at SNL.
- The project approach has been successful in addressing challenges and barriers and in meeting project goals and objectives. The project is on track to meet the DOE requirement for eight hours of continuous on-sun operation and production of greater than three liters of hydrogen.
- In general, the approach to solving any one problem is quite sound; however, the cost-effectiveness, longevity, and certainty with which each proposed/identified solution may deliver a system-wide technoeconomic advantage needs to be critically evaluated. For example, the principal investigator (PI) seems to propose 900ºC "waste" heat to run a Rankine cycle, and it is not clear why this would be

considered. The exergetic penalty would be great. Not many cycles, if any, run at 900ºC turbine input temperatures.

- The project's approach requires advances in multiple areas: identification and synthesis of efficient and robust high-temperature water-splitting catalysts, containment materials, reactor design, on-sun testing, and technoeconomic analysis (TEA) of the integrated system. Obviously, project success will depend on having multiple assumptions and diverse expertise.
- The focus has been primarily on developing the perovskite, which the project team has been working on for many years, including prior to this work. The reactor work is interesting but unlikely to work. The project is developing a coating technology.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **2.9** for its accomplishments and progress.

- This project looks to focus on individual components and not a large-scale reactor, which is probably a good plan for a university lead. The collaborators at the National Renewable Energy Laboratory (NREL) High-Flux Solar Furnace evaluated the particle performance, and performance was well above the projected outcome—but for a shorter period of time than eight hours. The TEA seems very promising, notably because the sensitivity analysis showed very little deviation from $2 per kilogram of hydrogen with seemingly large parameter ranges; the reasons for that were unclear. A <$0.70 variation in hydrogen cost with >2X change in heliostat cost is unexpected. Also, the stability results are promising but not earth-shattering, but irrespective, it is not clear that the cost of atomic layer deposition (ALD) was included in the TEA. The response to reviewer comments from last year does not quantify ALD cost but simply states it is not a problem. Separation results are exciting, too, as is demonstration using hercynite and three standard liters of hydrogen in eight hours. Perhaps the solar/electric furnace (Harper International Corporation) is relevant to this project on solar hydrogen. It seems the electronic component may be just an option. If so, a global minimum for ultimate cost based on the fraction of heat going to STCH vs. concentrated solar power (CSP) electricity (followed by hydrogen via electrolysis, for example) should be analyzed to identify the benefits of co-generation or whether solar thermal PV + electrolyzers is projected to be less expensive.
- There has been excellent progress on meeting the hydrogen production target. However, it is unclear how the demonstration experiment was able to succeed if cycled between 1350ºC and 1500ºC when oxidation occurs at 1000ºC. Also, it is not clear which scheme (fluidized bed or moving bed) was utilized for this demonstration. The project demonstrated sufficient efficiency of the ion transport membrane (ITM) solid electrolyte oxygen separation (SEOS) component. However, there was no discussion of the unavoidable trade-off between efficiency and flux, and the impact that might have on the process scheme, nor considerations of the potential for scaling up this technology. This seems to be a critical success factor. The plans to identify and mitigate showstoppers were not made clear. There were positive results for high-temperature oxygen barrier coating materials, but it is unclear what the material of choice is. It is not clear how any cost/performance tradeoffs will be addressed. The publication record is commendable.
- While the project has hit some intermediate milestones and may well hit the funding opportunity announcement target of three liters of hydrogen in eight hours, a higher level of sophistication is required to gauge (1) the cost of doing this and (2) the reliability with which it may be achieved. Still, were it not for the PI and team's accomplishments, we might not even be able yet to list these concerns.
- The project team has met their goal of moving their technology from technology readiness level (TRL) 2 to 3 through their work on materials of construction and coatings, design of the reactor and other components, efficiency determinations, and TEA of costs for an integrated system. The TEA shows that realization of the DOE cost goal is heavily dependent on reductions in the cost of heliostats. Although research in this area is outside the scope of the Fuel Cell Technologies Office, it would be helpful if DOE and/or the project teams gave updates on progress in this area when possible.
- Using a sweep gas is a good approach, but it does create the need for separations. The coating may be able to inhibit gas diffusion; however, it will be in an abrasive environment, which will likely wear it out quickly. The cycle time for this system is extremely long. The project has had a good budget for three years, and the progress has been modest. The presenter started his presentation by pointing out what he

perceived as problems with another project (by name). This was inappropriate and unprofessional. It lessened the accomplishments that the presenter has made.
- So far, the project's accomplishments represent a modest contribution toward development of future high-performing STCH materials and systems. That said, it is also important to recognize that this project and any other solar thermal concepts are far from achieving water-splitting systems capable of 50,000 kilograms of hydrogen per day at $2 per kilogram, the current DOE objective.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.4** for its collaboration and coordination.

- The collaboration of this project team with NREL and the NSF project team has been excellent. It is likely that this collaboration will continue after the end of these projects. This would be very helpful for the continued development of reactor materials, as would collaboration and communication with other groups developing and modeling these materials. The participation of industrial partners (e.g., CoorsTek and Ceramatec) has been valuable to the development of the reactor coatings and components and will be crucial for the scale-up and commercialization of their technologies.
- Collaborators are mostly from industry, which is somewhat unique for solar water-splitting projects, but this shows industrial support and further validates the promise of the concept. The university and national laboratory collaboration are also strong, and the models for coating stability match well with experiments. This project also nicely complements the STCH efforts at SNL.
- The project has a well-balanced team of collaborators: a national laboratory (NREL), other academic institutions (Australian National University), industry (CoorsTek, Ceramatec, SABIC), and consultants. Each collaborator seems to have made meaningful contributions to the project.
- This was done really well.
- There are several unfunded collaborators.
- The list of collaborators seems reasonable, although it is not clear what the contribution or commitment levels are from the paid and "non-paid" partners to the current project stage.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.4** for its relevance/potential impact.

- This group has a clear path to obtaining their final project metric of three standard liters of hydrogen in eight hours. This was deemed an appropriate target by DOE at this stage of development of the project and the field, and the result should therefore be commended. Also, the TEA is very promising and should be validated by Strategic Analysis, Inc., and NREL. This effort seems game-changing in the solar-water-splitting portfolio.
- The project fully supports the DOE goal of reducing the cost of hydrogen production from renewable sources to <$2 per kilogram. The project has made progress in demonstrating the competitiveness of STCH production through the technical progress made during the project. The efficiency comparisons between solar thermochemical and other forms of solar-based water splitting (e.g., PV electrolysis) are also very helpful.
- STCH needs projects like this one to move from paper concept to testable option. The work exposes critical issues. However, this is where a detailed TEA, beyond just a Hydrogen Analysis (H2A) case, is critical. It may be that the researchers are too invested to expose fatal flaws. For example, the huge impact of active material kinetics is acknowledged but does not show up in the H2A results. If the answer is that the H2A Advanced Water Splitting Materials Consortium (HydroGEN) needs to focus on kinetics over, say, activity, that is something DOE and the community need to root out.
- The project scope and objectives are very relevant to the Multi-Year Research, Development, and Demonstration Plan in advancing research toward affordable and renewable or low-carbon hydrogen sources.

- This project cited CSP with thermal storage for heat and electricity as enabling. This has not been well appended, and claims need further vetting.

Question 5: Proposed future work

This project was rated **2.9** for its proposed future work.

- The project is scheduled to end this year. Future work would presumably continue under a new project and/or through the HydroGEN consortium. The presentation provided a logical outline of what might be addressed in future work, which focused on continued modeling and testing of reactor and coating materials and components. Issues of scale-up and longer-term testing would also need to be addressed. For example, if particles of reaction were expected to last at least a year of one-hour cycles, 10 hours a day, that would be a necessary lifetime of 3650 cycles (3650 hours). Tests longer than 200 hours would be needed to adequately determine the reactivity stability and robustness of the particles. Acquisition and testing of a (>850ºC) temperature ITM SEOS membrane would allow for valuable updated estimates of the efficiency of the reactor system. A hybrid solar–electric receiver was proposed as a possible future endeavor. This sounds like a good idea, and efforts should be made as soon as possible to garner industry and utility interest in this design.
- The proposed work on detailed thermodynamic and kinetic optimization of current reactive materials is not likely to add much value, given that more efficient water-splitting materials need to be discovered to achieve the DOE goals. The materials discovery effort should be separated from the reactor or TEA work, perhaps moved to the new Energy Materials Network. If funding continues in 2018, this project should focus on reactor design and testing with existing and well-characterized reactive materials. Also, the proposed work on the hybrid solar–electric receiver could be a distraction. Although important, integrations with PV for parasitic loads or CSP storage systems are conventional engineering issues that are meaningful at large scale but not critical to the success of the STCH pathway. Besides, such considerations of heat and power integration are better handled by commercial CSP vendors.
- A few experiments could have been conducted more rigorously. For example, it was reported that SiC particles could be protected from reacting with steam by coating them with alumina. It seems that this has been reported in the literature numerous times. It would have been much more relevant to coat a slab of SiC with alumina and then allow the perovskite particles to fall against it, at temperature, followed by measurement of the persistence of the Al_2O_3 coating at the impact site. As hinted by the PI himself, we would probably have to completely throw out what is now claimed as success as actually inadequate. An alternate coating/approach would be required. Proving materials performance and lifetime/reliability is perhaps most value-added when those tests represent, as closely as possible, actual operating conditions.
- The future work is fine, but it is not certain that a larger focus on solar–electricity co-generation should be considered. Optimizing STCH alone still seems like a large challenge.
- This project is ending.

Project strengths:

- The project has a well-funded, creative team with a well-thought-out set of collaborators (e.g., NREL, NSF, industry). The focus on the reactor enabled more depth on that front, avoiding dilution by relying on the active sister materials project. Strengths also include integration of experiments and modeling across the board.
- The project strengths include the strong collaborations with the NSF materials discovery project, the innovative designs for reactor component materials coatings, and the modeling efforts (e.g., kinetics of reaction, inert gas sweep vs. vacuum).
- Strengths include an excellent PI, an excellent team, and great collaborations, as well as better use of science and theory to guide materials selection/discovery.
- Project strengths are the project team's experience with solar thermal and high-temperature systems, plus the availability of solar simulator and on-sun testing facilities.
- The reactor demonstration was fantastic.
- This was a well-funded project with a large team.

Project weaknesses:

- Any comprehensive STCH project is ambitious, so apparent lack of a project schedule (as mentioned in the last review but not addressed in this one) is disturbing. It is not certain that co-dependent milestones will be hit to ensure project completion by the end date. Also unclear is how sophisticated a process model has been developed. This would allow identification of critical challenges that may force design changes and support a detailed TEA. Of particular interest is the ability to predict/verify the 60% solar-to-hydrogen efficiency being assumed. Lack of active material attrition testing is another potential showstopper.
- The many compounded challenges, especially in integrating the discovered innovations, seems to have constrained the ability to prove viability of the innovation(s) in representative environments. This is not necessarily a consequent of funding and time alone but also planning of the experimental campaign.
- The project lacks perspective. A big-picture discussion and large-scale vision of the STCH system could be helpful to both the researchers and audiences in providing the significance of the project's effort with respect to the long-term goals.
- A strategy and/or schedule for eventual down-select of materials of reaction is not addressed. A realistic timeline for scale-up, commercialization, and deployment of the technology was never addressed.
- The TEA should be validated against practical current systems with the help of Strategic Analysis, Inc., and NREL, and bottlenecks should be more clearly identified.
- The reactor designs were overly simple. The material development was minimal. The project should have worked with SNL on material development.

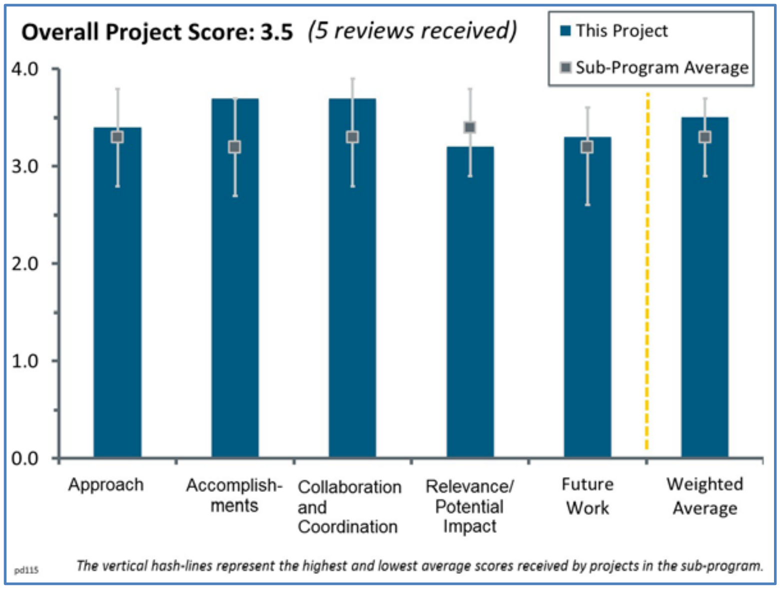
Recommendations for additions/deletions to project scope:

- The project should address the following big-picture questions: the conceptual solar field configuration to make 50,000 kilograms of hydrogen per day, how many acres and how many solar towers will be needed, what the output is from a single solar reactor, whether there are theoretical or practical limits to scaling up a reactor, the ideal STCH material performance vs. existing ones, etc. This is a low-TRL technology that will demand long-term and sustained commitment.
- As the project nears completion, the team should consider providing input to the HydroGEN effort on STCH materials to ensure the project's learnings are transferred to that community. In addition, the team should consider the impact of water feed—quantity and quality—so it can be incorporated into the TEA. (It would be good to know if the plant will need a sophisticated purification system.)
- The project should be allowed to complete its originally planned period of performance and then be subjected to re-compete through re-application and merit review.
- The scope is sufficient.
- The project is ending this fiscal year.

Project #PD-115: High-Efficiency Tandem Absorbers for Economical Solar Hydrogen Production

Todd Deutsch; National Renewable Energy Laboratory

Brief Summary of Project:



The long-term objective of this project is to develop highly efficient, durable photoelectrochemical (PEC) reactors that can operate under moderate solar concentration and generate renewable hydrogen for less than $2/kg from PEC water splitting. The objectives for the current year are to (1) push boundaries on achievable semiconductor PEC solar-to-hydrogen (STH) efficiencies, (2) benchmark STH efficiencies for multi-junction (tandem) PEC devices, and (3) improve material durability through approaches such as stabilizing surface modifications.

Question 1: Approach to performing the work

This project was rated **3.4** for its approach.

- All barriers are addressed with a multi-disciplinary team that fabricates, characterizes, and tests materials with a foundation in theory. The outstanding approach—to first maximize efficiency, then increase durability, and then scale up devices—should lead to DOE cost targets being met.
- The approach has been to focus on maximizing efficiency of tandem photoadsorbers through the development of buried junction 3-5 solar cells, and showing feasibility of a number of approaches to extending the durability of the devices. The project addresses the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan (MYRDDP) targets and leverages future cost reductions for photovoltaic (PV) fabrication based on other U.S. Department of Energy- (DOE)-funded efforts.
- This is the flagship project of the PEC solar hydrogen program. All the other project investigators look to these investigators for leadership and list them as major collaborators. Barriers are being addressed, although more weight should be thrown into durability than efficiency at this point. Nevertheless, bragging rights count for something, and world-record STH efficiency qualifies as such.
- The project has a good approach to achieving DOE efficiency goals. It seems that back illumination could have been helpful for these concentrator cells. Specifically, illumination from the back substrate could minimize parasitic optical losses associated with the protective coatings/counterelectrodes and/or liquid electrolyte. The best-performing devices have excess photovoltage, so the focus should be on increasing photocurrent to maximize STH. Additionally, back illumination would allow for thicker (more effective) protective coating and larger electrocatalytic area, which would be desirable for current densities >100 mA/cm^2.
- The approach observed is primarily related to improving the efficiency of the conversion process; while durability and material stabilization appears as an objective, it does not appear to be included in the individual partner approaches.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.7** for its accomplishments and progress.

- The team has shown great progress throughout the duration of the project and, most significantly, by achieving the world-record PEC STH efficiency. The team is on track to meet the final project target.
- This project has achieved a world-record STH conversion record with benchmarking. Collaborative efforts are underway to improve durability, and they appear to be promising.
- DOE has recognized STH conversion efficiency as the primary driver for a cost-effective cell. The National Renewable Energy Laboratory (NREL) group appears to be well on its way to reaching the 2020 target of 20% STH.
- This project has achieved a record-setting efficiency of >16%. That approaches the DOE targets for 2020.
- The world-record STH conversion efficiency of the tandem PEC device is commendable. It was mentioned that a project goal of 875 hours of operation with <20% loss in STH efficiency was achieved, but this result was not shown in the slides. In contrast, the result on slide 16 shows ~20% loss in photocurrent of the GaInP photoelectrode after 100 hours. There are nice pictures of the PEC flow cell reactor to be used for concentrator experiments, but it is concerning that no measurements have yet been done with the cell and/or any measurements under concentration, for that matter.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.7** for its collaboration and coordination.

- The project is well organized, and there is great interaction between the principal investigator and subcontractors, as evidenced by multiple accomplishments achieved through the collaborative. The investigators have reached out and gotten collaborative support from a number of non-funded groups. Examples include faradaic efficiency measurements and PEC device integration with Lawrence Berkeley National Laboratory.
- There is excellent collaboration with universities and relevant national laboratories. There are no industrial partners yet; as the results get more promising and scale-up is considered, the team will need to add industrial collaborations to ensure that the materials are truly scalable and manufacturable.
- Collaborators have included multiple organizations, some with high-risk approaches.
- It is evident that there are well-coordinated efforts across many research groups/institutions.
- There is a good balance of internal effort coupled with outside materials and expertise.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.2** for its relevance/potential impact.

- Direct PEC STH conversion has the potential to provide hydrogen at DOE cost targets; although these approaches are very much high-risk and high-reward, the payoff could be immense if they are successful.
- The project is well aligned with the DOE targets and goals for renewable hydrogen production.
- The project directly addresses the goals and targets set out in the MYRDDP goals and objectives.
- People who have worked in the PEC field have a good deal of respect for the NREL PEC program. Once you go outside the area, though, there is likely much wondering about whether it (PEC) is ever going to work. Those inside the field will say, "Of course it works!," but until we can put a large array in the desert and have it function for several years, we have not really turned the corner. There are many ways to make renewable, sustainable hydrogen, and aqueous PEC is way down the list in terms of affordability. It is hard to envision a scenario in which PEC could make hydrogen more inexpensively than hydro electrolysis, wind electrolysis, and various types of biomass conversions. Nevertheless, scenarios in which the aforementioned do not fit may exist, and it is not really wise for DOE to force all renewable hydrogen efforts to meet the same $2-per-kilogram goal. No single technology is going to win out under all circumstances. PEC's real competition always has been PV/electrolysis. The basic question is how much hydrogen can be made, and for how long, if the hermetic seal and front contacts are stripped from a PV cell and immersed in water. Looking at NREL's famous PV research cell timeline, all of the better cells are based on GaAs. It is concerning to see that the NREL PEC group is thinking of getting rid of it in order to have a 1.0 eV bandgap semiconductor in tandem with $GaInP_2$. Hitting the theoretical bullseye on the

bandgap chart may open up some serious band edge matching and other recombination issues. The main problem for PEC is the need for a front coating that is optically transparent, antireflective, electrically conductive, impervious to water and acid, and catalytic for hydrogen evolution. That is a tall order, but some progress has been made. Another concerning aspect is if DOE eventually wants the sunlight to be concentrated 10x. In theory it should help, but apparently there are no recent data on this, and it will not be good for durability.

- Developments in synthesis of III-V materials for this project set the stage for high-efficiency device demonstration that is on track to hit the DOE goal of 20% STH. It is unlikely that cost goals will be met in the near future, as these hinge on many assumptions and optimistic technology developments, especially relating to the manufacture of III-V-based devices.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- The team has largely focused on achieving high efficiency for the PEC cell while still maintaining efforts on durability enhancement through barrier coatings, thereby showing the feasibility of generating a PEC device that can achieve the targets. The outdoor tracker and cell have been built and tested. Therefore, the proposed work to meet the final project targets has a high probability of success.
- It will be interesting to hear about the device measurements for production of three liters of hydrogen in eight hours, as this will be an important first step toward trying to scale up this technology and test under concentrated illumination in a more realistic reactor set-up (as opposed to test cells with large electrolyte volume and counterelectrodes). Although the reactor has been fabricated, it is concerning that no preliminary tests have yet been done either with the reactor or to evaluate the stability/performance under 10-sun illumination. Troubleshooting with reactor operation and product gas collection can be anticipated. Additionally, it is surprising that stability measurements were not conducted at this light intensity from the outset, since achieving technoeconomic and throughput milestones depend on operation at the high light intensity and it is possible that stability issues could be amplified under these conditions.
- Future work includes demonstration of three liters of hydrogen in eight hours. While this seems like an important demonstration, it is far from the end goal. Resources should concentrate on meeting the 20% efficiency targets and the durability/lifetime targets of 5, 10, and 20 years. In fact, it would seem that increasing the efficiency targets beyond where the efficiency currently stands is less critical than addressing the photocorrosion issues and longevity issues. Durability of 100 hours seems trivial compared to the required years of service. It seems that the durability issue is continually ignored by all projects in this area; the researchers would rather concentrate on the efficiency target, which is already much closer to where it needs to be, as opposed to durability, which is essentially nowhere.
- Even with world-record efficiency, the project still had many caveats to explore: antireflective top coatings, reflective back contacts, non-noble metal hydrogen evolution catalysts, Ni/Ti epoxy meshes, and lower-bandgap energy materials to better capitalize on tandem effect. However, a word of caution: the real action is in stabilizing the photoelectrode–electrolyte interface without substantially reducing hydrogen evolution activity.
- The team will now demonstrate that three standard liters of hydrogen can be generated with eight hours of sun illumination. While this practical demonstration will be illuminating, resources could be better spent further refining the device to overcome remaining durability and cost issues.

Project strengths:

- Gallium-based semiconductors are generally accepted as affording the highest PV efficiencies and charge carrier mobilities. At this point, it is hard to imagine a PEC program without this technology. Other strengths include a strong internal III-V PV support group and a good team of collaborators.
- The project brings together a diverse team with highly complementary expertise to develop high-performance III-V-based photoelectrodes. The team is to be congratulated on the world record.
- The strength of the project resides in the world-class team assembled and the approach taken, which has generated excellent results to date.
- The project has world-class expertise, performance, and partners.

- The project has developed materials with world-record STH efficiencies.

Project weaknesses:

- DOE studies advocate concentrated sunlight to augment device efficiency, but this group has little to no experience as to what happens when the light gets really bright. We will all find out eventually, but durability issues will likely become even worse than they are already. Steady performance for 100 hours is better than it used to be, but to attract any attention outside the immediate scientific community, it will have to climb by more than an order of magnitude, and even higher if the cells remain as expensive as they are now. There are several strategies to improve efficiency but very few in the way of reducing cost. It is a harsh reality if this is to make it to the marketplace.
- Potentially too much reliance has been placed on a final Hail Mary test that integrates multiple innovations that have been proven only separately.
- Weaknesses include lack of durability and operating lifetime, and the fact that this is not really even being addressed is likely the show-stopping issue for this technology.
- More work is needed on durability and scale-up issues.

Recommendations for additions/deletions to project scope:

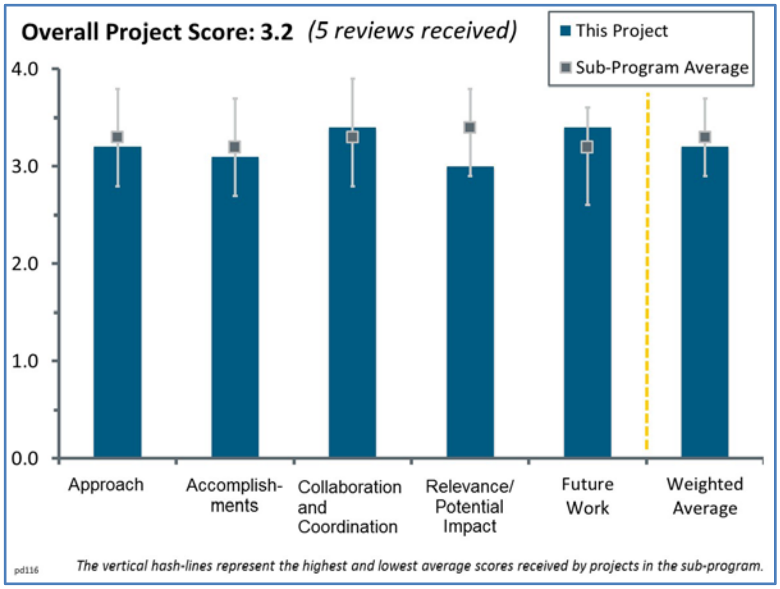
- The existing plans are fine, but it will be crucial to begin testing the reactor under concentrating conditions as soon as possible if the three-liters-in-eight-hours goal is to be achieved.
- Fiscal year 2017 durability tests seem a little short-term but nevertheless should be done if that is where the technology stands.
- This project needs to start addressing the lifetime.
- The project needs serious consideration of scale-up.

Project #PD-116: Wide-Bandgap Chalcopyrite Photoelectrodes for Direct Solar Water Splitting

Nicolas Gaillard; University of Hawaii

Brief Summary of Project:

The long-term objective of this project is to identify efficient and durable copper chalcopyrite-based materials that can operate under moderate solar concentration and are capable of generating hydrogen via photoelectrochemical (PEC) water splitting at a cost of $2 per kilogram or less. The Hawaii Natural Energy Institute (HNEI) will (1) develop new wide-bandgap (>1.7 eV) copper chalcopyrites compatible with the hybrid photoelectrode design, (2) demonstrate at least 15% solar-to-hydrogen (STH) efficiency, and (3) generate three liters of hydrogen under ten times concentration in eight hours.



Question 1: Approach to performing the work

This project was rated **3.2** for its approach.

- The project focuses on low-cost fabrication of chalcogenides and alloying in order to simultaneously meet activity, durability, and cost targets. Project partners include very relevant capabilities in corrosion protection, modeling, surface characterization, and device validation. The project addresses the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan (MYRDDP) targets for PEC hydrogen production. The chalcogenide approach leverages cheap, scalable earth-abundant materials as photovoltaic (PV) materials for the PEC devices. The research uses computational tools to tune the chalcogenide composition, then to fabricate and characterize the materials in a feedback loop.
- The HNEI group recognizes that they will have to develop a tandem cell to push chalcopyrite semiconductor performance past the 15% STH level. Given the evolution of the solid-state PV field, this effort is reasonable and complementary to the NREL effort. Both efficiency and durability issues are addressed.
- This is an attractive approach to achieving the U.S. Department of Energy's STH short-term goal of 15%. It is unlikely that the approach will achieve >20% STH based on current materials performance, especially if an all-chalcopyrite or chalcopyrite/Si tandem is used. If a III-V must be used for the bottom cell, with all of the processing/costs those materials entail, it seems like it would make more sense just to complete the monolithic tandem with a III-V top cell as well. A 900 mV open-circuit voltage (V_{oc}) (project goal) is far from where it would need to be, to be coupled with a Si-based tandem cell. It seems that perovskite would be a better approach in this respect (assuming perovskite stability issues are solved).
- The investigators are addressing the relevant technical barriers, though they seem to be fairly far from achieving them; there are many, many technical hurdles ahead. They have assembled a good team to work on the different challenges, which are daunting, from the hydrogen evolution reaction (HER), oxygen reduction reaction, and separator, not to mention the bandgap materials and corrosion/durability of all of these subcomponents, none of which have been demonstrated.
- The project has a good approach, combining synthesis, advanced characterization, and testing; but it is not clear how the Materials Genome Initiative and the Energy Materials Network are pushing toward true newly innovative approaches. It is not totally convincing that the efficiencies achieved in PV mode will translate to electrolyte exposure.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.1** for its accomplishments and progress.

- The project shows progress toward the final targets in that chalcopyrite materials with desired bandgaps have been fabricated and tested, and buffer layers and corrosion barriers have been evaluated. However, integration of both that would lead to the ultimate benefits desired have been challenging and have limited the project's capability to meet the durability targets. The team recognizes the challenges and has a path toward addressing them in order to meet the project targets.
- HNEI has worked out some pretty detailed and sophisticated synthesis and characterization methods to establish clean phases of various combinations of Cu, In, Ga, Se, and S with 1.7–1.8 eV bandgap energies, essential for tandem design. The project also examined In_2S_3 ink for the buffer layer as an alternative for CdS. The project also examined MoS_2 on TiO_2 as a catalytic top coating on the photoelectrode. A 40% increase in longevity was noted, but since baseline performance was only 250 hours, much greater improvement will be necessary.
- The investigators have shown some good improvements in current density and longevity through some truly impressive work. However, some of the numbers do not seem to add up; they have shown 300 hours of durability with a 50% drop in voltage and almost all of their Cu dissolved, yet they claim they are 45% of the way to their 750-hour 2016 goal. The metric needs to be better defined; simply running is not good enough; efficiency should come into play. The cost analysis just stretches any credibility without further demonstration. The investigators state that if they can hit their efficiency and materials cost targets, then they can generate hydrogen at $3 per kilogram, even if the system lasts only six months. This cannot include installation, service, etc. Also, they must not be considering compression, which generally costs >$1 per kilogram. The economic analysis is obviously an afterthought, but they should not present it unless they can seriously defend it.
- Good progress has been made toward increasing the performance of the chalcopyrite photoelectrodes, although significantly more progress must be made if the project is to achieve its final goals relating to V_{oc}, durability, and STH efficiency.
- Some of the new materials still seem to have issues, which are being worked out, although the team still does not know the exact cause. There has been a good deal of work achieved, but no device efficiencies under solar illumination are reported.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.4** for its collaboration and coordination.

- There is abundant evidence of collaboration among the project partners. There is good use of modeling and characterization capabilities with device and structure synthesis across institutions.
- There is an excellent set of university and national laboratory partners appropriate for this project that can provide all needed skill sets.
- The project has good collaborative efforts with Stanford University and University of Nevada, Las Vegas. Other collaborators were mentioned, but connections were less clear.
- There appears to be very good collaboration and coordination among the team partners.
- The project has proper delegation of tasks and seemingly good coordination among strong partners. It is doubtful that such a large number of collaborators is the most efficient way to run a project.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.0** for its relevance/potential impact.

- The investigators have made good progress, but it is doubtful that they can reach the goals of durability and especially cost. A big change might occur if they improve the separator, or if durability appears to be due to

imperfections in the separator as they suspect. Previously, their goal was to move to a monolithic device, but that goal seems to be abandoned. Although they will not reach the targets, they are making impressive progress toward them, just more slowly.
- Direct PEC can potentially provide hydrogen at a cost-competitive price. This project is still a ways from addressing durability and cost, as the materials do not yet seem to be achieving desired efficiencies.
- Basing a PEC hydrogen evolution cell on thin-film PV currently best addresses cost objectives.
- This project directly addresses the efficiency, cost, and durability targets set in the MYRDDP.

Question 5: Proposed future work

This project was rated **3.4** for its proposed future work.

- Future work will solve many of the remaining issues with these materials, such as durability, cost, and device integration; so while the materials are improving, further funding should really push the investigators toward device-level validation.
- Through the end of the project, the team will continue making refinements to the integration process in order to make a durable and efficient Cu-In-Ga-Se (CIGS)-based device with buried junctions and barrier coatings. The device fabrication will culminate in a final test demonstrating the capability in outdoor conditions.
- The proposed future work offers a logical progression of experiments focused on achieving project goals.
- Many photoelectrode materials were discussed in the presentation, all of which consisted of different combinations of the same five elements. Eventually, some type of down-selection needs to occur; it appears that indium and sulfur will be left out, and two different ratios of Cu:Ga:Se will be further studied. Employing them in combination with lower-bandgap but dissimilar materials such as Si or GaAs looks like a risky endeavor. The solid-state community does not seem to have had much luck in making tandem cells from CuInGaSSe.
- It is not clear how the investigators' work so far moves them closer to their monolithic goals, or why they are going through this intermediary step. There should be continued focus on durability and what is limiting that, though if the focus is working on improving durability for a system that is only temporary, it is not clear how that helps the project. It will be interesting to see what the team is using for HER and oxygen-evolution-reaction catalysts and how that effects the cost and efficiency.

Project strengths:

- The bandgap tunability and potentially low costs of chalcopyrite top cells make these materials attractive for efficiency and low-tandem devices. The team is very experienced in this area, with complementary expertise in materials synthesis, characterization, and modeling.
- The project receives good help from collaborators. Thin-film PV is thought to offer lower-cost electricity, which should ultimately translate into cheaper hydrogen. The team has well-developed understanding of a complex system (three or more major elements).
- The CIGS-based approach is relevant for achieving MYRDDP targets based on cost and scalability, with plenty of room for improvement relative to accomplishments made to date. A good team is assembled that is prepared to address and deal with any barriers that arise.
- Strengths include integration of synthesis, characterization, and theory.
- Strengths include a good team, characterization capabilities, and proper focus.

Project weaknesses:

- The system is becoming progressively more complicated (catalyst/conformal coating/buffer layer/wide-bandgap material/indium molybdenum oxide [IMO]/narrow-bandgap material/back contact), but the complexity may ultimately be justified to improve efficiency.
- The fill factor and photocurrents of the chalcopyrites being made thus far will very likely make the top cell the limiting component in a tandem device. It is not clear that there is a definitive plan in place to improve those values to levels necessary to achieve project goals. Similarly, it is not clear that the chalcopyrites

demonstrated thus far provide enough photovoltage for successful demonstration, even with a high-performing III-V bottom cell.

- The economic analysis is just not credible without more substance. If the investigators were using their system just to make electrons, it seems unlikely that they could achieve a price of $0.05 per kilowatt-hour in a system that lasts one year. If electrolysis and everything else were free, that would put them over $2.00 per kilogram, just for starters.
- The project relies too heavily on assisted PEC and PV measurements, considering the final project target.
- No real-world device testing is a weakness.

Recommendations for additions/deletions to project scope:

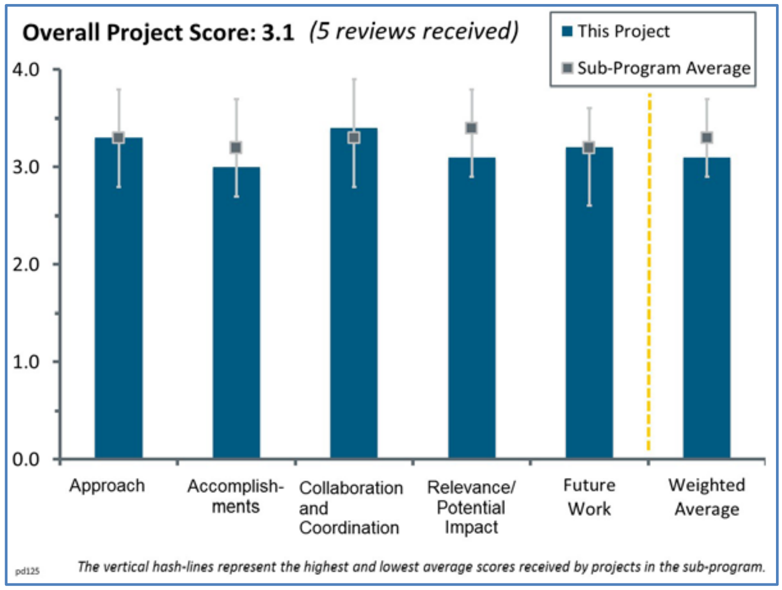
- Emphasis should be on preserving the photoelectrode–electrolyte interface. It is already known that CuInGaSSe cells produce a reasonable photovoltage and can do some electrochemistry. The more insightful question is for how long.
- Integration into devices should be added.

Project #PD-125: Tandem Particle-Slurry Batch Reactors for Solar Water Splitting

Shane Ardo; University of California, Irvine

Brief Summary of Project:

This project aims to experimentally validate a laboratory-scale particle suspension reactor as a scalable technology for photoelectrochemical (PEC) hydrogen production. The novel approach entails stacking the two slurry-reactor compartments in series instead of the more typical parallel, side-by-side arrangement to realize the tandem efficiency advantage and shorten the mass transport distance so that fewer pumps and pipes are needed. The project will perform numerical device-physics modeling and simulations of particle-slurry tandem solar reactors as well as design, fabricate, and experimentally test this reactor concept.



Question 1: Approach to performing the work

This project was rated **3.3** for its approach.

- The project approach is to meet Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan (MYRDDP) targets based on a new tandem particle PEC system including chemistry and cell design using a combination of modeling, experiment, and cell design. The project is novel and unique in that it approaches the problem from a low-technology-readiness-level- (TRL)-based concept that has a good deal of potential to meet the targets. The teaming is such that it uses modeling to assist in cell design and validation prior to confirming with experiment, which saves time and allows the team to address other issues such as particle and shuttle development.
- The project is well conceived and has a nice logical approach to the design, analysis, and demonstration of particle-based PEC reactors. The experimental and modeling efforts are nicely intertwined, and there is a logical progression in the experimental work in going from thin film to particles. The project goals are feasible.
- There are many barriers to be addressed, and the principal investigator (PI) would be hard-pressed to address all of them in the same contract year. Nevertheless, there should be a logical order to it, and doing a fair amount of photoreactor modeling before having a good basic theory of photoparticle function seems wrong. On the other hand, the PI was likely under pressure to show whether photoparticle systems can be affordable under any circumstance, and so this is how it played out. Much of the experimental work was done with semiconductor electrodes in traditional potentiostated electrochemical cells. There may be a limit as to the applicability of those results to photoparticle performance. Because the other two PEC efforts are squarely in the electrode configuration regime, there is a limit as to how well integrated this effort could be with the others. On the other hand, if $GaInP_2$ and $CuGaSe_2$ make good photocathodes, maybe the PI should obtain them as powders and give them a try.
- This is a modestly funded project with very ambitious goals. The project has a large number of technical hurdles: hydrogen evolution reactions, oxygen evolution reactions, passive convection/diffusion. With this modest budget, the project might be better off concentrating on one of the challenges. In the economic analysis and U.S. Department of Energy goals, the project assumes 5% or 10% efficiency. It does not seem to be on any pathway to achieving those numbers, and the intermediate goal is only 1%. Nevertheless, the approach is very interesting and appropriate if the team is happy with 1%.

- This project looks to be successfully integrating modeling and experimental synthesis from the various partners. While two approaches are being examined, these seem to be “reactor designs.” What is really needed is better photoelectrochemistry materials.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.0** for its accomplishments and progress.

- The modeling work is on schedule or ahead of schedule. Some of the experimental work is behind schedule, especially relating to the development of the PEC materials to be used as particles. For example, the photocurrent generated by the photoelectrodes (especially photocathodes) is below target. Part of this is due to unexpected low manpower on the project, so it is feasible that this can be made up. The photoreactor to be used in this work appears to be on track.
- The project has identified hydrogen evolution photocatalysts and oxygen evolution catalysts, as well as a couple reduction–oxidation reaction (redox) shuttle pairs, that appear to easily achieve the 1% solar-to-hydrogen (STH) efficiency threshold. Showing that natural convective flow can support sufficiently different concentration ratios of redox shuttle, obviating parasitic energy losses due to pumping, is an important result. It was clear that the photoparticle reactor model is becoming increasingly more sophisticated, aided in part by collaborators from Lawrence Berkeley National Laboratory (LBNL) and the California Institute of Technology (CalTech); however, it was difficult to grasp which phenomena have and have not been brought into the model. It would help if the PI would prepare one or two slides summarizing what has gone into the model and what is left to do. Several important experimental milestones have yet to be reached, so measuring overall progress relative to DOE goals is difficult.
- The projective main objective is to experimentally demonstrate a new design for a particle-based PEC device. The accomplishments to date include numerical validation and design of a concept that will meet the MYRDDP targets, as well as materials development and characterization for the particles themselves. Significantly, the system has been redesigned to eliminate plumbing by stacking the particle beds, which was validated numerically to be feasible through diffusion of the media. Meanwhile, the materials development to make the photoactive particles is showing progress toward reaching the 1% target. The project has been extended (no cost) in order to experimentally build and validate the device.
- The technoeconomic assessment was conducted, with promising results. Coupling the physics model to demonstrate stable operation is another promising result. The tandem reactor operates at 1% STH efficiency; it is unclear how this is approaching a realistic operating efficiency related to the DOE targets.
- The accomplishments are impressive if compared against the intermediary goals of 1% efficiency, so progress toward project goals is good. When measured toward Hydrogen and Fuel Cells Program goals, the project is an order of magnitude away, and it is difficult to see a pathway for it to achieve overall goals.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.4** for its collaboration and coordination.

- There is nice collaboration between experimental work at University of California, Irvine, and modeling work at LBNL. There is also an unfunded collaboration with a group in Japan.
- The project has good partners and a strong group. Collaboration is efficient in that work is centered at one group, with collaborators supplying either materials or analysis.
- There is evidence of strong collaboration and interaction between the project partners. The modeling side is communicating and interacting with the experimental side and device fabrication.
- Because the work has been mostly particle reactor modeling, it is difficult to identify common interests with the National Renewable Energy Laboratory and Hawaii Natural Energy Institute. Nevertheless, the PI has benefitted from collaborators at LBNL and CalTech.
- The project seems to be successfully integrating modeling and materials synthesis from the partners.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.1** for its relevance/potential impact.

- This project is addressing the hydrogen production targets and could be a critical pathway leading to renewable generation of hydrogen.
- It is unlikely that this project will achieve MYRDDP STH efficiency targets, but there is much value in demonstrating this type of PEC device that could pave the way for low-cost higher-efficiency systems based on better materials in future efforts. The potential to achieve low capital expenditure (capex) is the biggest merit of this project/approach.
- Photoelectrochemistry as a whole looks so expensive in comparison to other sustainable, renewable ways of making hydrogen that some kind of "think-outside-the-box" approach for the project is appropriate.
- While the efficiencies at this TRL are low, the innovative design has the potential to lead to a strong impact, if it can be experimentally verified.
- The project goals are a little difficult to accept. The researchers want to achieve a cost target of \$20/kg H_2 while achieving a 1% solar efficiency. Put another way, if they somehow miraculously achieved 20% efficiency, their costs would be \$1/kg H_2. This is difficult to accept, especially with the short lifetimes given in the analysis. Making these very muted targets will still be extremely challenging, as they have numerous technical challenges.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- The proposed future work extends the timeframe of the project in order for the experimental work to catch up with the numerical models. This seems like the right thing to do in order to complete active material development and scale up the device and particles for the final demonstration.
- It is clearly time to put real particle suspensions in the baggie and see what happens. It would be best if they can find time to develop a model of the nanoparticles before they start fabricating them.
- All of the future work plans are logical and consistent with achieving project goals.
- The demonstration of three liters of hydrogen is important; however, it is unclear if the current efficiencies are relevant to long-term targets. The project is proposing the demonstration at 1% efficiency; the 2020 target is 5%, and the ultimate is 10%. It seems that increasing the photo-efficiency should be the main driver of future work, as the project is an order of magnitude away from where it needs to be.
- Working on making a unit to generate three liters in eight hours seems like more of a stunt then a relevant metric. The time and energy might be better spent on solving some of the fundamental materials problems the project has. Having said that, there is value in seeing where you are and addressing practical considerations.

Project strengths:

- Type IIB reactors offer an attractive opportunity to achieve a combination of low capex and STH efficiency that could meet DOE hydrogen production goals. Although the project does not seem to be pushing the limits of knowledge/performance on the materials side of things, the modeling work and proof-of-principle demonstrations of the reactor should be very valuable for the PEC research community. Additionally, this would be the first demonstration of a Type IIB PEC particle reactor.
- The technoeconomic assessment suggests that this could have a positive impact—and without the durability issues that plague other PEC efforts.
- It is an effective answer to those who maintain that PEC hydrogen will always be too expensive. There is some earlier work to build on, so the PI does not have to start from scratch.
- The project has a good team and has made smart adjustments along the way. This is interesting work.
- Strengths include a good team, concept, and approach.

Project weaknesses:

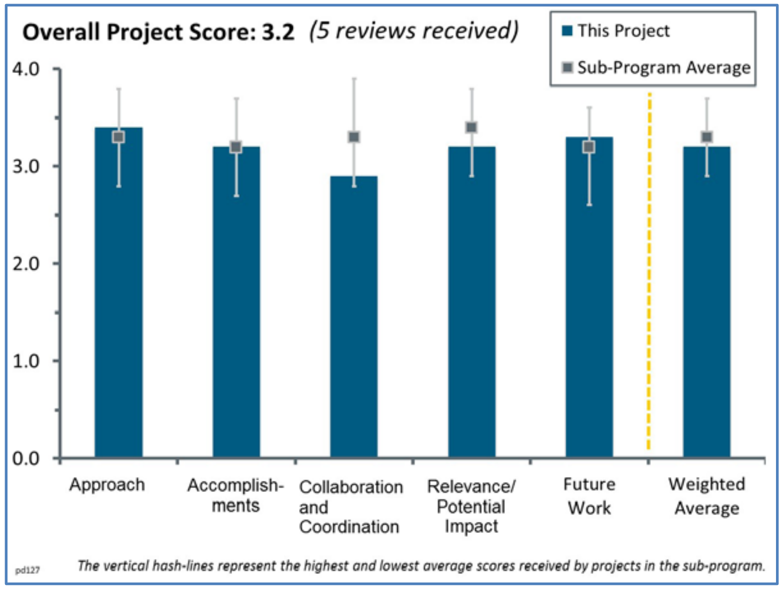
- Pace of materials development and iteration is slow and has led to an extension of the project. However, materials and synthesis are new (outside of scope of 3-5 and Cu-In-Ga-Se systems), and the project has reached out to external collaborators. Additionally, the investigators are addressing reactor design simultaneously.
- The photophysical model of the nanoparticles is still under development and not as well understood as electrode configurations. It remains to be seen how well results obtained with a semiconductor electrode can be translated into a nanoparticle suspension. Many fundamental materials and performance issues remain to be resolved.
- It will be a stretch to meet the STH goals. Selective catalysis (preventing back-reaction) would be very useful but may take a while to develop.
- The current efficiency is far from where it needs to be. The project seems to lack a fundamental understanding of why the yields are so low.
- The project has huge materials problems and a small budget and amount of time to address them.

Recommendations for additions/deletions to project scope:

- If the investigators have not already done so, they might consider trying photocathode in the presence of the redox shuttle; this might outcompete the hydrogen oxidation reaction. Also, including a co-catalyst might be helpful, as there could be a built-in electric field across the Schottky nanojunction. The project could also consider trying the particle suspensions (just one half) in the near future, even if the photoelectrodes are not performing well; it is possible that some of the poor performance of the photoelectrodes could be related to the photoelectrode form factor (issues with carrier collection, ohmic resistances, etc.). Regarding modeling, the project might consider generating theoretical STH iso-contour plots with Eg1 and Eg2 on the x- and y-axes (see old Miller paper, Pinaud & Jaramillo EES 2015, etc.). It is not clear what the optimal Eg1 and Eg2 ranges are for these systems, especially if you consider typical particle densities/cell thicknesses and the associated parasitic absorption losses, nor is it known how much the optimal Eg1, Eg2 values differ from prior analyses for conventional tandem photoelectrode systems. This team should be well situated to generate these plots, and they would be valuable for the community, especially if the values end up being very different from prior analyses for photoelectrodes.
- Better understanding of the fundamental solar conversion is needed, with concentration on why the yields are so low. Perhaps the modeling components should be enhanced or added to increase the understanding of what materials could be developed to achieve more relevant quantum yield efficiencies. What is really needed is better photoelectrochemistry materials; concentrating effort on developing those materials rather than optimizing reactor designs around inadequate materials will achieve more valuable results in the long term.
- The PI understands that the redox shuttle electrocatalysis must have asymmetry, yet there is no obvious effort to deal with that issue. The redox shuttle will have to have more structural complexity than simple inorganic salts. Maintaining particle suspensions is going to be tough if there is no fluid flow because of pumping.
- The project might drop the three-liter demonstration if it is a large distraction.

Project #PD-127: Sweet Hydrogen: High-Yield Production of Hydrogen from Biomass Sugars Catalyzed by in vitro Synthetic Biosystems

Y-H Percival Zhang; Virginia Tech



Brief Summary of Project:

This project addresses the Fuel Cell Technologies Office (FCTO) objective of developing cost-efficient advanced biological generation technologies to produce hydrogen. Investigators are using enzyme cocktails to catalyze the production of hydrogen from renewable sugars (e.g., biomass sugars or starch) and water. This approach is expected to yield high-purity hydrogen at high rates through low-carbon production using local resources.

Question 1: Approach to performing the work

This project was rated **3.4** for its approach.

- The project identifies a number of barriers to producing hydrogen from biomass and uses an approach that is different from others in the portfolio and those identified in the FCTO Multi-Year Research, Development, and Demonstration Plan (MYRDDP): using an in vitro enzyme system to convert starch to hydrogen at high yields, with the approach focusing on improving production rates, increasing the volume, and showing cost-competitiveness. The approaches for improving rates and reaction volume are based on genetic engineering and molecular biology techniques; for some of these subtasks, such as shifting coenzyme preference, multiple strategies are identified. For the cost analysis, the Hydrogen Analysis (H2A) model is identified in the milestone table. The overall approach could be clearer, with a description of the expected enzyme/coenzyme combinations and reactor set-up (scale, temperatures, batch time length) for the final or modeled system. Some of this is still in progress based on the project results, but with all the different experiments in developing conjugates and biomimetic coenzymes, it is not clear what the final "mix" will be.
- The project is well designed, as demonstrated by the hydrogen production rate's doubling each year while costs are reduced by producing four enzymes in one expression. Further use of the starch feedstock results in production of high-purity hydrogen. Also, since there are no side reactions, it is easier to get close to theoretical yield. However, it should be noted that what will happen with dirty biomass remains to be seen.
- The project presents high-level scientific results in a very well-designed timeline. The approach seems reasonable to address barriers associated with an early-stage project. However, regarding the high-demanding technology of the project, the research needs to move forward to overcome challenges, such as scaling up the overall process and enzyme/coenzyme cost production, to be considered as a practical hydrogen production technology in the long term.
- This is a very innovative project. It is good to see the support for a high-risk–high-reward proposal. The approach seems to be generally strong. However, at times it was not entirely clear how all of the different project pieces fit together. While the approach may be solid, it could be beneficial to spend a little time ensuring that the full scope of the project is accessible to the reviewers.
- The synthesis of the enzymes to hydrogen production seems very interesting and novel. However, it is not very clear whether, as the project scales up, the cost targets will continue to be met and whether the benefit of this will disappear entirely once the system begins to scale.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.2** for its accomplishments and progress.

- The principal investigator (PI) is demonstrating good progress on the stated project goals. The project has demonstrated complete starch utilization for hydrogen generation for the first time.
- The work related to improving the reaction rates and yields has shown progress, as has the work to shift the specificity of enzymes to utilize lower-cost coenzymes. The project has increased the volume of the reactor since the start, increasing from 1 ml to the 10 ml reactor size targeted by the fiscal year (FY) 2016 go/no-go milestone, but the FY 2017 third-quarter (Q3) milestone of a 1 L reactor has been delayed to December 2017. Based on the information in the presentation, the H2A cost analysis subtask has a significant amount of progress left to go and does not seem likely to meet its FY 2017 Q3 milestone deadline. All cost estimate information provided is based solely on the cost of the starches, the enzymes, and the coenzymes. The capital and operating expenditure (capex and opex) inputs are apparently in process, but these are a substantial part of the H2A model and are important for demonstrating that the system would be feasible, both from a cost and an application perspective.
- Scientifically speaking, the project succeeded in overcoming barriers such as co-expression of multiple enzymes in one host, enzyme/coenzyme production, and scale-up of enzyme production in a 1 L reactor. The hydrogen production rate is the highest ever obtained. However, although promising, these results were obtained at a very small scale. There are insufficient quantitative results to assess the price and scale in which this work can be accomplished. Moreover, not much information was given to ensure the stability of the hydrogen production rate in long-term operation.
- Reasonable progress is occurring toward the productivity target. However, it is not clear how the process will optimize to reduce costs of production from $1000 to $10 per kilogram of hydrogen between June and December 2017. There has been a nice increase of hydrogen from 200 mmole H_2/L/h in 2016 to 550 mmole H_2/L/h in June 2017, so it is conceivable that, during scale-up, the project may reach 750 mmole H_2/L/h by December 2017. However, it is not certain that the 2020 target can be met.
- The project seems a discovery-based fundamental research project. In this way, the project has completed or is on track to complete major milestones. However, sustaining peak hydrogen production may be critical for this project to be successful.

Question 3: Collaboration and coordination with other institutions

This project was rated **2.9** for its collaboration and coordination.

- The project involves work done in two laboratories: the PI's laboratory at Virginia Tech works on enzymes expressed in Escherichia coli (E. coli) and the improvements to increase rates and alter specificity, and a laboratory at the University of Georgia is doing mass production of the hydrogenase from the hyperthermophilic P. furiosus. The degree of interaction beyond sharing purified enzymes is not clear.
- There are only two universities participating in this project. It would be nice to see industry or national laboratory inclusion in the research for scale-up support.
- Very little information was given on collaboration details. An industrial partner would be important at this stage to analyze the feasibility of producing these enzymes on a large scale.
- There are collaborators in place. It was not evident that the PI is leveraging other resources to boost this study.
- There is insufficient information on collaboration details.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.2** for its relevance/potential impact.

- The combination of the enzyme complexes and new hydrogenase SH1 (once loss of catalytic subunit is solved) may allow scaled-up hydrogen production increases that may eventually reach the DOE 2020 hydrogen volume and cost targets.
- The PI has a novel approach that could potentially have an impact on other fields. This is an innovative project, and it would be good to see it continue.
- This project does not fall into the standard pathways identified by the MYRDDP, so the MYRDDP pathway-specific goals are not entirely relevant. The project does address barriers related to hydrogen production from biomass. The project is certainly making progress toward increasing hydrogen production and yield using enzymes. The main FCTO objective identified for the project is to develop an in vitro biosystem that can produce hydrogen at a projected cost of $10/gge by 2020, but without a clear cost analysis of the entire system, not just the enzyme and starch costs, it is difficult to evaluate whether this will be successful in meeting the goals. The totals provided for just the starch, enzymes, and the lowest-cost coenzyme listed (nicotinamide riboside [NR]) add up to just over $8 per kilogram, which means the impact of the other costs may be a barrier to meeting the $10-per-kilogram target identified by the project. The proposed "sugar car" model does not appear to be relevant to the FCTO goals. Even considering the sugar conversion system as an alternative hydrogen storage system, at least five separate containers or system units are listed that would be needed to replace the hydrogen storage tank. Without compression, little hydrogen could be stored, so the system would likely need to be able to produce hydrogen on demand. The presentation compares starch to onboard hydrogen storage by noting the 14.8% hydrogen by weight, but the presentation does not take into consideration the rest of the system required to produce the hydrogen, or even the water required for the reaction to produce that amount of hydrogen from the starch (based on the provided reaction formula and cost analysis inputs).
- This is a discovery-based fundamental research project. The results, besides being outstanding, succeeded in small scale. There is a long way ahead to overcome scaling-up barriers and so achieve Hydrogen and Fuel Cells Program goals.
- The project value appears to be in a discovery-based fundamental research project. The scale-up is also important.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- Stabilizing coenzymes, improving expression levels and specific activity of SH1 production, and getting assistance with scale-up appear to be logical next steps.
- The project is nearing its end, and the main technical roadblock to completion appears to be issues with producing enough hydrogenase to scale up to the 1 L reaction demonstration. There is only one future step identified related to this: moving in a second copy of the full suite of hydrogenase genes. If this is not successful, it is not clear what the alternatives are, and whether this is a show-stopper or if it will simply take more time and batches to make the required enzymes.
- The proposed future work for the project's remaining six months is very challenging. The final 1000 ml volume of hydrogen reaction is still too small to guarantee the hydrogen production rate's stability using this technology.
- The cost analysis needs to be expanded, but it appears that the PI is aware of this.
- The scale-up step is important in showing the feasibility of the project.

Project strengths:

- Strengths include the following: successful enzyme and coenzyme production, complete starch utilization for hydrogen generation through enzymatic phosphorylation of starch, ultra-high-speed production of

biohydrogen gas in vitro, development of analysis methodologies, development of technology, and several publications in high-impact journals.
- The project is developing a hydrogen production system that is significantly different from others in the DOE portfolio, which if successful may be a way to avoid some of the barriers that other production pathways face. The project has made strong progress in enzyme engineering, increasing reaction rates and identifying novel ways to shift the enzymes to work with lower-cost coenzymes.
- A clear strength is the biological generation technology that allows co-expressions of enzymes that can be anchored on a substrate to increase reaction rates.
- The project is highly innovative, with a novel approach.
- Important gains in enzyme production were obtained.

Project weaknesses:

- More analysis and support are needed for the claims on costs. In addition to missing key aspects such as capex and opex, some assumptions are provided with limited or no supporting data. For example, the claim that the cost for starch would drop by a third in the future does not have supporting data, and the source for the estimate of $200 per kilogram of enzymes is not entirely clear, given the various ranges provided for industrial enzyme costs.
- Weaknesses include the small-scale reactions, use of clean sugars, and insufficient results of hydrogen production rate stability. In addition, the cost reduction strategy was not clear.
- Not much information was given to determine how long certain hydrogen productivity rates could be achieved. More detail concerning hydrogen production rates is needed.
- It was not clear that the cost of maintaining the two plasmids is included in the analysis of the overall financial cost assessment.
- The lack of a suitable scale-up partner is a project weakness.

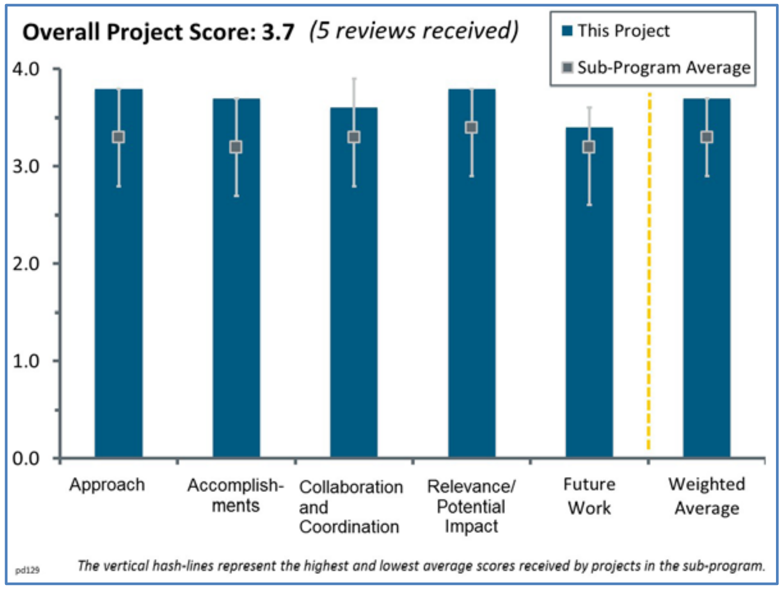
Recommendations for additions/deletions to project scope:

- The project should develop a clear cost analysis with information on all inputs and a description of expected reactor parameters (e.g., overall system size, reaction temperature, run times). In addition to their use for input to the cost analysis, the reactor parameters would be useful in understanding how feasible the system would be in different applications.
- More information about hydrogen production is needed. The approach appears to be primarily in demonstration of in vitro biochemistry of isolated enzymes and genetic tools for overexpression.
- Experiments with actual renewable feedstocks are recommended.
- The project has already noted the need for a scale-up partner.
- The cost analysis should be improved.

Project #PD-129: Novel Hybrid Microbial Electrochemical System for Efficient Hydrogen Generation from Biomass

Hong Liu; Oregon State University

Brief Summary of Project:



The project's target is to develop an efficient, hybrid fermentation and microbial electrolysis cell for hydrogen production that uses low-cost feedstocks (specifically lignocellulosic biomass and wastewater) at a cost close to or less than $2/kg hydrogen. The hybrid fermentation/microbial electrolysis cell system has the potential to be integrated with lignocellulose pretreatment/ hydrolysis or wastewater treatment processes. Specifically, the project is addressing the low hydrogen molar yield, high cathode cost, and low hydrogen production rate associated with current approaches. This is being done by (1) identifying a bacteria strain that produces >10% yield from all major sugars, (2) developing robust and low-cost cathode materials, and (3) performing system cost modeling to prioritize the critical factors and demonstrate potential to meet DOE cost goals.

Question 1: Approach to performing the work

This project was rated **3.8** for its approach.

- The project approach starts with an ambitious target, developing a microbial electrochemical system that can produce hydrogen from biomass sources at or below $2 per kilogram. The approach is to use a hybrid fermentation–microbial electrolysis cell (F-MEC) system, working the two systems separately first to improve performance and gather data, and then use analysis to develop and then demonstrate a reactor that is planned to produce 24 liters of hydrogen per liter of biomass per day. The strong focus on using cost and system analysis to guide later steps, including the design of the hybrid reactor, is a good approach. The approach of evaluating the viability of both biomass hydrolysates and wastewater increases the feasibility of the project—wastewater may be an attractive feedstock because it is low-cost and can even provide an avenue for revenue generation, but wastewater also has more challenges. Hydrolysates are more expensive but are a more consistent and less challenging feedstock. Evaluating both means that even if the wastewater challenges prove to be too high a barrier, hydrolysates may be used, and if both options can be demonstrated, the technology will have more potential applications.
- The project approach is excellent, despite the fact that it was not clear how the F-MEC system will be designed so that, optimally, both processes occur simultaneously. Having multiple teams has significantly improved their results to address the barriers, considering feasible strategies that target scale-up of the biomass-to-hydrogen technology, such as the use of mixed bacterial culture from environment sources, the use of a low-cost methanogens inhibitor at low concentration, and the study of a low-cost catalyst to the MEC system.
- The principal investigator (PI) has an innovative approach, and the use of wastewater is an asset. The work on the inhibition of methanogens is strong and will have a medium to high impact on the field. The work evaluating different catalysts is also strong and will complement other studies in the field.
- The project is well designed, as it starts with the evaluation of simple sugars processed in individual steps of fermentation, followed by MEC processing. Additionally, the use of wastewater in cost projections

allows one to see the impact of a feedstock credit that brings the hydrogen production cost close to the project target. However, actual testing using wastewater still needs to occur.
- The group is making progress on the stated aims while also addressing potential barriers and challenges.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.7** for its accomplishments and progress.

- The research groups involved in this project have had several accomplishments.
    - First of all, they successfully produced hydrogen from pretreated lignocellulosic biomass using mixed bacterial culture derived from environmental sources, which certainly has higher robustness and feasibility to grow at large scales. A hydrogen production rate of >10 liters of hydrogen per liter of biomass per day is a satisfactory result for continuous-flow hydrogen production, despite of the use of mixed pure sugars. However, it is necessary to apply the actual biomass hydrolysate to verify whether the hydrogen production rate will be maintained, since the hydrolysate is more complex than pure sugars.
    - Second, the MEC culture work was also successful, with hydrogen production from liquid fermentation products. However, it was possible to observe an increase in acetic acid concentration, despite the organic acid consumption. The strategy to inhibit homoacetogenesis in the system is unclear.
    - Third, the team synthesized low-cost MoP catalysts with low overpotential that demonstrated high activity and durability under ex situ testing, similar to Pt catalyst performance.
    - The cost performance modeling for hydrogen production from biomass hydrolysate and from wastewater completes the technical achievements of the work.
- The project milestones are being met on time; Milestone 1, Phase II, was completed since the slides were submitted. The project tasks are showing progress and building on the results; for example, the team demonstrated that their existing lab culture grown in the MEC can break down almost all the fermentation products. The team has also identified homoacetogenic bacteria growth as the likely cause of the significant acetate remaining and has started considering methods to suppress this activity.
- Developing a hybrid nonprecious metal (MoP) electrocatalyst for MEC with performance similar to Pt is a major accomplishment, as is the identification of a bacterial culture capable of producing hydrogen from all major sugars. Further, using mixed sugars, the fermentative hydrogen production rate of 8–10 liters of hydrogen per liter of biomass per day over an 80-day period shows noticeable progress towards the 24 liters expected from the hybrid system. However, the ultimate challenge is production from mixed waste, which has yet to be tried.
- The progress of the project is within what is expected for fiscal year (FY) 2016–FY 2017. Progress includes the optimization of fermentation and the MEC cathode development. The steps scheduled for FY 2017 are also in progress, with some results already presented. Some of the challenges listed in 2016, such as inhibition of methanogenesis, were also overcome.
- This is the first year that this project has been reviewed, and the progress in that year has been strong. The research team has demonstrated good progress on all of the stated tasks and has a clear path forward.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.6** for its collaboration and coordination.

- The project shows significant collaboration, both with other groups at Oregon State University (OSU) for biomass treatment and microbial community characterization, and with two laboratory staff at Pacific Northwest National Laboratory (PNNL) for work on the MEC cathode and cost analysis.
- Collaboration and coordination between OSU, PNNL, and Oregon Nanoscience and Microtechnologies Institute are clear and effective.
- Coordination is evident between partners. All collaborators seem well suited to their divisions of the work.
- The collaboration includes three of the major entities: a university, national laboratories, and DOE. It would be beneficial at some point to have industry input on the commercial feasibility of the technology.

- There seem to be strong collaborations in place.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.8** for its relevance/potential impact.

- As the PI noted in the presentation, the project has set ambitious targets. If successful, this would result in a pathway that could meet the DOE cost goals while using renewable biomass feedstocks; if the wastewater feedstock could be used, the analysis indicates that the ability to treat wastewater could be an added value equivalent to $10 per kilogram of hydrogen and open the system to applications in food processors and similar industries that generate and have to pay for water treatment. The project's achievements in developing the different components of the hybrid system indicate that there will be progress toward the targets, though the full impact will not be clear until the demonstration reactor is designed and tested and a full cost model developed.
- The project aims seem to be well aligned with the DOE goals. There are several advances that have been made that aim to move toward scaling up the process.
- This project meets the cost and performance requirements of the Hydrogen and Fuel Cells Program. A number of advances have been made that may also be applicable beyond this work.
- This work has direct, real-world applicability.

Question 5: Proposed future work

This project was rated **3.4** for its proposed future work.

- There is a clear path to keep addressing the barriers and challenges. It is important to obtain the stability of the cathode catalyst performance and to obtain stability of the hybrid reactor in continuous operation, which may be the main challenge of this project.
- The optimization of the individual steps, followed by building of the hybrid system, appears to be a logical set of next steps. However, the researchers should probably consider optimizing the bacteria and electrocatalyst for converting waste to hydrogen prior to building the hybrid system.
- The information about future plans is limited, but the plans are logical extensions of the current work. The project has identified barriers to the work and has noted plans to address these.
- The proposed MEC optimization, the hybrid system evaluation, and the model of costs seem reasonable for this project. It is important to test the long-term stability of hydrogen production through the hybrid system.
- The presenter responded well to questions in the room. The presenter was aware of possible concerns with the work and had a logical path to address the concerns.

Project strengths:

- The project provided particularly strong support for cost assumptions for the wastewater feedstock, based on data from 19 communities and interviews with 17 food and beverage companies to provide clear support for the credit for wastewater treatment. The work on different aspects of the system, for example, utilization of sugars or impact of flow rate, is aimed not only at improving the performance in isolation but also in gathering data to feed into the system and operation parameter analysis and design, increasing the likelihood that the hybrid reactor will be successful.
- One of the main project strengths is the approach to directly reducing the hydrogen production cost, such as the use of mixed bacterial culture as inoculum, which greatly simplifies the overall operating process, making it more feasible to scale up the system. In addition to that, the use of low-cost feedstock and the study of low-cost cathodes enable the use of MEC as an additional process to improve final hydrogen yield.
- The project is technically well designed and logically planned, and there is excellent expertise from the partners. Progress has been made in system design and analysis, as well as in investigations and consideration of designs and innovations that combine the strengths of dark fermentation and MEC processes. The tests conducted using mixed culture are also great strengths of the project. The use of mixed

culture is a major advance for the reduction of costs in the production of biohydrogen, since it allows the use of several sources of wastes that do not require the sterilization step.
- Strengths include real-world applicability (use of wastewater) and research output that could have medium to high impact on the field.
- The progress with the fermentative hydrogen production from multiple sugars using a single bacteria proves the concept is promising.

Project weaknesses:

- No weaknesses are noted at this time. The concerns that were raised during the question-and-answer session were already known to the PI, and there was a logical path to address the concerns.
- There are no apparent project weaknesses at this stage.
- Some of the information on the Hydrogen Analysis (H2A) analysis is confusing, particularly all the different options tested, making some comparisons difficult. In particular, the tornado chart assumptions do not seem to match any of the scenarios shown in the bar charts. This is at least partly because of the large number of options being modeled. The wastewater option is interesting, but few data are provided related to it.
- The identified weak point is very timely and refers to the demonstration of the fermentative hydrogen production stability results, which should be better presented with a larger number of production data.
- Rigorous MEC electrocatalyst stability work needs to be done.

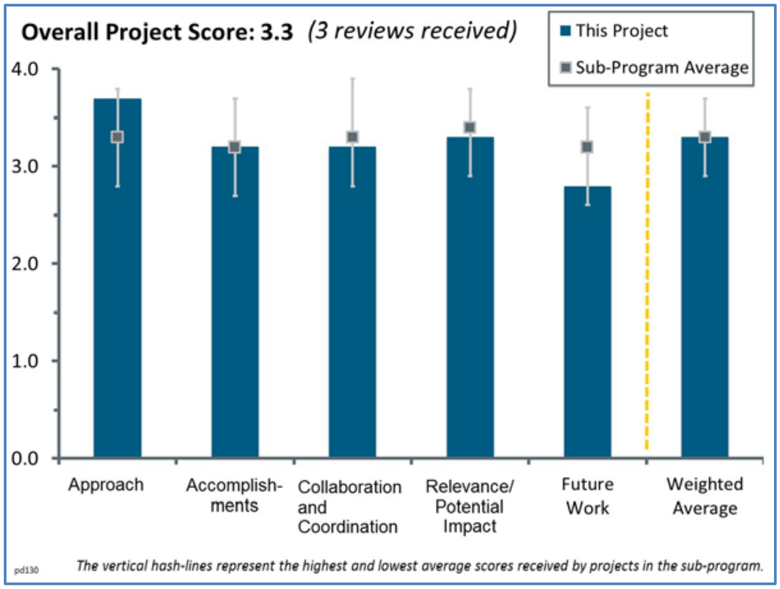
Recommendations for additions/deletions to project scope:

- The project covers all the important aspects to be considered in a low-cost hydrogen production target project: technical and operational improvement of engineered systems for hydrogen production from low-cost feedstocks; the use of low-cost and renewable feedstocks, such as biomass and wastewaters; the mixed bacterial culture performance optimization; and cost performance modeling. No addition or deletion to the project scope is recommended. However, there is a strong recommendation: to obtain experimental data of continuous hydrogen production using the actual feedstocks and to stabilize/optimize the hybrid system using the actual feedstock instead of synthetic wastewaters. This brings reliability and robustness to the project.
- The project is now on the right track. It would be important to aggregate other partners to conduct further system testing using other sources of waste.
- Clarification is needed of what, if any, work will be done using wastewater feedstocks.
- It would be good to test the robustness of the individual stages by using waste as the feedstock.

Project #PD-130: Improved Hydrogen Liquefaction through Heisenberg Vortex Separation of Para- and Orthohydrogen

Christopher Ainscough; National Renewable Energy Laboratory

Brief Summary of Project:



This project aims to utilize the endothermic conversion of hydrogen between isomers (para vs. ortho) to aid in cooling hydrogen. Researchers will develop vortex tubes to aid in hydrogen liquefaction, moving them from Technology Readiness Level (TRL) 2 to TRL 4 such that the technology can be commercialized to units that are 5–30 metric tons per day (MTPD) in size. Exothermic ortho–para conversion results in significant refrigerant use, whereas the vortex concept leverages catalysts for reverse endothermic reaction. The endothermic reaction is expected to cause bulk cooling of the mixture. This concept is expected to improve liquefaction efficiency by >40% by minimizing refrigerant use.

Question 1: Approach to performing the work

This project was rated **3.7** for its approach.

- Focusing on the vortex fundamental principles is the best approach. The team is using both experimental and simulation tools to that end. Once understood, the vortex needs to be optimized for this application, and the team seems to be doing just that. Looking at the integration of the vortex in the plant is critical too. The project is doing a good job.
- This project has a clear academic flavor. The thorough literature/experience history search, combined with detailed fluid dynamic/thermal analysis, including the development of relevant equations of state (EOS) is refreshing. This is excellent.
- The activity is logically structured, with relevant milestones and a clearly identified methodology. The vortex technology is a geometry-based thermofluidic device that can be complicated as it scales. A more clear identification of the actual technique for increasing the technology scale would be helpful. The activity expressly named partner organizations and identified a range of potential entities with which it could collaborate. However, no other formal U.S. Department of Energy program was explicitly identified as a customer or future potential partner. Based on the early presentation timeslot and answers provided to audience questions, it is likely that this was an oversight.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.2** for its accomplishments and progress.

- An unanticipated "near-miss" event generated an atypically long facility delay, but not an unreasonable one. The steps taken during this schedule shift reduce the risk for future facility-related delays on any project using this facility. Once the facility issues were resolved, the activity demonstrated proof of concept and clearly identified the design parameters necessary to drive the next stage of development.

- It looks like a fair amount of progress was made, especially regarding measurements of pressure ratio and outlet temperatures under different circumstances. Task 2 seems to be completed. It is not clear how the computational fluid dynamics work was used for fiscal year 2017, nor is it evident how the results on slides 19 and 20 were computed. The project made a good effort toward trying to quantify the performance regarding DOE targets (slides 21 and 22). However, the numbers do not match up exactly between the two slides. Also, the numbers on slide 21 are confusing: a value commonly accepted for work of liquefaction is 12 kWh/kg, assuming plant inefficiencies and all (ideal work is ~4 kWh/kg). However, the author claims numbers between 20.4 and 30.8 kWh/kg for the Linde–Hampson (L-H) cycle; these values look as if they were artificially "bumped." It seems the L-H cycle is more inefficient than a Claude cycle, although it is not clear that this is so. Perhaps the project could look at integrating the vortex in a Claude cycle and see the comparison with the baseline. On slide 21, the author wrote, "Vortex tube…decreased the work of liquefaction by ~25%." It would be helpful if the two numbers used to support this claim (perhaps 30.8 to 23.7 kWh/kg) were highlighted. It is unclear why only 16.7 kWh/kgLH$_2$ and 7.4-12 kWh/kgLH$_2$ are used on slide 22. The project did a good job on slide 25.
- The accomplishments and progress suffered from the power outage experienced by this project. The power outage was a random event for this project; however, regarding the response of the equipment to such an event, the effects can be mitigated by planning with a focus on safety—as evidenced by the suggestions of the Hydrogen Safety Panel and subsequent system modifications. This should have been done before the experiment was initiated.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.2** for its collaboration and coordination.

- This presentation cited informational sources well and clearly gave credit where it was due. While this particular activity formally lists few collaborators, the interplay between the multiple presenters in the room and answers provided to reviewer and audience inquiries strongly suggest an informal but strong collaboration among many entities in this technical area.
- The collaborators make up the essential talent and guidance needed to make this project relevant to the needs of the liquefaction industry and to potential end users.
- The relationship with Washington State University (WSU) seems to be working well, although it looks like the National Renewable Energy Laboratory's and WSU's tasks are complementary and do not rely on each other. Praxair's role is not clear; it seems possible that Praxair is giving directions as to where the research is going. Not enough information was given on the quality of the collaboration(s); hence, this category earns a "satisfactory" grade.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.3** for its relevance/potential impact.

- Assuming this project is successful in meeting its performance goals (and it is meeting or exceeding the goals), this technology will make a significant impact on cost and reliability of liquefaction systems.
- Reducing the system-level energy to liquefy hydrogen for general consumption is strongly in line with the Multi-Year Research, Development, and Demonstration Plan. Eliminating rotating components reduces parasitic power, increases system reliability, and reduces leak rates. The path to scaling up to meet the stated 5–50 MTPD is poorly communicated by this activity. The actual work of scaling up is clearly identified as a future activity, but having at least a conceptual plan would illustrate the team's thought process.
- The project supports the Fuel Cell Technologies Office goals and objectives by trying to improve the efficiency of liquefaction. The objectives for the life of the project are clear (to increase TRL), but the objectives for the current year are not mentioned, although this was required in the presentation template. The impact on the barrier is not mentioned either.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- Proposed work is well-thought-out and will keep this project on a track for success.
- The future work represents a logically laid-out plan of action. One micro-nit would be to include a tolerance on empirically validating calculations demonstrating "endothermic para/ortho conversion of [>] 5% of a stream." Depending on the labor distribution within the activity, it may be feasible to simultaneously pursue the empirical validation and portions of the technoeconomic analysis.
- The proposed Future Work slide is identical to last year's. Although the four-month delay is understandable, the duplicate future work is troublesome—and disappointing if it is not a typographical error. The same remark applies to the Summary slide and the Remaining Challenges and Barriers slide.

Project strengths:

- It is interesting to see how the concept has evolved from being based solely on the vortex tube (VT) technology to being integrated in existing L-H and Claude cycle-based designs. The characterization of the vortex through experimental and numerical investigation is appreciated. The project has done great work on developing the EOS for the refrigerant. The presenter has great oral presentation skills.
- The team's technical competence is the dominant advantage of this activity. All activities are clearly communicated and apparently laid out in a logical progression. The network supporting this area of research illustrates active collaboration among multiple projects across agencies and countries.
- The careful establishment of previous work (literature and hardware) is a strength, and careful development of models (fluid dynamic and thermal [EOS and transport]) to guide the development is very good.

Project weaknesses:

- There is no real weakness.
- There were difficulties presenting the results and relevance in a useful and clear manner. This makes it very challenging for the reviewer to evaluate the project's progress and relevance, and the evaluation then leans toward negative. For example:
    - On the summary slide, a claim such as "Increase efficiency" in "Relevance" does not appear to be accurate anymore (slide 22 shows lower efficiency).
    - A claim such as "world's leading researchers" in "Approach" may be a bit of a stretch, especially since this claim is not backed up throughout the presentation (no publications, no technology transfer other than a two-year-old patent application, etc.) and does not carry any information for the project in question (and to be honest, this claim could be made by 80% of the projects covered in the DOE Hydrogen and Fuel Cells Program Annual Merit Review [AMR]).
    - The "Accomplishment" claim is very vague. Besides, it may be the House of Quality and a proven concept (although both were already achieved last year).
    - The "Collaborations" claim is not backed up by any mentions throughout the presentation.
    - The "Future Work" is very vague and could be applied to 100% of AMR projects. In addition, this slide is 100% identical to last year's.
    - Slide 12 contains a good deal of information, but it is not clear where we want to be to have a successful working technology.
    - Slide 18 shows how to integrate the VT in the liquefaction plant, but it is not clear what the VT is replacing and what performance the VT should have (upstream pressure, outlet cold and hot temperatures) for this integration to be successful.
    - The last five slides of the presentation were 100% identical to last year's.
- Weaknesses include the impact on the system level from a unit cost basis. Range was mentioned as a key discriminator for the eventual system but ignored within this particular segment of the activity. It would be helpful to elucidate system parameter sensitivities later in the activity.

Recommendations for additions/deletions to project scope:

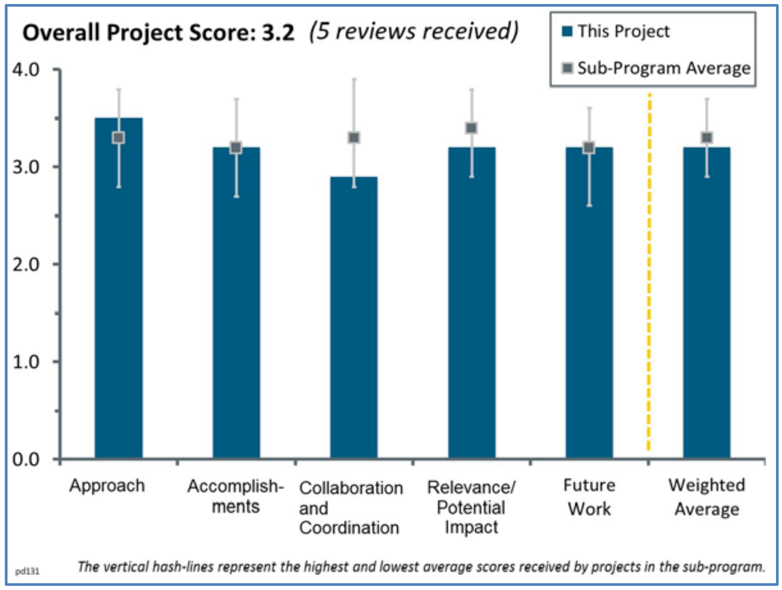
- The project should focus on the VT technology itself: how to improve the ΔT and what performances are needed to use this technology in a liquefaction plant. The project should also be boiled down to what the vortex technology replaces in a liquefaction plant and how it compares in terms of inlet and outlet pressure, temperature, and flow rates. It looks like the nationwide technoeconomic trade study for optimal placement has been dropped, which is great if it is the case. No more work on ternary refrigerants should be done at this point. The project should focus on Tasks 1 and 3 only. There is no need to talk much about para–ortho (cf. slide 5) since no para–ortho conversion is shown throughout the result, only speculated. The conversion would be a nice benefit, but it looks like wishful thinking at this stage. Although the presenter does a great job in front of an audience, the slide deck does not do justice to the project (confusing numbers, complicated figures [such as on slide 10] with no lines or legend for acronyms, lack of big picture, copy/paste from the last AMR, etc.). Much improvement is expected in that area for the next AMR.
- While it is tempting to recommend additional scope to this particular activity, the success to date results from the activity management and the development pace. Rather than risk upsetting the apple cart, no scope change is recommended.

Project #PD-131: Magnetocaloric Hydrogen Liquefaction

Jamie Holladay; Pacific Northwest National Laboratory

Brief Summary of Project:

The Pacific Northwest National Laboratory (PNNL) magnetocaloric hydrogen liquefaction system is expected to be considerably more energy-efficient than the Claude cycle. At 30 tonnes per day (tpd), the latter shows 40% efficiency, while the former is projected to be 70%–80% efficient. In this project, investigators will demonstrate the PNNL system liquefying ~25 kg/day. At industrial scales, the concept is expected to have a figure of merit (FOM) >0.5 (as compared to the Claude cycle system's FOM of <0.3). The project will also identify a pathway to a larger-scale system with an installed capital cost of less than $70 million.



Question 1: Approach to performing the work

This project was rated **3.5** for its approach.

- This project is on its second year, and the principal investigator has clearly demonstrated a strong focus on the barriers needed to be successful. The key approach is to increase efficiency by using bypass flow (which reduces ΔT in the process heat exchanger) and layered materials in the hope of increasing the FOM from <0.4 to >0.75. The U.S. Department of Energy target is 0.5.
- The approach appears to address all of the critical barriers in a methodical way. The project team has taken lessons learned from earlier phases of the project and acted on them in an organized fashion. The project team adequately makes attempts to predict future barriers and prepares for alternate approaches. The project has taken the necessary steps and applied resources to increase project scope when it is critical to success, e.g., atomized sphere generation.
- Although this process is in the early stages of development and more complex than existing processes, the work is well-thought-out, and the approach seems to be as practical as possible.
- This is a great incremental approach with high potential. The topic is highly complicated. The targets are ambitious.
- No doubt the team is working very hard to prove the concept and overcome barriers, but the presentation gave the sense of a wide gap between laboratory activity and the end-game objective of having a technology that delivers the product in a competitive manner as measured in terms of capital and energy consumption.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.2** for its accomplishments and progress.

- The project progress is impressive and clearly demonstrates targets and pathways toward achieving those targets. The project has successfully addressed setbacks and recommendations from earlier project phases.
- Given the complexity and some of the hurdles faced (e.g., powder production techniques for spheres), the project seems to be on track and moving toward the established goals.

- The accomplishments and progress toward the overall project and DOE goals are good, but the project is behind schedule. The milestones for the first quarter (Q1) are at only 75%. The quality of the work is high, and the investigators are on the right path. The presenter claims the team will be able to get back on track with respect to the schedule, but a strong case was not presented that they would be able to.
- The team came up with an interesting layered design, identified materials, and validated their model. Milestone progress on slide 7 is disappointing, but it has to be balanced with the fact that the slides were due in April (2017 Q2). Reports on milestone progress since the last time the slides were due (April 2016—i.e., fiscal year [FY] 2016 Q2, Q3, and Q4 and FY 2017 Q1 and possibly Q2) are needed for better progress assessment.
- The team members are extremely impressed with their accomplishments. The volume of data presented was awe-inspiring; however, it was not clear how this data demonstrated progress to an end goal as measured in energy consumption and specific capital (dollars per tonne). The 25-page presentation covers magnets, particles, heat capacity, etc. but fails to bring it together to show that the technology is progressing to the project's original goals.

Question 3: Collaboration and coordination with other institutions

This project was rated **2.9** for its collaboration and coordination.

- Collaborations with Ames Laboratory and Emerald Energy NW (Emerald) look strong, as do interactions with potential future partners and patent applications.
- The project team has reached out to outside institutions. As the technology readiness level increases, this will become increasingly important, as the project team has recognized in their presentation. That said, the project has progressed nicely with the current level of coordination with other institutions.
- This is one area in which the project could benefit from more industrial interactions. The project is mostly interacting with other national laboratories. This was a comment from the previous year and was addressed in the comment section, but the project needs more collaborations than just Emerald. The investigators should continue their discussions with several industry groups that expressed interest, including those that are interested in magnetocaloric hydrogen liquefier (MCHL) systems.
- This area is very weak. Emerald is the concept originator and current consultant. Ames Laboratory is working on materials, and PNNL is doing shape separation. None of these partners serves to challenge the project or assess its commercial value. If funding continues, DOE needs to ensure the concept is exposed to critical thinking, commercial evaluation, and alignment with the original project goals.
- Perhaps the team should explore other metal powder production processes (e.g., hot gas atomization). It is not clear if the spinning disk process is the most practical.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.2** for its relevance/potential impact.

- This project is focused on addressing the barrier of "High-Cost Low Energy Efficiency of Hydrogen Liquefaction." The project supports and advances progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan (MYRDDP). The only issue is that the DOE efficiency target for 30 tpd (for a small facility) is 85%, and this effort will get you to 70%–80%. However, the installed capital cost, operations and maintenance cost, and energy input numbers for this technology are very favorable and potentially could make this technology very successful.
- The potential to have an impact on MYRDDP targets is tremendous. Measuring the degree of impact remains difficult to predict; however, future work (laboratory demonstrations on the kilogram-per-day level) will shed more light on proposed capital, operating, and energy cost reduction for hydrogen liquefaction.

- Low-cost hydrogen liquefaction is a key to expanding hydrogen and fuel cell adoption to achieve scale. The efficiency goals, if achieved, will drive liquid hydrogen (LH_2) costs down if the capital expenditure does not negate the efficiency benefits.
- The project is very relevant to addressing the high cost of liquefaction. Questions remain concerning the claimed benefits (huge if accurate), given that the application relies heavily on very specific materials.
- The presenter was not able to advise on the forecasted energy requirement to liquefy a kilogram of hydrogen. This metric left the impression that the project is a science experiment, rather than an early-stage concept that has commercialization potential.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- The project has highly effective planning, impressive progress, and logical approaches. The project is extremely complex, and the accomplishments to date, given the funding level, are impressive.
- The proposed future work is very much focused on the final target (i.e., demonstrating hydrogen liquefaction).
- This is very complex project with many moving parts. It would have been good to see a table with all the key assumptions and how risk is being mitigated for each step. It is true that the investigators have focused this year on the demonstration of two critical aspects—bypass operation and multilayer design—but next year, more focus is required: refining the third generation (GEN III) design, designing/building/testing the GEN III system, characterizing the active magnetic regenerator liquefier (AMRL) for 1–25 kg/day LH_2, documenting the AMRL, and evaluating at least two non-rare-earth-based magnetocaloric materials and completing a cost analysis. These are complex tasks, and the future milestones planned for FY 2018 were not shown.
- Based on slide 22, the project wants to demonstrate some theoretical accomplishments (eight-layer operation) but is having a hard time translating activity to a real end game. A clear objective of work in 2017 is to determine whether the concept has potential to liquefy hydrogen and to determine the specific energy to do this. If it is a long shot, the project should focus on another objective that may be more attractive.
- The team needs to continue to address the impact of scale-up on the mechanical component reliability and maintenance costs. The sealing system should be a key focus. Some benchmarking should be performed on extrapolating the reliability and maintenance data gathered in the GEN III system versus current liquefaction plants.

Project strengths:

- This project has many strengths:
    - A principal investigator who is very strong in this field
    - Interactions with other researchers
    - An innovative approach and concept
    - An approach involving the elimination/reduction of the intrinsic irreversibility of the active magnetic regenerator cycle of magnetic refrigerants
    - 88% reduction in magnetic material
    - Increasing the FOM from <0.4 to >0.75
    - An approach involving characterizing Cp, Tc, and magnetic moment for each material
- The project addresses LH_2 production efficiency improvements using the bypass method, which seems compelling. The methodology and testing leverage some previous work on liquid petroleum gas. There seems to be a nice synergy with liquefied natural gas (LNG) to reduce capital expenditure. The cost benefits of a combined production facility—steam methane reforming ---> LH_2 and LNG—should be explored further.
- The technology has high potential and may be the only candidate susceptible to disrupting the state of the art. The project is very relevant to DOE's portfolio—and the rest of the hydrogen community, for that matter. The team is highly skilled, with great expertise in the process and the materials.

- Strengths include the project's potential, innovativeness, and the project approach in terms of both basic science and engineering.
- The team members are passionate.

Project weaknesses:

- The project would benefit from improved presentation skills. Granted that this is a complicated topic with many results, but an effort should be made to convey the technology, the challenges, and the progress to a non-MCHL audience. For example:
    - Slide 6 has too many layers of text.
    - Slide 8 has no takeaway message. It makes sense that heat capacity is temperature-dependent, but it is not clear whether the presentation is saying that low fields are good or bad. A few words on Curie temperature would also help.
    - Slide 9 is too wordy. Maybe a drawing would help.
    - On Slide 10, the equations may be acceptable, but the takeaway message is that the model was updated, which is not obvious from the slide.
    - It is not clear whether Slide 11 shows the temperature of the fluid or the magnets. There is no need for such a long legend, and no need to repeat the dotted line vs. the continuous line.

  Also, much of the work has been done in the high-temperature region, but surprises may show up in the sub-100 K zone. Lastly, some background about availability of materials is lacking.
- This is very complex project, with many moving parts and many key assumptions. It would be good to see a list of all of these key assumptions, either verifying them or confirming their sensitivity to the targets as being low and not on the critical path.
- It is not clear that the team has identified and addressed all the issues encountered with the Prometheus design. It is not certain that the powder production process is practical at scale. Other more common metal powder processes (e.g., inert and hot gas atomization and plasma atomization) have seemingly not been explored.
- Weaknesses include understanding scale-up and determining market potential/commercialization (more of a challenge than a weakness).
- It is not obvious that the team members can determine whether the project has any LH_2 value, nor that they really want to know that answer.

Recommendations for additions/deletions to project scope:

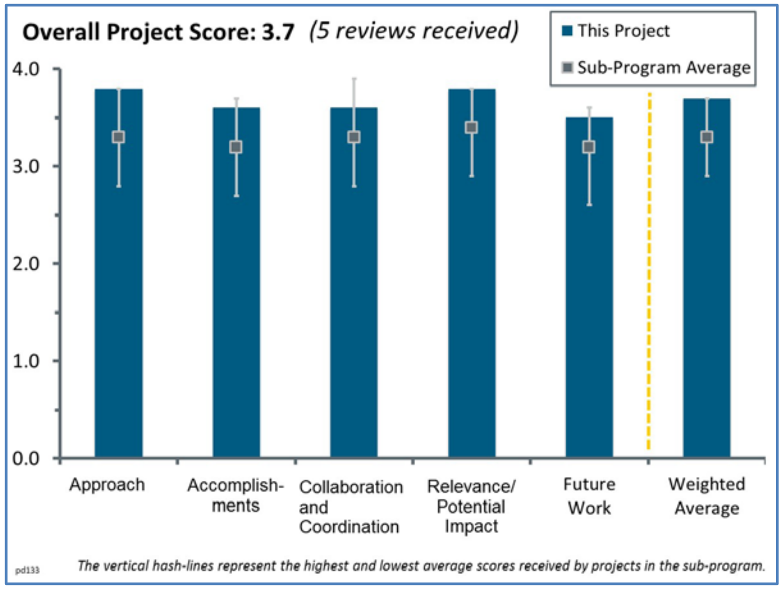
- There are no recommendations for changes to the project scope. This is excellent work.
- This is a very complex project with many moving parts. It would have been good to see a table showing all the key assumptions and how risk is being mitigated for each step. It is true that the investigators have focused this year on the demonstration of two critical aspects—bypass operation and multilayer design—but next year, more focus is required with respect to major steps. If the project is not able to meet its milestones for FY 2017, then the project's focus and scope should be reduced to address the challenges that are slowing the project down. This is a strong project overall.
- Milestone progress since the last time the slides were due (April 2016) should be shown. The project should try to simplify the slides for a stronger message. The presentation should give information about the availability of materials:
    - Which industry is typically using them today
    - How much they cost in dollars per pound today
    - How many pounds of materials are needed for an X-tpd liquefaction plant
    - Among the 10 different materials, which one is the most rare/expensive
    - Which of the alloys are already available today
    - Which alloys quickly reach <100 K conditions
- If funding continues, the project needs to include real partners to critique the technology, performance, and potential.
- The investigators should determine the importance of identifying the right magnetic powder production process and its impact on costs and operation.

Project #PD-133: Hydrogen Fueling Infrastructure Research and Station Technology (H2FIRST) – Consolidation

Christopher Ainscough; National Renewable Energy Laboratory

Brief Summary of Project:

This project aims to reduce at-the-pump hydrogen prices by decreasing the cost contribution of fueling station capital, specifically compression costs. Currently, compressors for large stations can cost up to $1 million. The project is designing and demonstrating a hydrogen station based on a tube–trailer consolidation concept that will increase compressor throughput and reduce compressor size.



Question 1: Approach to performing the work

This project was rated **3.8** for its approach.

- The approach to this "consolidation algorithm" is well designed, feasible, and integrated with other efforts. The approach includes the cost of compressors and their influence on overall station costs. A number of partners participated (companies that deliver hydrogen using tube trailers are needed). The set-up is extensive. The approach addresses how to succeed at peak fueling by keeping some of the pressure at the tube trailers. The approach used is to develop an algorithm to reduce the contribution of compression to the overall hydrogen cost per kilogram, in this case by 50%. The mean time between failures (MTBF) is increased, and back-to-back fills are maximized. A smaller compressor can be used. The analysis shows how a four- to five-time increase in the number of complete vehicle fills is possible. Achieving the SAE International J2160 standard's T40 (fuel delivery down to -40°C) rating is a goal of five 4 kg fills. The Hydrogen Infrastructure Testing and Research Facility (HITRF) is used and set up for two-way flow of hydrogen to/from storage tanks at three pressure levels. The hope is to make this algorithm implementable in everyday retail hydrogen stations. The approach is to allow the station compressor to deliver high throughput during peak refueling demand by supplying the compressor with a high-pressure stream of hydrogen from the storage tubes (consolidated during off hours). The hydrogen in the tubes of a tube trailer (during off-peak hours) can restore the high-pressure supply to the compressor, improving the refueling capacity during peak demand hours. The approach, after the work is refined/done, should be rolled out into the existing hydrogen refueling stations; the approach uses existing hydrogen refueling station equipment.
- This project has a good balance of analysis/modeling, along with the field testing. In a relatively short project, the researchers have made impressive progress in each area. This is the type of project that is most useful to the industry in that it produces relevant results in a timely fashion and demonstrates a usable technology that can be broadly applied by gas suppliers, station owners, component developers, etc.
- This project is the experimental validation of a consolidation algorithm/scheme developed by Argonne National Laboratory (ANL) (Amgad Elgowainy, specifically). This is important to note. The approach for this experimental validation is good, particularly the state of the experimental development. While it will not really affect the overall findings from this work, it is a bit surprising that no energy balance on this overall process has been performed. Unless heat is transferred out of the cascade tanks used to simulate the vehicle, the tanks will heat up from cycle to cycle. It would be good to see an energy balance analysis performed and/or temperature monitoring of the "vehicle" tank simulators. Should this be an issue, it will likely not have a significant influence on the overall conclusions of this work; hence this issue was not sufficient to significantly "ding" this project.

- The approach has been excellent, with the National Renewable Energy Laboratory (NREL), ANL, and PDC Machines (PDC) all contributing to the conceptualization and the method of demonstrating the benefits of the concept.
- As usual, the first steps are to question the assumptions. It was surprising to see a cost of $4.5 million for a reformer skid for 300 kg/day. In the 1990s, United Technologies Corporation was building phosphoric acid fuel cell power plants that generated 15 parts per billion (ppb) of hydrogen (~160 kg/hr) with a clean-up of CO down to 0.5%. The total power plant sold for $0.6 million. The reformer and gas shift reactor together ran about $75,000. The project team should speak with Doug Wheeler about the United Technologies Corporation PC25 fuel cell. Tailoring the duty cycle with a smaller compressor that is active more frequently is one solution. However, MTBF may become an issue. This is often more dependent on run time than on the number of start/stop cycles. Another option might be to generate a higher-efficiency, higher-MTBF, and lower-capital-expenditure (capex) design. The polymer electrolyte membrane (PEM) electrochemical design is intriguing. The PEM concept matches steam methane reforming and electrolyzers (PEM and alkaline). The pump is also a filter for all but water, and water is easier to remove at higher pressures. This project is not novel but is demonstrating the idea of expanding the boundaries of thought at the national laboratories while supplying PDC with a test stand.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.6** for its accomplishments and progress.

- The project has produced the following accomplishments:
    - Equipment is installed.
    - Station upgrades are complete.
    - Buffer storage requirements have been established.
    - Baseline and consolidation tests have been started.
    - Testing has started on the quantity of possible tank fills, evaluating the state of charge after the fills are complete, documenting the station storage pressures, and determining the energy use of the compressor.
    - The vehicle simulator is assembled and working.
    - Work has been started to determine the consolidation operation and how the station capacity can be extended.
- This project has been underway for about 1.5 years. Given that at this point the project is still in an experimental build-out, which is a time-consuming, difficult task, the accomplishments are quite impressive. Building a high-precision experimental facility to produce high-quality data is not an easy task. The project is doing a good job.
- To upgrade the test platform, install and test the new compressor, and validate the models in the short period of project time is impressive. It would be good to see the project continue beyond its end in that it is not certain that all of the cost and reliability issues will have been adequately addressed by the project's conclusion. It would appear that there is considerable potential value to be gained in the project by continuing to look into this topic.
- The project team has made good progress after some procurement delays and some unanticipated hospitalization of a key contributor because of some long-term back problems. The testing system is ready to go.
- The rationale of trading compressor size with storage size is interesting. The key point being missed is land cost as a key capex entry. This also needs to be factored into the cost. It is unclear whether doubling the footprint and doubling the storage hardware will offset the cost of a second compressor.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.6** for its collaboration and coordination.

- This project is the experimental verification of modeling and algorithm development from ANL. The collaborators are ANL (very appropriate) and a well-established compressor firm that is well known for exceptional efforts and unique compressor hardware. Collaborations are very appropriate—this is excellent.
- The collaboration between NREL, ANL, and PDC has been excellent, with all parties contributing to realizing the concept of consolidation and developing the test method to demonstrate the benefits of the concept.
- The project has a good mix of modeling and experimental work. The compressor partner is obviously key to project success. The project would be strengthened by adding a tube trailer supplier or (probably better) a station owner or industrial gas company with experience in managing stations and trailers.
- It is not certain that partnering with only one other national laboratory is enough. Further, partnering with a subcontractor can be an echo chamber. Perhaps the project could bring in other members of the H2FIRST organization. The presenter mentioned that optimization of the algorithm will occur after collecting test data. There are plans to integrate the companies that deliver hydrogen by tube trailer.
- Collaboration and coordination is typical of this type of simple exercise.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.8** for its relevance/potential impact.

- This project shows how station developers/operators can optimize existing hydrogen refueling station hardware. Potentially, station operation can extend the station capacity for full vehicle fills (with back-to-back capability) by a factor of 400%–500%. The relevance and potential impact are enormous since some retail hydrogen refueling stations require truck fills throughout the day since the station nameplate capacity is exceeded by the demand from the cars. Station operators think they need station upgrades that can cost as much as an original station, but if what is needed is a "consolidation," that certainly must be less expensive.
- Presuming that this algorithm works as intended, it will have significant impact on compressor reliability and overall throughput size, which goes to cost. This is elemental, and the impact is very high.
- Station owners see direct value in this evaluation and will be able to apply the learnings to both existing stations and the design of future stations.
- This concept will enable the lowest possible cost of compressed delivery to fueling hydrogen vehicle fueling stations.
- This project should have some impact on the DOE goals.

Question 5: Proposed future work

This project was rated **3.5** for its proposed future work.

- Although this project has ended, the speaker/author explained the need for more future work in this area. Specifically, there is a need to integrate companies that deliver hydrogen using tube trailers into this work and to optimize the algorithm. This project shows promise for the refueling industry.
- Proposed work is very relevant to the goal of this work. The project will finish the experimental hardware build-out and run the experiment. This is exactly what is expected.
- The future work is well planned, and the team has been developing many other parts of the test system to adequately test the system over the remaining months in fiscal year 2017.
- The value of the project is to be determined by the successful testing over the coming months, so a successful conclusion to the project is happily anticipated. At the presentation, a reviewer commented on taking steps to ensure that the vehicle simulator is able to meet the SAE International specifications for repeat fills in ambient tanks. This is an important step to ensure. Very little was presented on how the costs and reliability would be determined for the various operating scenarios, yet this is where the value in the

project resides. Based on the state of the project and results to date, it seems likely that there will not be sufficient time in this project to fully evaluate these parameters and that this evaluation is left as an important area for further future project work.

- The future work is to follow and complete the construction schedule.

Project strengths:

- The strengths of the project team include:
    - The concept of demonstrating the benefits of consolidation (ANL and PDC)
    - The PDC team that has developed the tri-mode compressor (Stage 1, Stage 2, or both stages at the same time)
    - The concept of how and where to do the demonstration (NREL)
    - The development of the sequential fueling "vehicle simulator"
    - The test plan
    - Preparation of the NREL HITRF facility with an upgraded dispenser chiller block and larger cooling machine
    - The project team
- Among the project strengths are the following:
    - The project uses existing equipment at a hydrogen refueling station in a new way.
    - The high capital and operating costs of hydrogen refueling station components (the compressor) may decrease as a result of this work.
    - The project is grounded in the supervisory control and data acquisition (SCADA) system at the HITRF.
    - The self-contained system that simulates vehicles is unique, needed, and can perhaps be used on a fee-for-use basis for station developers/operators to conduct tests.
    - Finally, the author has the motivation to refine and optimize the consolidation algorithm once this project ends (September 2017).
- Project strengths include the balance of analysis/modeling and experimental work. Also, the project has made impressive progress on the test location and the compressor design/build/implementation.
- This is the experimental verification of ANL work. This is well-thought-out and appropriate for the desired goal. This experimental team and NREL test facility are well suited to perform this work.
- Strengths include the project's simplicity and the presenter's skill; Mr. Turlip gave an excellent presentation.

Project weaknesses:

- At this stage of the project, no significant weaknesses were identified, with the exception of a missing energy balance to determine whether the system can indeed be operated for an infinite number of fills (whether the tanks heat up over time, which is a small issue).
- There are no obvious project weaknesses.
- The weaknesses of this project were the long time for contractual negotiation and some production delays at the compressor manufacturer, which leads to a shortened test program this summer.
- To date, there has not been enough emphasis on evaluating the effects on cost and reliability of the systems. The project needs a partner with experience in managing tube trailers.
- This project does not advance the art; it validates a station optimization of a compressor. The cost does not properly address capex.

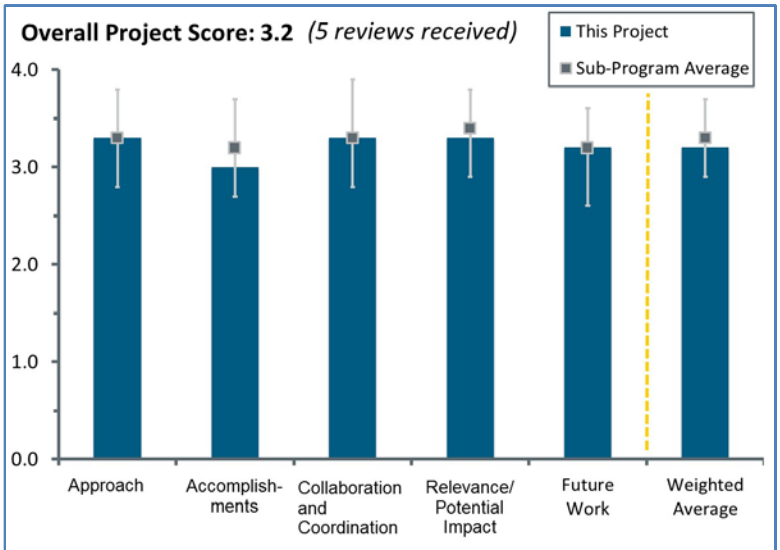
Recommendations for additions/deletions to project scope:

- Reliability and cost considerations need to balance capex versus complexity. It is not obvious that the net result of this process can achieve the 50% cost savings mentioned. Cost savings are primarily in the reduced size of the compressor, but it is not clear that this balances the added cost due to complexity of valving and flow path additions. The cost impact on cycling the tubes more often (hence shortening their lifetime) is unknown. Reliability issues have similar concerns. While we may experience better reliability

on the compressor, all of the valves and flow path complexity must also be considered. It is not clear that the system overall is more reliable; perhaps compressor reliability has been traded for system reliability.
- The project should perform an energy balance over many "vehicle" fill cycles to determine the temperature time history of the "vehicle" fill tanks.
- The cost estimate should be reworked.
- This project ends September 2017, so there will be no more additions to the existing project scope.

Project #PD-135: Liquid Hydrogen Infrastructure Analysis

Guillaume Petitpas; Lawrence Livermore National Laboratory



The vertical hash-lines represent the highest and lowest average scores received by projects in the sub-program.

Brief Summary of Project:

Liquid hydrogen has many benefits for the hydrogen infrastructure, especially at large scale. Two main technical barriers to using liquid hydrogen were addressed in the previous year: (1) "lack of hydrogen and infrastructure options analysis" and (2) "reliability and costs of hydrogen pumping." To accomplish this, the project simulated the liquid hydrogen pathway (from liquefaction plant to end use) using a thermodynamic model to estimate, then mitigate, the transfer and boil-off losses that occur. Real-life driving and parking data were collected from a large population to use as an input for the model. The project also identified the major hydrogen boil-off sources and investigated potential recovery technologies/processes (technical and cost) to eliminate/reduce these losses.

Question 1: Approach to performing the work

This project was rated **3.3** for its approach.

- Lawrence Livermore National Laboratory (LLNL) and partners have a well-thought-out approach to evaluating boil-off losses. The approach is comprehensive with respect to evaluating every transfer point. Simulation is a low-cost option to assess losses at both stations and onboard vehicles. Task 3 covers boil-off recovery and other mitigation options. The entire pathway approach is required to get a full view of all losses rather than at one location that is easiest to measure. It will be very important to look at reusing NASA's code and to not reinvent analysis that has already been done. Because of the strong effect of temperature on the equation of state and Z-value roll-off, the real gas equation of state is required to carefully consider the two-phase transition. The project approach of using real-world data rather than choosing arbitrary driving distances, as considered in the past, is important. By carefully reviewing past liquid hydrogen work from NASA, the investigators have access to a comprehensive list covering the main sources of loss and several different mitigation strategies. More quantitative details could be provided for mitigation options; however, those should be provided when the work is complete.
- The approach to performing the work is science-based, is clearly broken down into tasks, and addresses the critical stages of the liquid hydrogen (LH_2) delivery chain where losses occur.
- The concept appears to be relevant, especially for specific vehicle applications. The approach to performing the work appears to be scattered and lacks a clear destination of the end game. It may be too early to select a specific end game, but the project needs to have relevant goals.
- The project identifies the significant barriers, then limits its focus to contain the project scope. From the outside, the activity appears to focus almost exclusively on the thermodynamics of the cryogens and appears to treat heat transfer issues lightly. Including a list of assumptions would help to reduce the number of questions as the team restricts its scope to fit available resources.
- While the approach and analysis are reasonable, the approach of using liquid or cryo-compressed hydrogen (CCH_2) in vehicles appears to be a technological dead end. The authors should address this concern by asking what it would take for CCH_2 or liquid to be a more favorable solution than the current standard of 700 bar compressed gas systems. Without addressing this point, the value of this work is limited.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.0** for its accomplishments and progress.

- The project did a nice job presenting an understanding of cryo-compressed dynamics in a vehicle. The use and refinement of the NASA code is very convincing.
- Progress against goals has been good. Perhaps the project can develop a metric—perhaps a hydrogen efficiency measure or dollars-per-mile standard—to compare directly against the 700 bar standard.
- Boil-off losses are a key element of the overall energy efficiency and well-to-wheel energy consumption and emissions, and progress was made in this area toward meeting DOE's efficiency goals. Progress was made toward gathering data and finalizing sources of data. The project is 5% complete, so more details about additional accomplishments and progress should be available next year.
- The project is of a relatively short duration and has been underway for only a few months. The accomplishments and progress toward overall project and DOE goals will be highly dependent on the results the project delivers and how the results can be turned into action toward reducing sources of loss.
- The activity obviously faced some initialization issues. However, this presentation reported 5% completion and, along with the updated information during the review occurring at the halfway point in the project, suggests that there are underlying issues to resolve. Of particular concern are the validation of changes to the NASA model, compensating for differences between American and European driving habits/siting issues, and heat transfer issues contributing to boil-off. Validating changes to the NASA model is likely to be difficult and time-consuming. These issues are not insurmountable, but they merit increased monitoring.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.3** for its collaboration and coordination.

- This is the strongest advantage for the activity. International collaboration with the right array of partners provides fertile ground to yield accurate results. The principal investigator is well connected and would do well to take advantage of these connections to mitigate the issues occurring in other areas of the activity.
- Linde is the premier supplier of cryopump technology and LH_2 delivery. This collaboration is key to understanding the pump and potential mitigation strategies.
- Linde and BMW are the right industrial partners for this project, as they are the commercial leads for implementing these technologies.
- This project will require significant levels of interaction with other institutions, specifically gas companies. The project and the principal investigator have a long history of interaction with these institutions. However, this will require a deeper dive into industry practices upstream of the final point of delivery. In the next phase of the project, it will be very important to interact with key individuals in these institutions to understand standard practices, non-standard practices, regulatory requirements, and business-driven practices. The effectiveness of the project results will depend on the science-based calculations of the various losses but also, perhaps more importantly, on characterizing the input parameters of those losses that stem from industry practice, which may vary among institutions.
- This area seems weak, probably because cryo-compressed is not widely accepted, but effort needs to be given to draw in more collaborators. The concept might be interesting to large-scale fuel cell vehicle manufacturers (buses, trucks, etc.).

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.3** for its relevance/potential impact.

- The LH_2 supply chain will become an increasingly important option for hydrogen delivery to stations, especially for larger-capacity stations, e.g., truck and bus stations. Losses during the LH_2 delivery chain are a major opportunity for fuel cost reductions, efficiency gains, etc. LH_2 may also play a role in securing low-

cost renewable hydrogen sources and expanding the economic delivery range of the hydrogen, via liquefaction. Minimizing losses will play a role in meeting DOE targets for hydrogen cost at the pump.
- After liquefaction energy, losses are the biggest concern for LH_2 pathways. This topic is very important for success of the technology and can have a significant impact on advancing the Hydrogen and Fuel Cells Program and hydrogen infrastructure efforts.
- Many reviews from the industrial and commercial perspectives have been completed. A complete evaluation of the entire LH_2 market from the residential market perspective is both warranted and necessary. This activity is a great start, but being limited to a single year imposes scope restrictions. Depending on the results from this stage, a subsequent assessment delving more deeply into the assumptions is likely advantageous.
- The presentation made a convincing argument that there are likely applications in which this approach to fueling vehicles makes the most sense. During next year's presentation, it would be helpful to understand those applications and what the economic benefit of the technology for those applications is.
- While having good data and models for these approaches is important from a benchmarking perspective, it would appear that the industry has moved away from LH_2 and CCH_2 onboard.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- The project has effectively planned for future work with clear targets toward reaching the project objectives. It will be important to emphasize gathering information from industry on practices in the supply chain and using that information as inputs into the simulation to determine opportunities for improvement.
- The next steps include verifying the thermodynamic codes and beginning to run typical cases. The key work after this analysis is to determine where the most effort should be placed for mitigating boil-off losses and what technologies might be used.
- One goal for this year is to verify that the codes(s) are appropriate for the analysis being considered. The criteria for answering this—the quantitative measures used to determine code applicability/accuracy—should be more detailed. Secondly, there is no mention of a backup plan if the codes are deemed unsuitable. It seems that the project is working under the assumption that the codes will be deemed suitable in some fashion.
- The stated future work, both documented in the presentation package and expressed during the oral review, fits within the schedule and budget for this activity. It is likely that the validation effort for the NASA software modifications is underappreciated, as this validation is crucial to lending credibility to any results based on the modified model. Remarkably little was proposed for subsequent work beyond the end of this period of performance. This absence suggests a level of confidence in the results not fully substantiated from an external perspective with the provided documentation.
- It seems the project should be able to demonstrate the concept in a setting that replicates filling, fuel use, ambient conditions, and other environmental factors.

Project strengths:

- The project has the right partners. Unlike some projects that "reinvent the wheel," this project is leveraging the years of work done by others in developing the models and the building upon them and applying them to new areas.
- The project has a clear, science-based approach and a strong commitment to reach out to industry and institutions. The project is highly relevant to Multi-Year Research, Development, and Demonstration Plan (MYRDDP) targets. Progress to date is good.
- The project strengths include close collaboration with Linde and a deep technical knowledge of cryogenic hydrogen. The additional data analysis around real-world drive cycles is an important complement to the technical work and next steps.
- This project leverages many external partners with representative skill sets. From this network, the project is positioned to recover lost ground and meet activity objectives within a moderate tolerance.
- The project is reminding the community that this approach to fueling should not be overlooked, especially for large-scale segments of application.

Project weaknesses:

- Weaknesses include the limited commercial viability of the onboard LH_2/CCH_2 approach. Many assumptions are being made regarding parking and conditions under which the cars are used. Customers will cover the entire spectrum of usage options (not just some kind of average usage) and will need to understand the effects of all these extremes. There does not appear to be any prioritization of the loss mechanisms or their mitigation. Perhaps adding a more comprehensive review of the impacts leading to prioritization would be helpful.
- The project should show how industrial gas companies can adopt the analysis and what market effects, such as low-cost energy, lead to such large amounts of boil-off. Current industry practice does not prioritize reducing LH_2 boil-off because of how prices are negotiated and because of feed stock prices.
- The activity faced initialization issues that are apparently not fully resolved. The subtle differences between thermodynamics and heat transfer are poorly communicated and minimized, as are the behavioral differences between American and European drivers. These are not insurmountable issues, as team members are quite capable of resolving rather than mitigating these issues.
- There is an unclear degree of focus on LH_2 supply chain losses versus cryo-compressed park/drive/fill pattern analysis (i.e., which project objective will have more impact on MYRDDP targets). More emphasis is needed on results delivery and recommendations for improvements.
- More vision and physical action are needed regarding how to demonstrate the concept to prove the theoretical work.

Recommendations for additions/deletions to project scope:

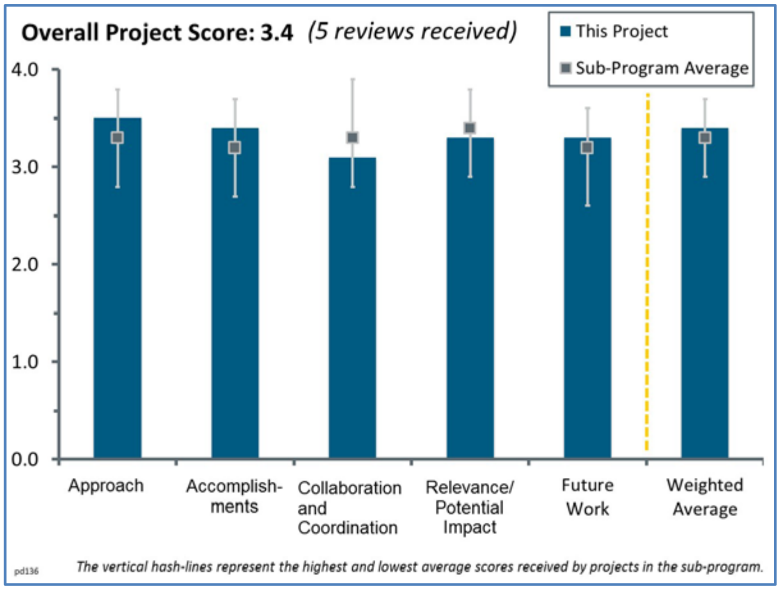
- The project should make a more direct comparison to 700 bar and develop a criterion by which the performance of the two systems can be directly measured. This comparison and analysis should be used to determine when/where LH_2 or CCH_2 would be a better solution than 700 bar. To make the work more relevant to today's and future infrastructure solutions, the project should start to focus less on the onboard storage losses and start to look at the LH_2 supply issues and mitigation strategies.
- The project should clarify an approach for results delivery in the form of a paper or other method to ensure widespread distribution to institutions and industry (specifically with regard to the LH_2 supply chain). The project should also ensure all uses of LH_2 at the station are considered in the pathway: low-pressure pumping, high-pressure pumping, vaporization/compression, cryo-compressed filling, etc.
- The activity has correctly identified what needs to be done and a methodology to complete it. It would impose programmatic risk to expand the project scope with the current state of progress. Simultaneously, descoping the activity would belittle its merit to DOE. At this time, this activity would benefit from additional monitoring temporarily as a mechanism to provide support until it is back on track.
- If the initial analysis is promising and specific technologies or industry best practices are recommended, the technologies and hardware should be tested at LLNL.
- More action is needed.

Project #PD-136: Electrochemical Compression

Monjid Hamdan; Giner, Inc.

Brief Summary of Project:

This project will develop and demonstrate an electrochemical hydrogen compressor (EHC) that is lower in cost, higher in efficiency, and more durable. Specifically, the project will (1) fabricate hydrocarbon membranes (HC) with enhanced properties for use in EHCs, (2) improve EHC water and thermal management, (3) optimize stack hardware and demonstrate cell performance, and (4) build a prototype system. Development of reliable and low-cost, high-pressure hydrogen systems is needed to enable market penetration of fuel cell electric vehicles.



Question 1: Approach to performing the work

This project was rated **3.5** for its approach.

- This project started in fiscal year (FY) 2017 (despite a confusing note that said FY 2016–2017). Considering the short time, the project has already achieved some important milestones. Barriers are well addressed, and the project seems to be well designed and well executed.
- Mr. Hamdan presents a concept for an electrochemical compression system using an HC membrane and a water management membrane. The use of an HC membrane could lead to lower-cost systems. This seems to be a feasible approach with merit.
- A substantial amount of work has been completed for a small percentage of the budget—indicative of the foundation on which Giner, Inc. (Giner) is building. Leaving a milestone at a lower-than-actual completion percentage to enable additional materials tests is an excellent contingency approach, given the early stage and ambitious goals. Cost will always be the driver.
- This project is very well designed and feasible. It aims at developing a reliable compressor with low maintenance cost. It fits very well with the other alternative projects, PD-137 and PD-138.
- Giner has taken a well-reasoned and -planned approach to the task and has made outstanding progress in Year 1.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.4** for its accomplishments and progress.

- This project is in an early stage, but it seems to be capable of addressing Hydrogen and Fuel Cells Program (the Program) goals and DOE targets. In the first several months, the principal investigators (PIs) made substantial improvements and demonstrated that the approach in this project is carefully planned and executed. Task 1 is fully accomplished, while Task 2, which is dedicated to membrane fabrication, is 60% accomplished, which is significant progress considering the short timeframe in the first year. Benefits from Task 2 are in utilization of cost-effective materials and improvement of mechanical properties while maintaining a high conductivity of 0.106 S/cm (the target was 0.100 S/cm). In addition, the cell performance was improved with an HC membrane to 0.110 V/cell. The PIs also reported progress in stack hardware development and initiated targeted evaluations at 350 bar, as well as stack design at 875 bar.

Overall, based on the progress in the first fiscal year, this project might be capable of addressing DOE targets in the future.

- If successful, this project could lead to hydrogen compressors without rotating parts; therefore, this project could lead to the development of novel high-pressure compressors with much higher reliability and eventually lower investment cost. It fits very well with the aims and goals of DOE.
- Giner has demonstrated a substantial jump on the progress to date for a small percentage of the budget. The project is consistent with the DOE goals and, based on the preliminary data, is on track to hit the technical performance targets.
- Giner has made great progress toward the targets. Economics are still an issue, but capital expenditure (capex) has not been addressed yet. The rational approach to membranes and stack has yielded outstanding results so far.
- During the presentation, the speaker was fairly confident that the project had overcome the technical barriers and was on its way to a successful completion. However, it is not clear how the goals on slide 2 are fully supported by the results on slide 12. On slide 12, the cell is operating at a voltage of 0.255 V/cell (from Nernst) and a current density of 890 mA/cm^2. The ideal cell voltage, per Nernst, should be 0.07 V/cell. Therefore, there is an overpotential of around 200 mOhm cm^2. This works out to around 5 kWh/kg required for hydrogen compression, which is very far from the DOE goal of 1.16 kWh/kg and does not match the project's reported status of 2.7 kWh/kg on slide 2. It is not clear if the team's indication that the project was on track to meet DOE goals was by extrapolation of slide 13. If indeed the project results are four times the power consumption goals, the team has a very long way to go to meet DOE's goals.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.1** for its collaboration and coordination.

- Giner's experience in cell, stack, and system development would not technically require much collaboration to complete the milestones for this project. That said, Giner has nonetheless assembled a strong team—the National Renewable Energy Laboratory (NREL) (cell to stack test and optimizations), Rensselaer Polytechnic Institute (HC membranes), and Gaia Energy Research Institute LLC (technoeconomic analysis and life-cycle analysis)—that uses each partner for its strengths. As usual, coordination for a timely execution will be the challenge going forward.
- Giner has great internal talent and capabilities but has gone outside of the company and identified appropriate partners to complement the internal expertise where needed.
- Giner has worked out a good collaboration with an HC membrane supplier. The project has the right team members to get the job done.
- Giner is collaborating with a national laboratory, academia, and a private business. The division of work seems to be logical (development of membranes, development of stacks, testing, and technoeconomic analysis) and enforces the collaboration between these entities. Further exchange of information with other domestic or international groups is not clear.
- The team is carefully assembled, and it seems to be well coordinated. The roles of participants are well defined; however, it was difficult to delineate contributions among collaborators. In the future, it would be beneficial to assign the results to each participant that contributed to progress and accomplishments.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.3** for its relevance/potential impact.

- The high-pressure hydrogen compressors are the most expensive part of a hydrogen fueling station, and they cause high maintenance costs for the station. Reliability so far is suboptimal. This project can significantly help to overcome these challenges if the possibility of membrane rupture at the envisioned high pressures could be excluded.

- This multiyear project aligns very well with the Program goals. This project is aimed at addressing critical barriers in deployment of fuel cell technology. In the first year, the PIs demonstrated the significant potential of this project to address limitations in hydrogen compression.
- The project targets lower cost, higher efficiency, and improved durability in a focused manner—aligned with the Multi-Year Research, Development, and Demonstration Plan. If the targets are hit, it will open the door for an additional technology candidate for forecourt hydrogen compression applications.
- Electrochemical compression is poised to be an important component of an energy-efficient hydrogen delivery system.
- This "no-moving-parts" compressor could be a real game changer, if successful.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- The proposed future work is expected to expand current project status by getting closer to the outlet pressure capability of 950 bar. The strategy of future work is well assembled, with the ability to deliver alternative options to the current state of the art. The PIs based their work on the metrics and proper decision-making points.
- The plans for the membrane, cell, stack, and system are spot on. Hitting performance at cost will be a challenge. The logistics of ensuring endurance and the tradeoff against repeated cell purges will need attention.
- Lifetime, scale, and cost reductions are all targeted for future work.
- The most critical aspects have been identified and will be addressed.
- Giner believes that the project is well through its technical hurdles, but this is not clear. The investigators should go back and double-check all of their assumptions about energy efficiency before proceeding further. A 1,000-hour test is impressive, but a longer test should be performed to be more compatible with a realistic equipment maintenance schedule.

Project strengths:

- Strengths include Giner's state-of-the-art status, the depth and breadth of their foundation in design-through-delivery of ultra-high-pressure electrolyzers, and NREL's Energy Systems Integration Facility testing and optimization capabilities. Rensselaer Polytechnic Institute and Gaia Energy Research Institute LLC are used for their key strengths also. Giner staff's ability to translate polymer-electrolyte-membrane-based electrolyzer system experience into high-pressure compression will be a key benefit for the project.
- This is a strong and experienced team that is capable of executing challenging issues in hydrogen compression. The approach is science-based, and it is being executed in a highly technical manner. The project offers alternative and innovative solutions for hydrogen compression.
- The project is run by a very experienced team. Different polymers and concepts are being tested. Results so far are promising. The contact and collaboration with the TÜV Rheinland Group in such an early stage is appreciated.
- The project looks at using HC membranes and an advanced water management membrane to improve the performance and lower the cost of electrochemical compression.
- Strengths include strong expertise, a well-planned approach, and a well-executed project.

Project weaknesses:

- There are no significant weaknesses.
- The project reports on progress made in FY 2017. However, considering timeframes for submission of this report, it would be premature to assign weaknesses to what has been achieved. The only obvious flaw is a discrepancy between the DOE target of 950 bar for the outlet pressure capability versus the 350 and 875 bar that are listed in this project.
- At this early stage of the project, these would be more accurately called challenges than weaknesses: as always, individual technical barriers (for example, specific energy) can be overcome—but the coupling of this and the simultaneous completion of other technical barriers is key, e.g., hitting $170,000 uninstalled

capex, plus a 10-year life, with a new cell/stack design that also enables 950 bar (along with a possible scale-up in active area). The effects of that cumulative challenge will become revealed only in the coming year.

- The team might be overconfident about their ability to reach DOE goals and their ability to deliver a working, useful prototype.
- Compared to the other projects using metal hydride compressors, such an electrochemical system has a high inherent risk of failure (membrane rupture), especially if operated under the high-end pressure. The risk assessment has to be started very early.

Recommendations for additions/deletions to project scope:

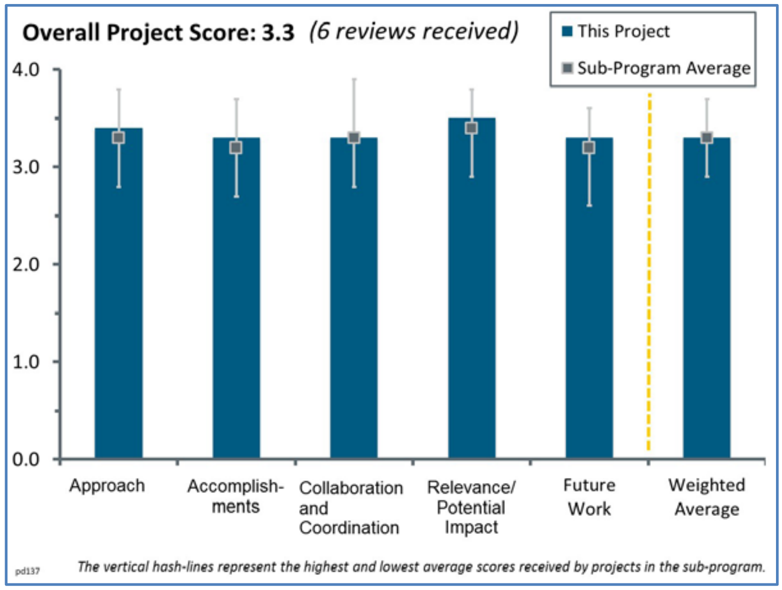
- The project scope seems to be well aligned with ongoing progress and proposed activities. There are no recommendations for addition or removal of existing efforts.
- At this time, there are no recommendations for additions or changes. The usual vigilance on the next scope-set is needed: HC membrane evaluations at 5,000 psi; 1,000-hour-duration test at low decay rate (especially needed); new stack design/fabrication/verification at 12,688 psi; prototype system design; and develop specifications/procure Class 1, Division 2, Group B components.
- The researchers should review their energy balance equations and take an honest look at whether the project is able to meet the DOE goals at a system level.
- Risk assessment for membrane rupture has to be done early. It should be determined whether other parts of the compressor would also fail in the case of a membrane rupture.

Project #PD-137: Hybrid Electrochemical–Metal Hydride Compression

Scott Greenway; Greenway Energy, Inc.

Brief Summary of Project:

There is a need to increase the reliability, reduce the cost, and improve the energy efficiency of gaseous hydrogen compressors. This project seeks to address this challenge by developing a hybrid electrochemical–metal hydride (EC-MH) compressor. The project will analyze and screen potential hybrid compressor systems and materials, conduct experimental tests, develop a hybrid compressor system model, and build a prototype unit.



Question 1: Approach to performing the work

This project was rated **3.4** for its approach.

- The project takes an excellent approach, combining EC compression and MH hydrogen compression to reduce total investment cost, reduce operation cost (by using waste heat), and avoid the risk of possible membrane failure at high pressures.
- The main goal of this project is to propose and deliver a hybrid EC-MH system for compression of hydrogen to be used in fuel cells. The approach is carefully made and seems capable of addressing the barriers. During the initial period of the project, principal investigators (PIs) have demonstrated that the approach is feasible and well aligned with other efforts.
- The presenter did a nice job of describing the potential advantages and disadvantages of three non-mechanical hydrogen compression schemes directed at improving the reliability, improving the energy efficiency, and reducing the cost of gaseous hydrogen compression. The three approaches described were (1) compression via staged electrolysis, (2) staged compression via MH adsorption–desorption, and (3) the subject of the presentation, compression of hydrogen via a "hybrid" EC-MH dual-stage process. This approach may take advantage of relatively inexpensive low-pressure electrolysis coupled to a high-pressure MH stage, if successful. Given that low-pressure and -temperature electrolysis is fairly well known, and that MH compression has been around for several decades (including greater-than-laboratory-scale demonstrations), perhaps the approach could be improved by increasing the focus on the technoeconomic analysis of the hybrid approach to discern at an earlier stage in the project whether the hybrid approach can be cost-competitive and meet the specific energy target.
- The approach taken to store hydrogen via a hybrid scheme using EC hydrogen compression followed by MH compression is a novel spin on EC hydrogen compression. The project is not necessarily clear on what its specific objective is. From the presentation, there appear to be four research tasks: (1) polybenzimidazole (PBI) EC cell, (2) metal hydride selection/development, (3) EC-MH hydrogen compression demonstration, and (4) system modeling. The researchers should focus on their efforts on Tasks 3 and 4. Task 1 should not be researched, because EC hydrogen compressors are already demonstrated and commercialized (although the demand and cost are not currently favorable). It is recommended that the researchers partner with a company to supply the EC hydrogen compressor. The researchers are not in a position to provide significant improvements or advancements in the area of EC hydrogen compression. For example, slides 16–18 are fundamental studies on PBI-based EC cells that have been heavily researched in the past. Task 2 has the flavor of MH development/discovery (slide 19). The models developed for the Hydrogen Storage Engineering Center of Excellence (HSECoE) and modified for this project should be used to identify the most appropriate and readily available MH and used as the

surrogate to demonstrate the system. The researchers must resist the temptation to turn this project into a materials development and characterization effort. The researchers are encouraged to pick an MH and go with it, for they will never have the ideal MH.

- The combination of EC compression and MH compression appears to be a reasonable approach, which could be an interesting way to eliminate mechanical compressors. The main issue is in the cost of the EC compressor. Accomplishing 10–100 bar compression at the rates proposed should be based off of electrolysis stack costs plus additional costs for the exotic metals required for phosphoric acid compatibility. At that point, it becomes more expensive than commercial 30 or 60 bar output polymer electrolyte membrane electrolysis without the need for management of phosphoric acid and drying hydrogen from water and acid. Nevertheless, there may be a niche where this approach may work. The cost analysis should be expanded to look at water electrolysis with MH compression.
- The development of a hybrid EC-MH compression system is attacked in the project with a reasonable approach to address the barriers. While it is early in the project and a substantial amount of work has been accomplished, the overall scope, schedule, budget, and targets of the work are ambitious.
    - Slide 8: the U.S. Department of Energy target (100–875 bar) is identified as "= 1.6 kWh/kg", and the graph for Nafion™ indicates that for the highest number of cells/lowest current density, the lowest/best total power is ~2.1 kWh/kg. It is not clear what the approach is for reaching 1.6 kWh/kg.
    - Slide 14 identifies that 2.5 A/cm^2 is required to match temperature and energy requirements. Slide 16 identifies that testing will be conducted at 1.5 A/cm^2 and that the inlet pressure is 1–30 bar. It is not clear what the approach is to hit 2.5 A/cm^2 at the earlier specification of an inlet of 10 bar.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.3** for its accomplishments and progress.

- This is a new project that started in fiscal year 2017, and the submitted report reflects the progress made over the first six months of this effort. During that period, PIs managed to launch the project and started to address barriers by implementation of what has been proposed for hybrid EC-MH compression of hydrogen. A technoeconomic evaluation has been fully executed, and the most promising systems have been selected based on Ti-MH and PBI membrane. It is estimated that waste heat from PBI-EC hydrogen compression, which operates at higher temperature, is supposed to provide enough energy to drive the MH compression. In addition, a new heat transfer for MH compression is proposed, which can diminish the heat transfer area and reduce the cost. Small-scale testing of MH systems is complete, and a new hybrid system is under development. The progress made is well aligned with milestones. On the other hand, the PIs did not provide direct comparison with the DOE barriers; however, considering that it is the initial phase of this project, that should be addressed in future reports.
- Very nice results were already obtained for both the EC compression system and the MH compression system. The accomplishments so far are promising. The chance to develop a highly reliable compressor system seems very good, considering the achievements reached so far.
- Given the ambitious combination of scope, schedule, budgets, and milestones, the accomplishments to date are commendable.
- The project appears to be on track, judging from the milestones achieved to date. While the project is making reasonable progress on the screening of materials for the EC stage, this team could perhaps accelerate progress by teaming/collaborating with other projects that are focused on low-temperature and -pressure electrolysis for hydrogen production to arrive more quickly at a possible configuration of the EC stage. Similarly, there is a good deal of published work on MH compressors up to and including near-commercial units; exploring the existing state of the art could accelerate this team's progress. If the experimental portion of the project was streamlined, perhaps the team could get at the crux of the problem (defining the cost and determining whether it can be competitive with that of mechanical compression). There is concern that the overall system efficiency can be met, given that slide 8 indicates that at low current density, the Nafion-based membrane achieves around 2 kWh/kg at 10–100 bar. Good progress is being made on the system model development (Task 1.4). Consideration should be given to accelerating

and enhancing this effort, as a good system model may help to reduce the amount of experimental work outlined in Tasks 1.1–1.3. Water and heat management issues are known to the researchers, and the team should provide updates in future presentations on how or if these can be handled economically and efficiently.
- This project is a new start, and the researchers are just getting their feet wet. However, the researchers would be better served to focus their efforts on the demonstration unit and modeling. The modified models generated in the HSECoE used in this project position the researchers to optimize operation and costs associated with the hybrid hydrogen compression approach.
- This project started recently. The team should revisit the cost analysis.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.3** for its collaboration and coordination.

- Besides the collaboration between the direct project partners, there seems to be a nice collaboration with other partners both at the MH side (Bob Bowman and Craig Jensen as well as Terry Johnson) and on the EC hydrogen compression side (Advent Energy).
- The team listed on slide 25 is excellent for this work: Oak Ridge National Laboratory/Bob Bowman for material property; University of Hawaii/Craig Jensen and Sandia National Laboratories/Terry Johnson for MH system and compressor modeling; and Advent Energy for membrane materials.
- Researchers should not be focused on the design of EC hydrogen compression hardware or MH development. The researchers are urged to collaborate with companies that already produce and/or have expertise in this area. Given the short time frame of the project, the focus should be on demonstration and modeling. The researchers should be talking with fuel cell researchers (national laboratories or companies) about the advantages and disadvantages of PBI- versus Nafion-based EC cells, for example, cost, platinum loading, and thickness.
- For a new project, the level of collaboration is adequate. It may help the project to develop additional collaborations with low-temperature and -pressure electrolysis projects to accelerate progress and to help populate the systems model with relevant information. Collaborations on the MH compressor portion of the project are appropriate and of high quality. It is nice to see that this project is collaborating with the two-stage MH project. This is a good indication that both teams want the best technology to emerge, and by working together, this is more likely to happen earlier rather than later.
- The participants in this project are clearly listed; however, the PIs should more precisely delineate the roles and contributions from each participant in accomplishment slides. In addition to participants, the project also interacts with a network of suppliers for materials of interest.
- There was not much interaction between the two partners until way late in the process. The difference between Milestones 1.1.2 and 1.6 are unclear.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.5** for its relevance/potential impact.

- The project aligns well with the DOE's Hydrogen and Fuel Cells Program. The approach and deliverables are well structured and are capable to address the barriers in hydrogen compression, which has been identified as one of the bottlenecks in the wide spread of hydrogen infrastructure and fuel cell technology. If successful, this project would deliver a new hybrid EC system for efficient compression of hydrogen and lower cost.
- The relevance and potential impact of non-mechanical gaseous hydrogen compressors may be high. Reducing operating costs with potentially enhanced reliability and energy efficiency is clearly beneficial to the bottom line of delivering hydrogen inexpensively at the fueling station.
- The approach is brilliant, and if the project is successful and cheap MH alloys can be identified, it can mean a breakthrough to improved reliability and reduced maintenance cost of hydrogen fueling stations.

- The concept of low pressure by EC compression and high pressure via MH is worth pursuing and is consistent with the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan (MYRDDP). The challenge is hitting the overall power goal and cost.
- The relevance of the project is rated as moderate not because of the proposed application of hydrogen refueling stations (which is a hard sell), but because of the intended use of this approach on a much, much broader and bigger scale (e.g., H2@ Scale applications). The researchers should take the time to perform a cost comparison of the current mechanical compression strategies to those of the project. In particular, the cost of maintenance, downtime, etc. of mechanical compression should be used to make the argument for using EC-MH hydrogen compression. The cost of ownership may be a suitable metric to use for this comparison.
- The project addresses some goals from the MYRDDP. It is unclear if efficiency goals optimistically appear to be three times worse than DOE targets: leakage rate MYRDDP target versus compressor leak rate through hydrogen diffusion.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- Considering this is an early stage of the project, future work will be critical in evaluating the success of this effort. The proposed activities, along with go/no-go decision steps in addressing the barriers, are carefully planned and seem to have logical flow as the project evolves.
- At the next review, it would be beneficial to hear more about the systems modeling effort and the detailed inputs to the model. Overall, the proposed future work followed logically from the current status.
- Proposed work appears to be adequate. It is recommended that the team focus on the demonstration and model validation efforts. System demonstration and model validation will allow the overall system to be further optimized. It is also recommended that the team collaborate with vendors or companies already producing Nafion-based EC hydrogen compression for bench-scale testing. The efforts in developing and testing membranes are severely diluting the project's primary research focus and should not be pursued. Savannah River National Laboratory was the MH lead in the HSECoE and performed some great modeling work on MH systems and the identification of MH material characteristics, which makes it difficult to understand the extended efforts in identifying a suitable MH for this demonstration. It is also recommended that the team use the highest-quality hydrogen to prevent contamination and complications. In the end, this is a demonstration/"proof-of-concept" effort in which the durability of the EC hydrogen compressor and MH compressor are not the focus, not to mention that the contaminants for Nafion- and PBI-based EC cells are known. The team should add purifiers to scrub the hydrogen of these contaminants to demonstrate and validate the models. There is interest in seeing the effects of a shifting plateau region of the isotherm (i.e., non-ideal) on the overall system efficiency, operation, and cost.
- The planned work is on the right track. For the high-pressure MH compression part, it is very important for the partners to measure the isotherms (plateau slopes and hysteresis) at the final temperatures and envisioned pressures. Looking at cheap alloy alternatives might be important for the economical evaluation.
- Emphasis is to be placed on hitting the energy target and evolving from the initial test conditions used for early verification and validation to the targeted values. The approach to running at 2.5 A/cm^2 is not clear It is also not clear what the tradeoff is between minimizing sensible heating, thermal losses, and void volume while also maximizing hydrogen flow rate. Finally, it is not clear what the anticipated decay rate is (percentage of initial capacity over ~1,000 cycles).
- The approach of separate EC and MH development leading to the Year 2 prototype design relies too heavily on both working without any prior knowledge. The cost analysis should be expanded to look at water electrolysis with MH compression.

Project strengths:

- The project is aimed at addressing the barriers in hydrogen compression by implementation of hybrid EC-MH systems that would enable more effective hydrogen compression and lower the cost. The initial phase of the project demonstrates positive development and reflects promise that this approach might be successful. The main strength can be viewed in already identified components that would become integral parts of the future hybrid system.

- This is a very competent group that follows a highly interesting alternative route for high-pressure hydrogen compression. Combining both low-pressure EC hydrogen compression and high-pressure hydride-based hydrogen compression is a very smart idea. The team has put together competence both from membrane/stack development and from the MH side.
- The team is exceptionally well qualified to perform the demonstration and modeling efforts. Using the "pioneering" foundations from the HSECoE modeling efforts, the team is well positioned to push the hybrid EC-MH hydrogen compression to the next level of operational understanding and development.
- This is a good team with a good approach to the critical engineering tasks. The team is working well with a "competing" team. The work is highly relevant and impactful to DOE targets and the potential for future commercialization of low-maintenance gaseous hydrogen compressors.
- The project jumped on some early EC compressor data and sensitivities. The project must continue to probe and understand the true potential amenability of phosphoric acid materials for this application; the early MH data indicating the near-feasibility of hitting the targeted pressure is also an excellent start.
- This project has taken an interesting approach.

Project weaknesses:

- There are almost no weaknesses to this project at all. To argue for this alternative route for hydrogen compression, it seems very important to estimate the costs of the whole potential design as soon as possible. For this estimate, the cost for actual MH alloys may be taken into account, as well as the assumption to shift to cheaper alloys. The team should be able to answer the question about the costs of such an alternative.
- The primary weaknesses of this project include the research efforts focused on membrane electrode assembly (MEA) development and MH identification. The MEA effort is a distraction, and the team is encouraged to contact companies with expertise in EC compression, or perhaps even acquire an EC hydrogen compression unit from them to include in the demonstration unit. Another notable weakness is the technoeconomic analysis (TEA) of Nafion- and PBI-based EC cells. For PBI-based systems, the membrane is typically thicker (increasing the overpotential) and has higher platinum loadings (~two to three times higher) than for their Nafion-based analogs; these differences are not reflected in the TEA analyses. The researchers should consult with the appropriate companies or researchers working on fuel cells to ensure realistic TEA analyses are performed.
- The PIs should demonstrate more clearly the individual roles of participants in accomplishment slides. Also, DOE technical targets should be listed versus the current status of this project. The progress that has been made should be listed as a percentage of accomplished work. Considering this is a new project, these comments should be addressed in next year's report.
- Given the significant amount of work in both EC compression and particularly MH compression, perhaps more emphasis should be placed on systems modeling to accelerate the project to developing a good cost model of the hybrid approach.
- The project's weaknesses are hitting the efficiency/power target and still being viable on cost.
- It is unclear whether the goals can be met, even theoretically. Electrolysis to hydride compression seems to be a more logical approach.

Recommendations for additions/deletions to project scope:

- At this early stage, there are no additions or deletions recommended. Vigilance will be required that the materials, stack design, and MH design enable testing and evolve to hit the operating window required for thermal alignment as well as the best/lowest power requirement. Of course, cost/utilization of the MH will be a driver.
- Considering project duration, it would be premature to suggest additions or deletions of activities.
- It is recommended that the team focus on demonstration and model validation of the EC-MH system and eliminate the work scope associated with EC hydrogen compression (i.e., hardware development and testing). It is also recommended that the PIs of PD-137 and PD-138 both use the same modeling framework

and collaborate in choosing the high-pressure MH. This approach allows for easy comparison of the two different hydrogen compression approaches.

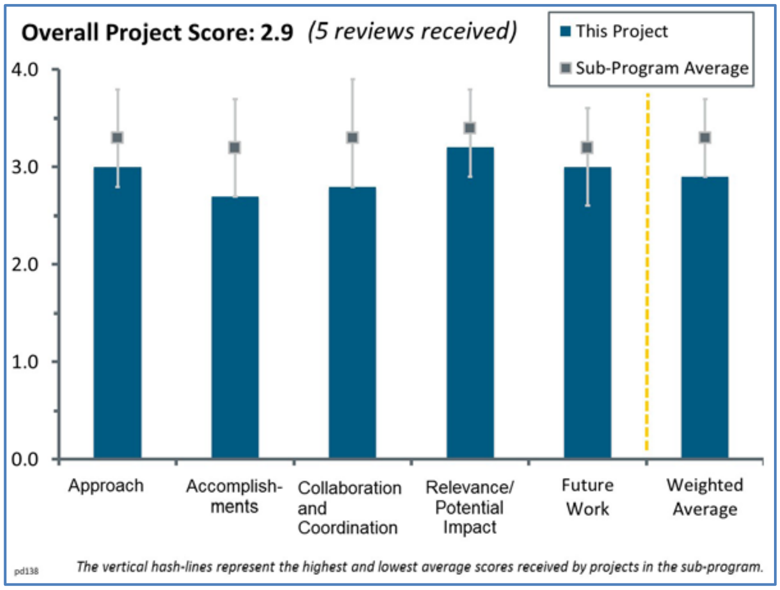
- A rough cost estimation should be performed to answer questions from the industry. Hysteresis and plateau slopes of the potential MH alloys must be measured at final temperatures and pressures.
- An earlier go/no-go based on cost or ability to meet the efficiency target is recommended. The cost analysis should be expanded to look at water electrolysis with MH compression.
- An added emphasis to cost modeling is recommended.

Project #PD-138: Metal Hydride Compression

Terry Johnson; Sandia National Laboratories

Brief Summary of Project:

The objective of this project is to demonstrate a two-stage metal hydride compressor with a feed pressure of 50–100 bar delivering high-purity hydrogen gas at an outlet pressure of 875 bar or more. At least two candidate alloys will be identified for both the low-pressure and high-pressure stages, a detailed design for the compressor completed, and a prototype compressor built. The developed technology seeks to address the need for less expensive and more reliable compressors for hydrogen fueling stations.



Question 1: Approach to performing the work

This project was rated **3.0** for its approach.

- This approach dovetails nicely with the other two non-mechanical gaseous hydrogen compressor projects, which are a two-stage electrochemical compressor and a “hybrid” electrochemical–metal hydride two-stage approach. The approach is highlighted by a rational down-selection process of two metal hydrides that have the appropriate hydride/dehydride properties to combine into a system that can compress hydrogen to 875 bar at an acceptable energy efficiency and overall cost. An experimental approach is balanced by a system model that will be used to demonstrate feasibility and assist in final bed design and demonstration.
- Metal hydride compressors are a sensible approach to reducing the maintenance and improving the reliability of compressors. However, the ability to meet the cost target is highly dependent upon the heat source—either waste heat (from somewhere) or incorporating a low-cost combustion (natural gas) system. Not much can be done from the material side because the thermodynamics are set.
- In a nutshell, the project is using metal hydrides to store and pressurize hydrogen by way of heat management. The researchers state that the main objective is to demonstrate a two-stage metal hydride compressor with a feed pressure of ~50 bar delivering high-purity hydrogen gas at 1 kg H_2/hr at an outlet pressure of 875 bar. However, demonstration can occur only if the appropriate metal hydrides for each of the two stages are identified. The approach to using metal hydride compression is not novel, but the overall challenge with the high pressures required is namely the development or identification of appropriate metal hydrides. The project’s efforts related to system modeling and cost analyses should be leveraging the extensive and thorough outputs of the Hydrogen Storage Engineering Center of Excellence (HSECoE), now available on the web. It seems that the project is attempting to reinvent the models. The team is strongly encouraged to contact the HSECoE metal hydride modeling team to take advantage of what has already been done at the system level, cost, and material properties. The primary issues identified with metal hydrides (aside from the gravimetric capacity) are kinetics and thermal management. The additional issue with this project is the absence of suitable high-pressure metal hydrides within the operational constraints. If the primary objective is to demonstrate metal hydride compression, then the effort should focus on off-the-shelf, readily available metal hydrides, even if the overall delivery pressure is less than the 875 bar target (within reason). This approach offers a proof-of-concept deliverable with model validation (in collaboration with HSECoE or using modified HSECoE web models), whereby the shortcomings of heat management, metal hydride performance and development, system operability, durability, and cost can be identified.

- The approach focuses on the development of a two-stage metal hydride compressor that has advantages over current compressor technology, such as reduced operating cost, low maintenance, passive (powered by waste heat), etc. The approach involves a trade study to evaluate bed designs, development of a system-level model to assess feasibility, and the identification and testing of candidate metal hydride materials capable of operating at appropriate conditions of temperature and pressure in the two-stage compressor. The approach is straightforward and clearly stated. However, there are two important issues that should be addressed. First, metal hydride compressor technologies have been described in the literature for decades. A compelling and definitive statement concerning the advantages of the technology being developed in this project is needed (there is concern the project is "reinventing the wheel"). Second, a detailed cost analysis is needed. A principal motivation for the work is that compressors dominate station costs in existing systems. The estimated cost for the more complex two-stage metal hydride compressor system proposed here is not known, nor how that cost compares with the conventional compressor cost (parts, fabrication, operation, etc.). It is understood that the cost of the metal hydride materials has yet to be determined. However, it seems reasonable that cost boundaries for materials could be established. A solid cost estimate is needed before it even makes sense to consider taking this approach further.
- Theoretically, the approach is sound. The implementation will be the challenge, as usual. Especially the simultaneous matching of thermals, the synchronizing of the hydrogenation and dehydrogenation cycles, and sizing and engineering the number of beds for continuous pumping at the desired pressure with *minimal* heat input. Consistent with the discussion after the presentation, it is known that metal hydride has been a candidate for replacing a mechanical compressor for a few generations, and it was not clear what specific uniqueness (e.g., newly established materials family of compositions and/or canister design with integrated thermal energy storage) sets this project apart from the past concepts that never made it in terms of the utilization of canister, performance/thermal shutoff limits, and cost, especially given that the initial modeling identifies an energy usage for heating of 12.5 kWh/kg H_2 (before an improved recuperator design could bring it down to 10). While it is true that the compressor cost dominates capital expenditures and operations and maintenance of a station, that nonetheless defines a "benchmark, or baseline budget," that alternative technologies are required to show a potential to beat. It is unclear what the value proposition is, i.e., what the benchmark cost is, and where the two-stage metal hydride system can land relative to that benchmark.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **2.7** for its accomplishments and progress.

- Good progress has been made on the development and application of the dynamic system model capable of predicting metal hydride system performance. Likewise, useful background work has been presented on the identification and preliminary testing of several metal hydride alloy candidates capable of operating at temperatures and pressures compatible with the compressor design. A high-pressure testing (cycling) apparatus has been designed, and testing is in progress. A detailed cost analysis and comparison with the cost of incumbent system components is a noteworthy omission.
- The project's progress was good. There is a fair amount of work still ahead toward screening the candidate low-pressure and high-pressure materials. It is preferred that for the materials analyses, the technical performance characteristics be integrated with cost to understand the trade on both metrics up front. This would force a more in-depth analysis on this trade up front (the relationship between the metal hydride materials costs as a percentage of overall metal hydride system cost would also need to be roughly estimated up front). The availability of the material, in the preferred as-fabricated shape, also appears to be a parameter on which materials may also receive at least a qualitative ranking.
- This is a new start. That said, the project's progress has been very limited in meeting the main objective. Significant efforts were placed on metal hydride selection (critical for the high-pressure stage). It seems this effort could have been expedited by using the available HSECoE materials property tools. The development of the high-pressure pressure–composition isotherm (PCI) for materials characterization (although necessary) diverted the focus from the main objective. Lastly, the system modeling efforts lacked significant development/maturity because the team is not leveraging the existing models developed in the HSECoE. The team and partners have a wealth of metal hydride knowledge and system experience, which was not reflected in their progress to date. No mention of system costs or efficiencies was presented. The

team will proceed with great success if they maintain focus on the main objective and resist the urge to turn this into a materials development and characterization effort.
- Progress to Milestone 2.2 (characterization of materials) is "delayed," and there must be some concern that there may be an impact on the milestones coming up in July 2017 and the go/no-go decision in October. The go/no-go decision includes demonstration of two-stage compression and exercising of the systems-level compressor model in the next four to five months—a schedule that seems daunting.
- Only one of two milestones has been met. The high-pressure system is delayed (no measurements yet) and expected by the end of the fiscal year. It is not clear why low-pressure measurements are incomplete. Alloy selection is based on literature data, with no experimental verification. This is probably okay, but it would be good to confirm. Vendors claim to be able to produce alloys, but this should be checked. Material purity and phase composition may not be exactly what is claimed.

Question 3: Collaboration and coordination with other institutions

This project was rated **2.8** for its collaboration and coordination.

- Close and beneficial collaborations among the Sandia National Laboratories (SNL) team (lead, management, bed design, and compressor development), Oak Ridge National Laboratory (ORNL) (hydride identification and characterization and support bed design), and Hawaii Hydrogen Carriers (hydride characterization and prototype fabrication) are evident. This cooperation is resulting in more rapid progress in all aspects of the project. However, the team is strongly urged to include an additional team member with expertise in cost and efficiency analysis (e.g., Strategic Analysis, Argonne National Laboratory) to assist in making accurate cost projections.
- The team itself is quite good, with Bowman and Jensen as team members. So perhaps the team is adequate to handle the laboratory aspects and demonstration of prototype, and the systems-level compressor model is in good hands at SNL. Where there may be a gap is in the cost modeling aspect, and perhaps a collaboration in that area would be a good addition to the skill set of the team.
- This is an experienced team with good coordination between team members, but there is no obvious external collaboration yet. One wonders why the project does not collaborate with a group that has an existing high-pressure Sievert's rather than building a new one.
- The teaming of SNL, ORNL, and Hawaii Hydrogen Carriers is a reasonably strong one, technically; however, the presence of a commercialization team member would be preferred for even such an early-stage project.
- The project is not using the system models and material property guidelines developed in the HSECoE. The project is focusing on the development of a two-stage metal hydride compressor that has the potential to be extremely valuable (especially for the H2@ Scale concept). This was clearly evident based on the cost and maintenance hours associated with mechanical compression of hydrogen. It is recommended that the project leverage existing models and focus on demonstrating the two-stage metal hydride compression concept. The principal investigators from PD-137 and PD-138 are encouraged to collaborate in choosing the same high-pressure metal hydride and use the same materials data, keeping in mind that this project is not a materials discovery project but rather a demonstration project.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.2** for its relevance/potential impact.

- Reducing the operating costs and improving the reliability of gaseous hydrogen compression at an acceptable capital cost is central to reducing the cost of hydrogen delivery to the consumer. Therefore, this project is very impactful and relevant to Fuel Cell Technologies Office goals, particularly in the context of the two companion projects, each seeking to find which of these three concurrent approaches may be most advantageous.
- The team did a good job highlighting the need for replacing the traditional mechanical compression approach by pointing out the current cost and maintenance hours associated with mechanical compression.

It would be worthwhile for the team to compare the cost of ownership of a mechanical compressor as compared to the proposed two-stage metal hydride compressor. The potential impact could be large, assuming an H2@ Scale economy.

- The development of an improved hydrogen compressor system with reduced operating costs, low maintenance, and higher reliability is an important development that could have positive impacts on hydrogen filling station cost and efficiency. In that sense, the project definitely has potential impact on advancing progress toward DOE goals and objectives. However, the cost and performance advantages must be stated up front in a more compelling and detailed way before the impact of this project can be fully assessed.
- The project holds strong relevance as an alternative to addressing the reliability versus mechanical compressors. However, it is not clear whether the project also serves as an alternative to mechanical compressors on the cost metric.
- The project addresses reliability and maintenance issues associated with hydrogen compression.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The proposed future work looks good. There is a need to demonstrate how the system will ultimately meet energy and/or cost targets. Currently, the energy requirement is approximately six times too high, so this should be a priority. Long term, there is a need to determine the regeneration capability/cost to determine a full system life cost.
- The team has identified that the path forward must address the effective utilization of "waste" or low-cost heat to drive the process. The researchers also identify that durability of the metal hydride beds while maintaining maximal hydrogen flow rate is of course crucial to a successful outcome of this project. So they are focused on key challenges and barriers as they move forward. Their upcoming go/no-go decision point is looming rapidly, and so their work in the immediate future must be efficient to achieve the intervening milestone(s).
- The future work follows straightforwardly from the current studies. An important component in the work plan is the characterization of at least two alloys for each pressure stage. In some ways, it is surprising that PCI data are not already available on the AB_2 systems being investigated. However, additional information is apparently required. The proposed future work should include a more detailed cost and efficiency analysis.
- At a high level, the plan for fiscal year 2017 (FY 2017) and FY 2018 are reasonable. In FY 2017, the characterization of "at least two alloys for each stage" would need to include testing over the full operating window, with as much system-like integration as possible. Also, laying off the subsystem-like testing and 1,000-cycle duration testing for FY 2018 appears to increase schedule risk, reducing opportunities for contingency and backup.
- The proposed work appears to be adequate; however, the cost analysis effort is not called out for either FY 2017 or FY 2018. Given that the cost analysis can be performed in parallel during FY 2018, it is recommended that this task be undertaken.

Project strengths:

- A strong project team has been assembled. The team comprises recognized experts in compressor system design and prototype development, metal hydride bed design and testing, and metal hydride materials and characterization. The work plan is logical and addresses the critical obstacles.
- This is an excellent team with a long history of working in this area. The work is highly relevant to DOE goals and objectives and to potential future commercial fueling station operation.
- This is a team of respected and knowledgeable metal hydride researchers that can achieve the project's main objective. The project relevance was clearly identified.
- The project has a strong technical lead/project manager, a strong SNL/ORNL technical background, and a good work breakdown structure/teaming.

- This is a strong team with considerable experience. The approach is reasonable. The metal hydride system could be a simpler, more reliable alternative to mechanical compression. There is a nice plan for follow-on prototype demonstrations.

Project weaknesses:

- Metal hydride has been a candidate for replacing a mechanical compressor for a few generations; it was not clear what specific uniqueness (e.g., newly established materials family of compositions and/or canister design with integrated thermal energy storage) sets this project apart from the past concepts that never made it in terms of utilization of canister, performance/thermal shutoff limits, and cost, especially given that the initial modeling identifies an energy usage for heating of 12.5 kWh/kg H_2 (before an improved recuperator design could bring it down to 10). While it is true that the compressor cost dominates capital expenditures and operations and maintenance of a station, that nonetheless defines a "benchmark, or baseline budget," that alternative technologies are required to show a potential to beat. It is unclear what the value proposition is, i.e., what that benchmark cost is, and where the two-stage metal hydride system can land relative to that benchmark.
- The project lacks a solid and persuasive argument about why this technology is an improvement over the metal hydride compressor systems that have been proposed and developed over the last several decades. In addition, a more comprehensive cost and efficiency analysis that focuses on how the proposed system compares with the conventional compressor technology in terms of cost, reliability, efficiency, maintenance, etc. is needed.
- The characterization of low-pressure and high-pressure hydrides is only 10% complete (milestone due April 2017). The selection of two alloys for each stage is based only on literature value; there is no experimental confirmation yet. There is a need to understand how much of a savings is possible with a hydride compressor versus a mechanical one.
- The project's primary weakness is not using the preexisting models developed within the HSECoE for system analyses, system cost, and material properties. Using these models will also allow a direct comparison to the current hybrid electrochemical–metal hydride approach and potentially future hydrogen compression designs. Leveraging the existing models affords the team the opportunity to focus on system designs, cost analyses, and system demonstration.
- The team may wish to consider moving some cost modeling forward in the project. If the project is technically successful but the capital costs are far too high, that would be good to know sooner rather than later.

Recommendations for additions/deletions to project scope:

- Projects PD-137 and PD-138 are both strongly encouraged to coordinate and collaborate on their research efforts. It is recommended that both projects employ the same high-pressure metal hydride and share materials data (thermal conductivity, isotherms, etc.) to ensure both approaches can be compared. In addition, the modeling efforts can also be coordinated between the two projects to ensure direct comparison and continuity. The team must resist the urge to turn this project into a materials project that will ultimately detract from the main objective. A sensitivity analysis on the effects of non-ideal plateaus and hysteresis on the overall system efficiency and cost would be worthwhile. The team should focus on demonstrating the concept with an off-the-shelf, readily available metal hydride (projects PD-138 and PD-137 should use the same metal hydride), even if the overall delivery pressure falls below the target value (within reason). The overall modeling of the system will point toward the necessary improvements in the overall system design, operation, and material characteristics that are required to meet the DOE targets.
- The addition of a systems analyst to the team is recommended, an individual or group capable of rapidly conducting a cost/efficiency analysis of the proposed system and comparison with existing (conventional) compressor approaches. It is recommended that this be done as soon as possible so that a solid foundation for conducting further work is in place. This does not have to be particularly time-consuming or costly; it simply needs to provide the basis for further project development.
- There is no cost analysis yet. Metal hydride materials will be a cost driver, and there are questions about how much they degrade and whether they can be regenerated (and at what cost). Researchers are

encouraged to look into full system cost, including energy/cost associated with each cycle, along with material and regeneration costs.

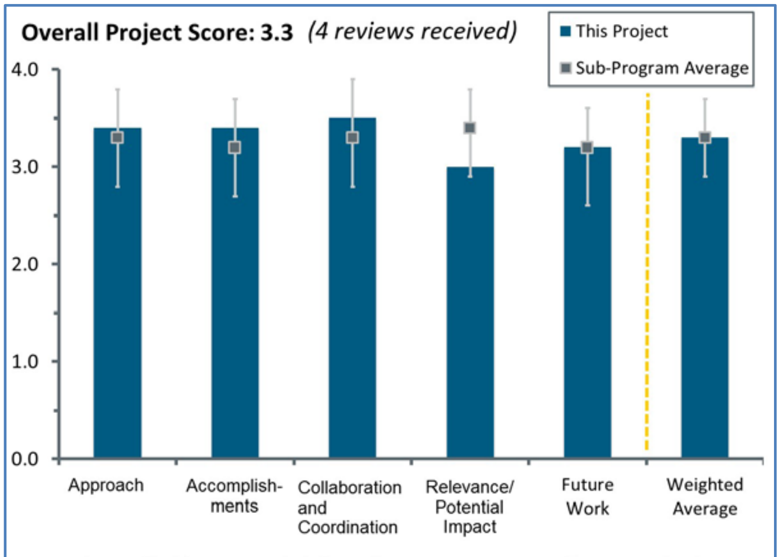
- The team should consider whether some small schedule/approach refinements are possible. Laying off the subsystem-like testing and 1,000-cycle duration testing for FY 2018 appears to increase schedule risk, reducing opportunities for contingency and backup.
- Cost modeling or an independent assessment based upon the systems-level compressor model output would inform as to the economic feasibility of this approach.

Project #PD-139: Reference Station Design, Phase II

Ethan Hecht; Sandia National Laboratories

Brief Summary of Project:

This project will provide publicly available details of different hydrogen fueling station equipment, designs, and economics. An "apples-to-apples" cost comparison of the entire hydrogen delivery chain with various station scenarios using data from industry collaborators will be developed. Evaluation includes stations supplied by centrally produced, delivered hydrogen and those with hydrogen produced on site. Some of the station designs are to be conventionally assembled on site, while others utilize a modular (containerized) construction approach.



The vertical hash-lines represent the highest and lowest average scores received by projects in the sub-program.

Question 1: Approach to performing the work

This project was rated **3.4** for its approach.

- The approach to this project covers a very good and fair range of hydrogen station costs and architectures. This project addresses central production, distributed production, and the impact of throughput on station costs. As such, this selection is what needs to be evaluated/studied. The approach of including the piping and instrumentation drawings for station components works well to communicate. Others may use the piping and instrumentation diagrams from the National Renewable Energy Laboratory (a neutral source) to explain/describe stations. The approach of showing the relative power needs of the system components is also appreciated. This is needed for the investment community so they can "pick up the project" quickly.
- Exploring the five design options is a reasonable approach to establish general parameters. Engagement with partners and collaborators to ensure the analysis will be most useful to industry in infrastructure rollout was performed very well. The project is to be commended, particularly for its success in obtaining data typically considered priority. The effort is broken out into reasonable phases that can be built upon, and there is hope that the design tool will be made available to industry with training, so that further refinement of assumptions could be made on an individual basis moving forward.
- This project demonstrates excellent modeling of the impact of station design.
- The chosen capacities from Phase I of this project are a weakness of this project because they rely too much on the previous projects. The usability of these outcomes loses value over the years because of market and technology developments. What applied for stations at the start of the project does not apply when the project is done (from a capacity perspective). It would have been better to look ahead to what was likely to be needed in three years (300, 400, and 500 kg/day instead of 100, 200, and 300 kg/day), which would have added much more value because current size stations are already in place and operational.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.4** for its accomplishments and progress.

- The accomplishments for this project include the development of a new Python model to evaluate/calculate the cost of hydrogen for station developers/operators and to show break-even over seven years based on delayed station rollout. The project team applied the model with industry surveys on station component costs with optimized station design principles; benchmarked against other models; and completed breakdowns of labor, insurance, and delivery costs, among other costs. The value of this project toward meeting DOE goals is high because this project articulates to the hydrogen community, including potential investors/station developers with a material interest in knowing, the various costs of equipping and building a station. Further, this project addresses the impacts of delivered hydrogen on overall station operation costs and the footprint required for tube trailer storage. The impact on overall costs of using a modular station design with conventional equipment is also covered. The modular station is integral to hydrogen refueling network planning, for it presents an alternative to stations designed and built with components that assembled together can take on any non-standard configuration.

- The project results improve available data on station design and therefore provide better understanding for future station deployment and investment decisions.
- This project is an essential step in identifying key cost drivers and beginning to understand the implications of key assumptions.
- There is some question as to whether DOE/Hydrogen Fueling Infrastructure Research and Station Technology (H2FIRST) should spend its effort and funding on these hypothetical stations. It is not clear what happens to stations where the demand ramp rate does not increase as modeled. In addition, only a small percentage of all stations will not be in urban areas; the assumptions used for this effort were too generous.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.5** for its collaboration and coordination.

- This project demonstrates a comprehensive collaboration between laboratories as well as stakeholder exchange.
- The list of collaborators shows that good effort has been taken to get market stakeholder feedback.
- The list of collaborators is impressive. The team is encouraged to add an asterisk on the Overview slide describing the partners, to reflect a much broader set of collaborators.
- The project's collaboration and coordination with other institutions is extensive, but it does not include utility representatives. More detail as to the collaborations (i.e., what happened) would have strengthened this presentation.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.0** for its relevance/potential impact.

- This project provides a valuable tool to facilitate design trade-off analysis, which contributes directly to the barriers identified in the presentation.
- Project results target future station design and deployment and therefore contribute to future hydrogen market development.
- This project is relevant and has a potential impact. This project contains details of various stations, their equipment, designs, and economics for stations of 100, 200, and 300 kg/day (stations operating today), with the idea to meet the DOE target: $2/kg of dispensed hydrogen. This includes the tube trailer lease costs for delivered hydrogen. This project supports and advances Hydrogen and Fuel Cells Program goals in that it addresses some of the issues associated with larger-scale stations (a part of the Multi-Year Research, Development, and Demonstration Plan), but it could have greater relevance and potential impact if it had included representatives from the utilities. The contribution to the cost of delivered hydrogen is relevant. This project summarizes that delivered gas is the most economical, but the footprint required is larger than a station with on-site production, and this presents issues in urban areas where space is at a premium.
- There are questions about whether this is real research, development, and demonstration or market assessment, and how this topic was prioritized over other topics.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- The future work proposal targets interesting questions with additional value.
- The plans to evaluate methods to reduce footprints are worthwhile. It is suggested that the project also consider putting the tool in the hands of station designers/developers who can then tease out potential scenarios, possibly identifying variables in assumptions made. It is also recommended that the project clarify on the Overview slide that the presentation includes plans for future phases of the project (under Future Work), as this puts the overall effort into a clearer context. As presented, the Overview slide gives the impression the project (rather than this phase of a larger project) is complete.
- The identification of footprint reduction for stations in urban locations as a high priority is good, but it is questionable whether developing a reference station for urban sites is the most effective use of funding.

Project strengths:

- The topics addressed in this project (delivered gas versus on-site hydrogen production) and the related costs are important to the public sector and the investor community, and they are presented in a logical approach. The topics address station capital and installation costs for modular hydrogen stations and those based on central fill. With modular stations, higher station capital costs are offset by lower installation costs. This project began to address the cost of power for stations: buy off-peak and use grid load balancing. This project assumes the highest cost of hydrogen comes from a small station, and this is likely true. This project provides detail on a modular station design (300 kg in a 20-foot container) and points out that such designs/systems have firewalls already built in, which could be a cost saver. The topics also include the cost of delivery, on-site storage, and on-site production and how these contribute to the cost of delivered hydrogen. The conclusion explains that replacing conventional station equipment with modular station equipment does little to change station economics or layout.
- The phased approach makes the effort easier to manage. The project makes it possible to compare trade-offs between conventional and modular hydrogen refueling stations and on-site production vs. delivery. The collaborations named in this project are appropriate to achieve project goals.
- The project contributes to a better understanding of different station designs and their strengths/weaknesses.
- This is an effort to understand how stations are built and attempt to make this information publicly available.

Project weaknesses:

- There is a real industry value of the outcomes. The market continues to develop rapidly—every year the context is different—and this may speed up even more within the coming three years, making results obsolete. There is no concrete plan to share this tool at this point, but funding is needed to continue the effort.
- The following are project weaknesses:
    - This project covers up to 300 kg/day stations (to address today's station), whereas somewhat larger stations are planned: 360 kg/day. This seems like a very minor point, but stations are expected to increase in size further (this is proposed to be covered in a potential Phase III: 600 kg/day). Attribution to the station developer and the location of the station shown on slide 15 would have been appreciated, as the network is at its infancy and attribution would be great.
    - The topics of station cost and the impact of on-site versus delivered hydrogen are complex and difficult to present in 18 slides, at in-depth technical levels that advance the state of the art, and the presentation is somewhat weakened by this.
    - This project/presentation explains that the modular station costs decrease because of standards but does not explain how.
    - Although this presentation mentions that the modular station design uses less square footage, the problem is that the modular design cannot be changed in its configuration, by definition. A project

  weakness is that a "factor" was not assigned to this issue. It could be that a modular station design does not fit into, potentially, as many as 30% of the potential gas station sites.
  - This project assumes that the highest cost of hydrogen comes from a small station, but this hinges on the ability of the station to operate at capacity, and that was not factored into this study.
  - No possibility of a double-decker station was included.
  - Plans to put the tool into the community were not presented.
- As the project identified new barriers and challenges of the current station infrastructure rollout effort, it would be helpful to see some future effort dedicated to working through some of those challenges. Liquid hydrogen was excluded from this phase of the project.

Recommendations for additions/deletions to project scope:

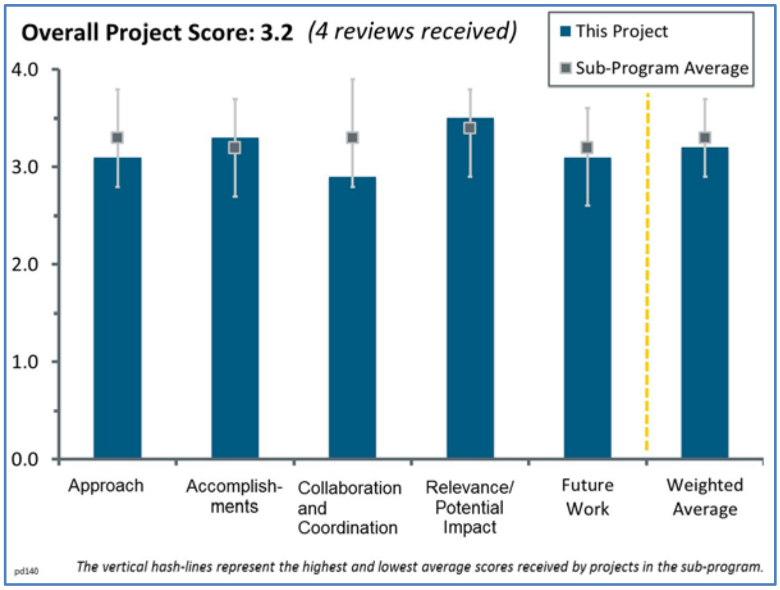
- Because this project is complete, there are no recommendations for additions/deletions to the project scope.
- Industry will be taking over, making its own decisions based on internal market assessments. Because this project does not contribute to the goal of $4–$7 per kilogram dispensed, it may be wise to discontinue this effort to find a more effective use for overall DOE funding.
- Liquid hydrogen delivery and storage compared to the alternatives has already been explored.

Project #PD-140: Dispenser Reliability

Christopher Ainscough; National Renewable Energy Laboratory

Brief Summary of Project:

Hydrogen fuel dispensers are a top cause of maintenance events and labor time at hydrogen fueling stations (HFSs). This project seeks to identify the proper balance between dispenser costs—both capital and operations and maintenance (O&M) costs—and performance. The project consists of three major tasks: (1) a technoeconomic analysis (TEA) of capital and O&M improvements to the chiller/heat exchanger, (2) reliability testing of dispenser components, and (3) development of an open-source and free hydrogen fueling model.



Question 1: Approach to performing the work

This project was rated **3.1** for its approach.

- Understanding the reliability of components is critical to identifying cost-limiting elements in an HFS. The TEA performed to date and the development of a "fill model" will prove to be very important tools/ suppliers of critical information on what needs to be addressed to cost-effectively advance HFS deployment. There is concern that the "hardware" testing of components by accelerated cycling of different components (such as valves and hoses) may yield misleading information. However, it may be the best that can be done at this very early stage of deployment, where actual field data are missing. The project is advised to use caution in the interpretation of results from the hardware part of this activity. There is a question about the need for 11 components per level, which results in an extraordinarily large number of components and tests, making this part of the project prohibitively expensive. There is also a question about the flow rates of 2–3 kg/min as a set of testing requirements. The SAE International J2601 standard is designed to fill a ~4 kg tank in four to five minutes, which makes the flow rate on the order of 1 kg/min. The rates specified of 2–3 kg/min seem high and require justification. The proposed modeling effort is very good and is needed to accelerate and verify fill protocols and characterize the behavior of the tank during a fill. This team is cautioned not to develop protocols but instead to use this validated capability to identify critical elements in need of attention during a fill, as well as those elements that can be identified in need of pre-normative research and development that currently result in rate-limiting and/or safety issues during a fill.
- The project approach is sound. Seeing the fuel dispenser as being the weakest link is a surprise; the compressor would be expected, followed by the refueling hoses and breakaways. The dispenser is a simple device and should have a high mean time between failures (MTBF). Having a low MTBF indicates a poor or incomplete design, poor construction process, or both. A visual design inspection of the device might be useful in identifying poor practices. Failures ranked by MTBF (frequency and life), repair cost, and lost time due to repair are metrics that would help prioritize development activities. These parameters could be compared to field data.
- The work plan shows a comprehensive approach to improve reliability and cost.
- Comments are provided by task:
    - The goal of Task 1 is to determine how dispenser reliability affects the fuel cell electric vehicle customer. The project's approach is to use a TEA to determine the cost to the consumer. However, cost is only part of the customer impact; station availability and uptime are more important in the early stages of introduction, as there are few stations, there is little redundancy, and the fuel costs

are included in the vehicle payments. It is not expected that the TEA will fairly reflect the impact on the consumer.
- The goal of Task 2 is to improve the reliability of the dispenser. The project's approach is to test component reliability. The methodology outlined for the tests seems flawed. Component reliability testing is best done when there are known failures that are identified and tested. Putting the entire system through a cycle test will only identify failure modes exposed in the test. However, it is not clear that cycle failure is even a mode of concern, nor whether the team has done a failure mode and effects analysis (FMEA) or root cause analysis (RCA) of any field failures or designs to identify the key component weaknesses. Without doing this evaluation on each component and then testing against each failure mode, this testing is not likely to be a robust mechanism to identify or improve components.
- For Task 3, it was not made clear how a fueling model would improve dispenser reliability. There are questions about what problem is being solved or investigated by the model and what kinds of solutions can be identified.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.3** for its accomplishments and progress.

- This project is fairly young but is still making good progress. The TEA performed to date has already highlighted critical cost elements of HFS operation.
- The project improves knowledge about reliability issues and cost.
- The accomplishments in Task 1 are interesting. It appears that the dispenser includes a heat exchanger and chiller. These should be off-the-shelf items. The coolant could be glycol water. The working fluid could be ammonia at these temperatures. Low-volume usage of the chiller will offer lower operational cost savings. The costs are actually heat loss. There is a question about what (if anything) is being done about proper insulation. For stations with liquid storage, this issue might be resolved by better energy utilization integration. For temperature, the team could have two tap points from the evaporator, one at ~–100°C and one at <10°C below ambient temperature. The taps would be controlled by a mixing valve (motorized three-way ball valve) controlled by the fuel temperature measured at the dispenser. This would potentially exchange the chiller and heat exchanger for a one-inch valve. Using the storage boil-off as a pressurizer would also help. Sandia National Laboratories (SNL) had been referencing valving reliability standards for its safety analyses. This may be a source of information. The project should also investigate whether the military generated a mechanical handbook comparable to the Department of Defense, Military Handbook: Electronic Reliability Design Handbook (MIL HDBK 338B), and whether American Petroleum Institute has a similar document. Shell might know.
- It looks like very little progress has been made to date on any of the tasks.

Question 3: Collaboration and coordination with other institutions

This project was rated **2.9** for its collaboration and coordination.

- Industry participation includes relevant stakeholders and therefore improves the relevance of the analysis.
- Collaboration is pretty good on the "want" side, but it seems lighter on the "component manufacturers" side. The component manufacturers could help with failure modes, MTBF, and remove-and replace-costs.
- Without a partnership with the component manufacturers, it is not obvious how this project can succeed. Component manufacturers have the ability to provide design reviews/information and perform RCA/FMEA on their components. This information could then be used to design experiments to validate/test the failure modes and component designs.
- Critical elements missing in the collaboration are the Joint Research Centre (JRC) and Argonne National Laboratory (ANL). JRC developed a very impressive tank fill model (fully validated computational fluid dynamics), and ANL developed station behavior (optimization) for the station side.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.5** for its relevance/potential impact.

- This project, if done carefully, could be very helpful in reducing component costs. It could also validate the product safety testing standards.
- This project has the potential to provide significant insight and identify critical elements of HFS operations.
- This project can contribute to the needed balance between performance and cost.
- The project topic is very important, as dispenser reliability is becoming a bigger and bigger issue. It is not clear, however, that the national laboratories should be taking this on as a task. Instead, it should be led by the component manufacturers (perhaps partnering with the national laboratories to develop test capabilities and standards).

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- The proposed future work is good. This project really needs to help define, measure, and/or establish (to the best of its ability) the MTBF of components.
- The future work plan develops project-specific and reasonable testing and modeling to improve and validate the interim results.
- The proposed future work seems fine.

Project strengths:

- This topic area is important. Testing and performance standards are needed to ensure component reliability at stations. This project has a broad, involved team from across the national laboratories.
- There is a good focus on TEA and modeling to understand the weak/strong points for HFS operations.
- The project improves knowledge about cost and reliability. It demonstrates excellent collaboration with industry stakeholders.

Project weaknesses:

- There is concern about the accelerated component testing. It is not clear that mechanical cycling will “mimic” the wear experienced in the field. Also, attention to MTBF as data needed for HFS deployment is lacking.
- The project tasks are not aligned with the goals of the project. Deliverables are not clearly defined, nor is it clear how the tasks will meet the deliverables. Partnerships with component manufacturers are needed.
- The project does not appear to be following standard reliability test protocols.

Recommendations for additions/deletions to project scope:

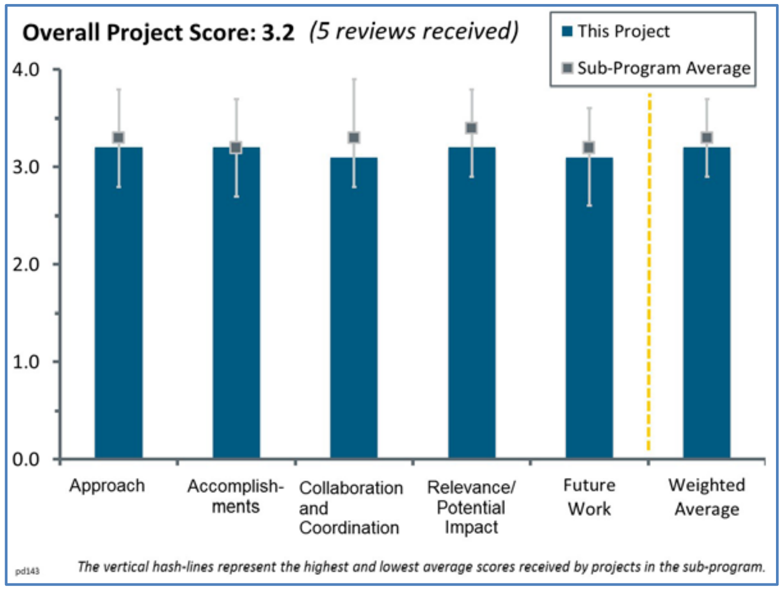
- It is recommended that the project work to keep the component reliability testing as representative to actual field data as possible and work to get the MTBF for these components. The project should not get caught up in designing filling protocols but should instead develop defensible, validated models of the station/vehicle fill physics. It is recommended that the project team with JRC and use SNL to provide validation of the fill model physics proposed as part of this project.
- The project might target a set of recommendations for future component development and station design.
- It is recommended that the project benchmark against other reliability programs (perhaps “Energy Star”).

Project #PD-143: High-Temperature Alkaline Water Electrolysis

Hui Xu; Giner, Inc.

Brief Summary of Project:

This project aims to develop high-temperature molten alkaline electrolyzers with improved electrical efficiency and reduced cost. The electrolyzer will operate in the temperature range of 300°C–550°C. Specific project tasks include (1) development of porous ceramic oxide matrices, (2) incorporation of molten hydroxide electrolytes into the porous matrices, (3) selection of anode and cathode catalysts, (4) assembly and testing of single cells, (5) construction and testing of a 1.8 kW electrolyzer stack, and (6) system and economic analysis.



Question 1: Approach to performing the work

This project was rated **3.2** for its approach.

- The approach is innovative. It is not clear whether the researchers will be able to achieve the high efficiency that they are claiming. The system will be extremely corrosive, and it is not clear whether the seals they are planning on using will resist the corrosion in this corrosive environment. If the researchers can develop the seals, there is a good chance they will be successful in demonstrating a device, but it is not certain if they will achieve the high efficiency they are targeting.
- The focus is on developing new high-temperature alkaline electrolysis. The approach to do this, developing tape-cast porous membranes, is appropriate and well designed. The primary issue is that system efficiency needs to be addressed. Using an OH^- transport membrane means that $2H_2O$ in the feed stream has to be heated to the vapor phase for every hydrogen molecule produced. These 2X O_2^- or H^+ transport membranes, given the high heat of vaporization, are a potentially high energy penalty for the process.
- Intermediate-temperature electrochemical technologies can benefit from moderate heating requirements and therefore facile kinetics. However, they then require advances in electrolytes to remain stable, often necessitating solid electrolytes while adequately conducting ions. The proposed solid/molten hydroxide conductors seem like a logical approach with clear barriers and a pathway forward, in a space where often $[O]_2^-$ or H^+ conductors are the norm.
- The approach to performing the work is feasible. However, it is not clear that the lessons learned and experience obtained from molten carbonate fuel cell systems (similar to this system) have been incorporated in this project.
- The approach to performing the work plan as currently defined is fine, but there needs to be more of a focus on identifying the key challenges and designing the work plan toward addressing these challenges.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.2** for its accomplishments and progress.

- The accomplishments and progress are notable, especially given that the project started approximately only four months prior to the deadline for the DOE Hydrogen and Fuel Cells Program (the Program) Annual Merit Review slides. However, all of the reported information is structural. An upcoming challenge will be the stability of the solid/molten electrolyte in a moist atmosphere, where the hygroscopic hydroxide materials will likely have an even larger dynamic restructuring. Another challenge may be the compatibility of layers and interfaces.

- This is a new start project that began only a few months ago. Given the short time that this project has been occurring, the team has made good progress. Ten-hour tests are not sufficient to state that the material is stable. Corrosion protection for the interconnects and cell assembly need to be demonstrated.
- This is very early (beginning in Quarter 2) in the project, but the Quarter 1 milestones appear to have been met, and progress made on other milestones was demonstrated.
- The project started only recently, and progress appears to be commensurate with the expenditures.
- Reasonable progress has been obtained since the project just started in January 2017.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.1** for its collaboration and coordination.

- Few collaborators are mentioned, but the scope of the work seems to be appropriate for a small team, and the lead principal investigator has a strong and proven track record for advances in the DOE Fuel Cell Technologies Office (FCTO) Program.
- The project needs to add a partner with experience in designing new seals and corrosion protection films. Having an unpaid advisor, while helpful, may not give the support that is needed.
- It is important that the team include a company with ceramic manufacturing experience because the concept requires a ceramic matrix material with a very challenging set of attributes.
- Expanding collaboration with FuelCell Energy (not just on stack assembly) is strongly recommended.
- There is planned collaboration with ZIRCAR Ceramics and FuelCell Energy.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.2** for its relevance/potential impact.

- This has good potential to develop a technology that has a higher efficiency than the current state of the art. It is unlikely to achieve the >90% efficiency target, but it still has potential to achieve high efficiency. The durability of the approach is not clear and will need to be tested extensively.
- Intermediate-temperature electrolyzers can be game-changing for large-scale electrolysis applications, and it is good to see that DOE's Office of Energy Efficiency and Renewable Energy (EERE) FCTO is funding this work.
- If successful, the project has potential to reduce the cost of hydrogen production via electrolysis.
- The project fully supports the Program. It is too early to evaluate its impact.
- The previously stated thermal efficiency of OH^- transport membranes was concerning.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- Since it is early in the project, proposed future work is the majority of the project and appears to be well planned.
- The metric of 1.0 A/cm^2 at <1.5 V seems unnecessarily ambitious, but it would be impressive if it can be met. The reviewer looks forward to learning more from the efforts of this group.
- The presenter was asked a number of questions about the technical challenges associated with his approach, and the responses indicated that the presenter had not previously considered these challenges. It is important that a critical technical review is performed so that the challenges can be identified and the work plan adjusted so that these challenges can be addressed sooner rather than later (with a go/no-go decision based on whether these challenges have been successfully retired).

- The work plan is extremely aggressive. The team is underestimating the sealing challenges. Traditional seals will not work in this environment. New seals will be needed, and this development is not in the work plan. The efficiency tests are not in the plan until the Quarter 10. The project should have some intermediate milestones. The cost analysis should specify a hydrogen cost target using the Hydrogen Analysis (H2A) model. As currently planned, an H2A analysis is not required.
- Identification of risks and issues to provide background/justification for future work is lacking.

Project strengths:

- While it is unclear whether molten hydroxide conductors will be successful for this proposed application, and therefore this may be too high-risk for DOE EERE FCTO, the team and project are well proposed, and the project has a chance for very high impact.
- This is a clever idea. Giner, Inc., has a long history of success. The team has made good progress in the short time that the project has been active.
- This is a novel concept with the potential for reducing electricity costs associated with electrolysis.
- The project is developing a new approach to electrolysis using high-temperature alkaline membranes.
- The approaches are feasible.

Project weaknesses:

- The project is too early to speculate on many weaknesses, but critical aspects will be electrolyte and interfacial stability. The efficiency target seems to be a little bit of a reach. The project seems a little long, but the budget is appropriate.
- The seals are not sufficiently developed, and there is no mention of how sealing will be done. The team lacks expertise in developing seals. The project has not done a sufficient thermodynamic analysis to see whether the 90% efficiency target is feasible.
- The thermal (latent heat of vaporization) energy penalty of using an OH^- conductor for hydrogen generation is a weakness.
- There is insufficient consideration of technical challenges in the design of the work plan.
- The identification of risks and issues is lacking.

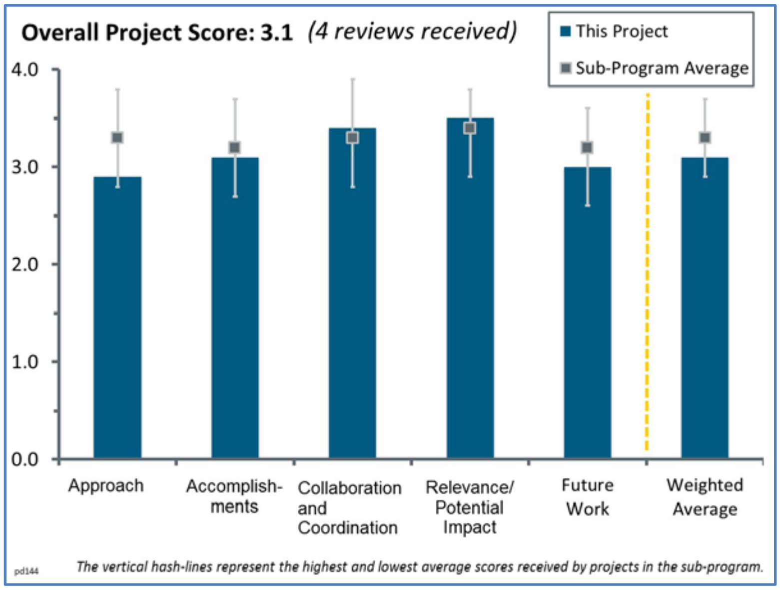
Recommendations for additions/deletions to project scope:

- The proposed historically low-temperature electrocatalysts seem to be warranted, but their stability at higher temperatures is likely poor. Evaluating electrocatalysts from the solid-oxide conductor field may be a better approach because it is unlikely that their kinetics at these reduced temperatures will be that poor.
- The researchers should do an H2A analysis now to see if they have a chance of achieving the cost targets. They should do a thermodynamic analysis to see if they can achieve the 90% efficiency (lower heating value).
- Recommendations include a critical technical review, identification of technical challenges, and a revised plan, as appropriate.
- Longer-term testing on material stability (only 10 hours to date) is recommended.
- The project should do a complete energy balance for the proposed process.

Project #PD-144: Multiscale Ordered Cell Structure for Cost-Effective Production of Hydrogen by High-Temperature Water Splitting

Elango Elangovan; Ceramatec

Brief Summary of Project:



The objective of this project is to develop and test a novel high-temperature electrolysis stack design with an advanced honeycomb-based cell architecture. The stack will combine advanced materials including stable electrode compositions for improved lifetime, a unique set of fabrication options, and cell performance improvements via the multiscale ordered cell structure design. The result will be a highly efficient advanced high-temperature water-splitting stack demonstrating a potential pathway to meet the U.S. Department of Energy Fuel Cell Technologies Office (FCTO) cost goals for hydrogen production. The ability of the stack to operate on intermittent energy sources, such as for energy storage and grid ancillary services applications, will also be tested.

Question 1: Approach to performing the work

This project was rated **2.9** for its approach.

- The solid oxide electrolysis cell (SOEC) approach to hydrogen production is excellent with potential high efficiency, especially when combined with a source of heat. Novel three-dimensional (3D) electrode structures have been proposed to address the gas diffusion limitations of conventional random porous electrodes. However, there is concern that 3D printing of a thick major structural support, versus a thin added layer, will not scale well or be cost-effective.
- Overall this seems like a reasonable approach, but there are a few concerns.
    - Scandium is rare and expensive. The team should calculate the cost and impediments to scale-up presented by Sc. Sc metal costs around $5,000/kg, and on the order of 10–15 tons/year are produced.
    - The goal is to operate at 1.2 V and 1 A/cm^2. That is about 0.3 V of overpotential, corresponding to an area-specific resistance (ASR) goal of 0.3 ohm-cm^2. However, the presentation mentioned an ASR target of 0.4 ohm-cm^2. There may be a disconnect here.

  Overall, this is a good team with an interesting approach. It is very early in the project, so there are not many results yet, as expected.
- Based on the proposed work plan, the approach is sound. Ceramatec is well positioned to be successful since the company is leveraging a considerable amount of previous work in this field. The concept has a number of extremely difficult technical challenges. Fortunately, the team is aware of these challenges and has identified approaches to address them. The following are the primary technical challenges for this project:
    - Achieving the required flatness of the multilayer structure will be difficult, especially as the area is increased to that required for stacks to produce meaningful hydrogen production levels.
    - It will be essential to reduce the resistance contribution of the honeycomb support layers. Ceramatec is aware of this challenge, and the team's calculations suggest it is possible. That said, experimental validation of the low support resistance levels is required.

  - The honeycomb support layer adds complexity to the sealing challenge, especially since it will be really difficult to make the unit cells with ultimate flatness.

  Future reviewers of this project should assess the progress toward retiring these technical challenges.
- The cells will be very complex to assemble. They need a flat surface for the seals, but the electrode fabrication will likely create a surface that will not be smooth and flat. This is a significant risk. The durability testing is not clear. There is no lifetime test, and there are no thermal cycling tests. The researchers need to set degradation standards and power and efficiency targets.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.1** for its accomplishments and progress.

- Ceramatec has extensive previous and ongoing work (e.g., the NASA Mars Oxygen In Situ Resource Utilization Experiment, or MOXIE), so the researchers could hit the ground running. Therefore, they are on track with their first milestones, although it is very early in the project.
- This is a new start, and the project has made good progress so far. The initial ink patterning is very encouraging.
- Progress is commensurate with project expenditures.
- The project is just getting started. There are no major results yet, as expected.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.4** for its collaboration and coordination.

- This project is a collaboration between two highly capable research and development companies (Ceramatec and Palo Alto Research Center [PARC]) and an experienced technoeconomic analysis firm (Gaia Energy Research Institute). A high level of collaboration between Ceramatec and PARC will be essential for success, given that different manufacturing processes for the unit cell structure will be performed at two different facilities. Their respective process development work cannot be performed successfully without a lot of back-and-forth communication.
- There is collaboration with PARC on 3D printing and Gaia Energy Research Institute on technoeconomic analysis. The question will be how well PARC's 3D electrode process matches with the rest of the cell by Ceramatec.
- The team has well-defined roles and responsibilities. The team has the skillset to accomplish the tasks.
- The effort appears to be well coordinated with the partner organizations.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.5** for its relevance/potential impact.

- If successful, this project has the potential to reduce the cost of hydrogen production via electrolysis.
- High-temperature SOECs should play a significant role in the DOE Office of Energy Efficiency and Renewable Energy Hydrogen Production and Delivery sub-program.
- High-temperature water splitting is relevant to the FCTO.
- The team is targeting an aggressive and relevant cost goal of $2/kg of hydrogen.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The team has established acceptable plans for achieving performance demonstration at the button cell level (the first go/no-go decision point metric) in the current project year. If feasible, some work aimed at retiring

technical challenges (mentioned previously) earlier rather than later would be good; some of these can be retired only after scale-up to larger cell areas is achieved (which is scheduled to be completed in the following project year).
- The proposed future work is consistent with the goals. The primary question is in the integration of thick 3D-printed structural support with the rest of cell manufacturing.
- The team appears to have a good plan for future work.
- The researchers need to include metrics for durability, power, efficiency, and an early, preliminary hydrogen analysis to show they have a pathway to achieve the cost target of \$2/kg H_2.

Project strengths:

- A potential high-efficiency SOEC approach with unique architecture to address gas diffusion limitations is a strength.
- This is a good team and an interesting approach, with significant previous experience on which to build.
- This is an exceptionally strong technical team.

Project weaknesses:

- Scandium is very expensive and rare, calling into question whether achieving cost targets and scale-up is feasible. It is not clear that the ASR target is aggressive enough to meet the 1.2 V and 1 A/cm^2 goal.
- The project is aimed at an SOEC stack that will be extremely challenging to make, and it will take a lot of time and funding to prove ultimate feasibility.
- There is concern over how that thick 3D layer integrates with the rest of cell fabrication in large-scale manufacturing.

Recommendations for additions/deletions to project scope:

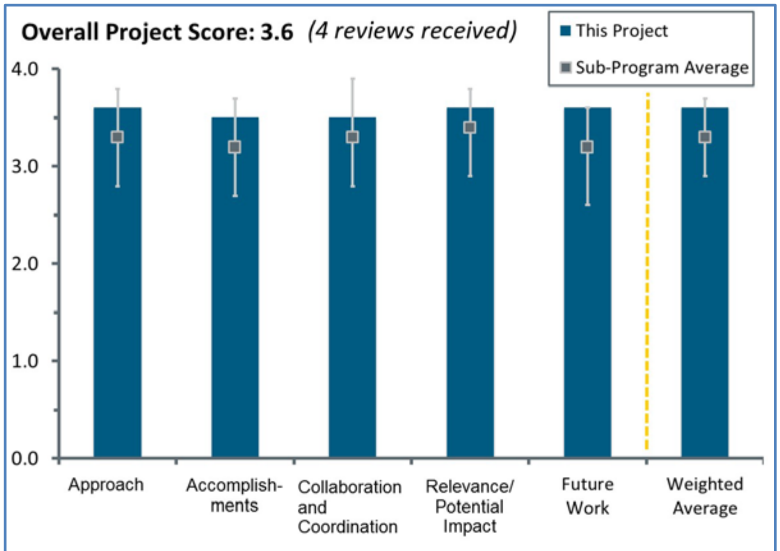
- Anything that can be done to prove ultimate feasibility of making the unit cell architecture with ultimate flatness and required large area should be done earlier rather than later in the project.

Project #PD-146: Advancing Hydrogen Dispenser Technology by Using Innovative Intelligent Networks

Darryl Pollica; Ivys Energy Solutions Inc.

Brief Summary of Project:

The primary objective of this project is to develop a robust and cost-effective system for dispensing and measuring hydrogen that further enables widespread commercialization of fuel cell electric vehicle (FCEV) technology. Key project activities include (1) development of robust sensor hardware and algorithms that improve accuracy based on empirical testing and enhanced meter temperature measurement; (2) development, testing, and demonstration of the use of dedicated short-range communications (DSRC) for use in vehicle refueling; and (3) simplification and cost reduction of flow control and hydrogen pre-cooling systems.



The vertical hash-lines represent the highest and lowest average scores received by projects in the sub-program.

Question 1: Approach to performing the work

This project was rated **3.6** for its approach.

- In terms of dispenser build and flowmeter testing, this team is well on track and focusing on the right areas. The DSRC will rely on original equipment manufacturer (OEM) participation for success. More feedback from OEMs presented to reviewers in the project may shed light on barriers to commercialization that remain unclear. The overall approach is promising.
- The project team presented a concise overview and clearly presented the technology objectives (metering and communications). The team also focused on the economic benefit of the project to demonstrate the relevance. The team did a nice job with highlighting the challenges (i.e., thermal fluctuations) to be overcome and showed interim physical progress.
- The Ivys Energy Solutions Inc. (Ivys)-led team is doing an excellent job of managing this project and has brought some very good creative thinking to an area where improvements are very much needed.
- The project is well organized and focused.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.5** for its accomplishments and progress.

- The project accomplishments and progress toward project objectives are outstanding. The project team is correctly addressing known issues with dispensing and is using standard automotive equipment to improve vehicle communication systems. The progress is measured clearly, with specific targets for completion of critical milestones. Cost reduction progress deserves more focus.
- The project is doing nice work with customizing the Coriolis meter development for thermal stability, understanding the IEEE Wireless Access in Vehicular Environment (WAVE) protocol, and articulating the related economic savings from simpler nozzle designs. The concise project schedule for tasks and milestone completion is appreciated.
- The project was slow to start but is on track to accomplish its first phase successfully. The approach and selection of DSRC and Coriolis flowmeter were consistent with the DOE goals and objectives.

- Except for a contracting delay, the team has made good progress.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.5** for its collaboration and coordination.

- The team seems to have a very close relationship with Rheonik, where they are providing technical assistance to overcome specific application challenges (i.e., thermal). The team is laying the groundwork to conduct field testing with Air Liquide and to advise on enclosures and dispensing locations. And naturally, the team is working with the National Renewable Energy Laboratory (NREL) to conduct testing. All are good steps at this point. To accelerate progress, the project should expand collaborations to include other dispenser organizations (e.g., First Element), work with Toyota or others on the WAVE protocol, and maybe add a software developer to develop a robust interface using the WAVE protocol.
- The partnership with ATLAS as a future industry collaborator for retail demonstration is a project strength. The partnership with Rheonik as a supplier represents a focus on a major flowmeter supplier in the industry and has already demonstrated value with controlled testing of the meter and improvements to the meter that can make immediate impacts on operating retail fueling stations. Areas for improvement include finding an FCEV OEM partner to ensure the vehicle communications approach mitigates barriers to commercial adoption.
- The collaborative work with NREL, Air Liquide, and Rheonik has been excellent. This is a great project for Ivys and will help solve a major problem for Air Liquide. It appears that one result of this collaboration will be a lower-cost, higher-performance dispenser design.
- Collaboration with other industry partners and contractor share funding are excellent.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.6** for its relevance/potential impact.

- Metering hydrogen is going to be very important, and helping to drive down the cost and maintenance of a dispensing station is also very important. The project team presented a convincing presentation on the efforts to achieve these goals.
- The results of this project are in line with the DOE Hydrogen and Fuel Cells Program goals and objectives. Its potential impact will be significant in the development of the infrastructure.
- This project is critical in making an effort to develop lower-cost fueling station dispensers.
- The alignment with the objectives of the DOE Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan deserves a high rating. However, the project results to date do not seem to show a pathway toward significant cost reduction of either dispensers or pre-cooling systems. The costs of the systems remain a significant barrier to FCEV adoption, and while this project does show a clear pathway toward reliability and accuracy improvements, it does not appear to address cost in a significant way. The project approach shows a low-volume dispenser cost target of $150,000 and a high-volume cost of $40,000, yet those targets are relatively unsubstantiated. Furthermore, these costs are for a dispenser with single dispensing capability, while dispensers with simultaneous dispensing capability are showing increasing demand in the market, as station developers try to maximize the fuel delivered in small footprints and during times of the day with high vehicle traffic.

Question 5: Proposed future work

This project was rated **3.6** for its proposed future work.

- The project clearly identifies the future work and predicts future barriers and mitigations. They are well documented and well presented, especially the scheduled targets. The project success relies on a strong and dedicated team at Ivys and at the NREL Hydrogen Infrastructure Testing and Research Facility. More

information about the project team individuals and their roles/responsibilities would be appreciated in future reviews.
- The plan for the rest of the project is well thought out and should proceed as soon as possible.
- The proposed future work is in line with the DOE goals and objectives.
- The schedule summary was clear and concise. It seems possible that the research team will fall behind schedule once they immerse themselves into the technical details of both the metering and the protocol. A schedule reassessment should be performed by the fourth quarter of 2017 and published.

Project strengths:

- The project team is very strong on technical competence, with a deep history of relevant work in the area of hydrogen vehicle fueling systems. The collaboration with the manufacturer of the Rheonik flowmeter is excellent, as this is the primary flowmeter used in this application. The focus on using the DSRC communications link for SAE International (SAE) J2799 is quite novel and has great potential.
- Project strengths include overall subject matter knowledge, having a retail fueling station partner, the flowmeter manufacturer partner, flowmeter testing and development, and the organization and schedule.
- There was excellent technical knowledge and coordination with other partners. The ability to adjust and meet the schedule and milestones is a strength.
- The project is focused. It has good partners who are engaged. The team has set clear goals (technology and economics).

Project weaknesses:

- No project weaknesses were noted.
- Cost reduction for the dispenser requires focus. Cost reduction on the precooling system received limited focus in the project. The lack of an FCEV OEM partner is a weakness. There is a lack of focus on (or at least presentation of) other component reliability (i.e., dispenser valves, sensors, and fueling hardware).
- There is concern about being adequately resourced to achieve the milestones presented. This should be reassessed on a quarterly basis.

Recommendations for additions/deletions to project scope:

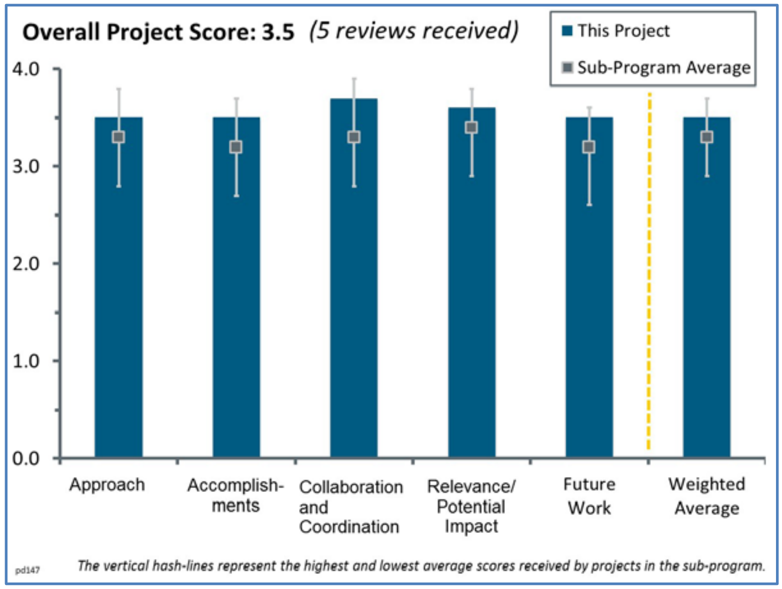
- In terms of additions, the proposal for using DSRC for SAE J2799 needs to be brought to the SAE Fuel Cell Interface Task Force for comment and feedback. In terms of deletions, the suggestion to use a radio frequency identification tag to identify the car at the dispenser nozzle is not needed, as the pressure pulses at the beginning of the SAE J2601 fueling process will identify which vehicle within wireless range is connected to the nozzle.
- More information should be included on project roles and responsibilities of the greater project team. For example:
    - Include more information on dispenser component selection and reliability considerations (e.g., valves, sensors, and fueling hardware). Detailed science on these components may be outside the scope of the project, but proper selection of these components and design of the dispenser to comply with fueling protocols will be critical to project success.
    - Include more information on cooling system design and design/reliability considerations (same reasoning as above).
- The project should continue to design and develop DSRC and improve the Coriolis meter. Field validation should be performed in the next steps.
- More collaborators would be a good addition.

Project #PD-147: Economical Production of Hydrogen through Development of Novel, High-Efficiency Electrocatalysts for Alkaline Membrane Electrolysis

Kathy Ayers; Proton OnSite

Brief Summary of Project:

This project aims to produce a high-performance anion-exchange membrane water electrolyzer (AEM-WE) with low-platinum-group-metal (PGM) electrodes. The anode ionomer will be optimized for improved stability and conductivity, and the lead ruthenate catalyst synthesis process will be refined and transferred to a commercial partner. A 10- to 12-cell prototype AEM electrolyzer system will be designed and built.



Question 1: Approach to performing the work

This project was rated **3.5** for its approach.

- The approach was excellent. Three barriers, a catalyst, an ionomer, and a cell stack design were selected toward the overall goal of system cost reduction for the AEM technology. Each barrier was addressed in a logical and feasible way, and the technical accomplishments show this.
- Developing AEM electrolyzer systems with low-PGM-loading catalysts is an attractive approach to bringing down the costs of producing hydrogen from water electrolysis. This is a well-rounded team with expertise in catalysis, ionomers, membranes, devices, and systems that is well equipped to achieve project goals.
  - There was very little information on the AEM itself and whether this is an impediment to achieving system goals. Some comments after/during the presentation imply that the membrane does indeed limit operating conditions (i.e., current densities, likely temperature) far below what an AEM electrolyzer would operate at in an economically competitive commercial system. There could be concern that these ionomers and catalysts are being developed/optimized for non-optimal conditions. Rotating disk electrode (RDE) experiments could still be useful in this respect.
- Using AEM is a significant step toward achieving the 2020 electrolyzer system capital cost targets of $0.5/kg and $300/kW by significantly reducing membrane electrode assembly (MEA) and flowfield material costs. Identifying the highest-activity catalyst and transferring the catalyst synthesis to Pajarito Powder's (Pajarito's) commercial facility enables validation in a prototype stack test.
- This project addresses the barriers for capital cost of electrolyzers by examining lower-cost anode catalysts and looking at alkaline technology that allows for the switch from Ti to stainless steel plates. The anode catalysts still contain PGM (Ru).
- This work is in its first year of the project, and it seems like a new direction that has little overlap with other projects in the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy portfolio. However, while the need for advances in this research and development space is high, it is unclear whether the approach taken is a pathway toward this. The rationale for alkaline electrolyzers is sound, but it is unclear how beneficial ruthenates are as a cost-effective alternative to acid-stable catalysts. A plot suggests that even replacement of Ir with Ru would constitute a large cost savings (>80% of polymer electrolyte membrane [PEM] oxygen evolution reaction [OER] cost). It is unclear how this affects the total cost as used in the motivation slide.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.5** for its accomplishments and progress.

- The project has made progress toward the project goals and has demonstrated lower-cost lead ruthenate catalysts with good activity. The OER catalyst composition has been selected, and scale-up has been initiated at Pajarito. Initial scaled-up material provided similar activity to the small batch material made at Washington University in St. Louis (WUSTL). The ionomer degradation rate for the block copolymer appears to be lower than that for the Tokuyama AS-4 ionomer. However, durability testing has not been sufficient in length yet. The stack and system concepts have been developed.
- There has been excellent progress by Pajarito in scaling up and reproducing/refining the catalyst synthesis. Promising initial ionomer stability should be validated in longer-term tests (>1,000 hours). This project integrated all new materials in an operational test in a small single cell.
- The plan is clear and feasible, although it could be argued that a 0.5 A/cm^2 current density is modest in comparison to the operational current density in acidic electrolyzers. Notwithstanding, most tasks are close to their expected targets by their expected due dates. The results show promise for this design in terms of stability, efficiency, etc., and this work will answer key questions about the suitability of the development of alkaline electrolyzers.
- It appears that the researchers are making good progress in hitting all of their targets, although the presentation did not include many technical performance milestones (e.g., target device efficiency at a given current density, stability level at given current density).
- The project is on target, and the milestone progress was clearly indicated.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.7** for its collaboration and coordination.

- The collaborations on this work are not as large as other projects, but the team is well justified and appropriate. Each team member brings unique expertise that is required for the overall success of the project, and therefore, a full team effort is required to advance this work. While a few hiccups were noted toward the beginning, the work and team seem to be on track now.
- The collaboration is appropriate in that each partner adds value. There are not too many partners, which can muck up some projects. Georgia Institute of Technology's and WUSTL's roles of providing ionomer technology are fine for this project. Ideally, it would be nice to see a company filling that role, as a company would stand to gain more value than a university should the technology be commercialized. However, it could be that no company exists to provide that step in the value chain at this time.
- There was good interaction between the partners, with WUSTL's catalyst being scaled up by Pajarito and then characterized at WUSTL and validated at Proton OnSite in cells and stacks.
- There seems to be good collaboration between the partners on this project. A single-cell device was tested that used components/contributions from all of the team members.
- Collaboration between partners appears to be working well. Hand-off of the synthesis process to Pajarito for scale-up has been successful.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.6** for its relevance/potential impact.

- The project is relevant and supports DOE goals to reduce costs of hydrogen by reducing costs of alkaline membrane electrolyzers. The reduction in PGM by going to lead ruthenates and the reduction in plate cost by going to an alkaline system offer large potential benefits. However, durability of these systems must be demonstrated, and alkaline membrane durability remains an issue.

- This project is a completely critical step toward overcoming the barriers associated with acidic electrolyzers and historical alkaline electrolyzers. Even the current project goals to replace one PGM (Ir) with another (Ru) have the opportunity to be hugely impactful in terms of the cost of hydrogen, but more detail on this should be shown in terms of technoeconomics.
- This project certainly shows progress toward lowering costs and expanding hydrogen production options. Demonstration at scale will be important if it will be relevant to reaching the desired 60 million tons/year.
- The overall approach sounds reasonable to achieving the stated goals, although it is hard to tell without more detailed technoeconomic analyses.
- High-performance, lower-cost electrolyzers can help meet the hydrogen production cost targets for small-scale distributed hydrogen production.

Question 5: Proposed future work

This project was rated **3.5** for its proposed future work.

- The down-selections have been rational, and the project plan moving forward seems sound and logical. Although risk mitigation was not directly spelled out, the lead principal investigator has a proven track record of succeeding in this type of project and organizational structure. Therefore, the risk in this work is low, but potential for impact is high.
- The proposed future work is appropriate and addresses remaining questions. The cost estimates will provide guidance for potential production. Testing in 1.0 L/min stack prototypes is appropriate and will provide needed system durability data as well as identify problems.
- The future work is well laid out to complete the remaining milestones.
- The proposed future work tasks all seem reasonable.
- Within the project, the future work is laid out very clearly. It is not clear what the next step would be beyond the close of this project.

Project strengths:

- This is an interdisciplinary and experienced team with the combined expertise to achieve the stated project goals. Exploring multiple catalyst and ionomer compositions helps reduce risk. The combination of component/RDE experiments and cell/MEA testing is also valuable for deconvoluting the degradation/loss mechanisms.
- This work is much needed in the DOE Fuel Cell Technologies Office portfolio and specifically for hydrogen production. It is to be hoped that DOE funds additional efforts in this project space by seriously considering the near-term potential.
- The electrolyzer experience of Proton OnSite and the staff’s knowledge of system requirements for the market are major strengths of the project.
- This is a strong team with good capabilities for catalyst scale-up, in-stack validation, and prototype system design.
- This project is very focused on barriers and goals and has very good technical understanding.

Project weaknesses:

- It is hard to find any weaknesses with this project, really. Beyond the scope of the project, it is not clear how the technical lessons may be translated to other projects, but that is not really the fault of this project, just something to think about.
- It is a little concerning that many tests are being performed at low current density (e.g., 200 mA/cm^2). That would make this technology uncompetitive. If this technology cannot get up to 500 mA/cm^2 or greater, it seems that it will have trouble competing with conventional alkaline electrolyzers in terms of cost, since they can, in principle, make use of the same catalysts but with simpler device structure. It is important that controls be included that are based on state-of-the-art RuO_2 and/or ionomers to serve as a basis for comparing the novel catalysts/ionomers being developed through this project. While present in some cases, it is not evident that these are always being included.

- The replacement of one PGM with another is admittedly not a long-term solution for a game-changing technology, and it would have been nice to see more in terms of the future plans for use of first-row transition-metal electrocatalysts. If not, it is unclear why they were not of interest.
- Ionomer and catalyst long-term stability and durability have yet to be confirmed.

Recommendations for additions/deletions to project scope:

- The project should consider moving up the technoeconomic analysis tasks to better inform the necessary operating performance metrics (e.g., current density, temperature, and lifetime).
- The project should consider adding a side-by-side performance comparison of AEM with PEM, using the new AEM technology developed in this project.
- Parallel assessment of state-of-the-art first-row transition-metal electrocatalysts, such as $Fe_xNi_yO_zH$, would be a useful addition to the project scope.
- If short-term tests continue to show promising results, longer-term in-cell tests (>1,000 hours) should be performed.

2017 – Hydrogen Storage
Summary of Annual Merit Review of the Hydrogen Storage Sub-Program

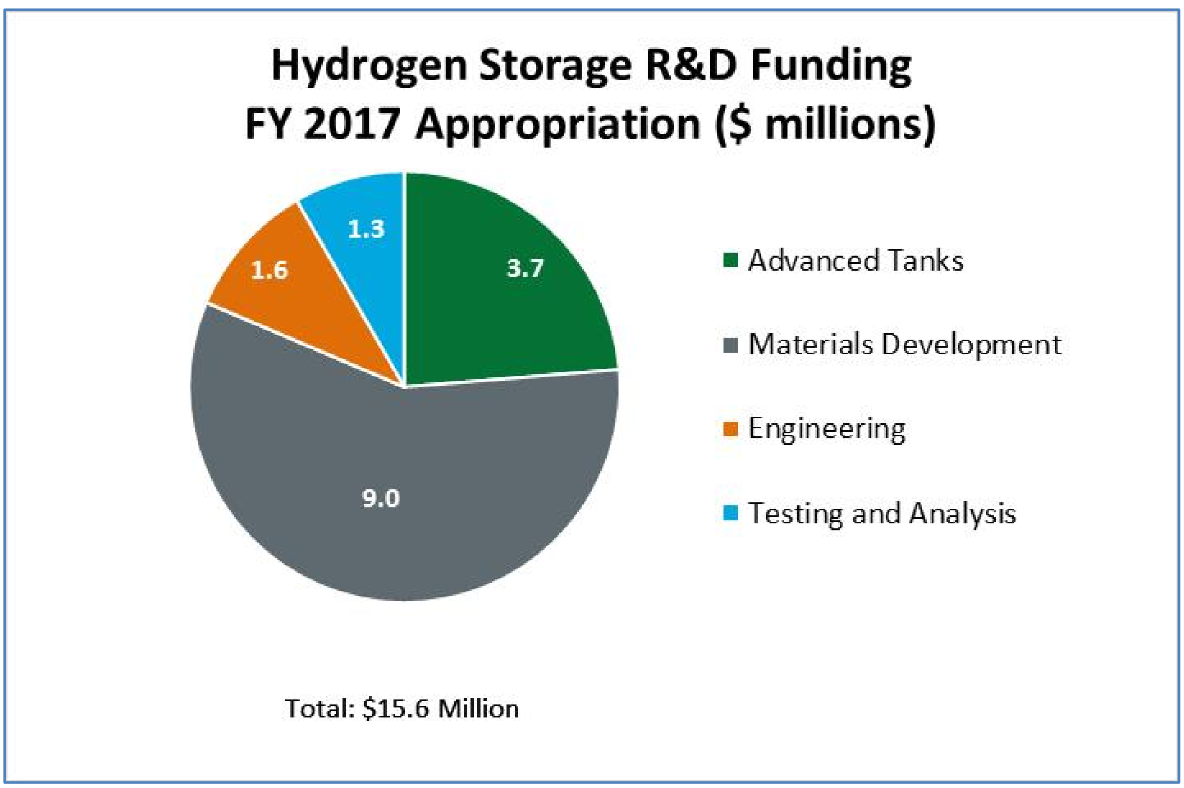
Summary of Reviewer Comments on the Hydrogen Storage Sub-Program:

In fiscal year (FY) 2017, the Hydrogen Storage sub-program portfolio continued to focus on onboard automotive applications through its two-pronged strategy, pursuing strategic near-term and long-term pathways with the potential to meet the cost and performance targets.

In general, reviewers noted there is an adequate balance within the sub-program's research and development (R&D) portfolio, resource allocation, priorities, and technical goals. They commended the sub-program's management and openness to engagement, communication, and collaboration with key partners in academia, national laboratories, industry, and other agencies in the federal government. The Hydrogen Materials–Advanced Research Consortium (HyMARC) was cited as an innovative approach to leveraging foundational scientific understanding and world-class resources and facilities across multiple stakeholders, and as a catalyzer for groundbreaking advances in hydrogen storage materials with the potential to meet the sub-program's ultimate goals. Reviewers encouraged continued and careful coordination across HyMARC's core and support teams as well as with individual materials development efforts to prevent overlap in activities and maximize results. In general, they recommended that greater attention be given to aligning progress made under the sub-program's R&D portfolio with the needs of and interface with hydrogen infrastructure.

Hydrogen Storage Funding:

The chart on the following page illustrates the appropriated funding for FY 2017. The sub-program received $15.6 million in funding in FY 2017. Under FY 2017 activities, HyMARC core and support teams continued work on the discovery, development, and validation of novel materials with the potential to store hydrogen and meet the targets. Multiple HyMARC seedling projects focused on materials development for metal hydrides and sorbents, and the sub-program also initiated an effort on advanced cryocompressed hydrogen storage systems.



Majority of Reviewer Comments and Recommendations:

The Hydrogen Storage portfolio was represented by 28 oral presentations in FY 2017. A total of 25 projects were reviewed. In general, the reviewers' scores for the storage projects were good, with scores of 3.4, 2.7, and 3.1 for the highest, lowest, and average scores, respectively.

Advanced Tanks: Three projects on advanced tanks were reviewed, with a high score of 3.0, a low score of 2.7, and an average score of 2.9.

Reviewers considered these projects to be relevant in addressing challenges unique to the development and manufacturing of promising high-pressure hydrogen storage systems. They commented favorably on the modeling and computational activities used across the advanced tanks portfolio to better understand phenomena affecting feasibility and market readiness of the concepts pursued, including balance of plant (BOP), materials compatibility, and required strength for alternative, conformable, high-pressure hydrogen storage systems. Overall, the reviewers thought the efforts under the advanced tanks portfolio incorporated strong experimental activities but recommended further leveraging collaborations with industry experts, including original equipment manufacturers, to maximize the potential for these approaches to be successfully demonstrated at greater scale and lower cost.

Materials Development: Eighteen materials-based hydrogen storage projects were reviewed, with a high score of 3.4, a low score of 2.7, and an average score of 3.1.

In general, reviewers commended the unique set of capabilities that has been expanded through the overall HyMARC effort, as well as the technical progress made through the wide range of projects in the sub-program's materials development portfolio. Reviewers praised the progress made by the HyMARC core and support teams in the past year as they address the foundational scientific gaps in the thermodynamics, kinetics, and capacity of hydrogen storage materials. They complimented the coherence of the effort and strong collaboration between the first round of HyMARC seedling projects and the national laboratory capabilities. They reiterated that the focus of the sub-program should continue to be on materials with a realistic chance to meet DOE's onboard storage targets that cannot be theoretically met by high-pressure hydrogen storage tanks. Reviewers are satisfied with the HyMARC core group's approach to utilizing model systems to understand material concepts and direct computational multiscale model development efforts, but suggested that the pathway from these model systems to more complex, relevant systems be more clearly described. Through close collaboration between the HyMARC core, support, and seedling projects, the materials-based projects will continue to have an increased level of coordination between experimental and theoretical efforts and to place more emphasis on meeting projected material-level property requirements to meet the system-level targets.

Engineering: Two projects related to hydrogen storage engineering were reviewed, with a high score of 3.3, a low score of 2.9, and an average score of 3.1.

In general, reviewers commended the improvement in accessibility, accuracy, and user interface of the system-level models developed by the Hydrogen Storage Engineering Center of Excellence (HSECoE) in prior years. Reviewers also commented favorably on the hydrogen storage system designs for unmanned underwater vehicle systems developed under the engineering portfolio and praised the teams for their ability to work closely with the U.S. Department of Defense (DOD) and DOE groups to demonstrate an important extension of fuel cell technology to a new type of mobile application. Overall, reviewers recommended that projects prioritize approaches that reduce cost, enable scale-up, and maximize potential to achieve goals beyond gravimetric and volumetric capacity.

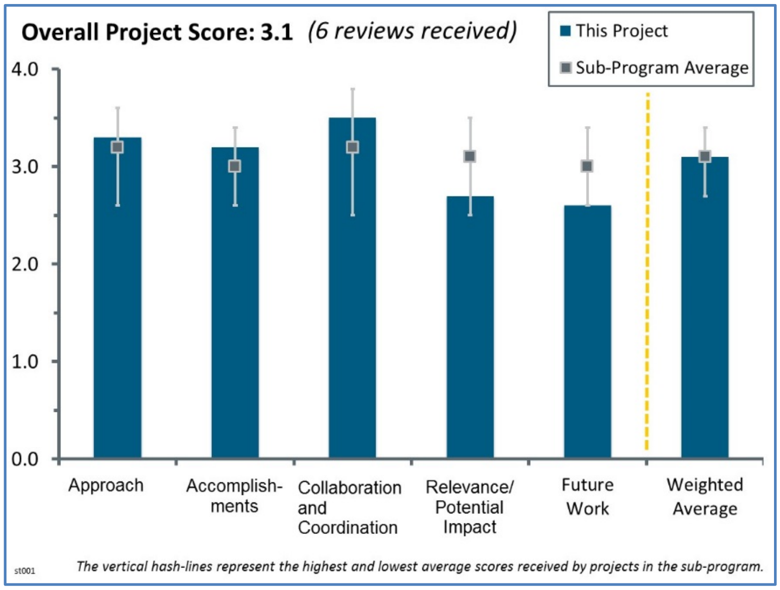
Testing and Analysis: Two projects related to testing and analysis were reviewed, with a high score of 3.4, a low score of 3.1, and an average score of 3.2.

In general, reviewers commended the projects for effectively applying strong physical and chemical modeling and analysis while providing sensitivity studies to understand tradeoffs for hydrogen storage system materials and performance. The reviewers commented on the projects' ability to foster strong collaborations with external researchers to provide increased technical background for more accurate cost analyses and commended the transparency of assumptions and technical rigor. The reviewers recommended more interaction with industry to validate some of the cost projections, such as those for compressed natural gas. Overall, the reviewers recommended that more experimental validation be considered in the analyses and that efforts focus more on breakthrough hydrogen storage system technologies. In general, reviewers agreed that the analyses should consider new hydrogen storage materials that are being commercialized for other applications, such as alane, and identify key cost drivers for new hydrogen storage materials where R&D could lead to cost reductions.

Project #ST-001: System-Level Analysis of Hydrogen Storage Options

Rajesh Ahluwalia; Argonne National Laboratory

Brief Summary of Project:



The vertical hash-lines represent the highest and lowest average scores received by projects in the sub-program.

The main objective of this project is to develop and use models to analyze the onboard and off-board performance of physical and materials-based automotive hydrogen storage systems. Specific goals include conducting independent systems analysis for the U.S. Department of Energy to gauge the performance of hydrogen storage systems, providing results to materials developers for assessment against system performance targets and goals and for guidance in focusing on areas requiring improvements, providing inputs for independent analysis of onboard system costs, identifying interface issues and opportunities and data needs for technology development, and performing reverse engineering to define material properties needed to meet the system-level targets.

Question 1: Approach to performing the work

This project was rated **3.3** for its approach.

- The Argonne National Laboratory (ANL) systems analysis project has served a very useful role by independently assessing design variations and engineering features for diverse hydrogen storage systems and materials. The project has identified areas that show potential for improvement and those that are already limited to current values. Most major factors have been considered and also reevaluated over the past eight years.
- The approach effectively utilizes thermodynamic and kinetic models to guide the hydrogen storage system designs and operating conditions. Overall, the project does excellent work to consider barriers and provide sensitivity analysis. The discussion of the results could be improved by including correlation data to increase confidence in modeling results whenever possible. The impact testing analysis is interesting but should be shown to align with a drop test in the industry standards. This impact test seems to be different from the industry standard testing.
- The approach to the work is soundly based in chemical engineering principles; however, some of the system models use reduced-order algorithms to approximate the results, which can add significant variability and skew the performance characteristics of the overall system. The project needs to ensure these factors are noted when reporting results.
- The project uses a good approach toward analysis, but more validation needs to be included, and the analysis needs to be refined.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.2** for its accomplishments and progress.

- The project has made notable progress in several technology areas. First, the analysis of cryo-compressed autofrettage, performance, and operating pressure versus dormancy was useful. Second, the updated

700 bar system based on the correct density at 15°C was necessary from the previous DOE record. Finally, the reverse engineering analysis for the improved thermal conductivity was a significant improvement.

- During fiscal year (FY) 2017, the ANL team focused mostly on cryo-compressed hydrogen storage systems with primary results for buses and other types of fleet vehicles. The team assessed issues such as the impact of liquid hydrogen (LH_2) pumping rates on filling efficiency, contributions on the factors influencing tank dormancy, and a comparison of stainless steel versus aluminum liners on these Type III vessels. The project team concluded that a 500 bar storage pressure and a 2 mm stainless steel liner gave the largest gravimetric and volumetric capacities. Nevertheless, there is little current interest in the United States in cryo-compressed storage for any vehicle class. ANL also reported work on a couple of issues with 700 bar gas storage vessels and found negative impacts from compact sorbent carbons on storage parameters. Apparently, the project team will look at completing its analyses of high-pressure (i.e., ~350 bar) metal hydride storage tanks, but no specific results were presented.
- Adequate progress was achieved on the compressed gas tanks, adsorption systems, and cryo-compressed systems that were analyzed.
- Assessment of life-cycle costs and durability of the more complex systems being studied—using compressed storage as the baseline—is suggested.
- Savings of 1.1% carbon fiber seems too small. It would be beneficial to see some more revolutionary approaches to reducing the thickness of the container, with more optimal design and better failure theories.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.5** for its collaboration and coordination.

- The project has a high level of collaboration with the key institutions involved in the technology being analyzed within the project. The coordination of the performance modeling within the project and the cost modeling performed by Strategic Analysis, Inc. (SA) is an excellent example of collaboration between projects.
- This ANL team continues to interact very well with the other organizations via both effective interchanges of technical inputs and communicating its outputs.
- It appears that the ANL group collaborates well with SA; however, it was somewhat unclear how much collaboration occurs with other technologists.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **2.7** for its relevance/potential impact.

- The project continues to provide important modeling results for assessing the Hydrogen Storage sub-program goals and strategies. The outcome of this project has the potential to direct hydrogen storage designs and operating parameters toward the DOE research and development goals and objectives. The effort from this year seemed to include other applications (e.g., buses) rather than just light-duty vehicles (LDVs). The project includes several tasks, and it would be useful during the presentation of results for the project slides to indicate the reason for conducting certain analyses. For example, the principal investigator (PI) did not explain the reason for considering cryo-compressed tanks for a bus application when this application has additional volume on the roof compared to an LDV.
- The potential of this effort for generating novel improvements is likely to be limited because additional variations for hydrogen storage systems have been considered during FY 2016 and FY 2017. While the cryo-compressed storage systems were shown by ANL to do very well with the onboard targets, severe issues remain with the necessary LH_2 infrastructure that is required. From current and past analyses by the ANL project and others, there are virtually no known solid storage media candidates that can simultaneously satisfy the updated 2020 DOE targets, let alone the ultimate targets. Over the past decade, ANL and others have found that the variety of design features is always a compromise of contradictory requirements and behavior for either physical or chemical storage systems. The probability of finding a breakthrough system that simultaneously meets all the 2020 vehicle targets is low.

- While this analysis project has provided insight and validation of other system performance characteristics in the past, the value of the projects or the focus of the analysis on those projects seems to provide neither significant impact nor insight into valid pathways for improvements in the performance of the technologies. The group should focus on forward-thinking ideas to quickly assess the potential improvements of various approaches.
- There is very incremental progress—savings of 1.1% on carbon fibers (carbon fibers are getting cheaper). The project needs to focus more on reducing the factor of safety used by improving the design and developing better capabilities to predict burst pressure.

Question 5: Proposed future work

This project was rated **2.6** for its proposed future work.

- A review of the technology from the ST-126 (Center for Transportation and the Environment) project is suggested. This project should also conduct a review of life-cycle costs and reliability pertaining to the more complex systems.
- The proposed future work is unclear at the moment with the substantial budget cuts under the current administration. This lack of clarity is not the PI's fault, but it has to be noted in an assessment of the project's future work.
- The proposed future work seems to be only an incremental progression of the current work. The project's role and effort in supporting ongoing tank projects is unclear. Additional sensitivity analysis regarding the reverse engineering or system designs would be helpful to increase the future impact of this project. It was good for the future work to include validation tasks for the various modeling.
- Future work seems incremental and more of the same. Better failure theories and conformable designs of pressure vessels are needed to make game-changing progress.
- Because the ANL team has now completed rather in-depth assessments of 700 bar compressed hydrogen gas and cryo-compressed storage vessels, further analyses on these approaches are not recommended at the present time; little payback can be expected. Because ANL has already published the comprehensive requirements that absorption and adsorption materials must achieve to meet the DOE targets within the past couple of years, there is little need for additional work on this topic at the moment. Furthermore, neither recent materials discovery projects nor the international research literature have identified viable new candidates for independent evaluation by ANL.

Project strengths:

- The project strength is that the effective modeling provides excellent guidance regarding key parameters for physical-based (e.g., tank designs) and material-based (e.g., reverse engineering) storage. Another project strength is the researchers involved in this project because they have the needed technical depth and attempt to integrate the latest information from other researchers.
- The ANL team has developed and implemented a variety of models for assessing and predicting the attributes and limitations of nearly all types of hydrogen storage systems. The team has provided the valuable constraints required for various storage media if they are to meet DOE targets.
- Project strengths include the many analysis tools and good integration.
- The project creates value for the Hydrogen Storage sub-program by validating approaches and evaluating forward-thinking ideas.
- The project has a good analytical assessment of various technologies.

Project weaknesses:

- The lack of experimental validation of results minimizes the impact of this effort.
- The project could be improved by highlighting the data or examples that validate the modeling results in the presentation. The PI received several questions regarding correlation with test results, which should be addressed in the slides to increase the confidence in the results.
- Because there have been limited design and materials advancements on hydrogen storage technology within the past couple of years, the ANL team has very few "new" storage systems presently available for it

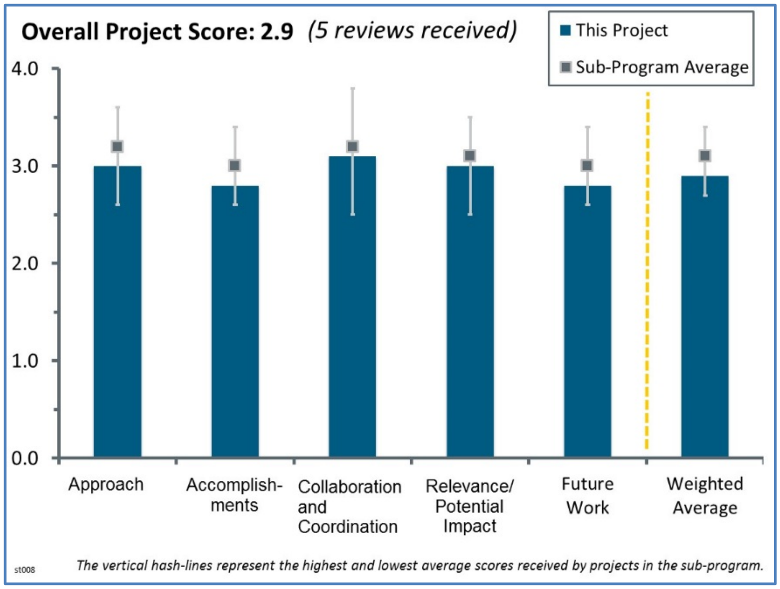
to evaluate at this time. It appears that its efforts are now addressing secondary aspects rather than those critical issues with the potential for a technological breakthrough.
- The project needs to focus more on evaluating forward-thinking ideas and continuing to assess ideas for improvement in balance of plant in systems because it is not likely that any new materials will be created under the current budget situation.
- Project weaknesses include the incremental approach and the need for more effective failure criteria.

Recommendations for additions/deletions to project scope:

- The project should pursue developing DOE records for the other hydrogen storage system, similar to the 700 bar compressed hydrogen system. Additional sensitivity analysis regarding the reverse engineering or system designs would be helpful in increasing the future impact of this project. This project should focus on developing strategies and proactive guidance for research and development to achieve the targets. The impact analysis should ensure the test approach aligns with the industry standard tests.
- It is recommended that the FY 2018 support for this project be reduced, with released funds allocated to projects that search experimentally for more promising hydrogen storage materials.
- The project should focus more on validation of the ANSYS analysis.

Project #ST-008: Hydrogen Storage System Modeling: Public Access, Maintenance, and Enhancements

Matt Thornton; National Renewable Energy Laboratory



Brief Summary of Project:

The ultimate goal of this project is to provide and enhance publicly available material-based hydrogen storage system models that will accept direct material property inputs from material developers to accurately predict material-based hydrogen storage system performance. In support of that goal, this project maintains, enhances, and updates the Hydrogen Storage Engineering Center of Excellence (HSECoE) hydrogen storage system modeling framework and model dissemination web page.

Question 1: Approach to performing the work

This project was rated **3.0** for its approach.

- The goal of this project is to provide hydrogen storage system models developed under the HSECoE to researchers to evaluate the performance of new materials in engineered systems relative to the U.S. Department of Energy (DOE) technical targets. Another task is to manage the HSECoE model dissemination webpage. The intent is that material researchers can input property values for their materials into the HSECoE models and assess whether the final storage system will meet DOE targets. The project is currently at its midway point. A number of models have been developed to date, including the tank cost model, the finite element model for metal hydrides (MHs), and the framework models for physical storage, chemical hydrogen (CH), MHs, and adsorbents (ADs). In the past year, the team has focused on the AD/CH system estimator and the AD isotherm fitting tool. The team has also improved the website access and support. All of these activities are important because automotive hydrogen storage is a challenge that needs to be overcome to ensure commercialization of fuel cell electric vehicles.
- This project has continued the development and refinements of predictive modeling techniques for alternative hydrogen storage media (e.g., MHs, CH, and ADs) started in fiscal year (FY) 2016. This task is currently focused on the media and storage configurations assessed during the completed HSECoE project. The intent of these online models is to allow outside users in the international hydrogen research and development community, who possess the appropriate software, to make comparisons over a range of parameters and operating scenarios against reference materials. The objective is to assist materials researchers in identifying viable candidates with the potential to meet the DOE vehicle performance targets. The project provides a level of technical support (at least for the near term) to the model website to assist outside users.
- The approach is appropriate and well defined. The user-friendly modeling framework is very useful to system analysts evaluating a candidate storage system. The tools allow users to do a scoping estimate of the system parameters and identify barriers to meeting the DOE technical targets.
- The web development and maintenance team is maintaining the website with the addition of minor tweaks and tools that eliminate the need for ancillary software.
- The approach is to enhance and disseminate hydrogen storage system models and provide guidance on material properties.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **2.8** for its accomplishments and progress.

- This task has made significant progress in updating, refining, and maintaining the HSECoE model dissemination website. Continual international interest and activity with the website were indicated by the tracking statistics given during the DOE Hydrogen and Fuel Cells Program Annual Merit Review (AMR) presentation. While such simulations are helpful tools in understanding behavior, they do not necessarily hasten discovery or development of the specified targets. The team spent considerable effort improving support documentation and making other changes to the formatting and approach to enhance the usefulness of the website. These activities should make this website a better resource.
- The team completed the isotherm fitting routine that converts raw data of excess hydrogen adsorption into Dubinin-Astakhov parameters. The agreement between the fitted model and data was good for compacted 0.4 g/cc MOF-5. There were notable improvements made in the system sizing functions for both AD and CH storage systems. There was significant decline in the website analytics. The number of users and sessions decreased 70% compared to the previous year.
- The main accomplishments seem to be in improving the models and making them more accessible to the wider hydrogen storage community.
- There is not much to comment on regarding the website and model maintenance. It appears to be on track.
- Most of the metrics presented pertained to gravimetric and volumetric efficiencies. One major bottleneck with these materials can be charging time. There appeared to be no mention at all of charging rates in the entire presentation. A material can have acceptable gravimetric and volumetric efficiencies, but if the charging time is too high, it will not be useful to the community.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.1** for its collaboration and coordination.

- A very close interaction reflecting technical interchanges among the team members from the different national laboratories as well as outside members has occurred throughout this project. The progress made on both the adsorption and CH storage models indicate excellent cooperation.
- There are strong collaborations among partners in the HSECoE. The project is well coordinated. Work is integrated seamlessly into the model framework.
- There is no real collaboration with other members of the HSECoE. The collaborations page lists a number of collaborations but provides no real documentation on their roles.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.0** for its relevance/potential impact.

- This project is essential in keeping all the developed models in one place and making them available to end users. The potential impact can be enhanced if the test data used for model validation are also included on the website so that users can validate their own models if needed.
- This project has made very good progress in making the numerical models developed during the HSECoE accessible to the general hydrogen storage community. It still remains unclear just how much other research groups are willing or able to fully utilize the tools being developed.
- The models and website are relevant, as demonstrated by the Internet analytics.
- Automotive hydrogen storage continues to be a major challenge, so this project is important and relevant.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- The specific tasks and goals presented for this project should lead to better experiences for the outside users. The level of effort and plans are well balanced.
- The future work is appropriate. The team should devise a plan to encourage outside users to provide user experience data.
- The proposed future work appears to be reasonable, although the development and incorporation of new models that have not been validated pose grave concerns. The new models have not been vetted or discussed with other members of the HSECoE, many of whom have had significant contributions to the inception of the original models.
- The team really needs to address metrics beyond just gravimetric and volumetric capacities.

Project strengths:

- The great strength of this project is the same as it was during the FY 2016 AMR review. Namely, the core team members have extensive knowledge and expertise on all of the hydrogen storage media as well as the appropriate software analytical packages to develop and execute the modeling codes for the website. This is an ideal collection of experienced individuals to continue and extend the HSECoE objectives.
- The team is made up of experienced researchers who are knowledgeable of the various hydrogen storage systems and are directly involved in the model development.
- The investigators appear to be maintaining a website of HSECoE models that is well received by the research community.
- The proposed hydrogen storage system models are useful for estimating the material properties required to satisfy the DOE system targets.

Project weaknesses:

- There are currently no significant weaknesses found with either the current approach or planned activities over the next year. The team is well focused to complete the project goals.
- The investigators should (as a sign of courtesy) at least recognize other team members of the HSECoE that have contributed significantly to the development of these models. Any new model should be vetted with the HSECoE team members to ensure accuracy and consistency.
- It was not clear how the proposed models will provide a full accounting of all important metrics pertaining to automotive hydrogen storage. For example, heat removal is a critical rate-determining step during hydriding with certain hydrogen storage materials, but it was not clear where and how different heat removal strategies could be explored within their models.
- The lack of feedback from outside users is a project weakness.

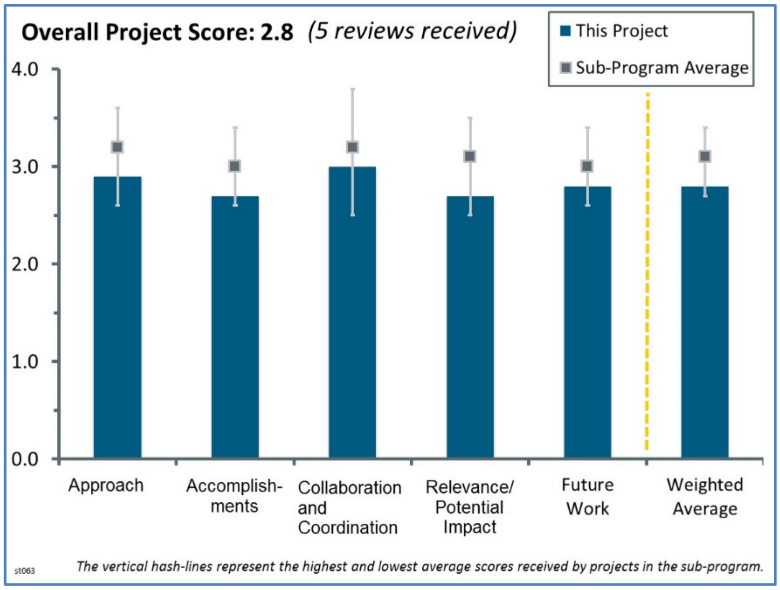
Recommendations for additions/deletions to project scope:

- This project has been making very good progress toward its objectives and has provided improved documentation for users on the website. It is recommended that the scope of the project be supported at its current level during FY 2018 in order to perform all of the tasks described in the future plans.
- The models seem to be optimized, and the data are accessible to the wider hydrogen storage community, so this effort seems to be close to completion.
- The team should consider including raw test data that have been collected by the HSECoE partners.

Project #ST-063: Formation and Regeneration of Alane

Ragaiy Zidan; Savannah River National Laboratory

Brief Summary of Project:



The overall goal of this project is to develop a low-cost rechargeable hydrogen storage material with favorable thermodynamics and kinetics, and high volumetric and gravimetric hydrogen density. Specific objectives include (1) development of cheaper techniques to synthesize alane (AlH_3), which avoids the chemical reaction route that leads to the formation of alkali halide salts such as LiCl or NaCl; (2) utilization of efficient electrolytic methods to form AlH_3; and (3) development of crystallization methods to produce α-AlH_3 of the appropriate phase, crystal size, and stability.

Question 1: Approach to performing the work

This project was rated **2.9** for its approach.

- High hydrogen density and low desorption temperature make AlH_3 one of the few materials with a chance to meet targets. The focus on cost reduction makes sense. However, the electrochemical method seems unlikely to ever come close to meeting cost targets. Replacing $LiAlH_4$ with $NaAlH_4$ seems like it would have a small decrease in cost, but there is a significant increase in cost/complexity associated with forming the tetrahydrofuran (THF) adduct.
- The project addresses barriers for production of a material that has potential to meet U.S. Department of Energy targets. The title suggests that the project looks at production and regeneration of AlH_3, but most of the work presented is relevant to production. Although first fill is a cost to be considered, the majority of a storage material needs to be produced from spent fuel if it is not simply rehydrogenated onboard.
- Previous work described the great benefits of electrochemical methods for AlH_3 production from $LiAlH_4$ and Al electrodes (made by compressing spent AlH_3). This year the focus appeared to be more on methods to make $NaAlH_4$ and using ball milling to make AlH_3. This was confusing, and it is not completely clear whether ball milling is now the preferred approach. If so, it seems to be consistent with the end of the project electrochemical work by Ardica.
- The barriers presented and those addressed were disjointed. The first barrier, reducing dendrite formation, was not discussed at all. The new "dry" mechanochemical method appears to bypass the electrochemical work completely. The focus was indeed on cost reduction, which was done well experimentally, but because of the nature of the material, it was not well integrated with the previous efforts.
- The approach taken to regenerate AlH_3 appears to be duplicative work performed by the Dow Chemical Company (Dow) and others many decades earlier. AlH_3 is not a hydrogen storage material that is expected to be used for automotive applications. However, AlH_3 does appear to be very promising for portable power because of the high-quality hydrogen produced and the relatively low dehydrogenation temperature.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **2.7** for its accomplishments and progress.

- There is nice progress with scaling up the conventional process. It is nice to see large quantities (200 g) of high-quality AlH_3 being produced. The electrochemical method seems to be stuck on separation of the AlH_3-THF adduct. There is limited progress toward recovering high yields of α-AlH_3. The electrochemical approach seems unlikely to bring down costs in any significant way.
- The accomplishments on the electrochemical portion appear to be the use of $NaAlH_4$/THF to increase conductivity. It is unclear how effectively this addresses the DOE goals because the main benefit is cost, and this has not been quantified, especially with respect to the cost of the subsequent ligand exchange before crystallization. The mechanochemical method shown is really only applicable to first fill. Crystallization appears successful with long-lived powders, but no details of what work has been carried out are given.
- Progress on some of the objectives is questionable in some aspects of this project. It seems like a waste of resources to use density functional theory (DFT) calculations to determine bond strength of various materials, state that it does not completely aid in crystallization prediction, and then use a known transamination process after the fact. There appears to be no progress regarding changes to the electrolyte and improvements in conductivity; there was no increase in conductivity shown over the previous year's results. The mechanochemical method developed to produce AlH_3 from $NaAlH_4$ is impressive and may reduce costs, but scaled cost projections were not detailed or discussed. The most impressive progress is the increase in crystallization scale and purity. A greater than 13 times increase in scale is encouraging and shows good strides toward optimizing the process.
- The presenter noted that the project team has been working on the regeneration of AlH_3 for over 10 years. The project title is "Formation and Regeneration of Alane." It seems this past year that the focus was on formation using a ball milling approach, and very little focus was on regeneration—at least, regeneration was not covered in the presentation.
- This is a difficult problem—regenerating spent AlH_3 back to high-purity α-AlH_3 that will meet the DOE cost and efficiency targets—as evidenced by the decades of research on perfecting the production of α-AlH_3. Given the fact that α-AlH_3 is not expected to be used for automotive use, the associated costs and efficiency may not apply. There is no graph or timeline detailing the progress of lowering the cost or increasing the efficiency of the process (e.g., waterfall plot), so the progress and accomplishments cannot be adequately assessed.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- Collaboration with several institutions was presented, and it appears that the engagement between groups is beneficial to all those involved.
- Some collaboration with Ardica and the California Institute of Technology (Caltech) is evident, with the latter providing nuclear magnetic resonance (NMR) analysis to strengthen characterization of shelf life. However, overall the project appears mostly self-contained within the parent institution.
- This is a relatively small project with its own focus. The team was sharing some calculation results with Ardica for separation and recover steps.
- There are few collaborations. The team is essentially just working with itself (project partners are SRI International and Ardica). With the exception of the NMR work at Caltech, there are no collaborations within the Hydrogen Storage Characterization Optimization Research Effort (HySCORE) or the Hydrogen Materials–Advanced Research Consortium (HyMARC).
- The collaboration was rated at 2.5 solely based on the fact that there were very few details given on what was collaborated on or with whom. Collaboration efforts with Ardica seem to be minimal at best.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **2.7** for its relevance/potential impact.

- This project may not meet current goals or objectives directly, but it is closer and more feasible than most other options currently being investigated. Other industries are interested in this technology beyond transportation, so possibly transitioning funding from the DOE Fuel Cell Technologies Office (FCTO) to a more relevant organization may be beneficial and more appropriate.
- In regard to relevance, the overview slide did not specifically address any barriers in the FCTO Multi-Year Research, Development, and Demonstration Plan. Listed barriers were more in line with project milestones likely negotiated with FCTO managers, so it is unfair to dock the project too much. For potential impact, it looks like the expertise developed in the project is being leveraged in support of new emerging applications in small power applications. It would have been helpful to see more quantitative connection to the FCTO goals on non-vehicular applications.
- The project has made some progress by improving the synthesis of AlH_3, which has potential to contribute to FCTO goals. Further progress could have been made if the project investigated a full refueling cycle or several cycles.
- From an automotive standpoint, the relevant impacts on regenerating AlH_3 appear to be minimal, because AlH_3 is not expected to be used as an automotive fuel (which is what the FCTO is focused on). However, the relevant impacts for portable power may be moderate.
- The project is primarily focused on development of an electrochemical method to form AlH_3. This method has been pursued for many years, and despite considerable effort, the team is not much closer to an economical method for the production of α-AlH_3. The Dow method with $NaAlH_4$ is unlikely to lower cost because formation of a THF adduct (as opposed to a diethyl ether adduct) requires exchanging with triethyl amine, which probably adds more cost than it reduces. This effort is unusual and therefore unlikely to have any significant impact on other projects.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- The future work proposed is logical to a point. Effective crystallization of AlH_3 from the adduct is the key to manufacturing the material at large scales at low cost. This is an appropriate focus and is critical to success. Developing guidelines for production and shipping is important and will indeed need to be addressed; however, effort should be directed toward identifying an optimized and automated process before standards and guidelines are produced.
- Although the presentation does not make this clear, it appears that the project is finishing shortly. There may be insufficient time to complete all the work proposed, and the researchers may need to prioritize. Optimization of crystallization parameters for other adducts seems open-ended and could be complex. Efforts directed at certification of AlH_3 quality and developing standards for shipping and storage could be more achievable and be of some value to the community.
- The future work is quite limited, so it is assumed that the project is coming to an end.
- No future work was proposed because the project is wrapping up.
- There does not seem to be any planned future work. It is not clear whether a cost estimate has ever been performed using the conventional Dow recipe. If so, it should be compared to the electrochemical route. The group has shown nice progress scaling up the Dow recipe to 200 g batches. A detailed understanding of the true costs associated with this method may help target future work on the most costly steps. Any future work on alternative methods should focus on AlH_3 recovery from adducts. This seems to be the critical step.

Project strengths:

- This project shows strength in its creative development of solutions to mitigate encountered problems. The reduction of feedstock cost and development of a new process are strong additions to the project and may help reduce the manufacturing cost. The increased batch size for crystallization is incredibly encouraging and may lead to an optimized process with larger yield. The stability of the material produced is also great to see.
- AlH_3 is a promising compound with useful capacity and hydrogen purity, so efforts to overcome cost and stability issues with this compound are valuable.
- There is nice progress with the scale-up to 200 g.
- The project strength is the application of AlH_3 for portable power.
- The 10 years of experience is a project strength.

Project weaknesses:

- The project appears defocused and lacking coordination. Modifying a method developed four years ago in the final year of the project comes unexpectedly and helps give the impression that the work is a series of experiments that are not part of a larger, well-considered strategy. There does not appear to be opportunity for any detailed, and perhaps more general, understanding to be communicated with the rest of the Program so that other projects can benefit. A publication describing the understanding learned would be desirable; the last paper (not patent) appears to be from 2012, before the current phase began.
- The project is disjointed in some regards. One of the main focus points, reducing dendrites during the electrochemical process, is not mentioned at all. The mechanochemical process seems to usurp the electrochemical method, and the path forward is unclear regarding which process will be used in the future. The use of DFT calculations on different adducts does not appear to have added any value to the project, as previously known methods were used.
- The project lacks focus. There is no clear plan for reducing costs. The electrochemical route has been pursued for a number of years with little success. Modifications to the Dow recipe do not seem to be targeting the most costly steps.
- From looking at the historical perspectives (patents and publications) of AlH_3 from the late 1940s to the present, it appears that no novel approaches have been explored. Most of the attempted ideas were looked at by Dow and others.

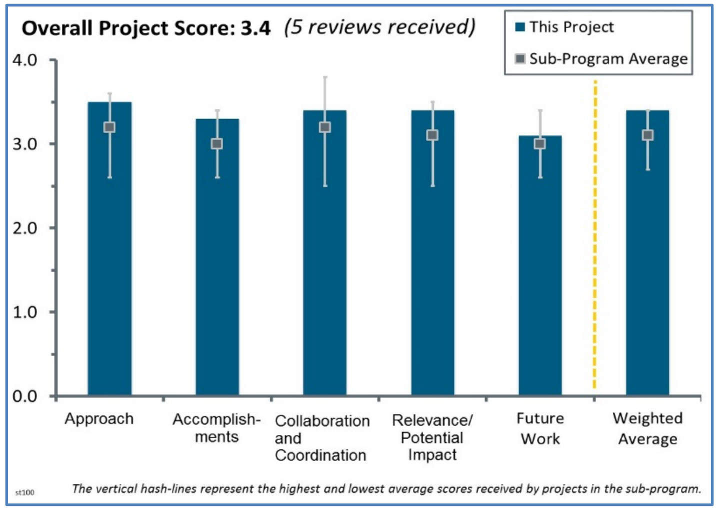
Recommendations for additions/deletions to project scope:

- The project should develop a detailed cost model of the Dow process that includes a realistic assessment of costs associated with each step. For example, solvent handling, materials storage issues, and safety aspects need to be considered along with the cost of precursors and energy requirements.
- The project should be focused on reducing feedstock costs and crystallizing larger batches of high-quality AlH_3. A single process should be selected and focused on to reign in the scope.
- This is not applicable because the project is ending.

Project #ST-100: Hydrogen Storage Cost Analysis

Brian James; Strategic Analysis, Inc.

Brief Summary of Project:



The goals of this project are to (1) conduct independent Design for Manufacture and Assembly (DFMA) cost analysis for multiple onboard hydrogen storage systems, and (2) assess/evaluate cost-reduction strategies to meet DOE cost targets for onboard hydrogen storage for light-duty fuel cell electric vehicles (FCEVs).

Question 1: Approach to performing the work

This project was rated **3.5** for its approach.

- The approach is to use DFMA to assess the cost of developing technologies, understand the manufacturing costs of the technologies, and project the ability to meet DOE's cost targets. The methodology is also used to identify some interesting areas for future cost avoidance.
- The project has an excellent team with clear goals.
- The approach of this project was focused on the key barrier of hydrogen storage, which is the cost. The project provides transparent assumptions and effective analysis for the various cost studies. An improvement in the approach could be to include additional verification of the results based on supplier cost estimates or confirmation.
- The analysis to address the cost comparison between four systems was completed in the first year in this five-year project. The weakness is that there is no way to validate how closely it will represent the real cost.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.3** for its accomplishments and progress.

- The accomplishments surrounding cryo-compressed tanks for buses—understanding the impact of multilayer vacuum insulation, understanding the balance of plant on tanks, and costing out the pathway for new ligands in the manufacturing of MOF-74—will contribute to the success of the Hydrogen Storage sub-program. It is recommended that the project focus on some of the materials that are closer to being commercialized in the DOE Hydrogen and Fuel Cells Program (the Program), such as AlH_3 manufacturing, and also cost out the metal hydride-based storage system for fuel cell electric forklifts, which could actually facilitate the commercialization of hydrogen storage technologies into the marketplace.
- The project was able to make progress with several key hydrogen storage systems, such as cryo-compressed system cost estimates, metal–organic framework (MOF) material cost, and compressed natural gas (CNG) tank cost assessment. The main presentation should have included the last reviewer slide with the cost comparison for cryo-compressed and cold-compressed for the light-duty vehicles (LDVs). The cold-compressed slide with the tool development would eventually be interesting, although it seemed incomplete.
- The goal was to compare the four ways, and the team has done this. Many simplifications have been made in the process, but overall it can be used to provide guidance.
- The team is making good progress, but there seems to be an overdependence on data from other models, some of which are becoming dated. A sanity check to go back to more current manufacturing and design data, rather than have this analysis rely upon another analysis, would make the project better.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.4** for its collaboration and coordination.

- The principal investigator clearly demonstrated collaboration with experts in the areas of compressed tanks (the Institute for Advanced Composites Manufacturing Innovation, Pacific Northwest National Laboratory, and Argonne National Laboratory [ANL]), cryo-compressed tanks (Lawrence Livermore National Laboratory), and MOFs (Lawrence Berkeley National Laboratory).
- The project appears to have a high level of collaboration with several experts in the field. In the past, ANL provided the performance analysis, and this project provided the cost analysis. It was interesting that this project was attempting to integrate the performance with the cost analysis in its development. It was unclear whether ANL was involved in this tool development. This project appears to have heavy collaboration with national laboratories, and it should expand to collaborate with industry to confirm its cost results.
- The team has done a great job. In addition to the current developers, some outside vantage points might be beneficial.
- The team has been collaborating with other laboratories to get a sense of the costs that are in circulations. However, more collaboration with different industries that are actually manufacturing different components would be beneficial. Also, some sort of validation, which can be obtained through collaboration with industry, is crucial.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.4** for its relevance/potential impact.

- The project is highly relevant for guiding hydrogen storage system designs and strategies toward commercialization. Without this project, it would be difficult for the Hydrogen Storage sub-program to discuss and assess cost projections.
- The project should continue to contribute practical costing guidance to the Hydrogen Storage sub-program and the hydrogen storage community for future decision making in these areas.
- The impact can be huge if the predictions take into account the actual drivers and have a way to validate them.
- This project is accomplishing the goals that it is tasked with, but the Program as a whole seems to be devoting a good deal of effort to analysis on a yearly basis, to the point that it is analyzing analysis.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- Good work is proposed.
- The future work appears to be the appropriate next steps. Additional discussions should occur with industry regarding confirming the CNG tank estimates and other cost estimates, if possible. The reverse engineering of material cost should be emphasized as a key item in the future work plan.
- It is recommended that the team steer the project to assess those technologies within the Hydrogen Storage sub-program that are nearing commercial success. Compressed tanks are on a solid pathway in the market, while adsorbent technology has a long way to go prior to being adopted in the commercial space for LDVs. However, metal hydrides for material handling equipment and AlH_3 for portable power are technologies that are being transitioned into the commercial space and could benefit tremendously from a thorough cost assessment.
- Coordinating a review with the ST-126 project (which is innovative but high-risk) is suggested. The project should also conduct a study of life-cycle costs and system reliability for the more complex systems being evaluated.

- The project is not a five-year project, as future work focused only on-fine tuning project methods, which will have only a secondary effect. It is suggested that the team focus more on validating cost predictions, as many component costs are very difficult to predict; anyone can have models, but it is important to apply error bars based on uncertainty, which will allow the team to compare different methods more effectively.

Project strengths:

- The strength of this project is the transparency of assumptions and disciplined approach to the cost analysis.
- The strong team that is familiar with the issues in hydrogen storage and good collaborations are project strengths.
- The project uses a good methodology to combine different costs of different materials and processes. It has a good approach for cost predictions.
- The quality of the people working on it is a project strength.

Project weaknesses:

- There are no glaring weaknesses.
- The overreliance on the analysis of others, as opposed to manufacturing data, is a project weakness.
- The project weakness is the lack of comparison of cost estimates with supplier values to provide confidence in the projections. The tool development for cold-compressed seems incomplete, and the team should consider other functional reasons for selection of Type III versus Type IV vessels, such as the permeation into the vacuum space and liner stability.
- There is no validation. The project needs to address cost with error bars because of the uncertainty of costs of composites due to the low fidelity of manufacturing processes, which leads to lower yield.

Recommendations for additions/deletions to project scope:

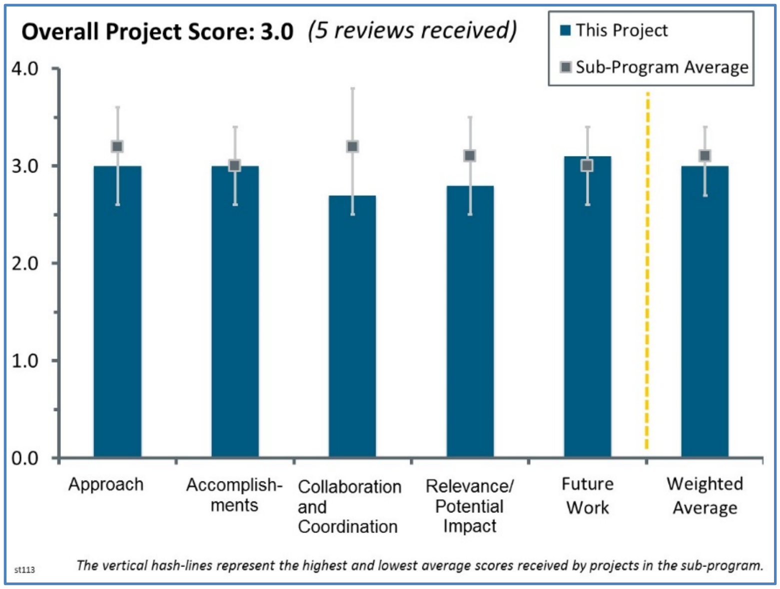
- Additional effort should be included to help guide research to achieve the DOE cost targets. For example, the reverse engineering of the material cost or determining the correct balance between performance and cost for carbon fiber for compressed tanks would be helpful.
- For the Hydrogen Storage sub-program, there should be larger but less frequent analyses.
- The project can be easily completed in three years based on the objectives. It should not be funded for five years unless other metrics are added to the project. There may be more deserving projects.

Project #ST-113: Innovative Development, Selection, and Testing to Reduce Cost and Weight of Materials for Balance-of-Plant Components

Jon Zimmerman; Sandia National Laboratories

Brief Summary of Project:

The overall objective of this project is to identify an alternative to high-cost metals for high-pressure balance-of-plant (BOP) components. The project goals are to (1) reduce weight by 50%, (2) reduce cost by 35%, and (3) expand the scope of construction materials for BOP.



Question 1: Approach to performing the work

This project was rated **3.0** for its approach.

- The use of stacking fault energy (SFE) to determine whether a material may be acceptable in a hydrogen environment may be a good screening tool, assuming the relative reduction in area is a good indicator for hydrogen compatibility. There are concerns that the methods of calculating the SFE may overpredict the measured SFE, especially in the case of Mn-containing materials. As a result, the calculated SFE may provide general guidance, but it may throw out acceptable materials and include unacceptable materials. The use of the face-centered cubic (FCC) lattice parameter is just one step further removed from providing a correct assessment of the acceptability of a particular alloy for use in hydrogen service.
- The premise of this project was that first-principles computations using density functional theory (DFT) and other simulation methods to assess chemical compositions and crystal structures of SFE values of alloys would identify suitable candidates for hydrogen storage BOP components. Experimental materials testing of test specimens either after hydrogen exposure or in a hydrogen gas environment would selectively verify predictions. The goal was to find higher-strength and lower-cost alloys compared to the industrial standard of 316L austenitic stainless steel. While the screening approach based upon SFE properties was extensive, this would address only a portion of the parameters necessary to design and manufacture cheaper and lighter BOP components. Important issues such as the impact of welding and fabrication methods were not addressed.
- The approach has some shortcomings. The materials discovery and experiments are being done without any reference to manufacturing. Even if the team discovers a new material that may be cheaper and may weigh less, the cost of manufacturing components with that material may make it prohibitive. This is an important issue that should have been taken into account. Also, the amount of weight and cost the team was trying to reduce was not made clear or stated. The type of BOP components being considered, their shape, their current weight, and current cost should have been the benchmarks.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.0** for its accomplishments and progress.

- The identification of specific commercially available alloys that meet the cost and strength targets is a significant accomplishment for this project.
- This project is scheduled to end in September 2017 after nearly three years of effort. The Sandia National Laboratories (SNL) researchers conducted an extensive series of simulations based upon DFT modeling of

SFE variation with alloy composition ratios. The impact of hydrogen on fatigue life was measured and related to model predictions. Two tentative candidates (i.e., XM-11 and Nitronic 60) that had ~40% the cost of 316L stainless steel were found favorable for hydrogen use. On the other hand, the figures on slides 14–17 showed substantial spreads on performance parameters with respect to lattice dimensions, Mn versus Ni ratios, and calculated SFE values. Hence, selection of specific "best" candidates seem problematical even without consideration of important characteristics that were presumably outside the scope of the project.

- After three years, the team has used materials discovery to identify other materials that may work, but there has been no testing or manufacturing of these materials for any BOP components. The team should have involved manufacturers of these components to see how the new materials will perform under manufacturing and how their properties hold up under pressure.
- It is unclear whether the modeling component of the project led to any specific alloys that are worth researching in more detail.

Question 3: Collaboration and coordination with other institutions

This project was rated **2.7** for its collaboration and coordination.

- The project has a variety of collaborators involved with the supply chain and to assist in testing: a metal manufacturer (Carpenter Technology), a metal user (Swagelok Company), and a company with high-pressure testing experience. It may be beneficial to involve original equipment manufacturers in the selection process to expose them to the project research and possible new materials.
- Most of the effort seems dominated at SNL, with very little direct communication or involvement with its project partners, Swagelok Company and Carpenter Technology. If these companies did provide some detailed technical support, it did not seem to be included during the DOE Hydrogen and Fuel Cells Program Annual Merit Review presentation. The Hy-Performance Materials Testing organization apparently performed fatigue evaluation in gaseous hydrogen as a subcontractor.
- It was expected that the team would collaborate with manufacturers and other parts of SNL that were dealing with the entire system.
- Collaboration is relatively limited in scope and number.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **2.8** for its relevance/potential impact.

- Reduction of system cost and mass are critical to successful acceptance and implementation of fuel cell electric vehicles. This research to identify new materials that can achieve these objectives is important to the research, development, and deployment portfolio for hydrogen storage.
- This project does examine one of the Achilles' heels in widespread utilization of hydrogen as a fuel for vehicle transportation and other applications (i.e., the high cost of hydrogen-compatible materials needed for the BOP components for both onboard storage systems and the infrastructure). The team has identified at least potential lower-cost candidates that maybe viable; however, this project did not evaluate a number of other critical factors that must be considered before BOP components become commercially acceptable.
- It is not clear how much weight and cost savings the team is talking about. It seems unlikely that the project will make a significant impact, as this may be a very small cost compared to the entire cost of the system. Also, materials discovery is just the beginning of the study, so it may be worthwhile to see in absolute what the cost of the BOP is compared to the pressurized tank cost before moving forward in this direction.
- It is unlikely that this project will have much relevance to future hydrogen transportation. The authors list a 35% reduction in cost and 50% reduction in weight for the material. However, the authors should list the likely reduction in weight and cost for the overall vehicle storage system resulting from the better materials. It is assumed that much of the cost of valves and regulators is manufacturing costs and not material costs, so the system gain may be much less than for the material. It seems that basing project relevance on today's high costs for BOP is inappropriate, because the high cost is most likely due to small-scale production, and costs are expected to drop as valves and regulators are manufactured in mass.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- The tasks planned for the remainder of fiscal year 2017 are reasonable to finish this stage of the project. It would be good to provide a web-based tool for SFE estimations based on composition to let other researchers test its performance.
- The proposed future work is more testing of different materials at high pressure, which is only a small part of the puzzle.
- There are concerns about having a web-based tool for general use. Others may use this data without understanding its limitations. A high-SFE, low-cost material may not be acceptable for use in hydrogen. A disclaimer should be included. Based on the unexpected results of Nitronic 60, it would be very beneficial to be able to evaluate fatigue characteristics of materials at high pressure and low temperature. The crack growth mechanisms of the new materials should be evaluated as compared to typical stainless steels in a variety of conditions to understand the similarities and differences of these materials in a hydrogen environment.

Project strengths:

- SNL has decades of hydrogen embrittlement and compatibility experience that provides a sound basis for this study. The SNL researchers have considerable expertise in DFT and other simulation methods, as well as extensive in-house capabilities for in situ high-pressure experimentation.
- The project was able to identify materials that met the strength and cost targets and develop methods that might be able to identify new materials that may have similar strength and cost characteristics.
- The project has a great approach to materials discovery and uses good testing methods to characterize strength.

Project weaknesses:

- The correlations between SFE and the FCC lattice parameter and a material's hydrogen compatibility are not strong. Further research is required to identify parameters that are better indicators of the material's acceptability.
- The project did not pay attention to actual costs and components of BOP to be manufactured, and it did not couple the calculation with manufacturability.
- The basis of this project rests primarily on making a correlation of SFE parameters with the ultimate discovery of low-cost and high-strength alloys for BOP components. It has neglected many of the other processing and manufacturing issues necessary to achieve this objective. Extrapolation of these current specific properties being evaluated by SNL to high-performance components still seems to be a very large stretch.

Recommendations for additions/deletions to project scope:

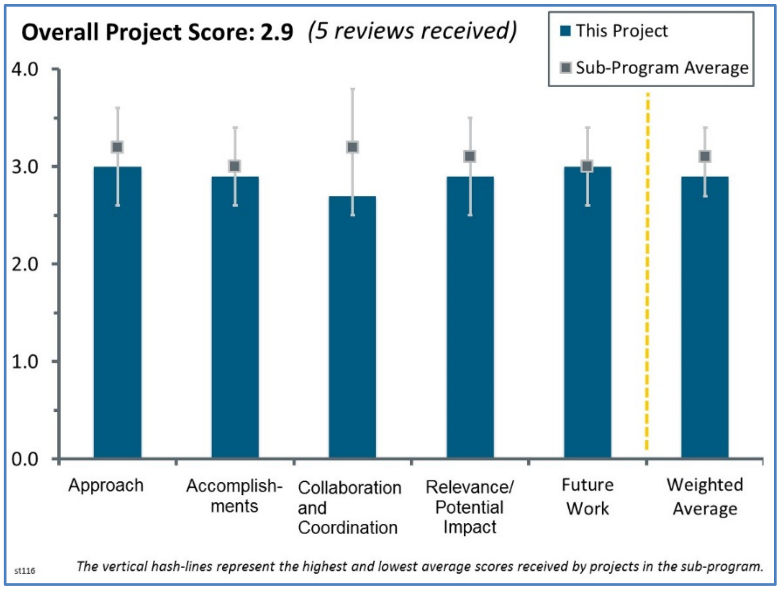
- Prior to initiating any of the future activities presented on the bottom portion of slide 21, an intense evaluation via relevant interested outside parties (e.g., materials researchers, alloy producers, and BOP component manufacturers) should be conducted by organizing a workshop or working group to assess whether any future project does provide sufficient insights to justify selections of any specific alloy for development of hydrogen components via the commercial entities. The ability of a national laboratory such as SNL to perform these activities has numerous benefits of objectivity and specialized expertise.
- An effort should be made to address issues in implementing the alloys identified. The machinability and formability of these materials and the ability to produce these materials in bulk should be evaluated.
- Collaboration with a systems group to address materials with manufacturing process feasibility that will reduce cost and weight is recommended.
- The project should eliminate the modeling work, which seems quite unproductive, and instead use the remaining resources to test whether one of the materials selected from the property tables (e.g., Nitronic 60) can be used for making BOP components (valves, regulators, etc.).

Project #ST-116: Low-Cost α-Alane for Hydrogen Storage

Tibor Fabian; Ardica

Brief Summary of Project:

Overall objectives of this project are to reduce production cost of α-alane (aluminum hydride, or AlH_3) to meet the U.S. Department of Energy 2015 and 2020 hydrogen storage system cost targets for portable low- and medium-power applications. Results will enable broader applications in consumer electronics (e.g., smart phones, tablets, and laptops), back-up power, unmanned aerial vehicles, forklifts, and vehicles.



Question 1: Approach to performing the work

This project was rated **3.0** for its approach.

- The work addresses lowering the cost of AlH_3 production through experiments and cost analysis of an electrochemical method. The approach is designed to provide much of the information needed to establish the economics of this process.
- It is a reasonable approach; looking at various strategies to lower costs makes sense. The cost model looks useful for understanding what it will take to meet cost targets. There is no clear path/strategy for getting from 0 to 300 MT/year. This is probably not going to happen in a single step, so it may be useful to develop a long-term plan that incorporates realistic intermediate steps and applications. The 92% $NaAlH_4$ yield at 2,200 psi is an exciting result and a nice development, but yields for conversion to AlH_3 are still very low (~20%). It is not clear what the plan to improve this is.
- The approach presented addresses most of the barriers well but falls short in a few areas. The process itself is in need of further investigation, because there are several important factors toward feasibility that have yet to be addressed. Capturing AlH_3 adduct at high yields from a continuous process before decomposition is a hurdle that needs to be overcome in order to prove that a continuous process is possible. The crystallization process is the main driving force behind cost, and it appears to have a relatively small amount of consideration put toward it. Recovering the cathode product will allow for cost to be reduced further, but optimization of the crystallization process should take precedent, as the amount of cathode material recovered from the reaction becomes trivial if the amount of AlH_3 produced remains low.
- The project does an economic evaluation of AlH_3 production from "spent AlH_3" using the electrochemical approach with experiments to benchmark and quantify assumptions about key steps in the process.
- Ardica's approach is based on the process proposed by Savannah River National Laboratory (SRNL). There does not appear to be a clear and obvious collaboration with SRNL or the other collaborators, resulting in the appearance of uncoordinated research efforts.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **2.9** for its accomplishments and progress.

- There is good progress toward establishing a baseline for the cost of making 320 MT of AlH_3 with semi-quantitative insight into some of the challenges reducing efficiency. This effort covers (1) $NaAlH_4$ utilization, (2) adduct formation, (3) adduct conversion, and (4) $NaAlH_4$ regeneration. The adduct formation and conversion have been investigated in detail previously. Some of the work on amine choice appeared repetitive, and it would have been helpful to put the current effort into perspective with this previous work that established a quantitative baseline. However, it would be recommended to have the electrochemists at Ardica focus remaining efforts on approaches to reach the target of 80% recovery of the $NaAlH_4$ in the limited time remaining.

- There is lots of nice work, but the 300 MT/year required to meet the cost target of $1/g seems impractical. Perhaps this could be improved with regeneration. It seems like the electrochemical process will be difficult to make this work. The switch from $LiAlH_4$ to $NaAlH_4$ seems like it provides a small cost reduction, but the additional hassle of using tetrahydrofuran (THF) and exchanging with triethyl amine seems like it outweighs any savings. Overall, it is good work, but the research does not seem to be much closer to significantly lowering costs.
- The most encouraging progress made has been the reduction in feedstock cost by changing the feedstock entirely, which is no easy feat late in a project. However, this cost reduction means nothing if process conversions and production rates remain low. A major assumption involved in the cost estimates (which still remain much higher than the goal) is that 90% of adduct is recovered in the crystallization process. Progress is slow in this area, with only roughly 30% recovered as of the time of presentation. The process is a difficult one; however, the low material yield is an indicator of poor progress. The use of a new membrane in the process is an accomplishment leading to a relatively high yield of adduct, bringing this aspect of the process closest to the assumed values in the cost model. Recovery of the cathode material and regeneration using spent AlH_3 needs optimization and further investigation, as yield is still too low.
- The project has made progress toward meeting goals by investigating individual steps in the production and identifying critical areas for improvement. The overall progress of preparing AlH_3 that meets the cost target is lagging.
- Ardica has verified that AlH_3 regeneration is a very difficult problem that is likely to be proven cost-ineffective. Historically, the critical step to the production scale-up of α-AlH_3 has been the solvent removal and crystallization processes.

Question 3: Collaboration and coordination with other institutions

This project was rated **2.7** for its collaboration and coordination.

- Collaboration with the groups involved in this research is clear and appears to be beneficial to all the other projects related to this work.
- The project might have been a little more successful through stronger collaboration. It had the appearance of not reaching out to experts in the AlH_3 field.
- Collaboration with SRNL is claimed to have improved since the last review, although the only outcome seems to have been the use of the density functional theory calculation as one factor in ligand selection for preparing an adduct suitable for crystallization trials. It is unclear so far how effective these calculations are in identifying new ligands.
- There are essentially no collaborations listed. The collaborations table lists Ardica (itself), its subcontractor (SRI International), and SRNL. James Evans at University of California, Berkeley, seems to be the only real collaborator here.
- There does not appear to be a clear and obvious collaboration with SRNL or the other collaborators, resulting in the appearance of uncoordinated research efforts.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **2.9** for its relevance/potential impact.

- Hydrogen density and low desorption temperature make AlH_3 one of the few materials that could meet targets. However, it is still not clear how a primary (non-rechargeable) system such as this could be used on a vehicle. Portable power, unmanned aerial vehicles, and unmanned underwater vehicles make more sense in the near term.

- Project aspects align with some of the DOE Hydrogen and Fuel Cells Program (the Program) and DOE research, development, and demonstration objectives, but relevance to vehicle targets is a stretch and may not be completely fair. It would have been informative to learn what markets benefit from a 320 MT quantity of AlH_3. It may be too small for vehicles and too big for small power applications. There seems to be a large cost increase to build infrastructure for smaller production facilities. Reducing the cost of AlH_3 production is important.
- This project is relevant toward the goals and objectives outlined in the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan in that it has the possibility to produce one of the best-fitting hydrogen storage materials currently available. Increasing scale and yield and reducing cost for AlH_3 will allow for further research into its use as a hydrogen storage material. However, the high cost and low yield currently demonstrated do not support progress toward those goals. The material still remains too costly, and the overall process yield is still much lower than it needs to be to be viable.
- The work does advance toward the Program goals by investigating a method for AlH_3 production with potential low cost. However, it is marginal whether the conversions and efficiencies achieved will meet the cost targets for low-power applications.
- Given the likelihood that AlH_3 will not be used as a hydrogen storage medium for automotive use, the production and regeneration of spent AlH_3 may not be as relevant or impactful. However, the use of AlH_3 for portable power does show a higher degree of relevancy for other program offices.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The project is nearing completion, so there is little opportunity to do much more. Overall, recovery of α-AlH_3 from adducts should be a focus for improving total yield. This is the hardest step. The final report should include everything: other AlH_3 phases, impurities, and stability. The null results are important for the general community. A good example is the intermediate adducts that have been identified. This is very useful information.
- The project is wrapping up with some proposed near-term future work.
- The project is near completion, and there is little time for future work. The work proposed is unlikely to be achieved in the remaining time and is not particularly well structured. “Further develop strategies…” is not clear or planned in a logical manner. The investigators should identify the most critical problem and direct efforts toward a solution.

Project strengths:

- The project is strong in its development of the initial step of the process. The cell design and optimized process yield a decent amount of adduct, which is a good starting point. The change of feedstock material is important and allows the material cost to drop slightly, which is a step in the right direction. The possibility to reuse spent AlH_3 to regenerate the feedstock with a non-catalytic process is encouraging, but the rate needs to be investigated in order to optimize recovery.
- There are some nice developments over the years. The team clearly has considerable experience with this system and a strong understanding of the various challenges involved in the synthesis. The cost model is a nice, realistic look at what it will take to make this a viable material. It is certainly challenging, but it is nice to see these business challenges/barriers becoming clearer.
- The project has developed a cost model that takes account of most of the factors relevant to AlH_3 production and has tested some of the important parameters underlying the model.
- Ardica took on the very challenging task of regenerating spent AlH_3, and it is commended on an honest effort. This project dovetailed nicely with its portable power applications.
- The team’s expertise in portable power applications is a strength.

Project weaknesses:

- There are no obvious weaknesses. Ardica attempted to solve a very difficult problem.

- The overall yield of the process is still too low to be viable. The focus was split between the three aspects of the process when most of the effort should have been placed on optimizing adduct recovery. Recycling the feedstock with spent product is not appealing if the process cannot produce product at a high enough yield to drastically reduce cost. The transition between the three areas of focus is also not clearly demonstrated. Removing large amounts of adduct from the electrochemical cell and transporting it to the crystallization process is a large challenge that will need to be demonstrated in order to develop a continuous process.
- The project relies on large-scale production, which does not appear to be consistent with the low-power applications central to the project. Cost targets for all efficiencies are short, and the approach to bridge gaps appears to be mostly Edisonian.
- Slide 24 ("Critical assumptions and issues") states THF-based adducts cannot be adequately converted to AlH_3. This was identified as a concern and one (of many) potential issues with the electrochemical method years ago. It is not clear why work has continued on AlH_3-THF. Issues with adduct separation have been known since previous work under the Metal Hydride Center of Excellence. Improvements in AlH_3 separation (recovery) are needed to get the cost closer to targets.

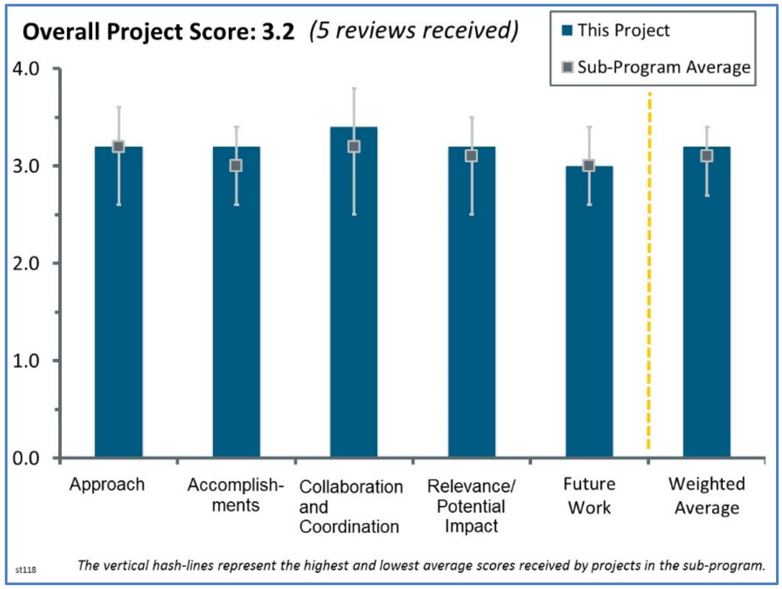
Recommendations for additions/deletions to project scope:

- The team should spend more effort on optimizing the crystallization process, and the recycling of spent material should not be investigated until the yield has increased dramatically enough to reduce cost.
- The key barrier is α-AlH_3 recovery. Future work in this area should focus on recovering α-AlH_3, either from adducts or from a more direct route.

Project #ST-118: Improving the Kinetics and Thermodynamics of $Mg(BH_4)_2$ for Hydrogen Storage

Brandon Wood; Lawrence Livermore National Laboratory

Brief Summary of Project:



The objectives of this project are (1) to combine theory, synthesis, and characterization techniques at multiple length/time scales to understand kinetic limitations and possible improvement strategies in $Mg(BH_4)_2$ with relevance to other light-metal hydrides, and (2) to deliver a flexible, validated, multiscale theoretical model of (de)hydrogenation kinetics in "real" Mg-B-H materials and use predictions to develop a practical material that satisfies 2020 onboard hydrogen storage targets. Current project year objectives are to synthesize MgB_2 nanoparticles with <10 nm diameter, measure x-ray absorption and emission spectra for bulk MgB_2/$Mg(BH_4)_2$ during stages of (de)hydrogenation, and compare measured and simulated spectra on informed models to determine local chemical pathways.

Question 1: Approach to performing the work

This project was rated **3.2** for its approach.

- The combination of validated theoretical models that incorporate anharmonicity and temperature to predict material properties and phase mixing in these complex hydrides and the parallel validation with experiments is the perfect approach. It will lead to a greater understanding of how the reaction pathways can be manipulated and has a reasonable chance of addressing some of the U.S. Department of Energy barriers.
- This is a nice combined computational/experimental approach. The focus on understanding mechanisms and pathways in $Mg(BH_4)_2$ addresses the key challenge(s) with this high-capacity material. Tailoring intermediates between dehydrogenated and hydrogenated makes sense. A confinement-free approach to nanosizing seems like a good one.
- Barriers are reasonably addressed, and the project is integrated with other efforts; however, removal of surfactants from the nanoparticle surface may be more difficult than it appears.
- Although the project is developing new models of $Mg(BH_4)_2$-related processes, it is not immediately clear what new insight is being gained.
- The study should balance thermodynamic and kinetic aspects of the hydrogen release process. It should build a testable model experimentally.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.2** for its accomplishments and progress.

- The insights gained into the Mg-borohydride system from bulk to nanoscale have been impressive. The thermodynamic and kinetic insights have been somewhat surprising and insightful. There are many results presented here, and the depth and improvements of the suite of tools should place the team in a position to

leverage this to other systems as needed in future programs in the DOE Office of Energy Efficiency and Renewable Energy.
- The progress validating the $Mg(BH_4)_2$ phase diagram and shedding new light on how nanosizing affects thermodynamics and reaction pathways is nice. Synthesis and characterization of high-purity nanoscale MgB_2 is an accomplishment. The kinetic analysis of hydrogen uptake confirms a lower initial hydrogenation barrier in nanoscale material, as predicted. The in-depth investigation into initial hydrogenation of MgB_2 may be useful for identifying ways of tailoring the reaction pathway.
- The team has made steady progress toward the overall project objectives.
- The work is technically good, and results are interesting. However, it is difficult to see how it may enable the development of a practical high-capacity hydrogen storage material in the foreseeable future.
- It appears little progress has been made regarding Phase III goals, yet the project is scheduled to end in two to three months.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.4** for its collaboration and coordination.

- The team works very well with the Hydrogen Materials–Advanced Research Consortium (HyMARC) and external collaborators.
- Collaborations are with the Hydrogen Storage Characterization Optimization Research Effort (HySCORE) and HyMARC partners. Collaborations beyond Lawrence Livermore National Laboratory (LLNL) and Sandia National Laboratories (SNL) with other consortium members or seedling projects are encouraged.
- The collaborations are great.
- There are strong collaborations with partner SNL. It is unclear how the University of Michigan is contributing to the project.
- The team is in a unique position to collaborate with other institutions.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.2** for its relevance/potential impact.

- The tools and methodologies are valuable in and of themselves, but the project has gained deeper insights in determining that the nanosizing of Mg-borohydride would probably not be a unique solution to the hydrogen storage problem (but perhaps in a hybrid situation or with catalysts, this could change). It is a shame that this project is ending, as the methodologies and insights have been the most impressive the reviewer has seen in this field.
- The project supports understanding reaction pathways in $Mg(BH_4)_2$ and how they are affected by nanosizing. The project is well aligned with the Hydrogen and Fuel Cells Program (the Program) objectives and goals. Considerable progress has been made in understanding these materials and explaining observed behavior, but the real value/impact comes with predicting and testing new materials systems. This should be the focus.
- This project is clearly relevant. However, the complexity of the $Mg(BH_4)_2$ system (and the unclear nature of the project's accomplishments to date) suggest that the impact on the Program will not be immense.
- The project tries to support and advance progress toward the Program goals and objectives. However, at the current stage, it is difficult to see how it may lead to the development of a practical material for on-board hydrogen storage.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- Overall, the plans for future work look good. The project will likely continue to provide new insights into reaction mechanisms. The project team needs to translate these new insights into new materials systems,

not just validate models with existing experimental data. Researchers should consider expanding collaborations to broaden the impact.
- Continued funding and effort in this project are beneficial for the overall DOE objective.
- The future work is logical, but there is only so much time left.
- The proposed catalyst work will add another layer of complexity to an already challenging system.
- Future work could be better defined. It is not quite clear why Ti catalysts are a specific focus. Also, other bullet points are quite generic.

Project strengths:

- The project is focused and well integrated with other efforts. It provides important new insights into these complex systems. Overall, it is excellent work.
- Project strengths include the good collaboration between LLNL and SNL. $Mg(BH_4)_2$ is an important hydrogen storage material, and an effort aimed toward making it function more efficiently is badly needed.
- The scope of the problem is well defined, and the approach has been excellent. The project team works strongly with other partners and is results-driven, publishing several good papers.
- A project strength is the unique position of the principal investigator and team in collaborating with other institutions.
- The collaborations are great.

Project weaknesses:

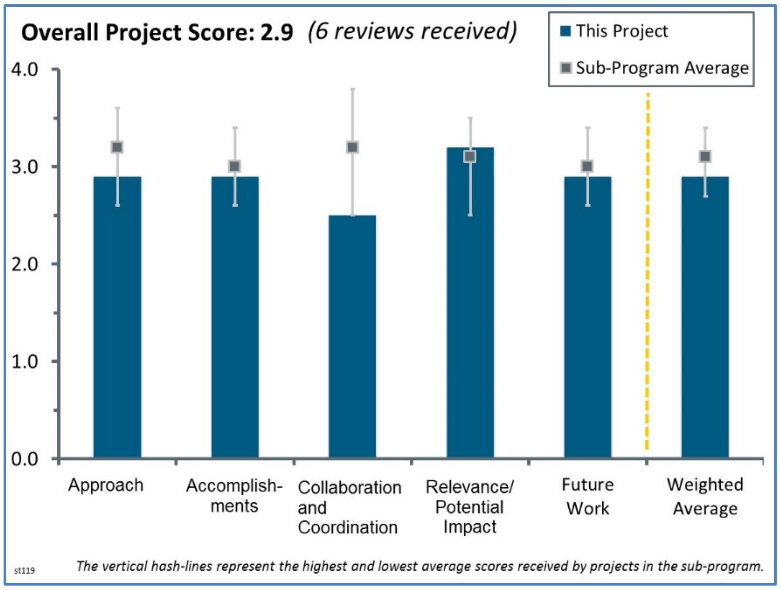
- It is unclear how the project has improved understanding of $Mg(BH_4)_2$.
- It is not clear that the project at the present stage shows the path to novel real-world materials.
- Understanding the catalysts moving forward might be too difficult to achieve without knowing the chemical specifications. Plans to deal with this are not obvious to the reviewer.
- Research has provided new insight into specific mechanisms, improving understanding. However, the goal is to ultimately guide development and optimization of new material systems. So far, it has fallen a little short in this area. Slide 7 indicates that confined systems are thermodynamically beneficial, while smaller particle sizes will tend to increase $B_{12}H_{12}$ formation. Given these results, it is not clear why was the focus was on synthesizing MgB_2 nanoparticles as opposed to confining MgB_2. Computational work should guide the synthesis efforts, not the other way around.
- The possibility of losing future funding is a project weakness.

Recommendations for additions/deletions to project scope:

- This project should be extended, if at all possible. The catalyst part is going to need more time.
- The project should focus on converting mechanistic insight into new materials or strategies for meeting targets. It is not clear whether there is any hope of forming $Mg(BH_4)_2$ without going through $B_{12}H_{12}$.

Project #ST-119: High-Capacity Hydrogen Storage Systems via Mechanochemistry

Vitalij Pecharsky; Ames Laboratory



Brief Summary of Project:

This project is developing novel high-hydrogen-capacity silicon-based borohydrides (Si-BH) and composites with the aim of achieving low-cost, high-performance hydrogen storage materials. Si-BH materials are predicted to have borderline thermodynamic stability. Researchers will use stabilization strategies based on hypersalt formation using alkali and alkaline-earth cation additions to bring the enthalpy of desorption into the targeted range. The project will also investigate borohydride/graphene nanocomposites that utilize graphene's advantageous properties.

Question 1: Approach to performing the work

This project was rated **2.9** for its approach.

- This project is investigating hydrides based upon B and Si to determine whether any combinations of these elements can be "discovered" to serve as viable hydrogen storage media with the potential to satisfy the U.S. Department of Energy vehicle requirements. This is a reasonable approach that examines systems not previously characterized to any significant extent. The researchers recognize the issues of limited reversibility, the risk of reaction temperatures that are too high for hydrogen absorption/desorption, and risk for extensive impurity contents. The preparation methods are acceptable, as are the characterization techniques (i.e., volumetric measurements with mass spectroscopy, nuclear magnetic resonance [NMR], x-ray diffraction [XRD], differential scanning calorimetry, thermogravimetric analysis, and Fourier transform infrared spectroscopy [FTIR]) being used to identify reaction and decomposition products along with the subcontracted computational modeling at University of Missouri, St. Louis (UMSL).
- The project is focused on developing Si-BH materials, which on paper have high gravimetric and volumetric hydrogen capacities. The theoretical approach seems to be very sound. As far as the experiments are concerned, the emphasis is on solid-state reactions, specifically mechanochemistry. One concern with mechanochemistry is that the energy formed during the ball milling decomposes the relatively unstable Si-BH species, even if they form during the process. It would be desirable to attempt to perform this under gentle conditions, for example through low-temperature solution approaches.
- The investigators utilize a standard "grind and find" approach, ball milling Group I borohydrides with reactive precursors to produce novel borohydrides. This work is novel in that reactive Si-based compounds are utilized in hopes of preparing Si-BH compounds. The hydrogen storage properties of the materials produced have been screened using standard analysis, and their characterization is attempted using standard methods.
- The overall approach is good, as the partners use theory and the literature to guide the most feasible candidates for mechanochemistry methods.
- The project has a very interesting approach. The search for Si-BH compounds could lead to a low-cost material.
- Ball milling as a means for materials synthesis offers a unique alternative method for materials synthesis. However, its scalability for large-scale application might be limited.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **2.9** for its accomplishments and progress.

- During the past year, the team has produced, via mechanochemistry methods, several MBH_4-SiS_2 and Li-B-Si-H systems and investigated their relevant properties for hydrogen storage applications. While these materials do not currently meet the required DOE performance targets necessary to pass the defined go/no-go decision, they do exhibit behavior that appears rather promising. The results obtained via NMR, XRD, and FTIR do help identify the formation of these Si-based complex borohydride phases. This study complements and extends prior results on other B-based hydrides.
- The product characterization effort of this project is much improved from last year. In addition to the "quick and dirty" temperature programmed desorption screening of the materials, NMR and infrared spectra have been obtained for the products. Most notably, one compound (sadly not a Si-containing product) has been structurally characterized through Rietveld analysis of powder X-ray data. Unfortunately, no isothermal desorption studies have been carried out, and only over-optimistic "onset desorption temperatures" are still reported. While the efforts to date have generated some very interesting new phases, the Si-containing phases remain poorly characterized. Moreover, none of the Si phases have been found to have an adequate hydrogen cycling capacity, and all of these phases are plagued by some level of B_2H_6 elimination during discharge.
- Reasonable progress has been made to find possible Si-BH materials since the last DOE Hydrogen and Fuel Cells Program Annual Merit Review (AMR), and the project has adapted its focus toward more promising combinations of materials.
- There is good progress toward overall DOE and go/no-go milestones, but the project would definitely benefit from collaboration with the Hydrogen Materials–Advanced Research Consortium (HyMARC).
- The most promising and high-capacity Si-BH species seem to be decomposing under ball-milling conditions. It is surprising that no other synthetic approaches have been attempted to isolate these species.
- The project has made adequate progress as defined.

Question 3: Collaboration and coordination with other institutions

This project was rated **2.5** for its collaboration and coordination.

- The collaboration is very good to good.
- During the first approximately 18 months of this project, essentially all tasks have been performed at Ames Laboratory (Ames) or, for the subcontracted computational work, at UMSL. However, the principal investigator (PI) indicated that plans are underway to utilize capabilities from Hydrogen Storage Characterization Optimization Research Efforts (HySCORE) and HyMARC. High-pressure synthesis of M-Si-B solids at the Sandia National Laboratories facility was explicitly mentioned. It is also recommended that the neutron capabilities at the National Institute of Standards and Technology and in situ NMR at Pacific Northwest National Laboratory are added for characterization of the reaction and decomposition products, as well as utilizing modeling and simulation capacities at Lawrence Livermore National Laboratory and Lawrence Berkeley National Laboratory.
- Interactions among partners concerning theory-driven experiments are good. Plans were presented for more needed collaboration with other partners, such as HyMARC, in the future.
- Collaboration would be much improved if the project were included with HyMARC.
- The authors should explore more avenues for collaboration with HyMARC and HySCORE.
- There is little collaboration outside of Ames.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.2** for its relevance/potential impact.

- The project definitely supports and advances progress toward the DOE Hydrogen and Fuel Cell Program goals by looking at alternative, new, and unexplored Si-based systems for reversible hydrogen storage.
- Demonstrating a fully reversible Si-BH material has the potential to significantly advance the state of the art in the area of hydrogen storage materials.
- The project has good alignment to DOE goals, and this project brings Ames' unique mechanical synthesis capacity to bear on the issues.
- Despite its great potential and the progress that has been made toward developing borohydride-based materials as hydrogen carriers, no compounds have yet been identified that can be utilized in practical applications. This project explores a previously uncharted section of borohydride compositional space in hopes of finally locating the "holy grail" material.
- If new Si-containing borohydride-based phases can be discovered and demonstrated to meet approximately the derived materials properties with respect to storage capacities and reversibility, possess absorption–desorption properties capable of withstanding polymer electrolyte membrane fuel cell operating temperatures, and have negligible contamination of the hydrogen supply gas to satisfy the DOE storage system targets, this project would be very useful to the DOE Fuel Cell Technologies Office goals. However, the challenge of simultaneously satisfying all of these requirements is very great, as clearly demonstrated by failures from essentially all boron-based hydrogen storage materials.
- Although the project specified addressing issues related to hydrogen storage is its major objective, its relevance to hydrogen storage is limited.

Question 5: Proposed future work

This project was rated **2.9** for its proposed future work.

- The proposed future work has been planned and modified in a sufficiently logical manner based on the successes and failures of the accumulated data collected.
- The PI provided a generally sound plan for preparing M-B-Si-H phases and characterizing both the hydrogen storage parameters and important structural properties. It is recommended that the project increase collaborative interactions with HySCORE and HyMARC to provide broader and more detailed characterizations. It is also recommended that the Ames team look more closely at the residual gas analyses (RGA) (i.e., mass spectrometry) assessments for the formation of critical gaseous impurities (e.g., B_2H_6, SiH_4, and H_2S) in the hydrogen gas released during reactions and desorption. Detection of these reactive species can be extremely elusive because of their decomposition or reactions prior to entering the RGA sampling chamber, unless the detector is mounted nearby and in the line of sight of the reaction vessels. Without this configuration, the RGA measurements will produce false negatives indicating that the primary causes for irreversible reactors are not occurring. Furthermore, that background pressure of hydrogen can influence the amount of impurity species formed. Finally, the team should look more thoroughly to identify decomposition products that do not contain boron (e.g., LiH) that may be in a nanocrystalline or amorphous form, thus preventing observations via XRD.
- There is good proposed work, but there are questions about moving to Li-based systems because of cost issues. The reason for starting with Li is understandable, but moving to Na, Ca, etc. is suggested.
- The project may offer some insight into hydrogen interaction in hydrogen storage, but its potential application is expected to be small.
- The authors should explore alternative synthetic approaches in instances when mechanochemistry fails to yield the desired product.

Project strengths:

- Mechanochemistry methods provide a powerful and unique means of developing new materials for reversible hydrogen storage that cannot be as easily accomplished in other ways. It is a worthwhile avenue of research for attempting to discover new materials to meet the DOE goals. Ames participants are experts in this area.
- The Ames team has extensive experience and expertise in preparing and characterizing diverse metal hydrides that are very valuable for conducting the tasks comprising this project. As summarized on slide 22, Ames also has a variety of good experimental techniques for preparing and characterizing metallic and complex metal hydrides.
- The project is focused on high-capacity materials that on paper could meet the DOE targets in terms of the gravimetric and volumetric hydrogen densities.
- The project is exploring a previously uncharted area of borohydride compositional space.
- The unique mechanical synthesis expertise at Ames is a project strength.
- The people involved in the project are a project strength.

Project weaknesses:

- The study may be useful for fundamental research in materials and chemistry, but its potential application is not clear.
- The project needs more collaboration with HyMARC.
- Although new compounds can be formed by the mechanochemistry technique, the resulting products are sometimes not single-phase or well understood. More characterization efforts will be needed to sort out what is actually forming in these cases. Also, the high-pressure mechanochemistry activity was slow to be re-established after an accident-induced shutdown, which likely had an adverse impact on the project.
- The project seems to put a good deal of emphasis on mechanochemistry, which was shown to be counterproductive for the synthesis of labile or unstable species. The synthetic conditions and the composition space should be expanded to increase the chance of isolating the desired Si-BH_4 species.
- Because of time constraints, the investigators are forced to take a much too Edisonian approach to their studies. As a result, a systematic structure–reactivity relationship cannot be established. Such a relationship could provide guidance to this otherwise random-walk effort.
- This project has been performed mostly in isolation, without involvement from the HySCORE or HyMARC members (although these interactions are apparently commencing at this time) or the international metal hydride research community. It appears that the only method used (or available) for preparing the various M-B-Si-H materials is via some type of mechanochemistry either with or without the presence of high-pressure hydrogen. Successful synthesis could well require other approaches. Also, there was no indication in the AMR package of conference presentations or publications for the work performed to date in this project.

Recommendations for additions/deletions to project scope:

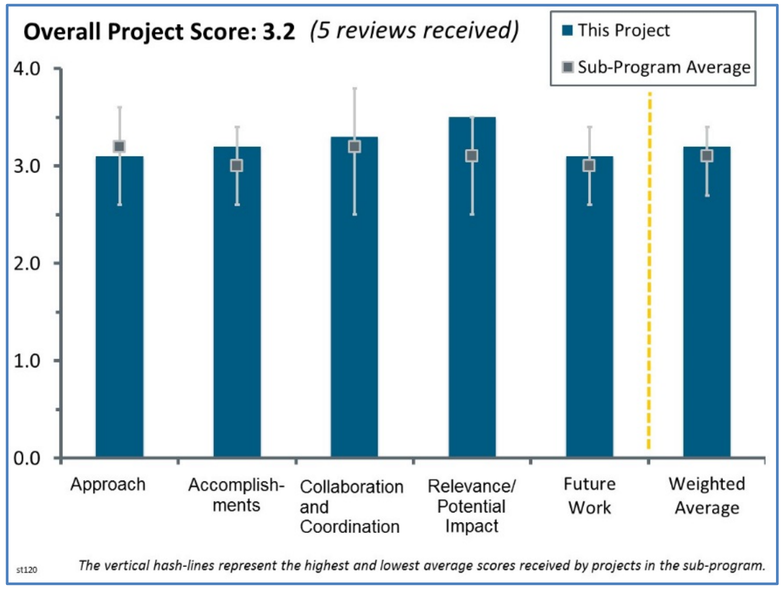
- The future plans for the remainder of the project, outlined on slide 19, are good, reasonable objectives. There are three specific recommendations beyond the more general comments made during this evaluation:
    - The project should search more diligently for volatile species such as B_2H_6, SiH_4, and H_2S using a mass spectrometer with its input close to the reaction vessel, because formation of these species will cause irreversible loss of hydride storage capacities.
    - The project should examine any promising candidate with elastic and inelastic neutron scattering methods.
    - The project should search for nanocrystalline or amorphous phases using magic-angle spinning NMR with the ^{2}H and ^{6}Li nuclei, which permit higher resolution spectra for phase identification compared to measurements of the ^{1}H and ^{7}Li isotopes.
- More product analysis capabilities would be desirable, and more collaborative interactions with HyMARC should help accelerate the results and attain the project goals.
- The investigators should utilize resources available from HySCORE and HyMARC to help them characterize the materials they have generated.
- The project should limit work on Li-based hypersalts.

Project #ST-120: Design and Synthesis of Materials with High Capacities for Hydrogen Physisorption

Brent Fultz; California Institute of Technology

Brief Summary of Project:

This project aims to address challenges related to the volumetric capacity of onboard hydrogen storage systems and the low temperature and low enthalpy of adsorption. Researchers are designing and synthesizing materials with high capacities for hydrogen physisorption. The focus is on graphene rather than activated carbon, as single-layer graphene is a platform with an excellent surface-to-volume ratio. The project will use graphene oxide chemical routes and plasma approaches to synthesize and functionalize the materials.



Question 1: Approach to performing the work

This project was rated **3.1** for its approach.

- The work is on graphene-based carbons for storage, with the focus on graphene because of its high stability and conductivity. The ability for this material to form the slit pore geometry is deemed optimal for gas diffusion. The approach to tune pore size and add metals (e.g., nanometer-sized Cu) onto the material has demonstrated increased hydrogen uptake capacity (0.015 wt.% near room temperature). Specifically noteworthy are the thermodynamic considerations in the approach to temperature-programmed desorption (TPD) measurements, including the following:
    - The need for absolute hydrogen uptake data for the Clausius–Clapeyron equation to be applied to gain enthalpy data has been established.
    - Constant enthalpy can be achieved with intercalated carbon systems and results in higher-temperature desorption at lower pressures.
- The modification of the chemistry of pores within high-surface-area carbon-based materials is a viable approach to increasing the heats of adsorption. However, this work seems very similar to that of Ted Baumann and Jie Liu during the Hydrogen Sorption Center of Excellence. It would have been beneficial for the principal investigator (PI) to specifically outline the uniqueness of the approach. The use of plasma for carbon modification was also part of the work overseen by Lin Simpson. The team should be specific about how this is a unique approach as compared to past work.
- The approach is to design new and evaluate existing carbon-based sorbents for hydrogen storage.
- The approach and work in terms of the carbon–graphene functionalization is well described, while future new routes for incorporation of Cu are not well described. The Cu is incorporated via Cu salt/reduction using eight different routes, most of which have been completed (slide 16). There are only two more routes to try. There has been little or no difference in the hydrogen adsorption between batches 5, 6, and 7. Slide 18 shows that the Cu has created a ~0.003 wt.% enhancement in the excess capacity. This is a very small difference, and it is questionable whether this difference is beyond the measurement accuracy (however, it is difficult to say without knowing the sample size). An enhancement of ~0.003 wt.% above MSC-30 is a small difference and would also produce a small shift in the isosteric heat of adsorption. The approach beyond the eight batches is not described.
- The work aims to improve the capacity of carbon-based sorbents by assembling materials from graphene or graphene oxide. This approach is meant to control the architecture more carefully, e.g., by creating a slit pore geometry with tuned dimensions. However, there is little evidence of an experimental design to control this. The approach to overcome barriers by functionalization (to improve adsorption enthalpy) appears somewhat speculative, as the synthesis route is less controlled.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.2** for its accomplishments and progress.

- This project addresses the important goal of creating high-surface-area carbon material and increasing the isosteric heat of adsorption. The addition of Cu particles to graphene materials with <10% reduction in surface area is aligned with the goals of DOE. The PI showed that large quantities could be synthesized, which has been a barrier to many research groups in the past. Synthetic reproducibility, in general, was also achieved, as four samples with a small change in the synthetic parameters resulted in materials with very similar surface areas. The amount of progress is good. It seems that the majority of the time for this project has been spent functionalizing the graphene. Although this is a critical step in creating the materials, the work will now be able to focus on the incorporation of the metal. This is the challenging step. The amount of progress seems very good. There are many questions the PI has yet to answer regarding incorporation of the Cu particles, dispersion, the role of the size of the Cu particle, and the effect of any oxide formation and hydrogen diffusion issues.
- This has been an ongoing effort that has yielded results related to thermodynamics, kinetics, and materials design. The researchers have achieved high-surface-area samples that are functionalized with Cu. These materials have demonstrated large hydrogen capacity (0.015 wt.%) at near-room temperature. It would be nice to see, in the future, that the high-surface area samples are tunable (i.e., surface areas of 2,000 m^2/g are achieved and controlled through well-defined processing parameters). Likewise, an assessment of the defect concentration, type, and their role in the hydrogen uptake process would be useful for further improvement of these materials. The stated future goal of changing the metal sites from Cu to Ni is a good one.
- The preparative work on the carbon materials has been very successful. In looking at slide 17, the graph in the bottom left is a little disconcerting. With all the past work the PI has done on metal-modified carbon materials, it is not clear why it would not be expected that one would observe an increase in excess uptake. Copper with multiple oxidation states is primed to undergo some reduction on exposure to hydrogen, or even formation of a surface hydride. The slopes after 0.2 bar seem to match the blank MSC-30 results. It puts this “accomplishment” into question. There should be a determination using TPD instead of a Brunauer–Emmett–Teller (BET) surface area analysis of whether any side reactions occur. The fact that the sample apparently contained 20% Cu also leads to some doubts.
- The team has produced small samples with high surface area that approximately match the capacity of previous carbon systems. The larger-scale syntheses have very low surface area, and the way forward appears to be through collaboration with Cealtech AS. The (small) increased uptake with Cu functionalization is questionable and could easily be attributable to reduction of Cu oxides or other non-sustainable effects. The goal is to improve adsorption capacity (and enthalpy), but only a few samples have been measured (or at least presented), despite many being synthesized. While the team has been active and completed a substantial amount of work, the results indicate that substantial gaps remain between the current performance and DOE goals.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.3** for its collaboration and coordination.

- The researchers have partnered with a Norwegian company, Cealtech AS, which is helping to scale up the graphene production to kilograms per day. Collaboration with the Hydrogen Storage Characterization Optimization Research Effort (HySCORE) has permitted the transmission electron microscopy examination of Cu metal on graphene using high-angle annular dark field imaging (HAADF). This is an optimum approach for examining metals within a carbon background. Further collaboration with HySCORE to examine defects in the graphene from reduced graphene oxide would be beneficial. Particularly, Fourier transform infrared spectroscopy (FTIR) and/or x-ray absorption spectroscopy (XAS) at in situ hydrogen uptake conditions will help determine whether the defects are beneficial to this process. Additionally, the HySCORE collaboration on characterization may help develop benchmarks of defect quantity, which could feed back into processing parameters to further tune defect concentration.

- Collaborations included work with HySCORE, Cealtech AS, and Liox Power, Inc. (Liox). The different roles of Cealtech AS and Liox are not clear. The Pacific Northwest National Laboratory component (HySCORE) is an important collaborator for pursuing the future research of understanding the Cu incorporation. The research team is very capable and will undoubtedly reach out to collaborators when needed to understand the effect of metal incorporation.
- It is suggested that the team work with the Hydrogen Materials–Advanced Research Consortium (HyMARC) and/or HySCORE to get some TPD and possibly diffuse reflectance Fourier-transformed infrared spectroscopy (DRIFTS) experiments to identify whether any side reactions are occurring.
- The role of Liox is not clear in the presentation, and although the role of Cealtech AS in making large quantities of graphene is understandable, it is not clear how this relates to efforts to make specimens in small scale by quite different methods. Cealtech AS appears to be the only option for making high-surface-area materials in larger quantities. Collaborations with HyMARC and HySCORE appear to be limited, although plans to increase these, and especially to seek confirmation of adsorption data, are desirable.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.5** for its relevance/potential impact.

- There are many reasons that this project is poised to affect the DOE Hydrogen and Fuel Cells Program (the Program) goals. Among them is the scale-up reactor design, which, if successful, will open the door to many researchers for examining graphene and its role in hydrogen storage. The researchers are one of the few groups to focus their successful demonstration on room temperature data for hydrogen uptake. The small (0.015 wt.%) but measurable uptake is noteworthy. This "holy grail" approach to adsorption isotherm data collection is commendable.
- The potential impact of determining how pore chemistry could be used to control binding energies without greatly altering sorption capacities is beyond significant.
- This project is investigating the role of metal clusters with high-surface-area carbons. The overall approach of this project enables a careful investigation of the metal–carbon and hydrogen interaction. The previous work has produced large-scale reproducible materials with which to work. The research team has valuable experience to achieve efficient findings.
- This effort is relevant to the overall Program goals. There is an interesting effect of Cu on the hydrogen uptake; however, the origin of this effect is unknown. A more detailed characterization of the chemical state and morphology of the Cu-doped materials is needed.
- The project has potential to advance the Program goals, but the evidence to date suggests this is far from certain. The capacities shown so far are similar to known materials, and any signs of enhancement are questionable.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- The proposed future work is a logical extension of the progress made to date. Further details into the plans for how these challenges will be tackled, coupled with descriptions for go/no-go decision measures, would have improved the future plans section of this work.
- The future work proposed is sensible and needed for this project, although some of the strategies are not entirely clear. For example, it is not clear why turbostratic stacking is desirable; it is not clear whether this will improve or diminish the ability to control slit pore geometry and pore dimensions. It is not clear what strategies will be followed to increase and control the distribution of metal functionalization. Validation of adsorption/enthalpy results with HySCORE should be a priority.
- The proposed future work is focused on gaining a fundamental understanding of hydrogen–carbon and hydrogen–metal interactions.
- More specifics on the metal incorporation would be helpful.
- The route forward in terms of metal incorporation and its characterization was not described well.

Project strengths:

- The project represents one of the few that demonstrate small room temperature uptake of hydrogen. The materials system is very promising because it provides at least three properties that could be controlled independently for gaining optimal hydrogen uptake. Those three variables are the (1) defect concentration on the graphene layers, (2) metal sites distributed on the graphene, and (3) surface area of the graphene. Other variables that were mentioned in the work and could be controlled are interlayer spacing for the slit pore geometries. Another major strength of the project is the incorporation of a scale-up processing technology.
- The ability to generate large-scale reproducible carbon materials is critical to the progress of the project. The team has successfully demonstrated this. The team has the knowledge and expertise to proceed down an efficient pathway to incorporate the metal to investigate the isosteric heats of adsorption.
- The project strengths are that it approaches the barriers from a reasonable theoretical basis and explores synthesis from a number of angles to increase chances of success.
- The project is well structured, with a good combination of theory and experiments.
- The collaborations established with Cealtech AS are a project strength.

Project weaknesses:

- It would have been useful to see further details into how the optimization of surface area and metal site distribution could be achieved. This is likely a weakness in the description of the project, rather than in the project itself. There were no major project weaknesses.
- The lack of characterization of materials is a project weakness.
- There is some lack of control over structure and stacking of graphene sheets, as well as their functionalization. Improvements over existing sorbents have not been convincingly demonstrated so far.
- One potential weakness is the limited collaboration with the HySCORE and HyMARC teams, and the project is not fully taking advantage of the theory and experimental tools available.
- The team has tried six different routes to incorporating Cu, and two more listed in the table on slide 16 are left to investigate. There has been little or no increase in the adsorption between three different batches. It is unclear what the approach for incorporating the metal beyond slide 16 will include.

Recommendations for additions/deletions to project scope:

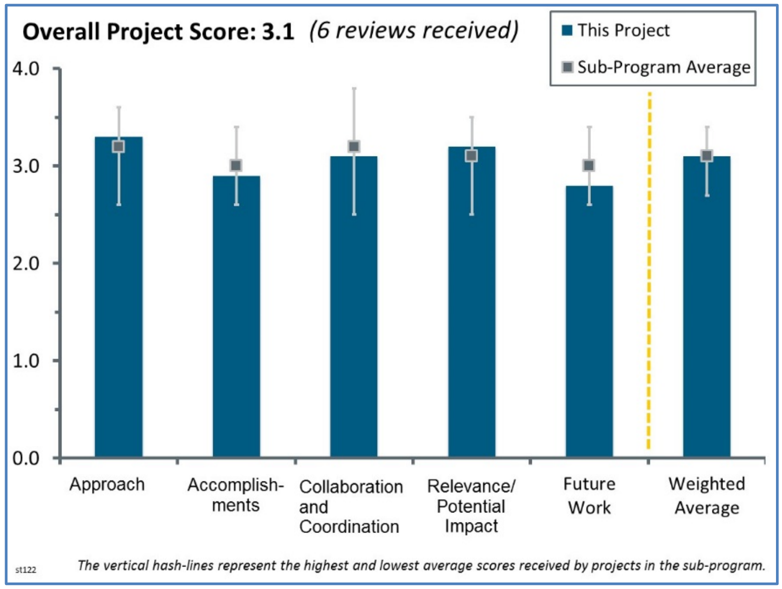
- There does not appear to be a need to significantly alter the project scope. However, it would have been good to see some strategy as to how the investigators intend to go about their efforts to improve their graphene structure and functionalization. Validation of uptake in functionalized samples is a priority.
- Suggested additions are further characterization in conjunction with HySCORE in order to determine the quantity of defects on the graphene. There are no suggested deletions.
- The work on materials with low isoteric heats of adsorption should be discontinued. There should be more focus on identifying materials with a binding energy of more than 10 kJ/mol hydrogen.

Project #ST-122: Hydrogen Adsorbents with High Volumetric Density: New Materials and System Projections

Don Siegel; University of Michigan

Brief Summary of Project:

A high-capacity, low-cost method for storing hydrogen remains one of the primary barriers to the widespread commercialization of fuel cell vehicles. Storage via adsorption is a promising approach, but high gravimetric densities typically come at the expense of volumetric density. This project's goal is to demonstrate best-in-class metal–organic frameworks (MOFs) that achieve high volumetric and gravimetric hydrogen densities simultaneously, while maintaining reversibility and fast kinetics. The approach entails high-throughput screening coupled with experimental synthesis, activation, and characterization.



Question 1: Approach to performing the work

This project was rated **3.3** for its approach.

- Adsorbents are the best bet to meet the Hydrogen Storage sub-program goals and need to be investigated in a systemic manner, as is being done here. This screening method is an efficient approach, assessing currently known candidates.
- This project seeks to demonstrate MOFs that achieve high volumetric and gravimetric hydrogen densities simultaneously, while maintaining reversibility and fast kinetics. This work combines atomic-scale, experimental synthesis/characterization with system-level modeling. This unique approach enables a broad view for assessing MOF materials. Progress and plans for each area of the project were relevant and well described.
- The approach is to use a combination of theoretical modeling and experiments to explore high-hydrogen-capacity MOFs. The advantage of this approach is the high throughput of the calculations, which allow rapid screening of >100,000 hypothetical MOFs.
- This has been a very successful project since its beginning. It has been a well-designed approach—and has helped enormously in the area. The only concern, which is the same every year, is the use of crystalline density instead of packing density in the calculations.
- The team has developed a nice approach for high-throughput screening of candidate materials through computation, synthesis, and characterization of the promising MOFs and circling back to computation for model validation. On slide 3, it was stated that "the [Hydrogen Storage Engineering Center of Excellence (HSECoE)] developed a 100 bar MOF-5 storage system that approached competitiveness with 700 bar compressed hydrogen." The results that have been presented by the HSECoE do not appear to support this statement. It is not clear whether the Grand Canonical Monte Carlo (GCMC) method is applicable to MOFs with more than one hydrogen molecule attached to a substrate atom.
- The high-throughput screening approach for materials in the Cambridge Structural Database (CSD) probes for surface area (and presumably skeletal density) of prospective adsorbent candidates. As such, this approach relies on a limited number of physical attributes to determine uptake. The metrics that are addressed are based on "total" values inferred from single crystal data. In presenting data this way, any ability to identify adsorption behavior that might suggest design routes for materials of this type is lost.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **2.9** for its accomplishments and progress.

- This project shows progress in each category with contributions from each collaborator, including synthesis, experimental measurement, and modeling. It is, however, somewhat difficult to distinguish the work completed this year versus the last year. It appears that this year eight new MOFs have been synthesized and three are in progress, numerous adsorption isotherm measurements at various temperatures have been performed, and the hydrogen capacity of 470,000 MOFs has been computationally screened. This project has made excellent progress. This work is in line with DOE goals and provides an important link between structural properties and capacities. The designation of "usable capacities" is an important distinction made in this work. All total volumetric capacities are based on the crystalline volume, which is known to over-estimate the capacity. Future work for the project included densification (of the samples), and it will be very interesting to see these results.
- The researchers have done a very good job, with significant accomplishments.
- Numerous MOF candidates have been screened and the best candidates synthesized and evaluated.
- The project seems to be focused exclusively on high-surface-area MOFs. While this is interesting from a fundamental point of view, it would be useful to expand these studies and put more emphasis on calculating and measuring the isosteric heats of adsorption.
- The team has made very good progress in the past year, having screened nearly 500,000 MOFs computationally and identified more than 2,000 compounds that might potentially surpass MOF-5 by at least 15%. The crystal density is used in this study, ignoring packing effects in a tank. While this is ideal to determine the limits of hydrogen storage, it is more realistic to account for loss (~25%) in volumetric uptake when projecting usable volumetric capacity. It does not appear that this project has the potential to uncover game-changer materials with the necessary capacities to meet the DOE technical targets in system gravimetric and volumetric capacities.
- It would help to use this information to identify any physical principle that could be discerned in order to help those involved in new materials synthesis to benefit from this survey. The metrics that are addressed are based on "total" values inferred from single crystal data, as on slide 14. In presenting data this way, any ability to identify adsorption behavior that might suggest design routes for materials of this type is lost. On the other hand, the GCMC calculations presumably generate what is essentially an absolute uptake value to which is added a gas law contribution. The usable capacity is then presumably calculated at 5 bar pressure. At least, this is an interpretation based on the slide 15 value for NU-100, which has been reported in the past by the group at Northwestern to have a much higher volumetric density than is listed in the table. In any event, all of the usable volumetric values noted here are less than 40 g/L. It is not clear whether this is an intrinsic limitation of materials of this type as far as volumetric density. These are also presumably calculated for single crystal values. While an engineering analysis was done for just a few materials, the improvements to performance appear to be marginal.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.1** for its collaboration and coordination.

- This project shows progress in each category with contributions from each collaborator, including synthesis, experimental measurement, and modeling. The overall project organization is well laid out to incorporate each aspect.
- The project is structured in a way that allows multiple collaborations with experimentalists and theoreticians working in the area of MOFs for hydrogen storage.
- There are strong synergies among the team members but limited collaboration/interaction with other institutions.
- Better use of the Hydrogen Storage Characterization Optimization Research Effort (HySCORE) capabilities should be made to gain a deeper insight into why the better MOFs identified are better.
- Save for system modeling work, the collaborations consist of the prime and subcontract participants.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.2** for its relevance/potential impact.

- This work provides a unique broad view to consider gravimetric and total capacities with structural material properties. The team has considerable expertise and experience in modeling, synthesis, and measurement.
- The effort is well aligned with the DOE Hydrogen and Fuel Cells Program (the Program) objectives. It is desirable to put more emphasis on increasing the hydrogen binding energy of this class of materials, so strategies to accomplish this should be explored both computationally and experimentally.
- This study forms a good overview of MOF adsorbent capabilities, but it does not address achieving materials for higher temperature adsorption. It is not clear how this approach can be modified to address the search for materials with higher adsorption energies.
- This project can enhance its relevance and impact by providing additional insights from calculations at room temperature.
- There appear to be some real limitations as to whether this class of adsorbents will make the substantive improvements to metrics that the Program seeks, because projections on slide 29 show some small improvement to volumetric density. Other issues such as material stability, actual packing density, and conductivity are also in need of analysis/resolution, and it is not clear that these are part of the research effort.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- The future work is well defined. Perhaps the project could investigate the possibility of tapping into the Materials Genome Initiative database.
- Some effort should be applied to a deeper understanding of how these MOFs adsorb hydrogen in order to give some insight to those developing new MOF structures.
- The experimental path forward was described as considering the top 20 MOF materials. The project should expand screening to real MOFs in the CSD. Understanding the effect of densification of the material will be important.
- The proposed future work is mostly based on the existing results. It would be desirable to test the effect of flexibility on hydrogen uptake in MOFs.
- This was really the only disappointing part of the project. It would be good to see more specifics about the actual pathways forward—it was too general as to what the actual future work would be.

Project strengths:

- The project is well balanced, with both experimental and theoretical components. The strengths are the high-throughput calculations, which allow many hypothetical MOFs to be screened and their hydrogen uptake estimated even before the materials are synthesized.
- This project provides a unique synergistic view of materials properties and system storage goals. It is a well-coordinated effort involving members with strong expertise.
- The team possesses the knowledge and tools to meet the goals for this project.
- The project is very inclusive of nearly all MOFs thus far identified in the literature.
- The significant amount of data compiled is a project strength.
- An overall assessment of the metrics studied to date is useful. As far as usable volumetric capacity, there seems to be remarkably little to distinguish the properties of these materials from one another.

Project weaknesses:

- The lack of any analytical analysis of synthesized MOFs, which could be achieved through a greater collaboration with HySCORE, is a project weakness.

- As a survey, some physical insight into the properties that have been evaluated would be of value. There appear to be real limitations to this class of materials, and some analysis of why/how this is the case might offer some fruitful directions for future work, rather than just expanding the screening effort.
- The project is focused mostly on high-surface-area materials. There should be more emphasis on increasing the isosteric heats of adsorption, as it is clear that high surface area alone is not sufficient to satisfy the DOE technical targets for onboard hydrogen storage.
- The use of crystalline density for calculations is a project weakness. Possibly more information on improved isosteric heat materials should be provided.
- The go/no-go milestone for identifying MOFs with hydrogen capacities exceeding MOF-5 by +15% falls well short of the capacities required for an MOF to be considered viable for meeting the DOE technical targets.

Recommendations for additions/deletions to project scope:

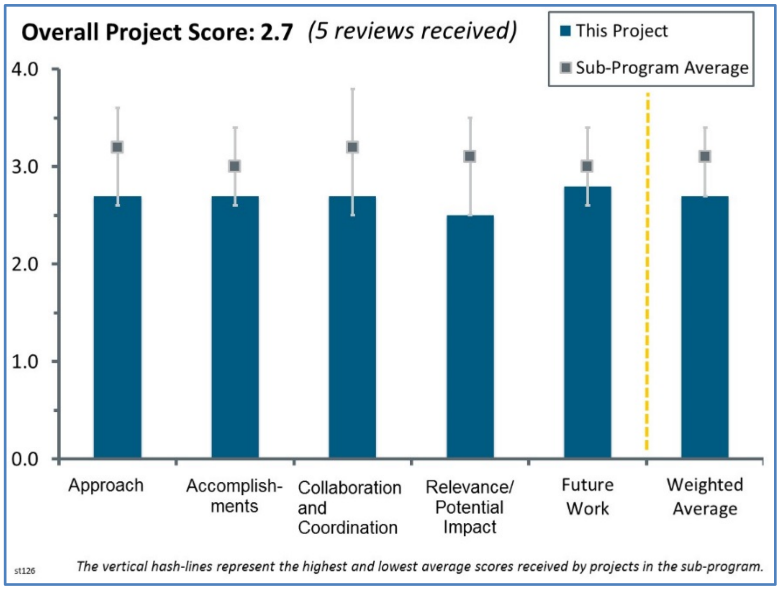
- The recommendation is to focus on narrowing down the list of candidate materials and exploring the temperature effects on hydrogen adsorption to compute and experimentally determine the isosteric heats of adsorption. Another recommendation is to explore the effect of flexibility, because such approaches have shown to have an effect on isotherm shape and overall hydrogen capacity.
- The team should use HySCORE and the Hydrogen Materials–Advanced Research Consortium as collaboration partners to investigate higher isosteric heat MOFs.
- Evaluation of improved isosteric heat materials sets would improve the project.

Project #ST-126: Conformable Hydrogen Storage Coil Reservoir

Erik Bigelow; Center for Transportation and the Environment

Brief Summary of Project:

The project goal is to develop storage systems for compressed hydrogen gas that will provide a cost-effective and conformable storage solution for hydrogen vehicles, thereby reducing the cost, weight, and packaging issues related to conventional high-pressure hydrogen tanks. The target is conformable, lightweight 700 bar gaseous hydrogen storage with around 10% gravimetric capacity. Researchers are aiming for continuous production processes for a storage system that can be extended, once proven at smaller sizes.



Question 1: Approach to performing the work

This project was rated **2.7** for its approach.

- This approach addresses the introduction of high-pressure hydrogen tanks into existing automotive designs, but new designs may not require conformal tanks when balanced against volumetric and cost considerations.
- The project is rather high-risk based on limitations of suitable liner materials, which must meet requirements for hydrogen permeation, formability, and mechanical properties. It is suggested that a risk assessment and mitigation plan be developed. Perhaps the braided overwrap will require a polymer matrix. It is not clear how that would affect cost, weight, durability, etc. Perhaps this technology is more suitable for compressed natural gas in which permeability is less of a concern.
- In the early stages, there should be a stronger effort on selection of the permeability resin. There should be a much, much greater focus on hybrid construction of the fiber reinforcement (i.e., carbon + Kevlar®), rather than a Kevlar-only solution. This would give less strain for a given pressure and thus partially alleviate the problems with resin brittleness.
- The main barrier is getting the permeability of the liner down to 0.01 g/(hr-kg H_2 stored) from the current 0.05 g/(hr-kg H_2 stored). The researchers do not seem to have a good idea of how they will achieve this. Without this, other components may not help it translate into commercial use. The only workable idea may be to reduce the pressure requirement to 350 bar from 700 bar. Also, the current process does not allow for higher thickness of the liner. Unless they can present a good plan forward to address this issue, this should be a no-go.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **2.7** for its accomplishments and progress.

- Progress has been made on the resin liner and fabrication approaches. Pressure testing and cyclic results of folded tanks will be critical to assessing the viability of this approach.
- Progress was made to show that the Kevlar braid could meet static pressure requirements and achieve the weight target. A dry braid may not be suitable for fatigue life and damage tolerance protection of the thin, fragile liner.

- The researchers have been able to make conformable tanks, but the permeability testing does not show any progress toward the target of 0.01 g/(hr-kg H_2 stored). They have tested various resins that meet most of the requirements, but resins are not a crucial issue.
- There are some accomplishments, but many challenging tasks remain, and it seems that the project team does not have a viable solution in mind.
- A satisfactory material selection has not yet occurred (fiber composition and resin), so the rest of the effort is on hold until that occurs.

Question 3: Collaboration and coordination with other institutions

This project was rated **2.7** for its collaboration and coordination.

- The team seems to be working well with the inventor and with Texas A&M University, where testing is being carried out. However, the team needs to change the process of manufacturing so it can allow for a thicker liner, which will help it move toward the goals set for hydrogen permeability. Hence, the team needs to bring a process engineer into the collaboration.
- There is good interaction between partners, but the team is lacking a true materials expert.
- Collaboration is sufficient for validation of this technology, but it is not extensive. Collaboration could be enhanced by engaging either commercial tank vendors or original equipment manufacturers (OEMs) to assess market drivers and economic opportunities.
- Some validation of the system-level approach toward the goals is suggested via collaboration with projects ST-001 and ST-100.
- There is no collaboration with industry, vessel manufacturers, or OEMs.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **2.5** for its relevance/potential impact.

- The progress will be excellent if the team can solve the problem of permeability. The strength around sharp corners, which can occur in non-conformal containers, is also a concern that has not been addressed here but will play a big role in commercialization.
- The project is focused on the right area. With the right materials selection, it could be very successful. The project team should get a materials expert (composites, polymers, and fiber reinforcement) on board.
- The project—if successful—has strong potential to provide a useful compressed gas storage (CGS) product form for hydrogen storage, while meeting cost and weight goals. Perhaps the permeability would be less of an issue for fleet vehicles that require refueling each evening. The project needs to establish the value proposition for the technology—even if it does not meet all the current performance goals.
- The project fully addresses only one barrier that is not critical in meeting the DOE targets.
- The presenter claims low vessel cost (ultimate) and low vessel weight (ultimate). However, the presenter did not show any evidence that this will be possible and was unable to explain how this claim will hold. Aside from this, volumetric efficiency is similar to a compressed gas vessel. It is therefore difficult to understand whether this project has a solid rationale.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- The plan is appropriate once the previously addressed hurdles are appropriately handled.
- Burst testing of the folded package and abrasion fatigue testing of the folded package will be necessary to assess this technology.
- The future progress hinges on addressing the permeability issue. It would likely be beneficial for the team to test all this for 350 bar and see whether it can meet all the metrics or/and modify the process so it can accommodate a thicker liner.

- The project has numerous risks; a risk assessment and mitigation plan was not presented for future work—although several key risks are identified. The limits of a 0.05" wall thickness for the blow molding process is a limitation that needs to be addressed. Perhaps the team should consider spray coating or infusing the braid.

Project strengths:

- It is an impactful project with good collaboration. It could be a game changer if successful.
- This novel approach seems suitable for mass production and offers extendable storage volumes and flexible geometric packing. Perhaps this class of CGS needs its own performance criteria if it is enabling for certain applications.
- The project has an excellent design concept.
- The project has a good concept for conformable storage.
- Initial results on resin permeability are encouraging.

Project weaknesses:

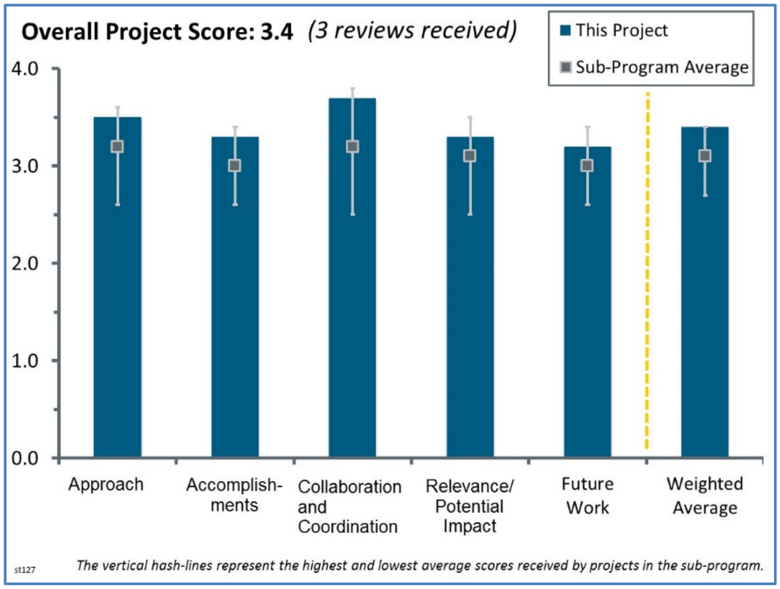
- The lack of materials expertise in polymers, composites, and fiber reinforcement is a project weakness. The team should get an expert on board.
- The team needs to change direction to address the permeability issue. It should bring in a process engineer or materials scientist who can help the project.
- Concept implementation is challenging because of high pressure, permeation, heating during fill-up, and durability.
- The project fully addresses only one barrier, and it is not critical in meeting the DOE targets. More efforts should be placed on strength and durability of the folded package and less on permeability, which can be addressed later if the concept is sound, because the resin does not contribute to burst strength.
- Most weaknesses have been addressed in prior questions. Another issue is fatigue failure at the end fitting. Even if permeability of the liner is satisfied, there is the likelihood of damage and failure during blow molding, overbraiding, final packaging, and service life.

Recommendations for additions/deletions to project scope:

- Fatigue and burst testing of the folded package needs to be completed as soon as possible.
- The team should work with projects ST-001 and ST-100 for project review and setting future priorities.
- The team should reduce the pressure requirement to 350 bar and show that it can be done for three to four different types of conformal containers, instead of spending all its energy to find this for 700 bar. There are many applications where 350 bar will be useful.
- There are many critical tasks that need to be accomplished. It may be best to focus on one, e.g., permeability, and either resolve it or cancel the project.

Project #ST-127: Hydrogen Materials–Advanced Research Consortium (HyMARC) – A Consortium for Advancing Solid-State Hydrogen Storage Materials

Mark Allendorf; Sandia National Laboratories



Brief Summary of Project:

Critical scientific roadblocks must be overcome to accelerate materials discovery for vehicular hydrogen storage. The project objective is to accelerate discovery of breakthrough storage materials by providing capabilities and foundational understanding. Capabilities will include computational models and databases, new characterization tools and methods, and customizable synthetic platforms. Foundational understanding is needed for phenomena governing the thermodynamics and kinetics limiting development of solid-state hydrogen storage materials.

Question 1: Approach to performing the work

This project was rated **3.5** for its approach.

- The project has a very good, multidisciplinary team. There is good integration of theory and experiment. The team seems to have “gelled” and is working in an efficient, collaborative fashion.
- The Hydrogen Materials–Advanced Research Consortium (HyMARC) team has formulated a comprehensive and well-reasoned approach that is providing a basis for understanding the detailed aspects of the thermodynamics, hydrogen diffusion, reaction kinetics, and interfacial processes operative during sorption reactions in hydrogen storage materials. The approach integrates important elements of theory/ modeling, materials synthesis, and diagnostics/characterization in a framework that is effective and straightforward. The charter of the HyMARC effort is daunting. However, the approach that has been adopted and the team that has been assembled seem to be fully capable of successfully addressing the principal project goals, namely understanding and elucidating the foundational issues and critical processes that control the hydrogen sorption behavior in storage media. Notably, significant improvements in the development and implementation of a more coherent and consolidated technical approach have become apparent over the last year. The approach provides a solid basis for facilitating and enhancing progress on the companion seedling projects devoted primarily to new materials discovery. That being said, it would be helpful if the principal investigator (PI) and his team could provide a more illustrative roadmap that clearly identifies the model systems being studied, provide criteria for their selection, articulate what critical questions will be answered by studying those specific systems, and describe whether and how that work is translatable to more complex and technologically relevant materials. Likewise, a more compelling statement concerning the direction of the Advanced Light Source (ALS) work would be helpful. The ALS activities could be game changers. However, limited beam time and funding resources demand that the most important problems must be addressed first. The identification and prioritization of those projects should be a high priority.
- The approach has been much better explained this year and better justified. The U.S. Department of Energy’s (DOE’s) “reset” approach of taking a step back to fill in some of the foundational science gaps in our knowledge of materials-based storage remains controversial to some, and it carries some risk, but HyMARC has addressed many of these concerns, and its approach mitigates much of the risk. The HyMARC approach has converged to a reasonable and well-explained strategy to address significant barriers that confront hydrogen storage technologies that strive to eclipse physical storage approaches. The

consortium is clearly focused on developing a more foundational understanding of the thermodynamics and kinetics that control hydrogen release and uptake in complex hydrides, and the controlling features of hydrogen physisorption in adsorbents. Much of the focus of the consortium lies in developing accurate computational models of these phenomena across multiple length and time scales—a grand challenge in itself. The consortium has also done a nice job of improving its definitions of what the characteristics of a good model system are that can then be subsequently used to help in the calibration and validation of computational models. This is an improvement over last year. The approach relies a great degree on seedling projects to add much of the experimental work to provide feedback to the theory effort, so there is some risk involved in having the appropriate topics addressed by seedling proposals and that the right balance of projects is populated via the funding opportunity announcement (FOA) process. It is a challenge for the DOE Hydrogen and Fuel Cells Program (the Program) managers to control this flux, and only time will tell if it can be successful.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.3** for its accomplishments and progress.

- Solid progress has been achieved in this reporting period on virtually all aspects of the project. In a project of this size and scope, it is critical that individual efforts on tasks and sub-tasks do not go “open loop,” leading to a random mix of technically interesting but disconnected efforts that are largely inconsistent with the overall project goals. The team has obviously given serious thought to this issue, and it should be commended for ensuring that the individual project elements are coordinated and cohesive. The progress thus far is meeting the DOE mandate for this effort, and together with the initial results on the companion seedling projects, it is on track to address the critical DOE goals for hydrogen storage. The progress is broadly based—solid results have been obtained in theory/modeling, synthesis and nanostructured material development, and advanced characterization. It goes without saying that in a project of this scope, it will be critical to maintain a keen focus on the most demanding issues and to avoid the temptation of pursuing “curiosities” that may be scientifically interesting in their own right but have only minimal impact on the overall project goals.
- Communication of the strategies and goals in such a large consortium effort is critical to the success of HyMARC, and the consortium director has done an excellent job of providing a communication infrastructure that has appeared to bring a focus to the overall effort. As a result, a number of modeling efforts have made substantial progress over the last year, with many models being made available to the at-large community. Also, as a result of the overall more focused communication, there is much better coordination among the experimental efforts to address critical pathway issues in several materials. This is an improvement over last year. HyMARC has also made large strides in bringing on external collaborators that are top-notch and help to fill key capability gaps in the overall technical portfolio of the consortium. A key accomplishment is the rapid integration of the seedling projects into the consortium’s efforts, and even though these seedlings are just getting started, they have mostly been actively engaged with HyMARC already in meaningful interactions.
- New insights to the reaction pathway of doped sodium alanate are a major accomplishment.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.7** for its collaboration and coordination.

- An impressive and effective network of collaborations has been developed over the last year. There was some concern at the outset of the project that the overall effort might become too insular. The PI and project team have clearly dispelled that notion and have instituted collaborations with numerous investigators (especially the Hydrogen Storage Characterization Optimization Research Effort—HySCORE) that broaden both the scope and the efficiency of the overall effort. Notable progress has been made on bringing the ALS activities into the project mainstream. It appeared initially that the ALS effort was not especially well integrated into the overall HyMARC project, but that concern was addressed effectively in the last year. However, it cannot be overstated that the ALS effort must continue to focus on the critical issues—this will demand input from the entire project team.

- The development of appropriate collaborations with best-in-class researchers has been very good over the last year. It was apparent that many, if not all, of these collaborations are strategic in filling in a few capability gaps within HyMARC, providing good scientific and technical leverage to the overall effort.
- Very strong collaborations have been developed.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.3** for its relevance/potential impact.

- The Program and the HyMARC project team should be commended for instituting and formulating this project. Although this kind of project generally falls outside of the traditional purview of the DOE Office of Energy Efficiency and Renewable Energy (EERE), it is nonetheless critical to the overall success of the EERE hydrogen storage activity. A comprehensive materials search-and-discovery effort was conducted previously in the Centers of Excellence and in independent projects. However, that work lacked the sufficient foundational understanding required to address critical obstacles in a systematic and effective way. (Of course, without that prior work, those obstacles would not have been so readily apparent.) The HyMARC project is exactly the kind of effort that is needed to truly address the major issues and challenges that underlie the development of new and advanced materials capable of meeting DOE goals for hydrogen storage.
- The relevance to Program goals is very high. As the problems that the project team is trying to solve are extremely rigid because of the very tough technical targets for onboard hydrogen storage, only time will tell whether this novel "reset" approach will pay dividends and the output will provide novel paths forward to materials that can successfully and simultaneously achieve the DOE technical targets. If successful, this approach will have a tremendous impact on the whole hydrogen fuel cell technology area.
- Unlike the individual (or seedling) projects, the core team does not seem to be pursuing high-risk–high-reward research.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- The consortium's future plans involve the integration of a diversity of models that cover a span of length and time scales—a rather grand undertaking for a single element, much less for complicated materials such as a complex metal hydride. The consortium has an outline for how this can be potentially achieved, so its future plans are solid in this area. A continued emphasis on maintaining communication across the consortium is a crucial part of HyMARC's plans. Gaining access to local structure/composition characterization techniques such as neutron scattering and light element x-ray photoelectron spectroscopy (XPS) at the Spallation Neutron Source and ALS is a valid tactical approach in the short-to-medium term to provide some key bounding properties as input and/or validation to the computational modeling efforts.
- The proposed future work follows logically from the studies currently underway. It will be important to carefully and thoroughly evaluate the overall hydrogen storage material landscape to ensure that, after more than a year of work on this project, the proper issues are still being addressed. The project must be sufficiently nimble so that the technical efforts continue to focus on the major issues as the project evolves; i.e., as understanding improves, the priorities may change. The project team must be willing and able to work with the Program and its technical teams to adapt to those changes if and when they arise.
- The project could be more impactful if the core participants invested more time in novel/speculative/risky materials.

Project strengths:

- This is a signature project for the Hydrogen Storage sub-program. The approach has been carefully formulated to address critical technical issues that affect the successful development of hydrogen storage materials. The project team is well coordinated and has expertise in all relevant areas. Excellent facilities

and instrumentation are available, and the core effort is augmented by strong collaborations with investigators in HySCORE and other independent activities. The project provides wide-ranging and solid support for companion seedling efforts devoted to new materials discovery.
- The consortium director has done a commendable job of bringing a set of strong communication plans to the consortium to "glue" the disparate efforts together and maintain the focus on critical path issues. The consortium is pulling together, via internal expertise and external collaborations, a powerful set of characterization tools to address phenomena at the appropriate length and/or time scales. HyMARC has rapidly engaged many of the new seedling projects, and it is likely to have engaged all of them in the near future. It has plans to make these fruitful interactions that should lead to technical advances.
- There is excellent collaboration and good fundamental science.

Project weaknesses:

- It is essential to provide a clear and persuasive argument about how the results obtained in model systems will translate to more complex systems. The successful extension of work from the model systems to materials that are relevant to DOE needs is crucial. For example, it is not clear what specific results from the studies of model systems will affect our understanding of hydrogen sorption reactions in the $MgB_2/Mg(BH_4)_2$ system. If that connection cannot be made in a compelling way, the project team must be willing to make the "mid-course corrections" necessary to maintain the focus on the overall project goals. This is especially important in the ALS studies, given the premium placed on beam time and availability. In addition, there is an often-confusing mix of technical efforts in HyMARC, HySCORE, and independent/seedling projects devoted to theory/modeling of sorbent materials (especially metal–organic frameworks) and functionalization to improve hydrogen reactivity. It would be helpful if HyMARC could take the lead in organizing and coordinating those efforts to ensure that the "right" questions are being addressed in the most efficient way.
- There is still some work to do in continuing to define what the ideal characteristics of model materials are; this would be helpful to maintain focus on the critical path, and it could provide DOE with potential FOA topics. There was not sufficient attention paid in the presentation to the justification or the goals of what the materials studied at ALS were intended to be.
- More emphasis on high-risk–high-reward research would be welcomed.

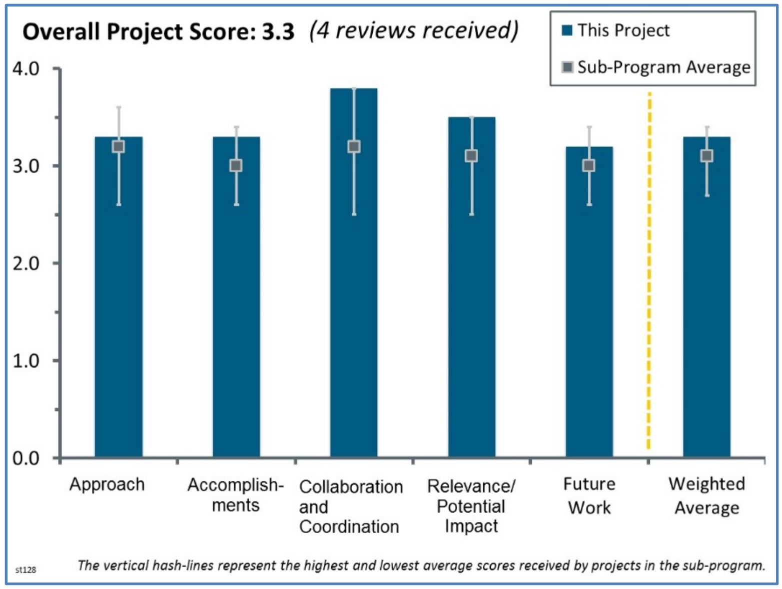
Recommendations for additions/deletions to project scope:

- By and large, the technical team approaches the problems from a materials science perspective; as many of the materials classes being explored rely on chemical frameworks, making and breaking chemical bonds, chemical kinetics, catalysis, etc., the consortium may want to enhance the complementary chemical sciences skill set.
- A very strong research and development team has been assembled—especially in the areas of modeling/simulation, materials synthesis, and characterization. However, the core team seems to lack an individual with in-depth chemical insight into the reactions involving major constituents and additives. Close collaboration with an individual (e.g., staff member, advisor, or consultant) having deep expertise in solid-state chemical reactions and/or reactions of gases with solid surfaces is recommended. As discussed at the Program Annual Merit Review, understanding the role of surface oxidation on the thermodynamics and kinetics of the hydrogen sorption reactions may be crucial to the development of improved storage materials. It certainly seems that this is a "foundational issue," and it is therefore subject to at least more consideration in the HyMARC project. At the conclusion of the HyMARC activity, it is hoped that a definitive statement can be made about the role of surface oxides in technologically relevant materials. Further discussions with the DOE Program management team concerning the level of effort that might be devoted to this issue are recommended.

Project #ST-128: Hydrogen Materials–Advanced Research Consortium (HyMARC) – Sandia National Laboratories' Technical Effort

Mark Allendorf; Sandia National Laboratories

Brief Summary of Project:



This project addresses a lack of knowledge about hydrogen physisorption and chemisorption. Researchers will develop foundational understanding of phenomena governing the thermodynamics and kinetics of hydrogen release and uptake in all classes of hydrogen storage materials. Sandia National Laboratories will (1) provide data required to develop and validate thermodynamic models of sorbents and metal hydrides, (2) identify the structure, composition, and reactivity of gas–surface and solid–solid hydride surfaces contributing to rate-limiting desorption and uptake, (3) synthesize metal hydrides and sorbents in a variety of formats and develop in situ techniques for their characterization, and (4) apply multiscale codes to discover new materials and new mechanisms of storing hydrogen.

Question 1: Approach to performing the work

This project was rated **3.3** for its approach.

- The various approaches to the diverse and insightful work being performed are well-thought-out. There is a lot of reach in the approach to some work, such as metal hydride improvement and understanding. Some of the work is material-specific; more of it should resemble the grand canonical Monte Carlo work that allows for models to be tied together, rather than be specific to certain situations or materials.
- The approach focuses on energetics (thermodynamics) in sorbents and metal hydrides, kinetics and the effect of nanostructuring and additives on reaction rates, and methods to improve reversibility. The approach is sensible and straightforward and addresses many of the critical obstacles that impede progress in development of improved storage materials. A more detailed statement of how the Advanced Light Source work will support the overall goals would be useful (specific systems and physical/chemical processes to be studied should be included). In addition, in the spirit of creating a "foundational understanding," as discussed at the Hydrogen and Fuel Cells Program (the Program) Annual Merit Review meeting, it would be helpful to augment the approach to include assessing the importance and role of surface oxides in hydrogen sorption reactions in relevant materials. The presence of a tenacious oxide could alter predictions derived from modeling of clean surfaces. A concerted effort to understand and mitigate those effects might turn out to be an important research direction.
- The approach as formulated is quite reasonable. However, it might make sense to dedicate more of the Hydrogen Materials–Advanced Research Consortium's (HyMARC's) time to the development of new experimental techniques and tools, and to studying novel phenomena that can enable the development of new hydrogen storage materials. An example is the exploration of new high-pressure-driven phenomena that are observed and can take place in various solid-state metal hydrogen systems. Such activity(ies) should not target the development of new material(s) as the main goal and may be carried out as a collaborative effort coordinated by HyMARC.
- The project should expand the scope of the effort and support more theory–experiment activities.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.3** for its accomplishments and progress.

- Solid progress was made on model development and validation for hydrogen sorption reactions in metal–organic frameworks (MOFs), hydrogen diffusion, segregation and reaction barriers in model systems, the effect of doping/additives in complex metal hydrides, reactivity of selected systems at high pressures, and improved kinetics in nanostructured systems. In addition, the development and implementation of sophisticated surface diagnostics are providing unique insight into surface characteristics and reaction mechanisms at relevant length scales. The low-energy ion scattering (LEIS) work will be especially important in understanding surface diffusion. However, validation of LEIS using the Ti-doped $NaAlH_4$ system is challenging (and might be misguided), given the fact that the diffusion and reaction processes in this system are so controversial to begin with. The project team must continue to carefully consider how the results will provide a payoff in understanding related processes in more promising complex hydrides. The project has clearly demonstrated progress toward meeting DOE goals. Over the last year, a much more cohesive and coherent effort has emerged. It will be important to rapidly transition from the simpler model systems to more complex materials. A clear and compelling pathway that shows how this transition will proceed would be helpful. This is especially important in transitioning from studies of diffusion rates and mechanisms in PdH(x) and MgH_2 and surface chemistry of Ti-doped $NaAlH_4$ to more technologically relevant materials. Specifically (as pointed out in the future work slide), rapidly extending the molecular dynamics model formalism(s) developed for MgH_2 to more complex systems, e.g., $Mg(BH_4)_2$, is imperative. Although the work on catalytic additives is important and initial results are intriguing, it is important to exercise caution in elucidating mechanisms—especially in those cases in which the additive species might directly react with the matrix elements.
- A great deal of good work was performed in the past year. The modeling work is impressive and will yield great insights into MOF performance without the need for synthesis, as well as the surface diffusion work with the LEIS.
- Accomplishments and progress toward overall project and DOE goals are commensurate with the funding level.
- HyMARC runs many diverse activities that are somewhat scattered over the hydrogen storage space. An updated model in which service-type activities and focused research are better balanced may be worth considering.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.8** for its collaboration and coordination.

- Numerous beneficial collaborations within HyMARC and with external projects and institutions are evident. Collaborations and interactions with the Hydrogen Storage Characterization Optimization Research Effort (HySCORE) are especially noteworthy. The project team has expertise and experience in all relevant areas. The technical effort is well coordinated, and tasks are synergistic.
- There is a great deal of collaboration on almost every aspect of the work done. This is a great example of use of the consortium set by the group leading it.
- HyMARC has been doing an excellent job supporting external partners and collaborators.
- Collaboration and coordination with other institutions with capabilities outside the current project organizations should be encouraged.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.5** for its relevance/potential impact.

- This project is a key element of the HyMARC project. It is focused on developing a fundamental and foundational understanding of relevant phenomena and processes in hydrogen storage materials. As such, it directly supports the overall HyMARC goals and, in turn, the research, development, and deployment goals of the Program.
- This project has continued to make great strides in developing models, measurement techniques, and test equipment. The discoveries and understanding that have come from this project help develop the fundamental understanding of hydrogen storage materials and technology, and it should continue to do so at this pace.
- HyMARC has been doing a great job advancing progress toward the Program goals and objectives.
- The success of HyMARC is critically important to establishing the capability of handling the evaluation and coordination of hydrogen storage research.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- The proposed future work follows the work previously done in a well-thought-out manner and will continue to improve our understanding of the different materials studied. The encapsulation work proposed is particularly exciting, as previous work has shown that this method can increase material resilience when exposed to air.
- The proposed future work is a straightforward and reasonable continuation of the current effort. However, there is no mention of ongoing work on the important role that additives/catalysts might play in enhancing reaction kinetics. In fact, the general topic of reaction kinetics and elucidation of reaction mechanisms is (surprisingly) marginalized in the future work slide (slide 21). It is not clear whether that de-emphasis is intentional. Clarification here would be helpful.
- HyMARC proposed a comprehensive list of future tasks that is extremely diverse. Some focus may be beneficial to the outcome of the consortium's activities.

Project strengths:

- This is an important project being conducted by a strong research and development (R&D) team with expertise and experience in all areas relevant to achieving HyMARC goals. The project approach and work plan are well formulated. Likewise, the combination of modeling, synthesis (including nanostructured materials), and advanced characterization/diagnostics, together with support from extensive collaborations, provides a solid foundation for addressing the critical technical issues identified in the HyMARC project.
- Project strengths include the following:
    - Unique experimental setup
    - High level of technical expertise
    - Openness to external collaborations and joint research activities
- This project has good, strong collaboration and access to some great technology. Though broad in scope, each aspect of the project is focused and has provided productive results.

Project weaknesses:

- HyMARC's scope may need to be further refined and balanced so that service-type activities are complemented by a clearly defined systematic research effort.
- A stronger emphasis on understanding reaction kinetics, mechanisms, and obstacles in complex hydrides is needed. Most notably, greater attention should be given to the role of additives and catalysts in enhancing reaction kinetics. The proposed future work seems to minimize that R&D imperative.

- Most of the project is focused on important areas of study, but pursuing the understanding of materials that may never work at ambient conditions, such as various MOFs, may be a waste of time and resources.

Recommendations for additions/deletions to project scope:

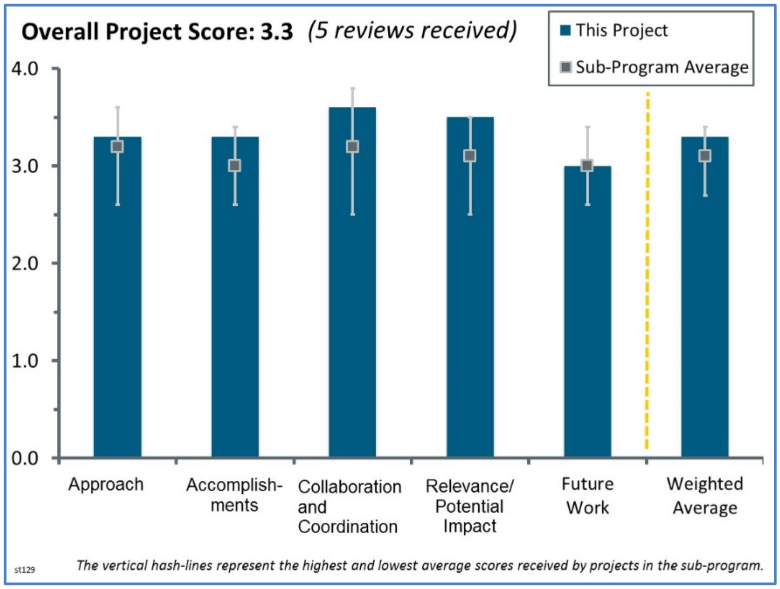
- The addition of an individual (staff member, advisor, consultant, etc.) with a deep understanding of solid-state chemistry, especially hydrogen sorption reactions in complex metal hydrides, would be useful. The insight provided by that individual could help to augment the technical effort and guide the future work in a more efficient and effective way. Discussions with DOE program managers concerning this addition to the project scope are recommended. (This was also suggested by this reviewer in companion reviews of the overall HyMARC and theory/modeling activities.)
- More focus should be placed on MOFs that can operate at near-ambient conditions rather than cryogenic conditions.

Project #ST-129: Hydrogen Materials–Advanced Research Consortium (HyMARC) – Lawrence Livermore National Laboratory's Technical Effort

Brandon Wood; Lawrence Livermore National Laboratory

Brief Summary of Project:

The Hydrogen Materials–Advanced Research Consortium (HyMARC) is providing community tools and foundational understanding of phenomena governing thermodynamics and kinetics to enable development of solid-phase hydrogen storage materials. HyMARC team member Lawrence Livermore National Laboratory is conducting porous carbon synthesis; x-ray absorption/emission spectroscopy; and multiscale modeling including density functional theory (DFT), ab initio molecular dynamics, phase-field mesoscale kinetic modeling, and kinetic and quantum Monte Carlo (QMC).



Question 1: Approach to performing the work

This project was rated **3.3** for its approach.

- The scope and depth of the theory and modeling effort in this project is most impressive. The approach combines existing theory and modeling methodologies with new capabilities (under development). The principal investigator (PI) and his team have a solid understanding of the critical problems and obstacles, and they have developed a theory/modeling framework that addresses those problems in a comprehensive way over extended time and length scales. Experimental validation of modeling results is a vital element of the project. That work is being performed in close collaboration between HyMARC and external investigators. The project integrates a large number of disparate modeling approaches in a coherent way.
- The approach is now better explained than last year. Last year, reviewers suggested the project looked more like a U.S. Department of Energy (DOE) Office of Basic Energy Sciences project than an applied DOE Office of Energy Efficiency and Renewable Energy project. The presenter did an excellent job of justifying the more foundational approach, and it was clear that this was well coordinated with the top-level HyMARC approach presented just before this talk. Hence, a tightly focused, better-justified approach has evolved in the last year. This was accompanied by a clearer explanation of which model systems can be useful to provide validation to the computational effort. Quite a stretch goal has been proposed to eventually provide a validated multiscale (length and time) computational model of hydrogen behavior in model hydrides. This is a grand challenge to be sure, and the approach lays out a logical approach to this attempt.
- The modeling approach taken for understanding the science behind metal hydride- and adsorbent-based hydrogen storage is laudable; however, until the models can be translated to produce or direct experimental research toward novel hydrogen storage materials, the outputs of this project are simply non-translatable models.
- The approach is adequate.
- It would be helpful if more experimental validation of computational models could be performed.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.3** for its accomplishments and progress.

- There has been excellent progress in a broad diversity of elements of the computational aspects of this project and excellent signatures of good interactions between the computational and experimental efforts, which is commendable. There has been demonstrated progress in this project in the initial interactions with the new seedling projects in devising logical pathways to address computationally key questions that the seedlings must address. The project has made available to the community spectroscopic and thermodynamics databases as well as the classical potentials derived for interfacial simulations in borohydrides that are important contributors to developing an understanding of key features of hydrogen mobilities in this class of hydride materials. Through its careful computational modeling combined with experimental insight, the project has identified key computational/theoretical aspects of hydrogen adsorption in high-surface-area metal–organic frameworks. These observations and results will help provide support in a computational sense for some of the seedling efforts. The new results on morphology-dependent thermodynamics was fascinating, and it will probably contribute to a better understanding of hydrogen mobility in these interfacial complex metal hydride materials and will support future research in a few of the seedling projects. The influence of strain was explored computationally and correlated with the current experimental understanding of the behavior of hydrides in confined environments, which will also be important in supporting a few of the seedling projects. The project is successful in contributing to the literature; in the last year, the project has generated one publication and six manuscripts that are in the review process.
- The serious challenge of bridging time and length scales and effectively integrating results from different modeling approaches has been confronted directly, and solid progress is being made. A more in-depth understanding has been obtained concerning diffusion and reaction kinetics. These are critical obstacles that have hampered prior work. The initial results on the development and application of a reactive interface nonlinear kinetics model are especially intriguing, and they should pave the way to providing a better understanding of how interfacial reactions and hydrogen sorption fronts actually proceed in a solid. Fully characterizing the interfacial reaction zone ("soup") as well as other amorphous materials remains a research challenge. Overall, the results are having an important impact on the direction of the project, and it remains a successful and critical element of the overall HyMARC effort.
- The project has made specific accomplishments and progress toward overall project and DOE goals.
- The project accomplishments with respect to model development appear to be adequate. It was unclear how the improved models (dubbed as accomplishments) translate to the real world. It is not clear how they are better or why they better. Clarification on these types of issues will benchmark the significance of these accomplishments. There were a number of accomplishment claims such as "predicted phase diagrams of MgB_xH_y..." but no phase diagrams were shown, and there is no experimental evidence of validation via x-ray diffraction (XRD) or nuclear magnetic resonance.
- There are some slow-downs in progress resulting from staffing issues.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.6** for its collaboration and coordination.

- The PI and his project team are working closely with other HyMARC investigators. Also, extensive collaborations with the Hydrogen Storage Characterization Optimization Research Effort (HySCORE), other external institutions, and HyMARC seedling projects are evident. A confirmation of the importance of this work is the fact that virtually all of the PIs of seedling projects state that these modeling and theory efforts are important/critical to the success of their projects. (In fact, a concern is that the Theory and Modeling team will be overwhelmed with requests from multiple investigators.) The project team is well coordinated, and communication among all investigators seems to be open and effective. The PI is fully engaged in all aspects of the project and seems eager to accommodate the theory and modeling needs of the HyMARC team and companion seedling efforts.

- The presentation included many signatures that identify very good collaboration among the theorists and the experimentalists in this project. There is excellent communication and collaboration with many principal researchers in HySCORE and across HyMARC. This project has rapidly developed effective collaborations with several of the new seedling projects and has already demonstrated computational support in several instances. This is clearly a well-led project.
- Collaborations are a major strength of this project.
- Close collaboration with multiple organizations has been established.
- Collaboration within HyMARC and HySCORE appears to be present. The obvious gap is the experimental data to validate the models. Model improvement with no data is at best an academic exercise.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.5** for its relevance/potential impact.

- This project seems to be the centerpiece of the overall HyMARC effort. As such, it is of vital importance to the DOE Hydrogen and Fuel Cells Program (the Program). This project is critical to meeting the goals set forth by the HyMARC team, namely, to develop tools and create a foundational understanding of the phenomena that control the thermodynamics and kinetics of hydrogen sorption reactions in existing and emerging hydrogen storage materials. This is fully consistent with the objectives outlined in the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan (MYRDDP).
- As a key HyMARC goal is to provide foundational understanding of hydrogen behavior in certain hydrides and in porous materials, this project is highly relevant and has had a high impact on the success to date of HyMARC. If the project continues to be successful and multiscale models are proven to be valuable in showing the way to successful future storage materials development efforts, it will have been highly impactful to the MYRDDP.
- The project strongly supports research and development in hydrogen storage and advances knowledge.
- From a fundamental science perspective, the relevance is high. From a hydrogen storage perspective, the potential impact is low.
- The impact could be improved by aiming for additional experimental validation of models.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The proposed future work is logical and follows in a straightforward way from the current effort. Appropriate decision points and milestones have been identified. It will be important to continue to develop a clear understanding (and compelling narrative) about how effectively the results obtained on model systems will translate to more complex materials. A strong emphasis on enhanced understanding of kinetics and interfacial reactions is encouraged. Understanding the participation of selected additives on reaction rates will also be useful. Specifically, a closer examination of possible side reactions between TiF_3 and MgB_2 is needed. As suggested in the Program Annual Merit Review meeting, Mg might react preferentially with F, thereby defeating the desired additive effect. Likewise, a concerted effort by the entire HyMARC project team to experimentally validate the predictions derived from this project is strongly encouraged.
- The proposed future work follows logically from the progress to date. An area of concern is that the project is apparently understaffed by two postdocs, delaying progress in two areas that may affect the team's ability to keep the future work on schedule.
- Continued improvements to the models are following a logical progression. However, actually validating the models with experiments is missing from the future work. The most challenging aspect of this project, or any other modeling project (e.g., DFT, QMC, and classical molecular dynamics), is designing and performing experiments to validate the models.

Project strengths:

- This project is vital to the overall success of the HyMARC effort. The project is well coordinated, and the scope and depth of the theory/modeling work are most impressive. The PI and his coworkers are highly qualified to conduct the work, and they have formulated a coherent and highly effective work plan that is yielding important results in all areas relevant to understanding the critical processes in emerging hydrogen storage materials.
- The project is highly collaborative both within HyMARC and HySCORE and with the new seedling projects. The project has become more tightly focused and has done a good job in providing for logical justification of the materials it has chosen to explore to develop the appropriate computational models that address key salient features of hydrogen behavior in these complex materials systems. The project is strong and has made significant progress; the list of accomplishments is substantial.
- A high-caliber, well-experienced team is tackling a very difficult problem in identifying the fundamental science behind hydrogen storage materials.
- Collaboration is a project strength.

Project weaknesses:

- Although not a weakness, per se, the dominant concern is that the knowledge gained from the studies on model systems will not translate effectively to more complex materials. The need to explore model systems in order to provide a solid foundation for understanding processes operative in more complex materials is understood and supported. However, it remains a constant challenge for the entire HyMARC team to ensure that representative model systems are selected and that the appropriate questions that will lead to deeper understandings in complex materials are addressed. As currently configured, the project team seems to lack an individual with extensive solid-state chemistry expertise. As the project moves into studies of more complex systems involving multiple reaction pathways, phases, intermediates, etc., the insight provided by such an individual could greatly benefit the overall project.
- The primary weakness is the lack of model validation and the currently untranslatable results to the real world. This level of model development is a very time-consuming effort that often lags significantly behind experiment throughput; therefore, a well-thought-out plan on what material characterization data are required for the modelers and how the models are performed should be a high priority. The models so far have been focused on the end states (i.e., initial and final states of hydrogenation), but none have been focused on the intermediate partially hydrogenated states.
- In a collaboration with Sandia National Laboratories, the work on the role of additives is an important one, but as it currently stands, it may not be well posed. Studying TiX_3 species on model hydride or boride surfaces may not reflect chemical reality. Some work should be done to explore where the thermodynamics of $TiX_3/MgBH_x$ lie; the TiX and MgX bond strengths may be quite similar, indicating that there is a reactive channel that their current model is not accounting for. Similarly, it is not clear whether TiX_3 on MgB_2 is a chemically realistic endpoint of a promoted borohydride. Depending on the outcome of an analysis of the reactivity of TiX_3 in these systems, the team may wish to adjust the experimental approach as well as the computational starting points.
- The project needs to involve more people/institutions.

Recommendations for additions/deletions to project scope:

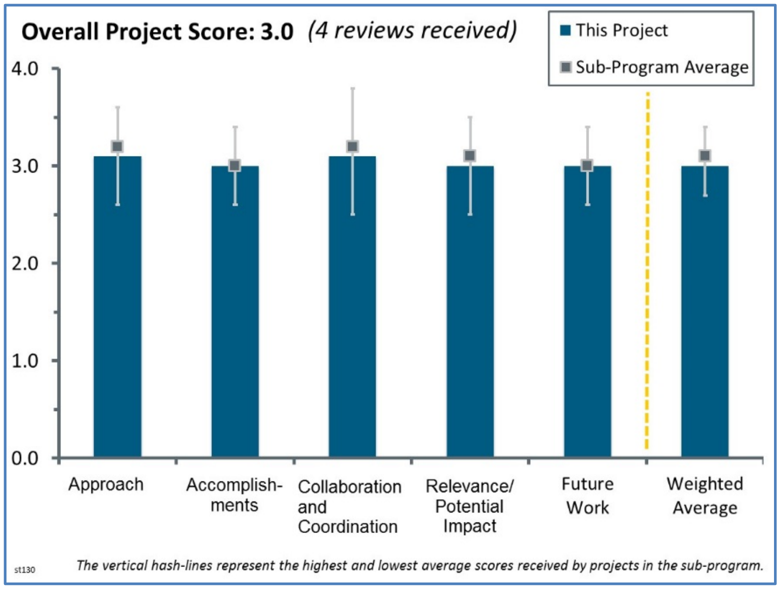
- The project is well scoped as it stands.
- It is recommended that the project add an individual with extensive solid-state chemistry expertise and experience to assist in guiding the project as it ventures into new territory involving more complex materials and reaction pathways. Discussions with DOE program management concerning this issue are encouraged.

The modeling team needs to sit down with the experimentalists to develop a materials characterization plan on how and what is to be measured to validate the models. With two years in, there should be significant and targeted characterization data available to the modelers; this is especially true given that experimentalists can collect data faster than the modelers can develop models. The modelers should start publishing materials characterization predictions as a function of hydrogenation that can be measured by the research community, e.g., XRD, infrared, kinetics, Raman, isotherms, heats of adsorption, phase diagrams, and binding energies. This approach offers a broader audience of researchers to validate or significantly improve the models. The ultimate test of a model is the time-based validation of an experiment. HyMARC should recognize that models are meant to be improved, and the first iteration of a model is never perfect; historically, data outlasts models.

Project #ST-130: Hydrogen Materials–Advanced Research Consortium (HyMARC) – Lawrence Berkeley National Laboratory's Technical Efforts

Jeffrey Urban; Lawrence Berkeley National Laboratory

Brief Summary of Project:



The Hydrogen Materials–Advanced Research Consortium (HyMARC) is providing community tools and foundational understanding of phenomena governing thermodynamics and kinetics to enable development of solid-phase hydrogen storage materials. Lawrence Berkeley National Laboratory (LBNL) will (1) focus on light materials and synthesis strategies with fine control of nanoscale dimensions to meet weight and volume requirements, (2) design interfaces with chemical specificity for control of hydrogen storage/sorption and selective transport, (3) explore storage concepts, (4) develop in situ/operando soft x-ray characterization capabilities in combination with first-principles simulations to extract details of functional materials and interfaces, and (5) refine chemical synthesis strategies based on atomic-/molecular-scale insight from characterization/theory.

Question 1: Approach to performing the work

This project was rated **3.1** for its approach.

- The HyMARC team has done a better job this year of ensuring that the participants in all the associated projects are aligned with respect to the overarching goals of HyMARC. In general, this is true for this LBNL project. With additional focus on providing the underpinning knowledge of what contributes to thermodynamics and kinetics barriers in hydrogen storage materials, this project could make real contributions to the model materials available for study and the computational aspects of the project. The characterization efforts using unique Advanced Light Source (ALS) capabilities are impressive and appear to be well posed to make a contribution to the understanding of hydrogen behavior in hydrogen storage materials. The project deserves kudos for dropping a few unpromising lines of research, as was recommended last year.
- The approach is strong and innovative, allowing for materials to be synthesized and characterized quickly and accurately. The completed computational modeling complements the work and allows discoveries to be made.
- Overall, the approach is very good. LBNL should concentrate on providing its excellent user facilities and computational tools to seedling projects.
- It is not quite clear what is meant by the following:
    - "Innovative synthetic routes to metal hydrides and hybrid nanoscale systems to reveal key phenomena governing hydrogen release/absorption and motivate new hydrogen storage materials"
    - "Developing new acid/base concepts to modify the enthalpy of hydrogen binding in sorbents"

  Also, in the light of the actual experiments described in the presentation, it is not quite clear how the following goal is going to be addressed: "Focus on light materials and synthesis strategies with fine control of nanoscale dimensions to meet weight and volume requirements via encapsulation, confinement." It is not clear how the control over stochastic chemical processes (slides 9 and 33–35) can be established.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.0** for its accomplishments and progress.

- There has been good progress made on studies of the encapsulation of magnesium borohydride and in demonstrating enhanced kinetics at relevant temperatures in Mg/Ni/reduced graphene oxide (rGO), and the characterization using in situ techniques, with the aid of computational modeling, hints about the role of partial oxidation of the metal surface. In collaboration with Sandia National Laboratories (SNL), computational modeling efforts have resulted in the ability to predict hydrogen sorption on metal–organic frameworks (MOFs) at high pressures and low temperatures. LBNL has collaborated well with HyMARC in developing pathways to access ALS capabilities and has provided fixtures for in situ studies at ALS.
- The team has made some great progress this year with regard to metal hydride encapsulation and MOF modeling. Most of the work is focused on Mg with the intent being to transition to Mg-borohydride, like the encapsulated rGO work.
- There are good progress and accomplishments overall. While good progress was made on calculating adsorbent properties, the presentation did not include the final selection of two improvement strategies to increase standard enthalpy, which was due March 31, 2017.
- Experimental results leave numerous questions unanswered. The nature of rGO coating is unclear. It is not clear why GO is used to modify water-sensitive Mg-borohydride when pristine oxygen-free graphene in an organic solvent would be more appropriate. These should be addressed soon.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.1** for its collaboration and coordination.

- Collaboration on gaining access to and performing HyMARC experiments at ALS has been excellent, as has been the collaboration between the computational efforts on hydrogen adsorption on MOFs and the experimental validation effort with SNL. It appears that the degree of interaction and collaboration with the graphene/rGO experimental effort is less well integrated with other organizations within HyMARC at this point. In the future, monitoring of the similar effort in encapsulation of hydrides within graphene at Argonne National Laboratory (ANL) (a new seedling) should provide an interesting collaboration.
- There is excellent collaboration with both HyMARC members and seedling projects.
- Collaboration within HyMARC appears to be strong. There seems to be a good network of researchers participating in this work.
- Collaborations are good and do not require further comments.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.0** for its relevance/potential impact.

- The increased air stability in the encapsulated hydrides is a great accomplishment. Work needs to be done to further control the air stability, but the work so far is well done. The in situ observance of hydride formation is also impressive, as well as the MOF model agreement with experimental data.
- The project is relevant to the DOE Hydrogen and Fuel Cells Program's goals and objectives.
- The potential impact of the information that can be ferreted out from studies of hydrogen storage materials using capabilities at ALS could be very high, but only time will tell whether the anticipated information can provide the foundational knowledge HyMARC seeks. The work on encapsulation of hydrides in various graphenes may be impactful if methods are found to control particle size, particle spacing/loading, etc. such that it provides for a useful platform to inform computational modeling efforts in examining nanoscale issues on kinetics and thermodynamics of hydrogen release and uptake. The work on computational modeling of hydrogen absorption in MOFs is impactful in providing an experimentally validated computational model that enables predictions of MOF isotherms. Because there are many complementary

and competing projects in this specific area, the team will need to demonstrate that its approach is powerful and unique.
- There is good potential impact so far in the project, but this type of project and effort needs more time to make more of an impact and should be continued.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The proposed future work follows logically from the current status and includes increased collaboration with at least two new seedling projects. The future work in encapsulation includes size control of the included borohydride; it is too early to tell whether the ANL seedling will come at this from a different strategy, but if so, this activity represents a risk mitigation strategy to get the computational modeling effort a size-controlled model material platform. The future work portion of the presentation could have benefitted from more description of how each model system proposed (Al nanoparticles, $LiAlH_4$, $NaAlH_4$, etc.) fits into the HyMARC scheme and priorities.
- The proposed future work will continue the great progress that is being made. It is encouraging to see that other hydrides will be investigated with the same tools and methods as the Mg-based hydrides. The results of the seedling efforts will be interesting to see.
- A move from the previous year to more complex materials, such as Mg to $MgBH_4$, is promising.
- The team may want to include an effort that can address what the nature of rGO coating is and how hydrogen diffuses through it. It should also address where pristine oxygen-free graphene would offer benefits compared to rGO.

Project strengths:

- The project includes supporting work at the ALS, which allows HyMARC users the opportunity to exercise this unique capability and explore its general usefulness in characterizing the structures and compositions of light element storage materials in situ. If the encapsulation work can lead to size-controlled nanoparticles of specific metal hydrides of interest to the HyMARC computational modeling effort, this would represent a significant strength and the basis of a powerful collaboration.
- The project involves great experimental techniques and processes that allow for new observations to be made. This is a great example to set for HyMARC and the other laboratories working with the team.
- The project strength lies in LBNL's excellent user facilities/capabilities and computational skills.
- Collaborations, which are very good, are a project strength.

Project weaknesses:

- The diversity and number of ongoing efforts is a project weakness, but this is common with large and complex projects and should improve with time and the advent of more seedling projects.
- The project needs to perform more characterization and analytical work on the Al-based hydride so that it can be compared to the current Mg work.
- The encapsulation effort did not appear to be laser-focused on providing an optimal model material platform for HyMARC collaborations, and it could benefit from better integrating with the HyMARC computational team's needs.
- It is not quite clear what is meant by the following:
    - "Innovative synthetic routes to metal hydrides and hybrid nanoscale systems to reveal key phenomena governing hydrogen release/absorption and motivate new hydrogen storage materials"
    - "Developing new acid/base concepts to modify the enthalpy of hydrogen binding in sorbents"

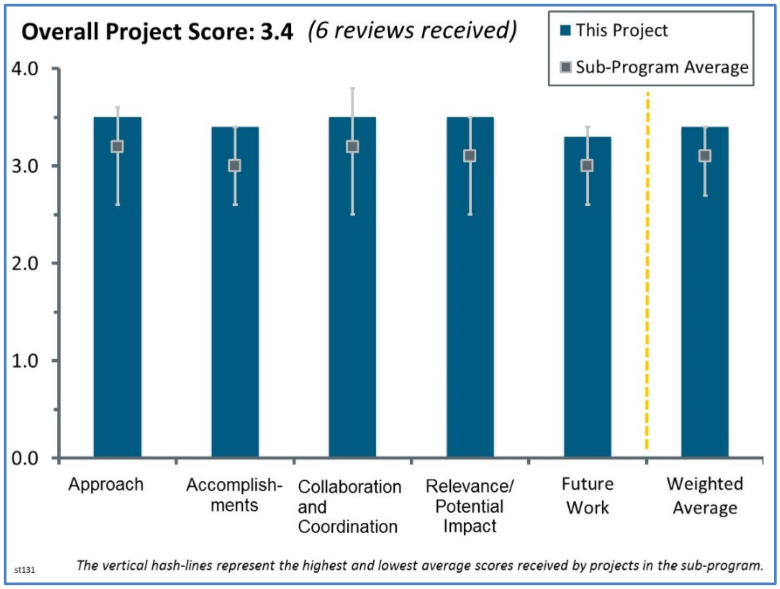
  Also, in the light of the actual experiments described in the presentation, it is not quite clear how the following goal is going to be addressed: "Focus on light materials and synthesis strategies with fine control of nanoscale dimensions to meet weight and volume requirements via encapsulation, confinement." It is not clear how the control over stochastic chemical processes (slides 9 and 33–35) can be established. Experimental results leave important questions unaddressed. It is not clear what the nature of rGO coating is or why GO is used to modify water-sensitive Mg-borohydride when pristine oxygen-free graphene in an organic solvent would be a more appropriate option.

Recommendations for additions/deletions to project scope:

- The scope is more focused than it was last year and is fine as it stands now.
- The project should perform similar encapsulation work and analysis to other metal hydrides to better understand the phenomena involved.
- The project should continue to investigate more complex metal hydrides.

Project #ST-131: Hydrogen Storage Characterization and Optimization Research Effort (HySCORE) – National Renewable Energy Laboratory's Technical Efforts

Thomas Gennett; National Renewable Energy Laboratory



Brief Summary of Project:

This project represents a collaboration between national laboratories to investigate the properties of promising new hydrogen storage materials, and works in coordination with the Hydrogen Materials–Advanced Research Consortium (HyMARC) core team. The National Renewable Energy Laboratory (NREL) leads the collaboration, which includes Lawrence Berkeley National Laboratory (LBNL), Pacific Northwest National Laboratory (PNNL), and the National Institute of Standards and Technology (NIST). The objectives are to (1) develop new characterization capabilities such as nuclear magnetic resonance (NMR) spectroscopy, diffuse reflectance Fourier-transform infrared spectroscopy (DRIFTS), calorimetry, diffraction, and scattering; and (2) validate performance claims and theories critical to the design of new hydrogen storage materials.

Question 1: Approach to performing the work

This project was rated **3.5** for its approach.

- This Hydrogen Storage Characterization and Optimization Research Effort (HySCORE) project (ST-131) actually has two major components: (1) NREL coordination of sophisticated diagnostic capabilities at NREL, LBNL, PNNL, and NIST to assess candidate hydrogen storage materials from the HyMARC and independent Fuel Cell Technologies Office (FCTO) projects and (2) NREL in-house activities for volumetric capacity determination of adsorbents, hydrogen-pressure-dependent thermal conductivity (TC) measurements of sorbents, and development of a reliable variable-temperature (i.e., ~ 50 K to 350 K) volumetric pressure–composition–temperature (PCT) system. More detailed descriptions of the second category tasks are thoroughly covered in Hydrogen and Fuel Cells Program (the Program) Annual Merit Review presentation ST-014 and will not be explicitly evaluated in this review. Although HySCORE is a multiple-laboratory project, the ST-131 presentation focused on the specific capabilities and activities for NREL, which were mainly to validate hydrogen sorbent properties and storage mechanisms. Hence, NREL, in leading HySCORE, is providing a valuable service to the fuel cell technology community.
- The broad purpose of HySCORE is met by this team. The approach is to tackle characterization related to sorbent materials by offering a broad range of tools, some of which are unique, while also systematically attacking quality control in measurement science. Since its inception, the project has expanded existing capabilities, including TC measurement and PCT analysis up to 200 bar of hydrogen over pressure; interacted with the seedling projects; and performed round-robin tests to ensure reliability of measurements across the hydrogen storage research area. Several of the HyMARC projects, in their presentations, mentioned the need for 200 bar of hydrogen overpressure.
- The approach is logically broken down along lines of materials and techniques. There is little if any duplication of effort. The project contributes critical diagnostic capabilities to the development of storage materials and provides synthetic, theoretical, and characterization capabilities.
- It is a well-designed project that is tightly integrated with the other HySCORE partners.
- The approach, especially developing core capacities with PCT and TC, is very good.

- The primary HySCORE effort appears to have been expanded beyond last year's "relevance" to include the doubling of hydrogen storage energy density from 25 to 50 g/L. The main concern in this regard is that, in addition to the core characterization and validation efforts that were presumably part of the original HySCORE mandate, this may represent a conflict of interest insofar as a materials development effort is not subject to the same peer review process as other projects funded through the FCTO. The attempt at validating theoretical models, especially in regard to multiple hydrogens per metal site, may be of value, but it appears that the modeling effort is based on metal containing catecholates. It has never been clear to what extent the binding enthalpies might be altered when these structures are contained within a backbone structure. These modeling efforts should also take into account the extent to which Mg or Ca might be hydrogenated and/or oxygenated, as opposed to accommodating the molecule via adsorption. The 15 kJ potentials can be relatively high, and at some point, if the technology gets advanced, safety may be an issue. The issue of multiple hydrogens per metal appears to result from a geometric constraint. Even if such an accommodating geometry were possible, it would seem that the rest of the non-metal structure would simply accommodate hydrogen at lower enthalpies, similar to generic carbons, unless the material is such that uniform charge transfer takes place throughout the functionalized structure.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.4** for its accomplishments and progress.

- One of the most noteworthy accomplishments of this work has been the initiation of a round-robin measurement activity that removed 400% spread in volumetric adsorption data among 12–15 laboratories. The measurement spread is now at 5%. These best practices in measurement will be disseminated to the community of researchers who undertake similar measurements. This research has made major contributions in other ways that inform hydrogen storage researchers on best practices (or better practices) in measurement. These other accomplishments include the following:
  - Proving that sorption temperatures could be tuned based on a metal site with a desorption temperature of around 150 K (which is relatively high)
  - Establishing that x-ray photoelectron spectroscopy (XPS) must be used judiciously, because prompt gamma-ray activation analysis (PGAA) led by the NIST group in the team shows deep spectra and showed 2% B doping instead of the 5% B doping reported by XPS
  - Suggesting that 77 K and room temperature temperature-programmed desorption (TPD) data do not tell the whole story and recommending the examination of temperatures where desorption is optimized
- The inter-laboratory round-robin study of hydrogen adsorption with feedback to contributors is a valuable exercise that should improve reproducibility and consistency of reported isotherms. A state-of-the-art theory to predict binding of multiple hydrogens to a metal–organic framework (MOF) metal site is essential for establishing whether this is feasible, especially given prior work predicting very large numbers (up to eight) of hydrogen molecules binding in Kubas compounds. Oxocarbon materials may represent a new strategy for sorbents. The same is true of the derivatized carbon nanotube. The shift of the desorption temperature for the polyether ether ketone (PEEK)–catechol–metal sorbent is remarkable. The material part is heavily weighted toward sorbents.
- Over the past year, the HySCORE partners have made considerable progress on joint work with several HyMARC members by providing complementary techniques for diverse materials ranging from borohydrides to different classes of adsorbents. These efforts have produced new explanations and insights into the hydrogen storage and release processes. NREL has experienced some delays with development of the TC apparatus and the implementation of its variable-temperature PCT volumetric system. However, both are expected to become fully operational within the next few months.
- The effort behind the inter-laboratory measurement studies is of value, and the effort expended by the laboratory in ensuring that the measured data are correctly analyzed is of value to the community. The variable-temperature effort will be important in understanding aspects of the temperature dependence of adsorption enthalpies. The PEEK–catechol data are intriguing. Given the size of the catechol, it is not clear that the pore dimensions of the pyrolyzed PEEK can accommodate the catechol. Perhaps there is a possibility that the catechol functionalization has taken place on the surface of the PEEK and not within the pores of this material. The lack of a low-temperature hydrogen signal in the red trace of slide 12 makes it

questionable whether complete pore blocking has occurred. The calcium oxalate (CaC_2O_4) data illustrate an odd sieving effect. Given the "ultra-microporous" nature of this material, the higher gas kinetic energy appears to be necessary to overcome the small pore dimensions. These are effects of interest pedagogically, but perhaps not for FCTO.

- The work on volumetric best practices and round-robin testing is extremely valuable. The description of new materials (and characterization thereof) was difficult to follow.
- There is good progress on developing characterization tools. Progress on experimental efforts to meet DOE targets was not as promising.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.5** for its collaboration and coordination.

- Some very productive joint studies were achieved from the HySCORE partners with HyMARC collaborators during the past year. A number of mutually beneficial joint efforts are still underway between NREL and its partners on some specific materials such as the MOFs and the metal–catecholate sorbents. NREL leads efforts to define and implement improved protocols on measuring and reporting the hydrogen storage parameters for various classes of materials.
- There is excellent collaboration with both HyMARC and HySCORE.
- The team has been relied upon by HyMARC seedling project partners for accessing unique measurement capabilities, including high-pressure TPD, TC, and PGAA for concentration measurements. Because of the central location of key measurement tools within this NREL team, the characterization of highly relevant sorbent materials systems and the coordination of round-robin measurements by this team are excellent services to the research community. Collaboration with other HySCORE groups is a bit less developed. Because this team works on the experimental and characterization side of the spectrum, it is likely that collaborations will develop naturally with the HyMARC team at LLNL, which leads in computational modeling.
- The collaborations are an inherent part of the HySCORE structure and appear to work well, at least as far as intra-HySCORE collaborations. It appears that the University of Wyoming effort is the only collaboration that was noted, although others are presumably happening with NIST and PNNL.
- Collaborations both within HySCORE and with HyMARC are occurring and appear to be meaningful. It is somewhat unclear how coordinated these are, but they appear to be flowing naturally from the partners' mutual interest and complementary scientific capabilities. Consequently, it does not seem necessary for them to be highly coordinated by the HySCORE leadership. Collaborations with HyMARC should be expanded, particularly in the area of materials development. Because HyMARC is charged with overcoming scientific barriers to materials discovery, the interesting new results for sorbents should be shared with HyMARC so that these can be evaluated in a more general way. For example, the "ultra-microporous" CaC_2O_4 should be considered in the context of both modeling by HyMARC and synthetic method development.
- NREL is an important resource and collaborator for many other hydrogen researchers.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.5** for its relevance/potential impact.

- This project is directly in line with supporting and advancing the Program. Because of collaborative efforts such as this one, years of manpower in measurement are more reliable, and a broad range of scientists has access to specialized tools for sample measurement. This particular HySCORE group is highly regarded for its contribution to the field.
- The project is focused on high-impact problems, such as the binding of multiple hydrogens to sorbent metal sites, the need for highly accurate gas sorption data, and understanding measurement errors and lack of reproducibility. Capabilities being developed will provide resources needed to advance the discovery and development of storage materials. New sorbent materials, such as the PEEK–catechol materials, are

revealing some surprising results that may lead to some completely new strategies for storage. This will no doubt have a substantial impact on the field if the results hold up and further investigations are performed to validate the results.
- Optimistically, the combined efforts of the collaborating NREL and HyMARC teams will lead to more significant characterization, and better validated results will be achieved through more cooperative in situ measurements with neutron scattering, NMR, and DRIFTS studies that complement enhanced PCT determinations of hydrogen storage capacities. Such information should provide critical insights into the various theoretical efforts on identifying and verifying reliable mechanisms for promising hydrogen storage materials.
- The analytical capabilities of HySCORE are critical. The degree of interaction with outside investigators is not so clear and, presumably, subject to non-disclosure agreements, so gauging the full extent of the interactions/impact on materials developments outside of HySCORE is difficult to assess.
- The benchmarking and best-practices work is highly impactful. A better/clearer description of the new materials work would aid in assessing the impact of this portion of the effort.
- There is good progress on adsorbent characterization capabilities and supporting other members to better understand and hopefully be able to predict the hydrogen interactions with materials, but progress in meeting DOE targets is challenging, and the targets should be revised by DOE.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- HySCORE has carefully described barriers and challenges and has put forth a plan to tackle those. The future plans seem to be made with consideration of the most promising platform (i.e., broad conceptual base) technologies within the sorbent hydrogen storage materials discipline. The team plans to examine metal site catechol with PEEK carbon absorbent. Broadly, findings related to measurement and materials developments for these particular catechol–PEEK structures could potentially extend to other metal sites on organic sorbent material systems. Other plans include the study of promising sorbent systems that (1) combine N-dopants onto nanocarbon materials and (2) are boron–carbon (BC_x) seeded materials. The team should continue working to find new platform technologies as well as the most promising material systems. The team should also consider developing go/no-go metrics for the decision on which materials systems are selected for study in future years. This idea is slightly different from a go/no-go decision on a material system itself in that a particular gravimetric capacity, volumetric capacity, temperature, etc. would not be the focus. Instead, a go/no-go metric stated by HySCORE would depend on whether the material system represents a material type or a fundamental phenomenon, or answers a particular scientific question (i.e., a platform system). It seems that this is already incorporated into the materials selection process. However, explicitly stating the features of the system and the other types of similar systems that could be affected by the study of it would be useful.
- The proposed future work is logically connected to the accomplishments thus far. Some of the materials accomplishments are pointing to new strategies for sorbents. A plan should be developed with HyMARC to determine how best to move forward with these discoveries.
- The future work will be especially useful if NMR, neutron scattering, and infrared and Raman spectroscopies could be simultaneously utilized to substantiate whether conflicting empirical or model interpretations could be either verified or dismissed for at least one promising system. Greater emphasis on obtaining new candidate materials from HyMARC and its seedling projects should be made, and less effort should be devoted to those systems with hydrogen capacities less than 2 wt.%, even though they could potentially serve as models.
- Future work appears reasonable. More support for current and upcoming seedling projects is encouraged.
- The BC_x work has had a long run, and it is still not clear that the materials (which presumably need to be synthesized as metastable materials in order to achieve high solubility limits) will yield adsorbents of interest. The same argument might be made for the N-rich materials.

Project strengths:

- Project strengths include the following:

- Outstanding scientific team
- Excellent capabilities
- Strong emphasis on problems that matter
- Effective leadership that is keeping things focused

- Results gained by HySCORE (focused on characterization of sorbent materials) far exceeds what could have been achieved by a single laboratory or small group project. Achieving the objectives to (1) advance instrumentation development and (2) conduct round-robin types of experiments in order to make the best tools and measurements available to hydrogen storage researchers necessitates a team effort of this scale.
- The NREL staff has excellent expertise in characterizing and validating the hydrogen storage capacities for diverse classes of materials. HySCORE members have published a considerable number of journal articles and given a number of presentations. The level of cooperation within HySCORE and with the HyMARC members has increased during the past year.
- The highly collaborative nature of the project is a strength; the benchmarking and best-practices work will have a global impact.
- The analytical capabilities are clearly the strength of HySCORE.
- The development of core capabilities in the area of adsorbents is a project strength.

Project weaknesses:

- As clearly shown in the figure on slide 32, there are no viable sorbents with properties that fit within the desired target box from the former Hydrogen Storage Engineering Center of Excellence. Hence, there is little chance that more in-depth characterization will identify a "golden" candidate that can satisfy these requirements. While a better understanding of currently proposed (but still inadequate) materials is desirable, this does not necessarily translate into making breakthrough discoveries. There is a heavy emphasis on sorbents, with only limited work on hydrides. In part, this reflects the historical development of the research by the component groups. However, HyMARC could benefit from some of the capabilities, and it needs to leverage these to a greater extent. Communication of technical results with HyMARC could be improved. Although the objective of HySCORE is nominally to develop, test, and maintain core capabilities, the materials work (which is quite strong) seems decoupled from HyMARC, which supposedly is tasked with evaluating new storage material concepts and developing tools for the seedling projects to accelerate their work.
- New materials development and synthesis areas seem too broad and need to be narrowed down to a few best prospects soon to meet current DOE targets.
- The new materials work is of uncertain impact.

Recommendations for additions/deletions to project scope:

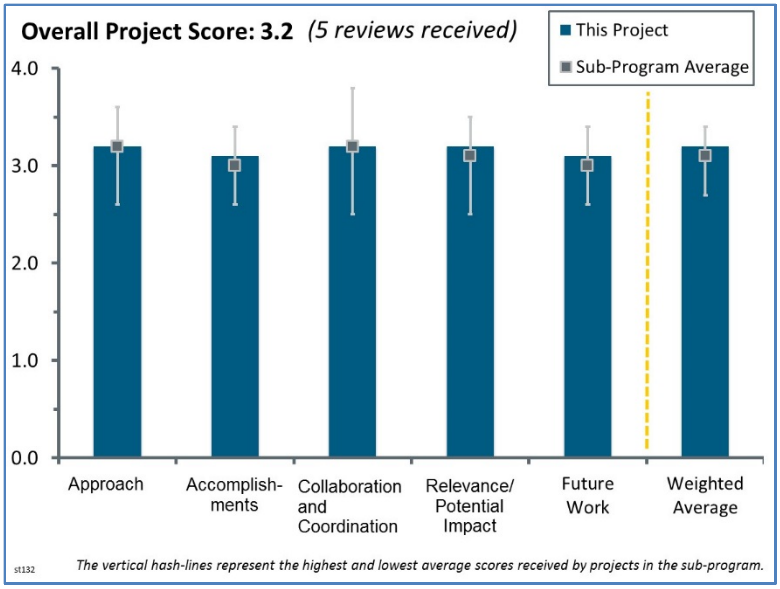
- The level of effort for both HySCORE as a whole and the NREL group is appropriate at this time. It is suggested that less effort be spent on lower-performance "model" sorbents in favor of focusing more attention on conducting complementary capacity and NMR/neutron characterization studies on more favorable candidates from HyMARC and seedling projects.
- The project should narrow down new materials synthesis to fewer higher-potential prospects.

Project #ST-132: Hydrogen Storage Characterization and Optimization Research Effort (HySCORE) – Pacific Northwest National Laboratory's Technical Efforts

Tom Autrey; Pacific Northwest National Laboratory

Brief Summary of Project:

This project is part of a collaboration between national laboratories to develop new characterization capabilities to investigate the properties of promising new hydrogen storage materials, and works in coordination with the Hydrogen Materials–Advanced Research Consortium (HyMARC) core team. Pacific Northwest National Laboratory (PNNL) will focus on nuclear magnetic resonance (NMR) spectroscopy and calorimetry to complement parallel efforts at other national laboratories. The project will also work toward validating claims and theories critical to the design of new hydrogen storage materials that show promise.



Question 1: Approach to performing the work

This project was rated **3.2** for its approach.

- The approach of utilizing theory to guide and interpret results and experiment to validate theory is powerful when well integrated. This project uses the chemical intuition developed over many years of experience in the area of reacting hydrogen storage materials systems to assist a wide variety of projects within the Hydrogen Storage sub-program. The excellent NMR capabilities that can access realistic temperatures and pressures to extract valuable information on thermodynamics, kinetics, and mechanisms in a variety of complex storage materials is perhaps unique to this project.
- A broadly based research and development (R&D) approach has been adopted. The overall approach builds upon the established expertise and experience at PNNL. The effort incorporates aspects of theory to guide experiments and interpret experimental results and uses experimental work (mainly characterization) to validate theory and to elucidate the details of complex reaction pathways and mechanisms. The approach is sensible, especially insofar as it provides effective support for the complementary efforts being conducted in the companion HyMARC effort (both core and seedling activities). The project also incorporates work on assessing the thermodynamic properties and kinetic processes in promising liquid organic hydrogen carriers (LOHCs)—notably triazine. For the most part, the approach focuses on the important barriers and obstacles that limit the development of hydrogen storage material having hydrogen sorption characteristics that meet U.S. Department of Energy goals.
- The approach makes available the PNNL Environmental Molecular Sciences Laboratory's NMR capabilities needed for the investigations of metal hydrides. The focus on thermodynamics of intermediates is much needed, as these may control the uptake and release kinetics of some metal hydrides. Calorimetry capability is also a valuable tool needed for monitoring phase changes in storage materials and for providing thermodynamic data needed to validate models.
- The approach seems reasonable—providing support for teams developing new materials through unique NMR and calorimetry capabilities. There is good connection/feedback between experiment and theory.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.1** for its accomplishments and progress.

- Good progress has been made on both LOHCs and metal hydrides. Useful recommendations to guide theory and experiments were made. New data concerning thermodynamics of $Mg(BH_4)_2$ intermediates is an important first step to understanding decomposition of this hydride. Experiments using tetrahydro furan (THF) to form adducts (via collaboration with C. Jensen) reveals a discrepancy between theory and experiment concerning thermodynamics of intermediates. Calorimetry experiments validate theory, showing THF binds to Mg more strongly than $Mg(BH_4)_2$ (via collaboration with the National Renewable Energy Laboratory [NREL]). NMR has been shown to be a valuable tool for following formation of intermediates that are amorphous. The team is working with HyMARC investigators to support the development of a phase field model of interfaces.
- All milestones are complete or on track. There is nice progress on liquid carriers and use of solvents to destabilize $Mg(BH_4)_2$. The search for additives or solvates that act to change reaction pathways in a favorable way makes sense. The in situ NMR is useful for tracking intermediates.
- Solid progress has been achieved during this reporting period. The results obtained using in situ NMR to monitor reaction intermediates and products during dehydrogenation of $Mg(BH_4)_2$*THF are helping to characterize the role of additives/adducts on improving reaction rates and selectivity in complex hydrides. The identification of an evolving $B_{10}H_{10}$ product is especially useful (an extension of work reported in 2016). It will clearly be important to understand more fully how the reaction rate varies with THF concentration (especially sub-stoichiometric amounts). This should provide useful insight to understanding the mechanism responsible for the rate enhancement (decreased temperature for dehydrogenation) and changes in product selectivity. The work on the triazine LOHC materials was confusing and, to a certain extent, misleading. At the 2016 DOE Hydrogen and Fuel Cells Program (the Program) Annual Merit Review meeting, the project team concluded, "Triazine not sufficiently stable; future NMR and calorimetry experiments will focus on diazines." However, the project continued to focus on triazine energetics (mainly differences in isomers) during this reporting period. If triazine had been discounted in 2016, it is unclear why so much additional effort was expended on that system in 2017. Some clarification is needed. Overall, the LOHC effort is not particularly compelling (unless the reviewer is missing something). A more definitive statement concerning the motivation and overall direction for the work would be helpful.
- The presenter reported a lot of interesting basic science. However, it does not seem likely that organic storage will produce a material with high hydrogen storage capacity and favorable absorption–desorption performance. The effort related to $Mg(BH_4)_2$ is mainly concerned with the basic polyborane chemistry. It might be useful to initially focus on actual polyboranes and then move to their magnesium salts, which are more complex systems with much more diverse chemistry. The stepwise formation and the decomposition of solvated Mg-borohydride/polyborane derivatives does not add much to the existing knowledge about the behavior of crystalohydrates and other solvent-containing salts. The stability of $Mg(BH_4)_2$–THF complexes is an interesting observation. However, it is hard to see how THF may promote the formation of $Mg(BH_4)_2$ from MgB_2, which does not seem to dissolve in THF or to form THF-solvates.
- While the driving force to finish tasks is strong, the work on LOHCs presented did not include much new information beyond what was learned last year, and perhaps more emphasis on the $Mg(BH_4)_2$ system would have provided more useful information via the HyMARC collaboration with the Hydrogen Storage Characterization and Optimization Research Effort (HySCORE), as there is no LOHC work in HyMARC. The work on thermodynamics and prediction of NMR parameters for solvates of $Mg(BH_4)_2$ indicated a good deal of progress and has direct impact on the new HyMARC seedling project at the University of Hawaii. The role of solvates in controlling kinetics and reaction pathways is very interesting and useful to consider in the context of HyMARC's interests in interfacial phenomena in hydrogen mobility.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.2** for its collaboration and coordination.

- There is excellent collaboration across HySCORE and HyMARC, including new seedling projects. Areas of collaboration are broad, including NMR spectroscopy studies of reacting systems, computational modeling of thermodynamics, and NMR chemical shifts, all of which are important to a rather broad cross-section of researchers in the hydrogen storage community.
- The project team is fully integrated with both HySCORE and HyMARC activities (including seedling projects). Collaborations that rely on the extensive NMR experience, expertise, and facilities at PNNL are especially noteworthy. A slide that summarizes the collaborations (who and what) would have been helpful.
- There are strong collaborations with HyMARC and HySCORE partners on focused topics. There is continuing collaboration with the University of Hawaii and the associated seedling project. There is a new collaboration on electrolyte-assisted reactions with the Liox seedling project. A collaboration with the University of Missouri–St. Louis (UMSL) seedling project should be started to provide additional information to UMSL regarding structure and chemistry of N-doped carbons.
- Collaborations are excellent and do not require any additional comments.
- There is a long list of collaborators/teams that could be supported by these resources, but it is not clear how many were engaged in 2016/2017. With the exception of the work done with the University of Hawaii, it appears that most of the work was done within PNNL or HySCORE team. A broader, more substantial list of active collaborations would be expected for HySCORE team members.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.2** for its relevance/potential impact.

- The PNNL project is vital to the overall success of the HySCORE activity. In particular, the unique experimental capabilities (especially high-pressure, temperature-variable in situ NMR, and variable-pressure reaction calorimetry) are powerful tools that are being employed effectively in both the HySCORE and HyMARC work. Likewise, the solid-state chemistry expertise at PNNL is providing useful new insight into important chemical problems being explored in both projects. The PNNL project is well aligned with the Program mandates for hydrogen storage materials R&D.
- PNNL provides access to unique high-pressure NMR capabilities that are needed by the seedling projects and HyMARC to carry out their missions. Variable-pressure reaction calorimetry is another important capability available at PNNL that is not available at other laboratories working on hydrogen storage projects. The computational effort to predict chemical kinetics and thermodynamics of borohydride intermediates is highly relevant, focusing on a class of materials that could be practical if kinetic limitations are understood and resolved. Substantive interactions with some seedling projects are accelerating materials discovery.
- There is an impressive list of capabilities to support materials development, but it seems to be underutilized. The 2016/2017 focus was on relevant systems, liquid carriers, and $Mg(BH_4)_2$. An in situ NMR could be really useful; the ability to track noncrystalline intermediates may be a key piece to the puzzle.
- The work on LOHC has reduced relevance at this time, but the project team's work on the $Mg(BH_4)_2$ system with and without solvates is highly impactful to the HyMARC effort in providing supporting data and observations that contribute to a greater foundational understanding of this important model storage material. This project's work also directly contributes to a new HyMARC seedling effort at the University of Hawaii. Interaction with the HyMARC computational modeling effort brings some chemical science expertise to a largely materials-science-dominated approach. This should allow the team to more rapidly develop computational approaches that get at both chemical and physical behavior of hydrogen in storage materials.
- HySCORE is relevant to the Program's goals.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- The future work follows logically from the activities currently being conducted. The future work on the effects of solvates on $Mg(BH_4)_2$ sorption reaction kinetics is especially important. It provides (at least in part) a basis for understanding how adducts and other additives can alter reaction pathways and kinetics in complex hydride systems. The proposed work on physisorption and hydrogen interactions with metal centers and B/N-doped carbons (with NREL, the National Institute of Standards, and Lawrence Berkeley National Laboratory) is intriguing. However, it will be important to compare and efficiently integrate that work with all of the other efforts underway for HySCORE and HyMARC (including seedling projects) devoted to enhancement of hydrogen physisorption by addition of reactive centers to solid-state sorption templates. The proposed PNNL contribution to the HyMARC effort on modeling the "soup" is not stated in sufficient detail; additional information concerning the PNNL work is needed. In addition, a more definitive and compelling statement about the impact of the future LOHC materials work should be provided.
- This project's future plans are very appropriate to approaching HySCORE and HyMARC goals. The proposed future plans include employing unique low-temperature, and perhaps moderate-pressure, NMR techniques to obtain information on hydrogen interactions with so-called doped and undoped adsorbate surfaces or "naked" metal ions, e.g., in metal–organic frameworks. These techniques are a unique contribution to the field and will likely lead to impactful results when incorporated into, or used to validate, computational models.
- Future work plans continue the experiments and theory already underway through collaborations with other HySCORE partners as well as with the seedling projects and HyMARC. The logical next steps are planned for the coming 12 months. The work on N-doped carbons has strong synergies with the UMSL seedling project. Although UMSL is focused on stabilizing metal hydrides within the pores, the need to understand the structure and chemistry of the N dopants is the same for both physisorption and hydride applications. At a minimum, PNNL should be sharing data with UMSL, and preferably, starting a collaboration for some joint experiments. The proposed work to validate the "soup" model is very important for both specific hydrides and in general for understanding any storage materials involving phase changes or reactions at buried interfaces.
- Future work is described in much detail. However, it is designed to address very fundamental questions such as chemical behavior of magnesium polyboranes, hydrogen interactions with metal centers, or B-N in carbon(s). Although this is very useful in the long run, the proposed effort(s) may offer few short-term benefits.
- It is not clear what is planned with the LOHCs. It was indicated that a success will be using calorimetry to optimize catalysis (kinetics), but it is not clear where this is in the future work slides. There appear to be plans to support a variety of different projects this year. More support of activities outside of PNNL and HySCORE is strongly encouraged. For work on solvates, the project should consider estimating hydrogen capacities based on the minimum solvent (or ligand) required to tweak the reaction pathways. Ideally, the solvent acts as a shuttle (not a final stabilizing agent) and therefore can be useful in small quantities (<1 mole equivalent).

Project strengths:

- The project provides vital support to both the HySCORE and HyMARC activities. The contributions derived from the use of the unique PNNL diagnostic capabilities are especially significant. The PNNL team has broad expertise and experience in solid-state chemistry and advanced characterization methods. The team is well coordinated, and strong/beneficial collaborations with related projects are evident.
- The project has an outstanding scientific team with important capabilities not available elsewhere in the Hydrogen Storage sub-program. It has a strong emphasis on high-impact problems.
- The project makes very good use of a quite powerful NMR capability resident at PNNL, and it uses that capability to form strong and appropriate collaborations with a variety of hydrogen storage projects within HyMARC and HySCORE. Coupling this capability with its chemical computational modeling capability lends strength to its technical contribution.

- Project strengths include the broad activity with nice balance between LOHCs, complex hydrides, and sorbents and a good connection between theory and experiment. Although current (active) collaborations are somewhat limited, this group is experienced and well connected. Collaborations this next year will likely increase as more projects get underway.
- The project team and the collaborations are very good.

Project weaknesses:

- This is not a major weakness, but perhaps the effort expended on finishing the LOHC work could have been more effectively spent in accelerating the $Mg(BH_4)_2$ and other computational work.
- HySCORE and HyMARC are complementary, and it may be a good idea to combine them into one larger organization. The research is drifting toward fundamental science with long-term benefits for general materials/inorganic chemistry. However, it is not clear whether its results could be translated into a practical hydrogen storage systems.
- Collaborations with other seedling projects with related work have not been established.
- The technical effort on the LOHC materials lacks a compelling and convincing motivation. Although work on triazine was apparently discontinued last year ("triazine not sufficiently stable, future NMR and calorimetry experiments will focus on diazines"), the triazine effort was resurrected during this reporting period. The overall impact of the work is ambiguous. The project team should provide a more persuasive case regarding future work on that class of materials. The specific contributions of PNNL to the HyMARC reactive interface phase field modeling ("soup") effort should be described in greater detail.
- Previous work seems to be primarily focused on new materials development—LOHCs and improving $Mg(BH_4)_2$ reaction pathways. Based on overview presentations from HyMARC and HySCORE, it seems that these organizations are supposed to support materials development activities at other institutions, not lead their own work. The level of effort dedicated to materials development here seems to be significant—the PNNL group is driving the work, not just providing characterization support. This is really a broader criticism of HySCORE (and HyMARC) in general; its scope/charter does not seem to be well defined. It is expected that HySCORE (and HyMARC) would be developing advanced tools and techniques, not developing new materials.

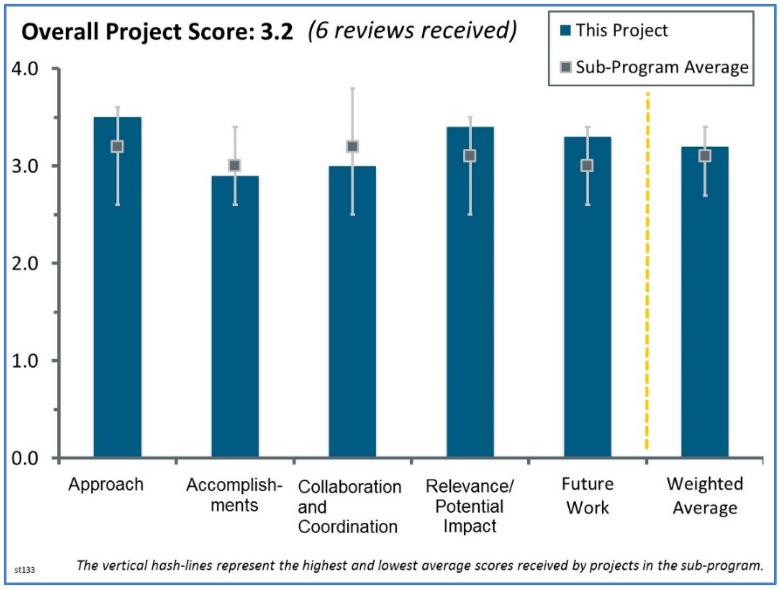
Recommendations for additions/deletions to project scope:

- The scope of the project is appropriate as it stands now.
- HySCORE needs to be better defined. Materials development seems to be showing nice progress, but it does not seem well aligned with HySCORE charter. The materials development part of this project may be better suited to a separate seedling effort (not under HySCORE).
- This recommendation is mainly for DOE. Numerous sub-projects within HySCORE, HyMARC (core and seedling), and independent projects are devoted to understanding whether functionalized templates can lead to enhanced physisorption of hydrogen (higher capacity and larger enthalpy). For example, PNNL is conducting work on understanding the role of metal centers and B/N substituted carbons on hydrogen sorption properties of physisorption frameworks. Although these multiple efforts are not necessarily duplicative, they are (often) similar, leading to a concern that this overall category of technical work is becoming increasingly defocused. It is recommended that careful thought be given to this issue, and steps be taken to clarify and definitively state the contributions of the different projects/sub-tasks to this technical area. This clarification would alleviate the confusion and provide a basis for consolidation of technical efforts where appropriate.

Project #ST-133: Hydrogen Storage Characterization and Optimization Research Effort (HySCORE) – Lawrence Berkeley National Laboratory's Technical Efforts

Jeffrey Long; Lawrence Berkeley National Laboratory

Brief Summary of Project:



This project is part of a collaboration between national laboratories to develop new characterization capabilities to investigate the properties of promising new hydrogen storage materials, and works in coordination with the Hydrogen Materials–Advanced Research Consortium (HyMARC) core team. Researchers will also validate new concepts for hydrogen storage mechanisms in adsorbents and provide accurate computational modeling for hydrogen adsorbed in porous materials. Specifically, Lawrence Berkeley National Laboratory (LBNL) is developing in situ infrared (IR) spectroscopy as a tool for characterizing emerging hydrogen storage materials as well as developing metal–organic framework (MOF) materials that will allow for more than one hydrogen molecule per open metal site that will increase hydrogen capacities for sorbent materials.

Question 1: Approach to performing the work

This project was rated **3.5** for its approach.

- Assuming that a MOF-based system is ultimately deemed to be a practical and useful medium for hydrogen storage (there is some concern/controversy about that), the approach that has been adopted by the LBNL group is sensible, and the proposed methods for multiple hydrogen binding are certainly intriguing. The project comprises a combination of first-rate experimental and computational/theory work to comprehensively explore candidate systems that may be capable of adsorbing up to four hydrogen molecules on a single metal cation in a functionalized MOF template. In addition, the development and application of high-pressure, in situ IR spectroscopy has been shown to be a powerful method to probe the characteristics of hydrogen binding on metal sites. The approach to developing MOF systems with improved hydrogen-binding properties is novel and builds upon earlier successes demonstrated in the project. However, the application of these techniques to studying hydrogen uptake in calcium oxalate seems to be a diversion. Unless a more persuasive case can be made for further development of calcium oxalate as a useful hydrogen storage medium, it is recommended that work by the LBNL group focus primarily on the MOF systems and catecholate-bound metal cations.
- MOFs are clearly one of the top candidates for successful sorbents. Binding of greater than one hydrogen per metal cation is a strategy that could enable the U.S. Department of Energy volumetric capacity target to be met. The synthetic approach looks feasible and consistent with what this team and others have learned so far. The use of protecting groups is clearly required to enable the reactive sites to remain free of solvents and other species in the pores.
- The innovative approach focuses on binding two to four hydrogen molecules to one metal cation site to achieve high storage capacity at ambient temperature. The use of in situ IR spectroscopy allows for accurate and fast measurements of total gas capacity over a wide range of temperature and pressure.
- The project aims to address important and highly relevant barriers.
- The general approach of this project is aligned with the efforts of the Hydrogen Storage Characterization and Optimization Research Effort (HySCORE) team, although the specific strategies could have been

focused on materials that maximize the benefit of the multiple hydrogens bound to a single metal site. The project did not seem to build on the momentum from last year and pursued other activities.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **2.9** for its accomplishments and progress.

- Excellent progress has been made since the last DOE Hydrogen Fuel Cells Program (the Program) Annual Merit Review. The technoeconomic analysis is very valuable, particularly because it helps put to rest the stereotype of MOFs as impractical because of cost. Good progress is being made toward creating a MOF with highly under-coordinated metal sites. If anyone can pull this off, it is this group. It is good to see that the high-pressure Fourier transform infrared spectroscopy (FTIR) instrument is finally assembled and being tested. The computational effort made progress in two areas: (1) calcium oxalate, which is possibly a new strategy for creating an effective sorbent material, and (2) binding of multiple hydrogens to metallated catecholates. The results in both cases are encouraging and support continued experimental efforts in these areas. It is good to see calculations addressing solvent effects, which are almost always ignored in modeling of gas sorption by MOFs.
- Following on the success achieved last year on the first demonstration of the binding of two hydrogen molecules on a single metal cation in the Mn_2 (2,5-disulfhydrylbenzene-1,4-dicarboxylate) MOF system, the work during this reporting period has been incremental, focusing on finding ways to increase the density of bound hydrogen molecules and developing more robust platforms for functionalization. Particularly noteworthy progress has been made in the computational/theory studies—i.e., solvent effects, addition of other metals (e.g., Sc^{3+}), and predicted capacities resulting from metal atom insertion. Likewise, the effort to bring the diffuse reflectance Fourier transform infrared spectroscopy (DRIFTS) instrument to full functionality should pay big dividends in the detailed characterization of emerging materials. Although it is understood that the calcium oxalate work supports other efforts within the HySCORE project, that effort seems to be an unneeded diversion from the principal goals of this project.
- The team installed the DRIFTS instrument and demonstrated that it was operating within the needed resolution. Good progress was made in computation to understand the solvent effects on hydrogen binding energy in catechols and calcium oxalate. The technoeconomic analysis of MOF production was a nice addition to the scope of the project that was not initially planned for in last year’s future work. The crystal density is used in this study for calculating usable capacity, ignoring packing effects in a tank. It is suggested that the principal investigator should clarify this point in future presentations.
- Experimental validation of multimolecule adsorption is key for assessing the validity of this approach. Some thought has been given to manufacturing, and more work needs to be performed to assess the potential technical impact of this effort.
- Assisting with the MOF technoeconomic analysis and de-protection of the Zr-based MOF, BOC-cat-UiO-68, were good accomplishments over the past year. Last year, this project made significant progress in identifying the phenomenon of multiple hydrogen molecules binding to an open metal site. This year, there seemed to be a notable lack of progress in this key area.
- Despite last year’s important report on binding two hydrogens per metal site, this year’s presentation made no mention of progress toward extending (or demonstrating) that approach on other MOFs. It is not clear whether any other systems were examined. On the computational side, the predictions of the thermodynamics of multiple hydrogen binding to Ca-catecholates and Mg-catecholates were largely repeats of last year’s presentation. The Mg-thio-catecholates were added this year, but this is a small addition (only four more calculations). Overall, the quantity of new results presented was well below expectations for an $800,000/year project.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- The collaboration of this project is apparent among the HySCORE effort. It was good that this project collaborated with other entities for the cost analysis.
- There are strong collaborations between the team partners.
- There are only a few strong, good collaborations internal to HySCORE, and none external to HySCORE. The internal collaborations are also limited in that most of the work is done at LBNL (theory by Martin Head-Gordon), with a little joint work with the National Renewable Energy Laboratory. The internal collaboration on theory is very strong. Jeff Long's collaboration with the National Institute of Standards and Technology is presumably ongoing, although this was not mentioned in the presentation. However, there is no mention of any collaborations with Pacific Northwest National Laboratory, the seedling projects, or HyMARC.
- Close collaborations with the HySCORE and HyMARC project teams are evident. However, clarification of how this project relates to the MOF effort within HyMARC and to what extent collaborations are underway would be helpful. In addition, a more complete description of the collaborative effort with Brandon Wood (HyMARC) would be useful. There seems to be considerable overlap between this project and the HyMARC effort—a clearly delineated description of the roles and responsibilities is needed.
- There is good collaboration with the HySCORE effort, but it could be expanded to groups outside of this sphere.
- The level of collaboration is appropriate.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.4** for its relevance/potential impact.

- The LBNL group is at the leading edge in the development of functionalized MOFs for hydrogen storage. Insofar as MOF work in general is deemed by DOE to be a promising pathway to addressing the goals/ objectives of the Program, this project is essential to meeting those needs.
- The work at LBNL is highly relevant to the mission and goals of the Office of Energy Efficiency and Renewable Energy/Fuel Cell Technologies Office (FCTO). Efforts are highly focused on key targets, and the strategies employed hold great promise to meeting unattained storage goals (volumetric capacity and operation at ambient temperature). The new high-pressure FTIR capability and the theoretical models are state of the art. If these can be extended to problems outside those that are the immediate focus of HySCORE, their impact could be great. Perhaps at this stage it is premature to expect a high extent of external use, particularly because the seedling projects were only recently funded.
- The project includes highly relevant objectives to advance the Hydrogen Storage sub-program goals. In particular, the impact of doubling the hydrogen storage volumetric density would be significant, as would increasing the adsorbent operating conditions to ambient temperatures.
- This is a highly relevant project. It aligns well with the Program goals.
- The project objectives are relevant to Program goals and objectives for system gravimetric and volumetric capacities.
- The work thus far is promising, but synthesis is key.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- The proposed future work follows directly from the success achieved last year on demonstrating multiple hydrogen binding on metal sites in functionalized MOFs. Attempts to metallate new structures (e.g., catechol MOFs) are fully consistent with the project goals. Likewise, the computational exploration of new MOF systems and new metal sites will be useful for guiding future experiments.

- Proposed future work, both in the synthetic and theory efforts, has its eyes on the prize and is consistent with the approach defined at the outset of the project.
- The proposed future work is well thought out and consistent with the project goals.
- The proposed future work seems appropriate for the remaining challenges and barriers, although there should be additional effort to identify an MOF with improved performance based on the multiple binding site mechanism.
- The future work is on track.

Project strengths:

- The project strengths include an outstanding scientific team with excellent capabilities, the strong emphasis on problems that matter, and cutting-edge synthetic and theory efforts; it is difficult to imagine any group that could address these problems more effectively.
- The LBNL project scientists are recognized experts in experimental and computational development of functionalized MOFs for hydrogen storage. The approach adopted in this project is novel and innovative, and the project builds strongly upon the demonstrated success achieved by this group in prior work. The project is well coordinated, and beneficial collaborations are in place. Solid work is being conducted to validate and employ a new IR spectrometer for materials characterization.
- The project strength is the technical depth and capability of the individuals involved with this effort. The project has an effective balance of computational and experimental activities.
- This is a capable team with a good track record of success. The project is well aligned with DOE goals.
- Modeling of potential multimolecule adsorbent sites with reasonable bonding energies for higher-temperature adsorption and release have been completed.

Project weaknesses:

- Experimental validation experiments are eagerly anticipated.
- This project has no clearly identifiable technical weaknesses. However, the immediate impact on other hydrogen storage projects supported by the FCTO is limited at this stage. Capabilities and tools developed are not being accessed outside of HySCORE. A plan for what to do next if the metalated-catecholate strategy fails is missing.
- There is an issue for both DOE and LBNL/HySCORE: in general, a hydrogen storage concept based on the use of a functionalized high-surface-area MOF that serves as host for metal centers that bind multiple (two or more) hydrogen molecules is not particularly compelling. The approach is encumbered by a notable gravimetric penalty (from the MOF), sensitivity to contaminants (bare metals are highly reactive), limited binding energy for molecular hydrogen (sufficient binding only at low temperatures), and serious questions concerning the efficacy of multiple hydrogen binding. A candid and comprehensive examination of this issue is needed.
- The project weakness is the lack of progression in demonstrating a material that can benefit from the multiple hydrogen molecules on a metal site. The project should have utilized the discovery from the last review to indicate a potential material improvement.
- There were limited accomplishments (poor progress, based on the presentation) in the previous year.

Recommendations for additions/deletions to project scope:

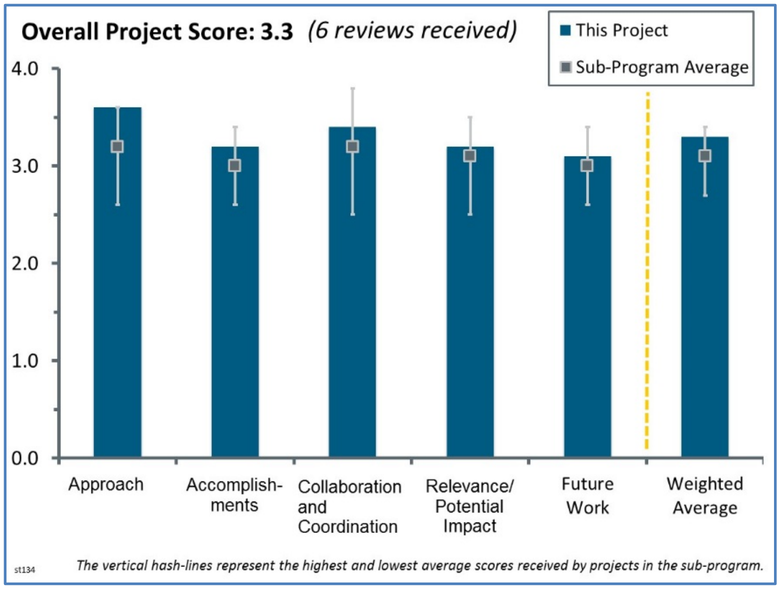
- Volumetric capacities will need to be closely examined to assess attainment of this critical goal.
- The project should focus back on synthesizing and advancing materials that can utilize the multiple binding on a metal site to demonstrate an improvement in material performance.
- The attention paid by the LBNL group to support the HySCORE effort on calcium oxalate is an unnecessary diversion. The focus should be keenly on exploring and improving hydrogen storage in functionalized MOFs. It is recommended that the calcium oxalate effort at LBNL be discontinued.

Project #ST-134: Investigation of Solid-State Hydrides for Autonomous Fuel Cell Vehicles

Joseph Teprovich; Savannah River National Laboratory

Brief Summary of Project:

This project, which is a collaboration between the U.S. Department of Energy and the U.S. Department of Defense (DOD), will develop a methodology that incorporates engineering modeling and analyses to efficiently screen, design, and select storage materials and material systems against cost and performance targets leading to an initial system design for an unmanned underwater vehicle (UUV) application. Project activities include screening of hydrogen storage systems against DOD targets and requirements, a detailed design of a hydrogen storage system for use in an integrated system design, and development of a preliminary design for an integrated UUV platform.



Question 1: Approach to performing the work

This project was rated **3.6** for its approach.

- The goal of this project is to extend UUV mission length for ocean floor mapping to 96 hours by replacing the auxiliary battery with an 11.3 kg AlH_3 bed for hydrogen supply, an H_2O_2 tank for oxygen supply, and a polymer electrolyte membrane fuel cell to convert the evolved H_2/O_2 to electric power. The H_2O_2 is converted to oxygen via a catalytic cracking process, which releases substantial waste heat that can be captured and transferred with a heat exchanger to the AlH_3 bed to release hydrogen on demand. This is an extremely well-conceived project. The entire system design is elegant, synergistic, and very convincing. The materials selected for this project are highly appropriate, and the methods of testing and evaluation (experiments with a model tank as well as numerical simulations) are rigorous and ensure a high probability of success. The team deserves kudos.
- AlH_3 as a hydrogen storage material for an unmanned aerial vehicle (UAV) is a perfect application of AlH_3 because of its high net usable hydrogen capacity and hydrogen quality.
- The project's excellent work moves prior work into alternative applications that reduce prior unknown risk to design and develop novel applications.
- The approach to this work is very thorough. Using the tried and true method from the Hydrogen Storage Engineering Center of Excellence (HSECoE) to design and develop a hydrogen storage system for a vehicle is smart. It will allow for previously developed methods to be put to the test and used.
- The approach appears to be sound, combining experiments to determine, e.g., hydrogen release in test reactors with design considerations and heat-flow modeling. The project is different from many others in that it is not addressing barriers to develop storage materials but is developing a storage system for a specific application outside the mainstream light-duty vehicle or portable power applications. In this respect, the design of the project is good.
- The stated approach calls for developing a methodology to efficiently screen, design, and select materials and systems for UUV applications.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.2** for its accomplishments and progress.

- The achievements to date are very impressive. The system design is extremely robust and synergistic. All of the calculations for weight, volume, energy and power requirements, heat release, etc. are quite meticulous. Experiments have been conducted to test hydrogen evolution from a laboratory AlH_3 bed with good results. The experiments seem to agree well with numerical simulations for pressure and hydrogen release rate as a function of the applied temperature. The entire research and development protocol is quite sound.
- The project is progressing forward through alternative designs for use in UUVs, pushing the gravimetric and volumetric targets with AlH_3.
- The project has made good progress toward the goals set. Various levels of characterization were performed, and the transient modeling is a great step forward. However, some of the goals do not translate exactly to DOE goals and requirements. This is the nature of the project, as it is a UUV rather than an automobile or ground vehicle. Great progress has been made on both sets of the project's goals, which should be commended.
- This project was not reviewed in 2016, and the presentation this year has combined results over two years. Progress over these years has been good, with results evident from materials screening, system design, and laboratory-scaled testing of prototype reactor performance.
- Accomplishments and progress seem to correlate with the funding level.
- Many accomplishments included in 2017 slides were previously reported in 2016. It is not clear why the Office of Naval Research (ONR) did not fund the project in fiscal year (FY) 2017.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.4** for its collaboration and coordination.

- The collaboration between the team members appears to be well coordinated, with each role clearly identified and focused. There appears to be good communication between the partners on understanding the thermal management issues that have critical effects for control of the two key system components: the peroxide and the hydrogen storage sub-systems.
- The design aspects necessitate collaboration with Navy partners, and there appears to be good communication with this organization. The collaboration with Ardica does not appear to involve much beyond some AlH_3 supply, but there does not seem to be value in greater collaboration. The design and engineering considerations for the storage component seem to be handled within the team, and perhaps the team would benefit from reaching out to others in the DOE Hydrogen and Fuel Cell Program (the Program) who have been involved in the HSECoE.
- Collaboration on this effort between the three parties involved was good. It appears that everyone is contributing to the project and working toward progress as quickly as possible.
- Collaboration with the Navy is strong and directed at a specific application.
- The project lists the Naval Undersea Warfare Center, ONR, and Ardica as partners. ONR provided funding in fiscal year (FY) 2015 and FY 2016. Ardica's contributions were not identified.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.2** for its relevance/potential impact.

- The impact of this project advances the Program into new demonstration opportunities outside of transportation and into the DOD. The cross-collaboration between DOE and DOD helps both departments in demonstrating the benefits of teaming to share cost to advance the respective goals.

- The project has good relevance to the Program by providing a low-power demonstration of a hydrogen storage materials system. This has potential to be a useful demonstration of materials storage as well as a testbed in which systems challenges are addressed as the Program scales to larger hydrogen capacities and more stringent performance targets.
- The project addresses a somewhat niche application for a unique hydrogen storage system for new fuel cell applications. It represents a good example of partnership between DOE and DOD for hydrogen and renewable energy systems.
- Although not relevant for automotive applications, the project has significant relevance and impact for the UUV application.
- This project does help the development of a possibly viable storage material, but it does so in an unconventional manner. Some of the work will not translate directly to DOE work.
- The project objectives are directed to DOD applications and fostering the relationship between DOE and DOD.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- The project is clearly focused on the next steps, and the researchers know where their efforts need to be and who is responsible for the team members. The next steps are logical, and they appear to be progressing to their future direction.
- The path forward is to work with the Navy to develop a final design, fabrication, and testing of the prototype UUV system. The current rate of progress ensures high likelihood of the success of this objective.
- The proposed future work is good; however, it does not include any specifics on the development of the system. If there are issues with producing large batches of AlH_3, it is not clear what will happen. Risk mitigation was not covered deeply enough.
- The path forward is not described in great detail, amounting to developing prototypes based on work completed so far. While this is an appropriate near-term goal, there is not too much evidence of planning, risk mitigation, etc.
- The presentation did not specifically identify future work, suggesting that the project will end in FY 2017.
- The project appears to be ending.

Project strengths:

- Project strengths include the excellent system design for the chosen mission; good materials selection; strong, rigorous experimental and computational test protocols; and good partnership between participating teams.
- This project has strong collaboration and the ability to leverage some great work performed by the HSECoE. The modeling effort has progressed well and should allow for optimized system design. Most of the bases have been covered with regard to design and analysis of the system.
- The project has great collaboration, has the right team members for success, and is a good demonstration of storage system design for alternative uses with fuel cells.
- The project chose a good system (i.e., UUV with the Navy partner) to learn and demonstrate hydrogen storage for medium-power applications.
- The team has a wealth of experience and knowledge in modeling metal hydrides. The project demonstrates an ideal application of metal hydrides.
- The credible team is a project strength.

Project weaknesses:

- There are no obvious weaknesses.
- Despite a feeling that this is a good test application, it does not have strong cost constraints and has an unusual system for oxygen delivery that aids hydrogen generation. These aspects limit the more widespread application of the outcomes from this project to others in the Program.

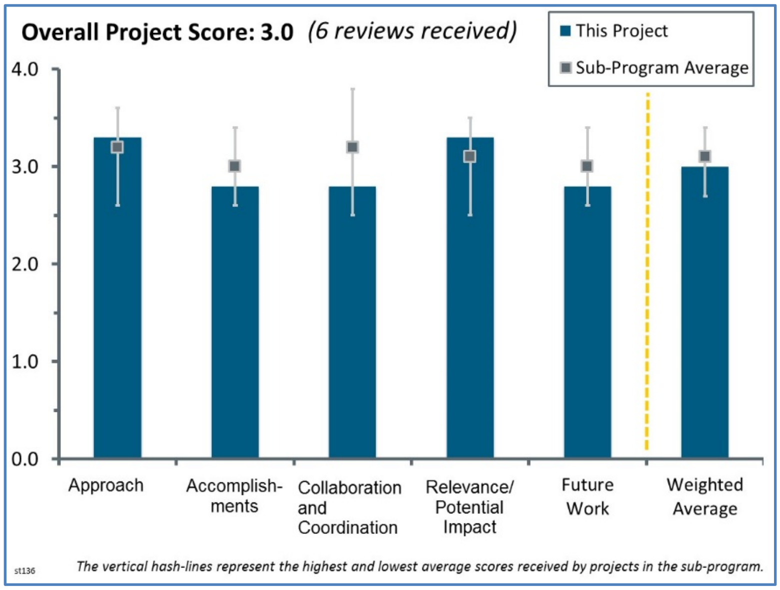
- The future of the project depends on the viability of a scaled-up production process for AlH_3. The performance of the system will also be dependent on the price of AlH_3. If the small batches produced for testing are used at the system level, it is not clear whether there will be enough funding to sufficiently test the system in operational conditions.
- It would be good to highlight a few more of the risks, such as the thermal management of the system design and the external environment. Once those risks are identified, the team should provide a good explanation on how they are being addressed to mitigate them.
- The material and system are not of interest in automotive applications.

Recommendations for additions/deletions to project scope:

- There are no recommendations; the scope seems to cover everything required for the system and not a bit more.
- The project appears to be progressing well, and it should drive toward a realistic prototype storage system that meets the physical and environmental constraints as quickly as possible.
- The project should continue in some form.

Project #ST-136: Hydrogen Materials–Advanced Research Consortium (HyMARC) Seedling: "Graphene-Wrapped" Complex Hydrides as High-Capacity, Regenerable Hydrogen Storage Materials

Di Jia Liu; Argonne National Laboratory



Brief Summary of Project:

"Graphene-wrapped" hydrides (i.e., complex hydride nanoparticles wrapped by graphene) show promise as a hydrogen storage material. The objective of this project is to produce one or more hydride@graphene composite materials with regenerable and reversible hydrogen storage capacity, targeting total gravimetric capacity greater than 10 wt.% and volumetric capacity greater than 0.055 kg H_2/L. Project tasks include the exploration of new hydride@graphene materials, material characterization and optimization, and development of modeling and simulation capabilities.

Question 1: Approach to performing the work

This project was rated **3.3** for its approach.

- The approach adopted in this project is unique and innovative. The high gravimetric capacity of $NaBH_4$ makes it an interesting hydrogen storage candidate. However, it has been largely discounted owing to its high intrinsic decomposition temperature. This project utilizes graphene as an encapsulant to significantly alter the thermodynamics and kinetics of hydrogen sorption reactions in nanostructured $NaBH_4$. This novel approach has now made this material a much more promising candidate for practical application. The approach to preparing the nano-encapsulated hydride appears to be scalable. The project team has outlined a reasonable and logical research and development strategy involving synthesis, characterization, and modeling/simulation. Sensible project milestones and a well-coordinated work plan are in place. Extensive collaborations with the Hydrogen Materials–Advanced Research Consortium (HyMARC) are in place to address the critical issues concerning the reaction mechanisms and characterization of sorption reactions in the nano-encapsulated material.
- One of the strengths of this project is the novelty of encapsulating the material to improve the reversibility and the kinetics. Since the techniques and procedures related to this approach are relatively new and therefore untested, this project is a high-risk project, but one very much worth exploring. It is not known how well this technique will overcome the barriers, but it seems reasonable to expect that it just may improve the hydrogen storage technology. It has been a relatively short time since the project started; therefore, most criticisms may be premature. The project could have initiated the modeling work sooner.
- This project is a follow-up on the remarkable finding that composites of $NaBH_4$ and 14 wt.% added graphene will undergo complete and reversible dehydrogenation. The basic approach of the project is reasonable, including verifying the initial observations and exploring graphene composites of other complex hydrides in hope of identifying a practically relevant material.
- The project is nicely focused, the barriers are clear, and the needed integration with other partners is exceptional.
- The project's focus is on $NaBH_4$ (10.6 wt.% hydrogen maximum). The team is trying to demonstrate 8 wt.% reversible. Therefore, there is not much room for error. In published work with collaborators at Shanghai Jiao Tong University, the project team demonstrated 7 wt.% hydrogen. To get to 8 wt.%, they will have to have higher loading of $NaBH_4$ in the graphene. It is surprising, given the demonstrated success

with $NaBH_4$, that the team did not choose to work with $LiBH_4$ or $Mg(BH_4)_2$, where there is much more room for error. It is not clear if there is something special about $NaBH_4$. It is unclear whether the approach works with $LiBH_4$ or $Mg(BH_4)_2$. If true, it might be more interesting to understand the apparent failures and how to overcome them.

- The principal investigator (PI) presented a good approach. While there are some limitations, the concept of encapsulation of materials to enhance hydrogen sorption is a viable pathway forward. However, this work does seems to overlap extensively with the work done and reported in the literature by Jeff Urban in HyMARC. That work encapsulated magnesium in various polymers and graphene sheets with the same net result of being impervious to various gases. While the approach to encapsulation from solution as presented was a great new approach, the significance of the research is lost, considering those previous publications in *Nature Communications*. Finally, one would expect that upon cycling, the expansion/contraction, along with the site heating, will be detrimental to any applicable long-term application.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **2.8** for its accomplishments and progress.

- Impressive results were obtained on hydrogen sorption reaction temperatures and (de)hydrogenation rates. The temperatures observed for hydrogen release from the nano-encapsulated $NaBH_4$ samples are still high, but significant improvements over the bulk material are evident. Important new results on ReH_2/DeH_2 cycling have been obtained, especially on the regeneration yield. The promising initial results provide confidence that further improvements in the use of catalysts/additives and optimized graphene–hydride ratios in the graphene-wrapped systems will be forthcoming. It will be important to develop a more comprehensive understanding of the mechanism(s) and rate-controlling processes operative in this nanostructured system.
- The researchers have shown excellent progress concerning the $NaBH_4$ wrapped in graphene. The material performance was clearly shown, and the researchers have done a good job explaining their strategy going forward, based on their initial results to attain the DOE goals.
- Given the relatively short time since the project started to this current review, criticisms may be premature. Promising results have been obtained but suffer from the lack of completeness. For example, the PI claims that good hydrogen yield occurs during dehydrogenation, but the graphs on slides 10 and 12 show a significant degradation occurs with each cycle. It is unclear what the nature of this degradation is. The PI should have acknowledged this issue and described the efforts to understand more. The top micrograph on slide 6 shows just how good the encapsulation is, but it is unclear if it is really representative. The lower micrograph shows particles either sitting on a carbon substrate or perhaps sandwiched in between sheets of carbon. It is unclear how the audience is expected to tell the difference. It is also unclear what percentage of the particles are encapsulated. The kinetics appears to be sluggish, as it takes significant time (several hours) to both dehydrogenate and rehydrogenate. It seems that $NaBH_4$ may need re-evaluation as a good candidate for storing hydrogen.
- There does not seem to be a significant amount of work that has been accomplished in the first year, compared to what was presented in the initial kick-off presentations. If there is indeed a formation of sodium hydride as presented, it infers that the mechanism is not as straightforward as presented. Slide 12 seems to indicate a hysteresis that occurs is quite significant. In addition, the high temperatures at which hydrogenation occurs do not seem applicable or have any significant improvement on past work in this area of $NaBH_4$. It would be good to see a more detailed evaluation of this with a more appropriate mechanism. In addition, it is surprising that the hysteresis was not worse on the site heating of graphene during hydrogenation. With the expansion and contraction expected in these materials, the extent of "edge" encapsulation materials and an evaluation of the efficiency of encapsulation would all seem to be very important to investigate/report. A simple transmission electron microscope (TEM) scan before and after hydrogenation cycles is essential, and is surprising by its omission. Finally, the recent nuclear magnetic resonance (NMR) results in the additional slides make absolutely no sense. It is unclear how the boron peak can disappear.

- There is something amiss with the results that have been obtained to date. The claim that $NaBH_4$ and 14 wt.% graphene will release 9.1 wt.% hydrogen to give NaH and B is clearly false, as the stoichiometric maximum is only 6.9 wt.%. In addition, the infrared results, which supposedly demonstrate the production of NaH, clearly show that a B-H stretch persists at 430˚C. The NMR results are the most disconcerting, as the dehydrogenated product does not contain a resonance for elemental boron or a boride. In fact, the results contain no ^{11}B signal at all, as if the boron has disappeared, only to reappear when the material is rehydrogenated.
- This is a new fiscal year 2017 seedling project. The team was able to make another batch of $NaBH_4$@graphene and reproduce their previous work with Shanghai Jiao Tong University, published last year in *Advanced Materials*. It is not very apparent what material was new. It was also unclear whether higher loading was new. It would have been more insightful to compare with the new work. It was unclear whether loading or particle size was different.

Question 3: Collaboration and coordination with other institutions

This project was rated **2.8** for its collaboration and coordination.

- Close collaborations with HyMARC, the Hydrogen Storage Characterization Optimization Research Effort (HySCORE), and external institutions are evident. This cooperation is clearly augmenting and supporting the Argonne National Laboratory-led project and is leading to rapid progress on most project tasks. The project appears to be well coordinated, with clearly defined roles and responsibilities for participating organizations.
- There seems to be extensive and very worthwhile active collaboration with HyMARC, and other necessary collaborations are in the planning stage. The researchers appear to be leveraging these outside resources well.
- The project is working well with both HyMARC and HySCORE.
- Professor Ge at Southern Illinois University has good background on computational approaches to hydrogen storage materials. Asking HyMARC for assistance to understand mechanisms is a big ask. It will be valuable to get more scoping work accomplished by Professor Ge to make this a more reasonable request.
- Almost all of the collaborations appear to be at a very initial stage with no substantial progress made. It is unclear whether this is caused by a lack of initiative, a lack of resources within HyMARC, or some other reason. It is also unclear if the Southern Illinois University work was initiated because the HyMARC resources were unavailable. This may be an issue outside the control of this PI; it may be a larger issue that needs to be addressed at a higher level.
- The project suffers from a lack of expert collaborations. Help from HyMARC and/or HySCORE is clearly needed to sort out the many irrational results that have been obtained.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.3** for its relevance/potential impact.

- This is a high-risk, high-payoff project that is an archetype HyMARC seedling. The approach is innovative, and the initial results are promising. It is an important addition to the HyMARC project portfolio. The project directly supports the goals/objectives of the DOE Hydrogen and Fuel Cells Program (the Program).
- One of the bottlenecks for practical use of complex hydrides is slow kinetics for hydrogen uptake and release from carriers that have the “optimum” thermodynamic range for reversibility. The proposed work is investigating approaches to enhance kinetics of hydrogen release from complex hydrides to address this bottleneck.
- This project’s high degree of novelty may lead to real advances toward the DOE goals, and it is definitely worth pursuing. It is also a high-risk project because of the several unknowns with this new approach. When the novelty and high-risk considerations are combined, it reduces the likelihood of making an impact, but the project still has high potential.

- This project appears to be at the cutting edge of using new innovative composite materials to accomplish the Program goals and objectives. There is clearly high relevance and impact.
- This project targets developing composite materials that will enable hydrogen cycling of high-hydrogen-capacity complex hydrides. However, the actual relevance and eventual impact of the project is questionable, as it targets achieving reversibility below 400˚C rather than at polymer electrolyte membrane cell relevant temperatures.
- Encapsulation/confinement is a viable pathway to improving kinetics of hydrogen adsorption on hydrides. However, while this research is interesting, it does not seem to have a pathway toward achieving the DOE goals.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- The proposed future work is clearly stated and follows logically from the present studies. Very little information has been provided concerning the hydrogen sorption reaction mechanism(s). Elucidation of mechanisms and rate-controlling processes should be important topics for work in the near future. This will undoubtedly require an even closer collaboration with the HyMARC core team. Several other questions also should be addressed. For example, it is unclear whether carbon in the graphene wrapping is an active participant in the sorption reaction processes. It is also unclear whether other encapsulants (e.g., aerogels) are as effective as (or more effective than) graphene. It is also unclear whether data are available on the dependence of sorption temperatures and the ReH_2/DeH_2 kinetics on the hydride–graphene ratio.
- Future work proposed is well thought out and tries to expand the project toward the most useful composite materials.
- The proposed future work and go/no-go's all seem reasonable.
- It was a little disappointing to see many slides on accomplishments came from work that was published in the peer-reviewed literature before the project was initiated. The team shared four bullet points on future work. It is understood that they have a go/no-go decision point milestone before the next Annual Merit Review, so their first bullet was to increase the storage capacity in $NaBH_4$@graphene through optimizing the hydride–graphene ratio. There may not be room to do this if they are currently at 86% $NaBH_4$. The second bullet was to improve kinetics, which would not be critical at this point. Showing the approach works for more than just $NaBH_4$ should be a higher priority. It is a surprise that this seems to be delayed to Phase II. If the project does not make the go/no-go decision point milestone because of a focus on $NaBH_4$, it would be a shame. The third bullet is to improve fundamental understanding of mechanisms through computational modeling. Experimental data on other complex borohydrides may provide some additional insight to help focus the approaches on specific mechanisms in the modeling tasks.
- It seems like the real project goal should be to optimize the encapsulation's effectiveness. This may involve the hydride–graphene ratio but is more than just that. It is unclear what the other parameters are that can be explored to enhance the effects of encapsulation. Looking at catalysts to improve kinetics is key, but the team should not linger too long on trying to fix $NaBH_4$. It is unclear whether it is more effective to search for better or "more suitable" hydrides. Fundamental understanding through modeling is essential and is an important component for future work.

Project strengths:

- This is a novel and innovative technical effort that has the potential for high payoff. The project team has demonstrated solid progress in the first project phase. A well-crafted future work plan is in place, and strong connections with HyMARC core team members are facilitating project success.
- Novelty is the project's best strength, and the concept appears to be promising. The project approach may overcome barriers that hinder hydrogen storage technology. The team has strong teaming with HyMARC planned, which should be highly beneficial.
- The graphene wrap idea is highly innovative since it addresses some property shortcomings of more conventional materials. In addition, the idea can probably be successfully adapted to different hydrogen storage compounds.

- This project shows very exciting results for $NaBH_4$. The pressure-composition isotherm (PCT) curves in the published paper show that the equilibrium pressure may be in a desirable target area.
- The strength is the new technique for material encapsulation.

Project weaknesses:

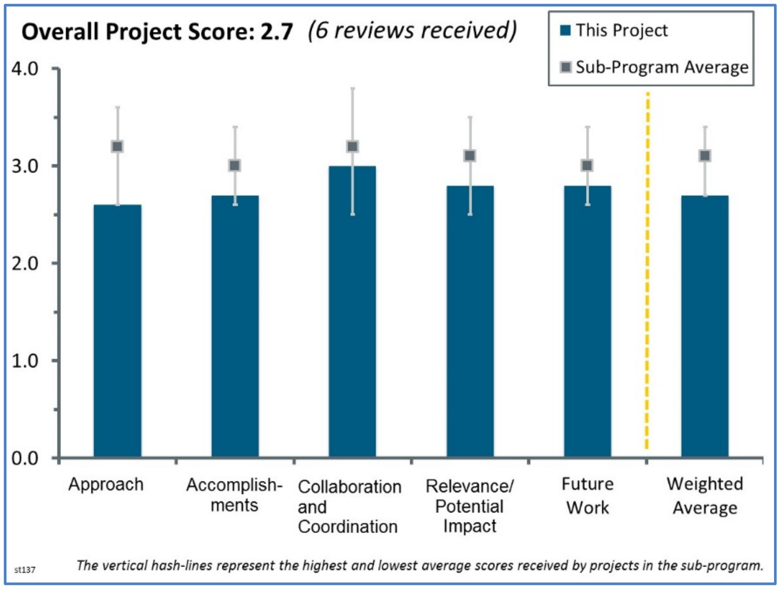
- The (de)/(re)hydrogenation temperatures are still very high and far outside the range of acceptance for fuel cell applications. Overcoming that obstacle is a major challenge, and it seems unlikely that, without tremendous success on implementation of the future work plans/ideas, those temperatures will be reduced to acceptable levels. That remains the dominant challenge for the project team.
- It is not clear whether this approach works for other borohydrides or if it is unique for $NaBH_4$. According to the team's published paper, $NaBH_4$@graphene is "unstable" at 40°C, which could be a problem. TEM pictures show a lot of apparent empty space. It is not clear what the volumetric density is or what the error bars are for the cycle measurements. It was interesting that from cycle 3 to cycle 4 the capacity dropped by 3% and from cycle 4 to cycle 5 it increased by 2%. It is unclear whether the increase is real or within the measurement error. Maybe the materials should be cycled under hydrogen for longer time periods and/or at higher temperature.
- It is hard to tell enough about such things as ultimate material costs. Additionally, there is still some degeneration of material upon cycling, so it is not clear if this can ever be improved enough to be commercially feasible.
- The edge effects, volume contraction/expansion, and formation of side products were not addressed in this initial presentation.
- The degradation seen with cycling is not addressed adequately. This project had a slow start with collaborations.
- The project suffers from a lack of expert collaborations. Help from HyMARC and/or HySCORE is clearly needed to sort out the many irrational results that have been obtained.
- This project has obtained several irrational results.

Recommendations for additions/deletions to project scope:

- The ^{11}B NMR data for decomposition of $NaBH_4$@graphene published in the team's *Advanced Materials* paper show the formation of $Na_2B_{12}H_{12}$ after one cycle of hydrogen release. It is also interesting that the published NMR data look different from the ^{11}B NMR data provided in the presentation. As $B_{12}H_{12}$ formation is occurring, it would be interesting to investigate a lower temperature for hydrogen release to see if $B_{12}H_{12}$ can be avoided. The kinetics would be slower, but it might help reach the milestone of 8 wt.% over the promised number of cycles. The team could also learn important information about the equilibrium pressure with more PCT experiments.
- It would be valuable to have some early explicit effort to look for the optimum hydride that would benefit from encapsulation. Maybe this has been done implicitly, but it was not reported on explicitly. Phase II has some effort mentioned. However, it is not clear what the nature of that effort is or if it is an exploration by modeling or measurements. The former would be able to cover much more ground faster and easier with more and longer cycling data. Exploration of the degradation mechanisms seen should be done in order to understand the degradation.
- It would be interesting to determine somehow whether the graphene is mainly providing a means to create tiny reactor vessels for bulk hydrogen storage materials or whether is there an additional alteration of the bulk thermodynamic properties. In addition, one reviewer pointed out that the formation of closo-borate-type clusters is evident in the NMR, which might explain the slow degradation with cycling and might put a limit on the reversibility over extended cycling. This should be investigated more closely since it has an impact on the entire project and might steer the researchers toward non-borohydride-type materials in future efforts.
- The weight-percent hydrogen that can be cycled by $NaBH_4$@graphene should be independently verified. The infrared studies and, more importantly, the ^{11}B NMR studies should be repeated at HyMARC or HySCORE facilities.
- The project needs more characterization after cycling and new mechanisms that explain the formation of sodium hydride.

Project #ST-137: Hydrogen Materials–Advanced Research Consortium (HyMARC) Seedling: Electrolyte-Assisted Hydrogen Storage Reactions

Channing Ahn; Liox Power



Brief Summary of Project:

Most hydrogen storage candidates with high capacities and appropriate thermodynamics for polymer electrolyte membrane fuel cell use contain multiple solid phases that must nucleate, grow, and be consumed during cycling; the presence of these multiple phases hinders kinetics. This project seeks to address the kinetics of multiphase hydrogen storage reactions by exploring the use of electrolytes and/or electrochemical approaches to "solubilize" or promote diffusion of reacting species.

Question 1: Approach to performing the work

This project was rated **2.6** for its approach.

- The novel concept of using electrolytes to decrease the kinetic barrier is well conceived. If the concept is applicable, the researchers predict the reduction of the kinetic barrier down to 4 kJ/mol, enabling charging and discharging at a temperature well below 80°C. This likely assumes that diffusion is the major kinetic limitation, as it is for electrochemical reactions in which there is a negligible chemical barrier for electron transfer. On the other hand, complex hydrides require the breaking of B-H bonds to release hydrogen or the breaking of H-H bonds to recharge the material. The homolytic bond strengths of B-H and H-H bonds are on the order of 400 kJ/mol; therefore, a "catalyst" to overcome these thermal barriers will likely be required.
- The project is outside the box but worth the effort to see if there is a viable path forward. It appears to be well integrated with and designed around the current status quo efforts.
- The approach seems reasonable for what the project is trying to accomplish.
- The electrolytes and complex hydride systems selected are reasonable and worthy of study. However, it is unclear how the systems under study could be modified into systems that meet the gravimetric density target.
- The use of a liquid electrolyte to assist in hydrogen storage reactions is a unique idea. However, in looking at it in more detail, it seems the large activation barrier to the electron tunneling of charge between the two species, as shown in slide 6, will be difficult to overcome. First, it would seem that the solvation sphere would still be a barrier instead of an aid. The only apparent benefit would be more uniform heating of the sample in a slurry, but the bulk diffusion and structural changes that occur were not fully addressed. The slide also shows an ideal case of a sphere. It is doubtful that any of the species in this work would have such a uniform shape, and it may be even less of a point-to-point contact than depicted. Also, on slide 10, the ideal case is very misleading with the calculation. It assumes no activation overpotential, which is expected to be quite large for a material undergoing significant volume changes. The eutectic molten salts is an intriguing idea, but it would be preferable to see the investigation of some ionic liquids (i.e., room-temperature molten salts) instead (slide 15). The use of the other solvents, while informative, did not seem to be relevant to the project. Overall, the approach and progress to date are very disappointing, even though it is still early in the project.
- This project is focusing on assessing the idea of electrolytes to overcome kinetic barriers in metal hydride materials. It is a lower technology readiness level concept evaluation that may not ever be a viable

approach to developing materials that can meet the light-duty vehicle targets. A simple assessment using the tools developed by the Hydrogen Storage Engineering Center of Excellence acceptability envelope should be performed to assess the feasibility of this idea.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **2.7** for its accomplishments and progress.

- The project has only a few months under its belt. From what has been reported so far, the number and impact of preliminary results is more than satisfactory.
- This is a recently started, fiscal year 2017 seedling project that is making progress toward understanding the limitations and potential advantages of the approach.
- The presentation was diffuse, making it difficult to evaluate how much progress has been made. The principal investigator (PI) seemed to be saying that ethers were found to undergo significant decomposition at 200˚C. It is unclear if the dehydrogenation of $Mg(BH_4)_2$ in the presence of ethers will be studied further. It was shown that the kinetics of the dehydrogenation of MgH_2/Si is significantly improved in the LiI:NaI:KI eutectic; however, it is unclear whether weight percent reported includes the eutectic and whether this system is reversible in the eutectic.
- While the project is new and is just getting started, no significant accomplishments were presented. It may be unfair to have it evaluated at this point.
- This is a new project, so ranking the accomplishments is difficult, or perhaps even premature.
- While the project is quite early, it was still disappointing to see so little progress. In reality, there will be no well-defined answer until further work is completed.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- Collaboration with HRL Laboratories (HRL), the Hydrogen Materials–Advanced Research Consortium (HyMARC), and the Hydrogen Storage Characterization Optimization Research Effort (HySCORE) provides a firm grounding in modeling and experimental expertise.
- The investigators have reached out to the HyMARC team, and it is expected that more interactions will be forthcoming.
- The strong team brings together expertise in different fields from Liox, HRL, and the California Institute of Technology (Caltech).
- There is not significant collaboration yet, but this is mainly due to the short age of the project. The collaborations are scheduled to occur in the near future, which is reasonable.
- The project will collaborate with Caltech for nuclear magnetic resonance spectroscopy, with HySCORE, and with HyMARC. It is unclear which capabilities in HyMARC will be useful, and the role of HRL in the collaboration is unclear as well.
- The project has been underway for only a short time, but plans for collaboration with the HyMARC core seem to be very underdeveloped.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **2.8** for its relevance/potential impact.

- The project as laid out shows high relevance and potential impact.
- One of the bottlenecks to utilization of complex hydrides for fuel cell electric vehicle applications is for charging and discharging hydrogen. The proposed work investigates the use of electrolytes (or solvents) to enhance the kinetics by decreasing the activation barrier to diffusion.

- This project addresses the key issue in the development of complex hydrides: improvement of kinetics. However, the relevance and eventual impact of this project are questionable, as the weight incurred by the use of electrolytes is completely ignored. The project is perhaps more relevant to the development of batteries than hydrogen storage materials.
- Electrolyte-mediated hydrogen storage reactions may offer advantages in the release of hydrogen but may be negated by the increased diffusional resistance (accompanied by a very low hydrogen solubility) of hydrogen through the electrolyte—assuming, of course, that the reaction will be reversible. Currently, there are no known materials that will meet the gravimetric capacities, so the addition of an electrolyte only reduces the capacity.
- While the idea of understanding the ability of electrochemical-driven systems to overcome kinetic barriers in higher-gravimetric-capacity materials could be valuable to the overall Hydrogen and Fuel Cells Program achievements, it is not certain that this concept can ever be a viable approach.
- The potential impact is significant, but unless the researchers are able to find viable ionic liquid systems, it will be very difficult for the project to be successful.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- The team recognizes the need to discover more stable solvents, even with a goal of working at lower temperatures. The team has been working at low concentrations (0.1 M) with limited success. It will be beneficial to investigate higher concentrations of borohydride. The project should increase hydride concentration by a factor of 10 and decrease solvent by a factor of 10. A slurry or paste will provide significantly higher gravimetric density and should reduce solvent decomposition and be more aligned with the components of a battery that is being used as an analog for enhanced kinetics (e.g., 40% active material + 12% electrolyte). The use of solvents will increase rates of diffusion, but the presence/need of a catalyst is likely to be critical and should be explored in future work.
- This was hard to assess since the project is in the early stages, but the presenter appeared to have a coherent vision of the future plans.
- It will be interesting to see whether the project can find a material that demonstrates the initial properties and capacities that would allow this concept to be viable.
- The proposed future work will quickly determine the viability of the project.
- The proposed future work (milestones and go/no-go) has a very low bar of around 1 wt.% hydrogen. It is unclear what materials the project is focusing on, e.g., MgH_2, $Mg(BH_4)_2$. The potential for gas phase contamination should be a concern.

Project strengths:

- This is a unique and intriguing approach to a difficult problem. It pushes the boundaries of what has already been tried.
- This is a well-respected team of hydrogen storage researchers.
- The team has a strong understanding of fundamental hydrogen storage limitations.
- This is a strong team of experts looking at approaches to enhance kinetics.
- John Vajo, Channing Ahn, and the strength of the HRL collaboration are project strengths.
- This is a world-class team of co-investigators.

Project weaknesses:

- The team will find a solvent that will enhance the dehydrogenation rate, but it is unclear what this will provide in the grand scheme of hydrogen storage for automotive applications. The increased diffusional resistance of hydrogen through the electrolyte for the reverse reaction (i.e., hydrogenation) will be problematic.
- This is a great approach to investigate kinetics but a long shot to meet gravimetric targets. There is no planned computational work. It would be interesting to ask for theory assistance to calculate the barrier for

hydrogen release from MBH_4 to make MB + $2H_2$. If the barrier is high and not a diffusion limited process, the risk could be mitigated through HyMARC for assistance with theory and potential catalysts.

- It is not clear whether the electrolyte-assisted approach will actually work. Although tantalizing, there is no consensus concerning success from the early data presented so far.
- This project has a very soft Year 1 go/no-go. There is high potential for the project to drift off into irrelevance.
- This is probably not a viable concept that can meet the light-duty vehicle system targets in its current conception.

Recommendations for additions/deletions to project scope:

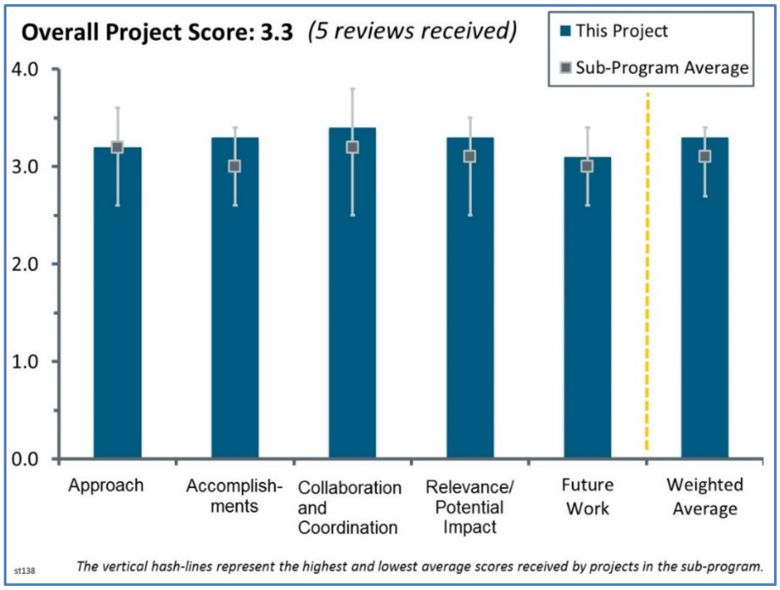
- The PI should place more emphasis on investigating the various possible eutectic salt mixtures. Also, the project should expand the scope to investigate the effects of particle size on performance, since the theory suggests that the mechanism is surface-area dependent.
- The project direction and goals need to be better defined.

Project #ST-138: Hydrogen Materials–Advanced Research Consortium (HyMARC) Seedling: Development of Magnesium Boride Etherates as Hydrogen Storage Materials

Godwin Severa; University of Hawaii

Brief Summary of Project:

The objective of this project is to synthesize and characterize magnesium boride etherate hydrogen storage materials that are capable of meeting the U.S. Department of Energy's performance targets. The project will synthesize magnesium boride etherates using ball milling and heat treatment techniques, study hydrogenation of the materials using variable pressure and time, study and optimize hydrogen cycling of the materials, and develop theoretical models.



Question 1: Approach to performing the work

This project was rated **3.2** for its approach.

- This is a nicely described approach that appears to derive from earlier observations that the kinetics of dehydrogenation of $Mg(BH_4)_2NH_3$ were enhanced over the parent compound, $Mg(BH_4)_2$, but that unfortunately released some ammonia and formed stable BN compounds that could not be rehydrogenated. This appears to have provided the inspiration for this current project. Rather than employing ammonia as a ligand to enhance kinetics, the project has proposed using ethers as ligands to enhance the kinetics of de/rehydrogenation. This work thus addresses a potential solution to one of the vexing problems with the $MgBH_x$ system that generally suffers from very slow kinetics of dehydrogenation and rehydrogenation at practical temperatures. This project's approach is well designed in that it examines reversibility of the ether system and incorporates computational modeling appropriately. The chemistry appears highly feasible, and there is good overlap with efforts within the Hydrogen Materials–Advanced Research Consortium (HyMARC) and the Hydrogen Storage Characterization Optimization Research Effort (HySCORE), both experimentally and computationally. Multiple pathways to synthesis of the target species are employed, which is a good risk mitigation strategy.
- An intriguing and innovative approach is being employed to improve hydrogen storage properties in the $MgB_2/Mg(BH_4)_2$ system. The participation of etherate adducts in the hydrogen sorption reactions in the magnesium boride system has been shown to greatly enhance the reaction kinetics. The approach employs a combination of synthetic methods, detailed characterization/diagnostics, and theoretical studies (HyMARC collaborations) to demonstrate improved hydrogen sorption properties and to understand the underlying mechanism(s). A detailed and compelling work plan is provided. It provides confidence that the critical issues will be successfully addressed and a promising new material will be developed.
- Given the Fuel Cell Technologies Office (FCTO) commitment to Mg-B-based systems, this effort offers a path toward reducing dehydrogenation temperatures and possible rehydrogenation using various solvents, probing both dehydrogenation of a range of borohydrides that appear along reaction pathways and also concentrating on the rehydrogenation of MgB_2.
- The overall approach is clear and encompasses two different ways to enhance the kinetics of Mg borohydride materials by synthesizing MgB_2 etherates: reactive ball milling and heat treatments from Mg borane etherates, and MgB_2 in presence of ethers. The milestones do not appear to plan for feedback on the synthesis. Future work includes investigations of the mechanism and understanding kinetics of reactions;

however, this may require changes in the synthesis (i.e., concentration of tetrahydrofuran [THF] (slide 5), particle size, etc.). From the milestone summary, it appears that all synthesis is 95% complete. It seems surprising that all synthetic efforts will be completed in the first quarter. Instead, identifying what works and investigating it further would improve the outcome of this research. The THF etherates have proven better than the others, so focusing efforts on this system will provide exciting results, as the team appears to have decided.
- Other metal etherates have been examined, but not MgB_2. This project can see if there is some potential here.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.3** for its accomplishments and progress.

- The project has made very good progress quickly. The researchers have explored the stability of MgB_2-THF complexes in collaboration with the computational capability within HyMARC that helps to elucidate the structures and energetics of complex formation. In parallel, they have succeeded in developing, demonstrating, and characterizing the products from a nice chemical synthesis of the diboride-THF complex, in addition to a “heat and beat” brute force approach. This work has identified that the THF complex of the diboride is chemically stable to above 400°C, whereas polyethers decompose at temperatures less than 200°C. As the presence of THF in the complex diminishes the gravimetric hydrogen capacity of the complex, the researchers are in the process of determining whether substoichiometric THF complexes may be prepared, thereby reducing the gravimetric penalty of adding THF. Most importantly, the project has been able to demonstrate with quite high confidence, using a variety of characterization techniques, that the complexes may be hydrogenated at high pressures (1000 bar) but moderate temperatures of 300°C. This work has employed good collaborations in computation, characterization, and high-pressure hydrogen capabilities resident within the HyMARC and HySCORE consortia.
- Solid progress has been achieved on synthesis and characterization of strongly coordinated MgB_2 etherate species. Reaction of ball-milled MgB_2-THF with hydrogen at high pressure has shown that the system can be hydrided, producing $Mg(BH_4)_2$ at temperatures as low as 300°C. This is a particularly noteworthy result that provides an important motivation for continuing this work. Interesting and potentially important information concerning the reaction mechanism has been provided from molecular dynamics modeling conducted in collaboration with HyMARC (Wood, Kang, et al). The results suggest that the interaction of the MgB_2 surfaces results in stabilization of the Mg-exposed surfaces. Direct bond formation between MgB_2 and THF molecules could be a vital aspect leading to enhanced hydrogenation kinetics.
- Accomplishments include the synthesis of MgB_2 etherates by two routes: heat treatment of MgB_2 and THF, tetraglyme or dioxane, and by MgB_3H_8-THF. Currently, ball-milled MgB_2-THF samples show greatest promise at 300°C hydrogenations. This work has produced the exciting result for the first time of the formation of a significant amount of beta-$Mg(BH_4)_2$ at 300°C, through evidence via thermogravimetric analysis (TGA)/differential scanning calorimetry (DSC), Fourier transform infrared spectroscopy (FTIR), and x-ray diffraction (XRD). This shows important progress toward the project and DOE goals.
- There is good progress so far, especially in synthesizing materials.
- The work described represents less than six months of effort into this project, but the principal investigator has had a longer timeline of experience in studying this system. For the study of MgB_2, the layered nature of the material appears to be problematic, with the greatest possibility for reaction taking place along the edge of these structures. There are presumably reasons during MgB_2 formation that involve free energy minimization that presumably yields a high aspect ratio of basal to edge plane morphologies, even though the opposite is preferred. The only alternative in this case is to be sure that the MgB_2 has a small overall morphology. The successful hydrogenation of MgB_2 with THF, albeit at high pressure and temperature, points to possibilities for more moderate hydrogenation.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.4** for its collaboration and coordination.

- Close and highly beneficial collaborations between the University of Hawaii (UH) project team and numerous other investigators, most notably the HyMARC core team, are apparent. These collaborations have been vital to the rapid progress achieved thus far. The reliance on fruitful collaborations to accelerate progress and inspire new research and development (R&D) ideas has been a hallmark of the work by the UH investigators. This project is no exception.
- Collaboration in this project is critical. HyMARC provides characterization of samples by XRD and TGA/DSC and hydrogenation of samples, and the National Renewable Energy Laboratory will do temperature-programmed desorption (TPD). Correlating theoretical work supports the stability and observation of the bond formation between MgB_2 and THF. This is a very collaborative effort with a large portion being done outside of UH.
- This project has meaningfully and very quickly taken advantage of multiple capabilities ranging from computation to diffraction to high-pressure hydrogen synthesis and off-gas analysis resident within the HyMARC and HySCORE consortia.
- This work has a fairly high level of integration with HySCORE (Pacific Northwest National Laboratory team) and HyMARC (Sandia National Laboratories team), and has presumably been aided by some of the computational work at Lawrence Livermore National Laboratory.
- Collaborations were mentioned, but the presentation was not that obvious as to exactly how and where the collaborators were involved. The collaboration should be more evident as the project proceeds.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.3** for its relevance/potential impact.

- This is an excellent high-risk, high-payoff seedling project that is being conducted in close collaboration with the HyMARC team. The $MgB_2/Mg(BH_4)_2$ system has emerged as one of the only metal hydride systems that has the potential to meet the DOE targets for hydrogen storage. The principal obstacles (mainly kinetics) to the successful development and use of this material in practical system applications are being directly addressed in this project. The project is tied closely to the overall HyMARC goals and objectives, and it directly supports the HyMARC mission and the FCTO Multi-Year Research, Development, and Demonstration Plan goals.
- This work is highly relevant to Hydrogen and Fuel Cells Program goals in that the project is exploring pathways to enhance the kinetics and reversibility within the MgB_xH_y system. This work is likely to determine the role that complexing ligands play in enabling the observed, enhanced kinetics that may provide guidance to allied computational and experimental efforts and inspire other ideas and approaches to achieving kinetically facile, reversible high-capacity hydrogen storage in materials. If this project can elucidate pathways to minimizing the amount of complexant while achieving high rates of de/rehydrogenation, this will be very impactful on FCTO R&D goals.
- This project provides important work to address the capacity and kinetics for hydrogen storage using magnesium boride etherates. The project goals are consistent with DOE targets for capacity, kinetics, and cyclability. The project go/no-go decision is to demonstrate >7 wt.% hydrogen uptake by a MgB_2 etherate at <300°C, 700 bar, 48 hours, and reversible release of >2 wt.%. The final milestone for the "dehydrogenation of one hydrogenated MgB_2 etherate" is somewhat unclear as to whether there is a capacity associated with this.
- This project in the time available probably has only a small potential in developing a high-capacity storage material, but it has a good potential to add to the understanding of hydrogen interactions in materials.
- This project is in its early stages, and it is difficult to tell whether it will meet the aggressive go/no-go target.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- The proposed future work follows naturally from the current studies. The reviewer fully supports a strong emphasis on the MgB_2-THF system as stated by the project team. Likewise, a focus on characterization using the range of techniques outlined in the presentation should provide critical information that will be needed to facilitate progress. The computational work on size-dependent stability of MgB_2 clusters is intriguing. It should provide information to guide future experiments. At this point, only limited information has been provided concerning the mechanism for hydrogenation enhancement. As stated in the presentation, elucidating the reaction mechanism and understanding the rate-controlling processes in the $MgB_2/Mg(BH_4)_2$–etherate system will be an important future direction. It will undoubtedly be facilitated through extensive collaborations with the HyMARC core team. However, it seems apparent, based on comments made at the presentation, that more insight concerning the mechanism is available than was provided at the review. It is to be hoped that details will emerge in future DOE Hydrogen and Fuel Cells Program Annual Merit Review meetings and technical team reviews. It will also be important to clarify how the hydrogenation characteristics vary with the mole ratio of THF:MgB_2, especially in samples containing substoichiometric amounts of THF. Results from those investigations may have important implications in understanding the enhancement mechanism(s). The ability to achieve significant rate enhancements with reduced quantities of THF also has positive impacts on the overall gravimetric capacity of the system.
- A logical progression of R&D tasks is proposed as future work. Given the high quality of the team and its high-quality collaborations with HyMARC and HySCORE, it is very likely that significant progress will be made. Given the experience of the team, one can say with confidence that if additional R&D challenges arise in the future, the researchers will be able to navigate around or through them.
- Future work suggests understanding the mechanism of kinetic enhancement by etherates. This will be studied using TPD, but it is unclear what parameters will be studied. Hydrogen cycling will also be investigated. This will provide important materials performance characterization to optimize cycling in these systems.
- As with all of the seedling projects, a lot of effort is being asked of the investigators to be completed in a short time.

Project strengths:

- The project team comprises recognized experts in the field of complex hydride chemistry and hydrogen sorption reactions. Extensive collaborations (especially with the HyMARC core team) are being used effectively to augment the overall R&D effort. A solid work plan is in place, and the future work on this project will undoubtedly provide important new information concerning the efficacy of the promising $MgB_2/Mg(BH_4)_2$ system for practical storage applications.
- This is a highly collaborative effort with HyMARC and HySCORE in areas that will have impact on the success of the project. The researchers have quickly made very good progress toward their goals. A nicely balanced set of synthetic strategies are employed to mitigate any risks that may arise due to problems in the synthesis of materials. The team has tremendous strength in performing chemical synthesis, chemical characterization, and interpretation of results in this materials system.
- This work has provided the hydrogenation of ball-milled MgB_2-THF at 300°C. The team presented the first evidence for the formation of a significant amount of beta-$Mg(BH_4)_2$ at 300°C (through evidence via TGA/DSC, FTIR, and XRD). The project provides a promising route forward and has a team with strong expertise.
- There is clear evidence that an approach such as this will be necessary to promote lower-temperature cycling of Mg-B systems.
- Materials synthesis is a project strength.

Project weaknesses:

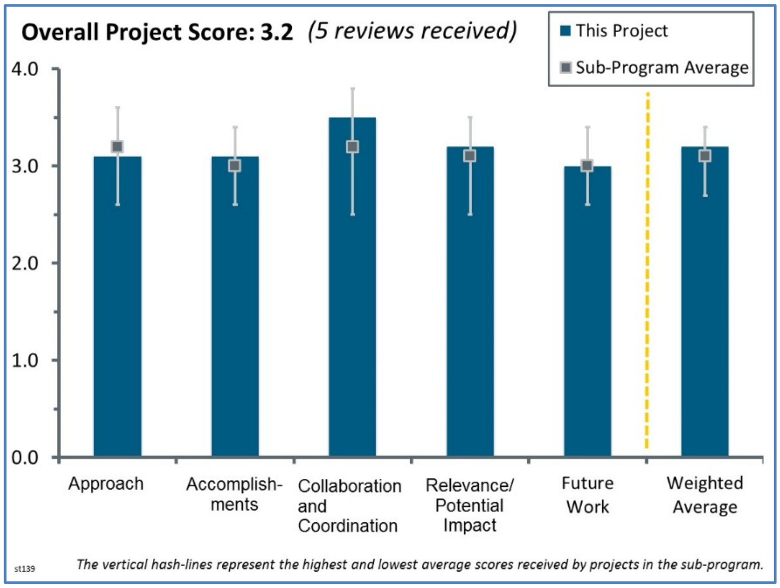
- Reducing the (de)hydrogenation temperatures at practical pressures to values commensurate with fuel cell operation remains a daunting challenge. Although excellent progress has been made using the etherate adduct approach, there is a long way to go. A clear pathway to achieving sorption characteristics at practical temperatures and pressures is not apparent.
- The approach of having all of the synthetic work in the first quarter limits the findings of this project. Instead, feedback from the characterization should provide thoughtful synthetic routes forward. For example, the future computational work includes size-dependent stability and morphology of MgB_2 clusters and particles. This sounds like important work; however there is no apparent plan to incorporate this feedback into the synthetic work.
- Too much work is being tasked to discern a proper mechanism, with limited time to accomplish the work.
- The project would be helped by more computational modeling collaborations.

Recommendations for additions/deletions to project scope:

- It could be useful to explore how catalysts/other additives might affect the hydrogen sorption kinetics in the MgB_2–etherate system. The project team might consider adding that to the future work plan.
- It is a well-balanced project as it stands. No additions or deletions to the scope are recommended.
- Feedback-driven synthetic work is recommended.
- More interactions with the HyMARC modeling team are encouraged.

Project #ST-139: Hydrogen Materials–Advanced Research Consortium (HyMARC) Seedling: Fundamental Studies of Surface-Functionalized Mesoporous Carbons for Thermodynamic Stabilization and Reversibility of Metal Hydrides

Eric Majzoub; University of Missouri–St. Louis



Brief Summary of Project:

The objective of this project is to utilize the surface chemistry of the hydride/ active-framework interactions to design functionalities that allow the use of unstable complex hydrides for hydrogen storage. Project tasks include demonstration of (1) Lewis acid–Lewis base interaction between aluminum in aluminum hydride (alane, AlH_3) and pyridinic nitrogen in nitrogen-doped carbon nanoframeworks, (2) differences between functionalized and non-functionalized carbon nanoframeworks, and (3) reversibility of aluminum hydride de- and re-hydriding.

Question 1: Approach to performing the work

This project was rated **3.1** for its approach.

- An approach for altering kinetic barriers and thermodynamics of emerging hydrogen storage materials through the use of high-surface-area functionalized support frameworks is novel and innovative. The approach may be also applicable to modifying reaction rates in other related chemical systems. It is not entirely clear why alane was selected as the initial test system for this work. Even with the benefits attendant to a functionalized nanostructured template, the prospects for reversibility and high cycling yield for alane are remote. It seems that incorporation and characterization of a complex hydride that has more promising properties would be more desirable (although the reviewer, by admission, may be missing something here). That concern notwithstanding, the approach is solid and provides confidence that promising results will emerge. There remains some concern about ambiguities that might arise from the possible retention of tenacious solvent molecules after the infiltration process. The project team is undoubtedly aware that great care must be taken to ensure that the solvent is removed or, at the very least, fully accounted for.
- The project approach is directed at exploring the influence of nanoconfinement of model metal hydrides on the thermodynamics and presumably kinetics of de/rehydrogenation. The strategy is to prepare functionalized nanoporous carbon frameworks, where the functionalization is anticipated to provide the necessary sorbent–sorbate interaction to stabilize small clusters of hydride within the nanoporous environment. Each portion of these strategies comes with significant characterization challenges, and the project approach addresses them in order. The team has already utilized some of the capability of the Hydrogen Materials–Advanced Research Consortium (HyMARC) and the Hydrogen Storage Characterization Optimization Research Effort (HySCORE) in the characterization of some of the project's initial materials and is exploring additional collaborations with these consortia. As such, the project supports the goals of HyMARC to develop the foundational understanding of what the nanoscale confinement features are that may affect important hydrogen storage parameters such as the thermodynamics and kinetics of hydrogen release and rehydrogenation and the influence of nanoscale on phase behavior, among others. The approach of this project includes a significant materials characterization effort, as elucidating whether the metal hydrides chosen for study are indeed nanoconfined or simply

deposited on the outside of the porous host framework. This is a challenge, and the approach is designed to ferret this out in the short term.

- The approach is to study the formation of high-surface-area materials—up to 1,650 m^2/g (in a nanoporous carbon)—and to insert hydrides (AlH_3 and $NaAlH_4$) onto the pore walls. Since nanostructuring hydrides is known to alter the thermodynamics of the material, this work will experimentally reveal these altered thermodynamic pathways.
- The altering of the kinetics and thermodynamics of hydrides through confinement in carbons and other nanoporous materials has been explored by a wide number of research groups over the past 10 years. While various levels of success have been achieved with complex hydrides, no successes have been reported for AlH_3. This is primarily due to the difficulty in preparing alane-composite materials. The approach of infiltrating base adducts of AlH_3 is reasonable and worthy of investigation. However, the approach of infiltrating $NaAlH_4$ with the hope of then converting it to AlH_3 is at best dubious. It is unclear if it was a simple slip of the lip when the principal investigator (PI) stated that the rationale for the selection of N-doped graphene as a host is that "N cannot be hydridized." If not, the PI should consider the structure of pyridine.
- Lewis acid–base reactions make sense for alane stabilization. Previous work on $LiBH_4$ suggests it could work, as there is strong interaction between borane and N (in N-doped C). It is not clear whether the targets can be met with this system.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.1** for its accomplishments and progress.

- Early work shows success in preparation of the nanocarbon materials. Slit pore structures are formed and were confirmed using Brunauer–Emmett–Teller (BET) surface area analysis. $NaAlH_4$ and AlH_3 have been inserted into these pore structures. Preliminary data have revealed some issues that the PI is investigating: (1) oxidation occurring during transfer into measurement equipment, (2) solution nuclear magnetic resonance (NMR) imaging to reveal the structure of the alane and solvent, and (3) formation of AlH_3 on regions outside of the pore wall (likewise, the crystalline phase of this AlH_3 is not easily determined). It is very early in the performance of this research, and the early successes of isolating the relevant carbon material and insertion trials are highly commended.
- The project is quite new, and the researchers are already making good progress. They have employed several materials synthesis schemes designed to explore how to selectively incorporate most of the metal hydride within the nanoporous host. The team is doing the necessary initial characterization work to answer the key question as to whether the metal hydride has or has not been selectively infiltrated within the porous host. This determination requires careful characterization to distinguish "inside" versus "outside," and the researchers are making good initial progress here. As their discussions with HyMARC and HySCORE proceed, perhaps additional characterization approaches will arise that address the difficult question of whether the metal hydride is "in" versus "out."
- Good progress was obtained on demonstrating proof of concept. Further work is clearly needed to unambiguously assess whether alane is really in the pores and whether the majority of the AlH_3 molecules are in direct contact with the walls of the pores. NMR characterization was especially effective in isolating and identifying phases present in the functionalized materials. X-ray photoelectron spectroscopy (XPS) was useful in confirming the existence and bonding environment of N in N-doped carbon frameworks.
- All milestones appear to be on track. The team is focused. There has been good progress, especially with synthesis and characterization of two types of N-doped carbons and infiltration of alane. There is significant NMR work to investigate where AlH is going.
- Given the short time that this project has been underway, it is understandable that not much progress has been made. However, it appears that the project is becoming sidetracked by trying to dig evidence for low-level infiltration of $NaAlH_4$ "out of the weeds" rather than focusing on developing methods for higher levels of infiltration.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.5** for its collaboration and coordination.

- Beneficial collaborations are ongoing with investigators from the HyMARC core team, the HySCORE team, the National Institute of Standards and Technology (NIST), and the National Institute of Advanced Industrial Science and Technology (AIST). These collaborations have facilitated rapid progress on understanding the interactions between reactants and the functionalized C frameworks. The project is well coordinated, and the roles of external collaborators in reinforcing and supporting the effort are clearly stated.
- Collaborations on NMR with the University of Washington (Professor Conradi), the NIST Center for Neutron Research (Udovic), and AIST (Japan) for pair distribution function are already underway. There are planned collaborations with Sandia National Laboratories (SNL) (through HyMARC).
- A graduate student from the University of Missouri–St. Louis has already spent significant time at SNL working with HyMARC scientists on characterization and some work in the SNL high-pressure hydrogen reactor. The university also has had another graduate student spend time at NIST performing neutron scattering experiments via the HySCORE collaboration. As this project relies very heavily on advanced characterization, a greater breadth and depth of collaborations with the two consortia will likely ensue.
- The PI has assembled an excellent team of collaborators and appears to be establishing strong collaborations with the HyMARC core.
- The list of real collaborations (domestic and international) is excellent. The project is making good use of consortium resources.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.2** for its relevance/potential impact.

- This project combines, in a clever way, two fundamental areas that are prevalent in hydrogen storage research: (1) designing high-surface-area materials and (2) nanostructuring hydrides to alter their thermodynamic performance. Discoveries in either of these two areas will have broad-ranging impacts on sorbent materials for hydrogen storage researchers and on metal hydride and complex metal hydride researchers. It is likely that, through the HyMARC and HySCORE collaborations, novel measurement methods will also be developed. This project is poised to have large impacts on advancing the DOE Hydrogen and Fuel Cells Program (the Program) goals.
- The use of functionalized nanostructure templates as framework structures that may facilitate enhanced reaction kinetics in complex hydrides is novel and has potentially broad-ranging utility. This seedling project is an important element in the overall HyMARC portfolio; it directly complements and is supported by related work by the HyMARC core team. If the project is successful, the payoff could be large. It directly supports the goals/objectives of the Program.
- This project's strategy is to explore whether functionalization of nanoporous space can lead to enhanced hydrogen storage properties (e.g., thermodynamics, kinetics, and phase separation) by controlling the host–sorbate interaction to control the nanoscale features of a model metal hydride. If successful, this project will help to inform the community and HyMARC and support HyMARC's goals of developing a foundational understanding of key barriers to practical hydrogen storage materials.
- In many respects, alane represents an ideal solution to the hydrogen storage challenge. The major drawback remains its inability for direct recharging. This project is another installment in the quest to develop a direct alane synthesis. However, the relevance of this project is significantly reduced by the lack of even a suggestion of a viable path toward eventually producing a material with gravimetric hydrogen density that would meet the DOE targets with positive results being obtained.
- Although work is currently focused on alane, surface-functionalized nanoporous carbons could be more broadly useful for hydrogen storage. Careful synthesis and characterization work being performed here could be useful in other projects. Overall, it is difficult to see how this effort will have a significant impact on meeting the Program's goals. Even if successful, weight and volume penalty associated with a functionalized scaffold will likely result in a system that falls short of targets.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The future work is specific, logical, and in line with the project's stated goals. The PI should give some ideas on how these nanosized AlH_3 molecular islands will be stabilized (i.e., not transform or agglomerate) once the structures are formed.
- The future work is a direct and logical extension of the current studies. Identifying and implementing an efficient and unequivocal method for infiltrating reactants into the porous framework remain serious challenges. Although this is clearly recognized by the project team, a detailed strategy that will be employed to fully infiltrate the frameworks has not been provided. The use of ^{15}N labeled N-doped carbons for advanced NMR studies should be especially effective in helping to understand the details of binding and (possibly) transport of reactant molecules and whether the template atoms actually participate in the sorption reactions.
- The future work proposed follows on logically from the current status. A key short-term challenge remains in developing synthetic approaches to selectively sorbing the metal hydride within the nanoporous space and providing concrete characterization of the interaction. It seems that this must be accomplished prior to initiating the rather expensive ^{15}N labeled nanoporous host experiments. The inability to gain selective infiltration of metal hydride into the pores might result in materials wherein a mixture of "in" versus "out" convolutes the interpretation of results, hindering future progress.
- Models/estimates to predict the amount of loading (best case scenario) would be a good idea. Previous work has shown large amounts of amine required for one alane. High-pressure experiments should be interesting. It may also be worth looking into what happens to aluminum after dehydrogenation. For this system to work, the aluminum will need to remain near the N and not nucleate Al particles. This should be a priority once infiltration levels are optimized (overloading reduced).

Project strengths:

- A strong research and development team having expertise in all relevant areas is conducting the work on this project. Extensive and highly beneficial collaborations with HyMARC, HySCORE, and AIST are providing solid project support. A clear work plan has been formulated, and initial results are promising.
- The project is well connected to other efforts and nicely engaged with HyMARC/HySCORE partners. N functionalized C to stabilize alane is a neat idea, and capabilities developed under this effort could be useful in other projects. The effort is showing nice progress.
- The project, if successful, will offer a new paradigm in hydrogen storage materials design by nanostructuring the hydrides into isolated islands (a few molecular units in size) that are attached to the pore walls.
- This is a good team with excellent capabilities that is working with a good approach. The project is beginning good and important collaborations with HyMARC and HySCORE consortia.
- An excellent team has been assembled.

Project weaknesses:

- There are no major weaknesses of this project.
- The project has the overly soft Year 1 go/no-go milestone of just showing any degree of rehydrogenation of the infiltrated Al. This opens the door to paths to this project getting lost in the weeds: (1) a frequent problem in 27 Al studies of alane hydrogenation is that the signals for alane and aluminum oxides are in the same region, thus low levels of oxidation can be interpreted as low levels of hydrogenation—this could easily occur in the rush to clear a go/no-go decision, and 2) low levels of hydrogenation could be occurring only on the surface of the infiltrated Al. This is perhaps interesting but far from anything of value to the Program goals.
- The reason for selecting alane as the principal test vehicle for the functionalized carbon framework approach is not entirely clear. It would be useful if this issue could be clarified, and reasons for selecting alane over other (possibly more promising) alternatives could be articulated. Also, identifying and implementing efficient ways to infiltrate reactants into the framework without introducing unwanted

contaminants remains a daunting challenge. Additional detail should be provided concerning a proposed strategy for efficient reactant infiltration.

- A potential weakness lies in determining with high confidence how much of the metal hydride material is sorbed within the nanoporous space versus how much is adsorbed to the external surface. This may convolute the interpretation of experimental data going forward.
- It is hard to imagine how this approach could ultimately meet targets. Even with a small amount of C, one N would need to stabilize multiple AlH_3 units in order to get close to 5.5 wt.% (2020 target).

Recommendations for additions/deletions to project scope:

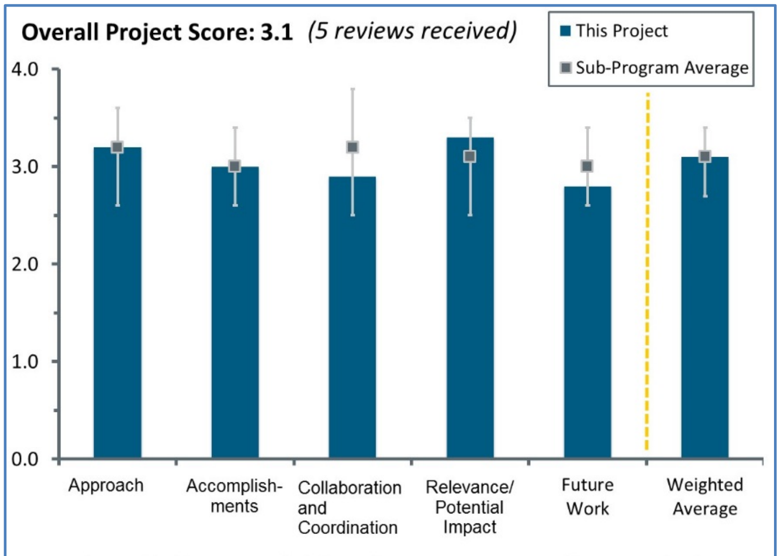
- The scope is appropriate at this stage of the research.
- It is probably worth making a rough calculation to see what the minimum realistic C and N contents are in these scenarios (it is hard to imagine more than 1 N per AlH_3, but maybe there is evidence out there). Based on this estimate, it is unclear what the likelihood of meeting targets is. It would be especially interesting/ useful to know what happens to Al after dehydrogenation. It is not clear if it stays put (near N) or nucleates an Al particle. It seems that any hope of reversibility will require the Al to stay near the N.
- It is unclear whether alane is the best choice for illustrating the power and impact of this approach. The project team is encouraged to consider other possibilities that may be more promising. (This should be done in consultation with the HyMARC core team and the DOE Program office.)
- The project's emphasis should be on finding methods for high levels of alane loading and useful levels of Al hydrogenation.

Project #ST-140: Hydrogen Materials–Advanced Research Consortium (HyMARC) Seedling: Developing a Novel Hydrogen Sponge with Ideal Binding Energy and High Surface Area for Practical Hydrogen Storage

Mike Chung; The Pennsylvania State University

Brief Summary of Project:

This project seeks to develop a new hydrogen sponge—a microporous polymer—that can simultaneously exhibit a hydrogen binding energy greater than 15 kJ/mol, a specific surface area greater than 4,000 m^2/g, and material density greater than 0.6 g/cm^3. A new class of boron-containing polymers with specific boron moieties and repeating microporous morphology will be designed, synthesized, and evaluated. Molecular simulation and advanced structural characterization will be conducted to support scientific understanding and further development of polymer materials.



The vertical hash-lines represent the highest and lowest average scores received by projects in the sub-program.

Question 1: Approach to performing the work

This project was rated **3.2** for its approach.

- The project's goal is to develop a new class of materials for sorption of hydrogen gases. These materials boast a 4,000 m^2/g surface area. Of particular interest is the ability to tune the pore sizes using boron additions onto the structure. An additional level of nanostructure design is achieved by changing the organic (-R-) spacer groups. Given the success of BC_x materials as sorbents with tunable binding energies (tuned by the B substitutions), organoborane polymeric structures is a next logical step for hydrogen storage research.
- The approach is worth pursuing: making a high-surface-area/porous polymer with enhanced binding that exposes these boron-doped sites that achieve the theoretical DH_{ads} values needed for room-temperature storage. The benefits of a material such as this and the motivation behind the approach are listed in the presentation.
- B-containing systems have long been sought as a means of minimizing the mass of adsorbents while perhaps offering higher adsorption enthalpies. As opposed to substitutional B in graphitic-like structures that have limited B solubility, this effort offers an alternative based on molecular design approaches.
- The approach looks reasonable. However, a high probability exists that the developed materials may not meet the expectations because of chemistry limitations (i.e., inability to obtain the desired structures) or low concentration of active hydrogen absorption sites in the polymer.
- This is a high-risk, high-reward project. The major risk centers on achieving a well-dispersed, high loading of B.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.0** for its accomplishments and progress.

- Current achievements in the project (six months in) include (1) some monomer and polymer synthesis and characterization and (2) preliminary hydrogen characterization using isotherms. Clearly, the time spent working on the project is a major hindrance to having greater accomplishments at the moment.
- The principal investigator (PI) has a long history of organoborane synthesis. For this project, several synthesis routes have been undertaken, and the organoborane structures have been verified using Fourier transformation infrared spectroscopy (FTIR) and nuclear magnetic resonance (NMR). Pore sizes have been determined using Brunauer–Emmett–Teller (BET) surface area analysis, leading the PI to declare some compositions as "no-go" because pores are too small. Plans for altering the synthesis chemistry (i.e., adding -R- linkers) to increase pore size are underway.
- The following refer to project accomplishments:
    - Two samples appear to have been synthesized and evaluated. While it is understood that synthesis efforts are difficult, there does seem to be some indication that, at least from a pore dimension standpoint, one material, B-PBS-300, has dimensions of relevance even though the surface area is small. On that basis, this is the system that should be the object of focus.
    - The data on slide 18 is problematic, as the difference between 0°C and 25°C data is much larger than one would normally expect. The curves also have unusual kinks.
    - There was an inference during the presentation that appropriate charge transfer along the CH chain is effected through an unterminated B, but during the question-and-answer session, it was less clear that this might be the case. If an unterminated B is necessary, this would be a fairly unstable material. It would be useful to have this clarified.
    - Thermal conductivity of these materials also needs to be considered. At 15–20 kJ/mole, substantial heat generation during hydrogenation would be expected. Polymers as a class of materials have limited conductivity, and this should be addressed at some point.
- This is a relatively new project. Progress to date has been satisfactory.
- It is not clear what the hydrogen absorption sites are that might allow the developed polymeric materials to meet performance expectations. The reaction course and the absence of B-H groups in the polymer before its heat treatment need to be addressed. The PI should provide evidence of boron's influence on the C=C bonds that may support the claim about enhanced absorption of hydrogen by unsaturated fragments of the polymeric framework.

Question 3: Collaboration and coordination with other institutions

This project was rated **2.9** for its collaboration and coordination.

- Excellent collaborations with the Hydrogen Materials–Advanced Research Consortium (HyMARC) and other partners are worth noting.
- There is satisfactory collaboration at this early stage.
- Collaborative efforts with the HyMARC/HySCORE teams have begun with BET, and surface area measurements were performed at Sandia National Laboratories (SNL) (Stavila). Other plans to collaborate with teams include computational research (with Lawrence Livermore National Laboratory) and adsorption isotherms (with SNL and NREL). The PI should consider other useful characterization tools that could be accessed, including x-ray photoelectron spectroscopy (XPS), which would inform about the electronic structures of the C and B species. X-ray absorption spectroscopy (XAS) could likewise be considered for giving similar information.
- The collaboration for uptake measurements really needs to take place with one of the HySCORE team laboratories that have expertise in adsorbent measurements. While NREL is listed on the collaboration slide, there was no mention of NREL involvement with this effort.
- It is still early in the project, but further collaborations with HyMARC are needed to speed up the characterization and theoretical understanding.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.3** for its relevance/potential impact.

- This project, if successful, will have an impact on the field of hydrogen adsorption onto lightweight materials. There are many efforts underway in the topic areas of (1) nano-BCx, (2) tailored nanopore geometries for sorbent materials, and (3) tailored nanopore geometry for insertion of hydrides. Success of (and findings from) this project will have an impact upon many researchers in (at least) these three areas.
- It was suggested during the presentation that a B-PBS-300 material had been prepared with a 2,600 m^2/g surface area. This would be an almost ideal surface area for this effort if validated.
- The project, as formulated, supports progression toward the Hydrogen and Fuel Cells Program goals and objectives.
- There is potential for high impact. The project is focused on relevant goals.
- Items that are perhaps of most immediate interest are:
    - Regarding maximum surface area, the PI clearly sees the difference between high surface area and low material density of metal–organic frameworks (MOFs) and the ideal material, but he needs to consider this in the context of volumetric capacities for his actual materials.
    - The project should develop methodologies such as scattering or positron annihilation spectroscopy to determine the porosity characteristics, especially the dead porosity.
    - It is unclear how much and what the speciation of active boron sites is. It is not clear whether polymer processing changes this distribution on heating. It is unclear whether the conjugation is better for the adsorption of hydrogen and whether it can be controlled. It might be difficult to distinguish B versus C=C as active sites. Perhaps a non-boron containing material should also be studied.

  Better isotherms are needed.
    - The temperature dependence of the uptake is not terribly encouraging. It seems to lose capacity very fast over 25°C. The project should work with NREL to get better isotherms and look at the uptakes at lower temperature using temperature programmed desorption (TPD). The B-PBS-300 should also be looked at to see the pore size dependence.

  Overall, the largest weakness in this approach is that the spatial density of boron seems small compared to the carbon scaffolding. It is unclear whether these materials can really reach DOE's goals. More theoretical efforts are needed here.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- The proposed future work is logical and has clear go/no-go decision points for the material systems. Because the HySCORE team program offers many materials characterization tools (beyond temperature programmed desorption), the PI should consider inclusion of one or more of them.
- Future work may benefit from adding tasks that address mechanism(s) of chemical transformations that take place during the preparation of polymeric materials and the chemistry/structure of hydrogen absorption sites.
- The use of any electron microscopy approach for observing micropore morphology would be pointless. These materials would not be stable under an electron beam and would suffer from both ionization and knock-on damage. Pore morphology is still best performed using BET/Horvath Kawazoe (or variant) approach.
- The presentation lacks details related to proposed future work, and perhaps working closer with HyMARC leadership can help speed progress.

Project strengths:

- The project really builds upon the PI's strength in boron organic chemistry and the promise of the BCx material systems to tune hydrogen binding energy to make a new polymer for hydrogen sorption. The tunability of the pore structure and the content of B, as well as the high efficiency and seeming ease of reaction, makes this project ideal for development of novel hydrogen storage materials.
- The approach is worth pursuing: making a high-surface-area/porous polymer with enhanced binding that exposes these boron-doped sites that achieve the theoretical H_{ads} values needed for room-temperature

storage. The benefits of a material such as this, and the motivation behind the approach, are evident and interesting.

- This appears to be an interesting class of polymer materials that are application-specific.
- Collaborations are certainly the project's major strength.
- The technology could be a breakthrough, if successful.

Project weaknesses:

- It is not clear what the hydrogen absorption sites are that might allow the developed polymeric materials to meet the performance expectations. Reaction course and the absence of B-H groups in the polymer before its heat treatment need to be addressed. The PI should provide evidence of boron's influence on the C=C bonds that may support the claim about enhanced absorption of hydrogen by unsaturated fragments of the polymeric framework.
- The largest weakness in this approach is that the spatial density of boron seems small compared to carbon scaffolding. It is not clear that these materials can really reach DOE goals. More theoretical efforts are needed here.
- The PI has not considered all available characterization tools that would be accessible through the HySCORE team.
- There are high risks. This is a challenging system.

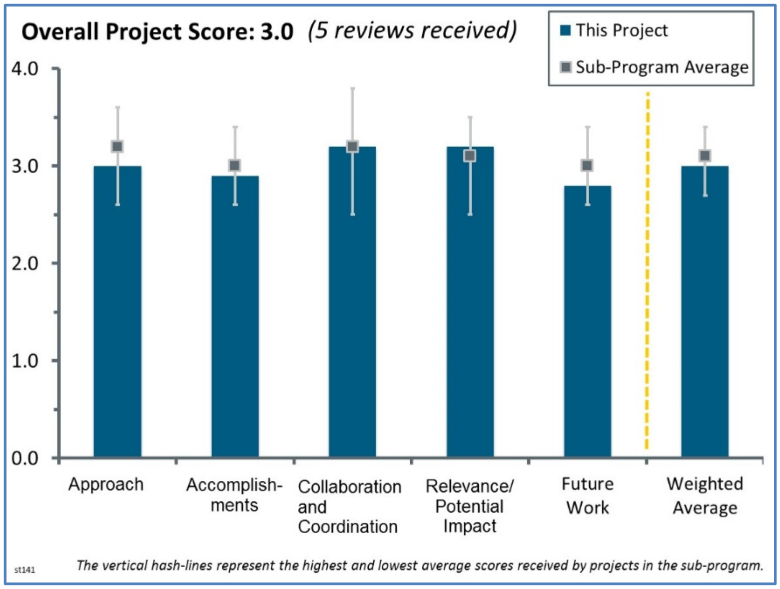
Recommendations for additions/deletions to project scope:

- XPS would be useful for understanding the binding environment and concentration of B in the final structures. Since XPS is a surface-sensitive technique, other techniques that yield similar data might also be accessible (e.g., soft XAS at Lawrence Berkeley National Laboratory is able to reach the B K-edge).

Project #ST-141: Integrated Insulation System for Automotive Cryogenic Storage Tanks

Barry Meneghelli; Vencore

Brief Summary of Project:



The project applies integrated cryogenic tank development approaches and novel technologies developed by NASA's Cryogenics Test Laboratory (CTL) to build an integrated subscale insulation system prototype demonstrating the DOE dormancy targets for a 100-liter cryogenic hydrogen storage tank for fuel-cell-powered automobiles. The approach leverages models developed by Savannah River National Laboratory (SRNL) and applies materials, technologies, and a system-level methodology developed by NASA's CTL to deliver a state-of-the-art advanced cryogenic storage tank concept for fuel-cell-powered vehicles. This approach addresses and mitigates the shortcomings of current multilayer vacuum insulation systems, including improved performance under soft vacuum conditions, for overall higher performance and durability.

Question 1: Approach to performing the work

This project was rated **3.0** for its approach.

- With a more general title for this new fiscal year (FY) 2017 project, "Integrated Insulation System for Automotive Cryogenic Storage Tanks," the primary focus is actually on assessments of methods to reduce heat leaks into the hydrogen storage volume of Type 3 and Type 4 vessels. Improved thermal management of these vessels, for both cryo-compressed hydrogen and cryogenic adsorbents, is very important in order to extend dormancy periods and minimize undesirable hydrogen venting. Key aspects of this project include modeling and simulation of various tank configurations and alternative insulating methods, which is being performed at SRNL. Thermal testing on various components and subscale vessels will be conducted mainly at the Kennedy Space Center (KSC) facilities. These measurements should provide valuable experimental results of predicted performance for different insulating designs and materials. Since only limited information is available in the general literature and past DOE Fuel Cell Technologies Office projects on options for cost-effective thermal management, this project should provide significant insights into whether thermally efficient cryogenic hydrogen storage systems can be made more practical and less expensive for vehicle applications.
- A system-level approach was used, which addressed the concerning issues. The project is well designed and had different cryogenic systems to characterize the heat loss and thermal conductivity.
- The use of both modeling and prototype testing is important to addressing the issues of dormancy in tanks. The experimental work can validate the model, and then the model can be used to identify the primary heat leakage pathways and where additional research must be done to meet the DOE targets. The model may also elucidate the areas where additional research will not yield significant improvement.
- The approach of this project is not clear regarding addressing the issue with vacuum stability. It is helpful to have a system approach, although the project does not have a specific plan to improve vacuum stability. The project work seems to be focused on the characterization of the current status rather than developing an improved approach. The project should not have included or considered Type 4 for this effort.

- The authors chose 0.1 Torr as the design vacuum quality, and this election seems artificially low. It is not clear why the authors selected this value. In reality, composite resins are quite volatile and will raise the vacuum pressure to higher values.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **2.9** for its accomplishments and progress.

- Good progress has been made toward the goal. The project has good systems in place for measurements through its cryogenic series.
- Since this project started in FY 2017, most progress has been in the development and implementation of cryogenic hydrogen system designs and intensive thermal performance modeling. Both thermal insulating aerogels and prototype reduced-scale Type 3 vessels have been provided by team partners (i.e., Aspen Aerogels and Hexagon Lincoln, respectively) for laboratory assessments. Initial test results were reported at the DOE Hydrogen and Fuel Cells Program Annual Merit Review (AMR) for the thermal conductivities of several aerogels, and preparations are apparently in progress to test thermal properties of the vessels shortly. It is currently too soon to compare the results of these first tests with model predictions and to the DOE targets. Presumably, sufficient information will be available by September 2017 to hold a decisive go/no-go review on whether improved thermal isolation can be achieved. On the other hand, one aspect that was only briefly mentioned during the AMR presentation/slides was related to the outgassing behavior of the insulation materials and vessel walls on degradation of the thermal isolation behavior with both time and temperature. This issue does merit close scrutiny.
- The project is relatively new. As a result, the accomplishments include only data mining, obtaining insulation materials and tanks, and initiating the development of a model. One concern is that the insulation materials identified to date from Aspen Aerogels do not meet the targets selected. The insulation materials need to be much better than what has been evaluated to date, especially in light of the challenges in maintaining vacuum on the system.
- This project is relatively new, although it still should have made further progress based on the extensive experience of NASA in the area of cryogenic insulation.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.2** for its collaboration and coordination.

- The collaborators on this project are one of its strengths. By involving insulation and tank manufacturers and NASA with its experience in cryogenic storage, the project should be able to pull in the right expertise to address issues and identify opportunities.
- There appear to be very cooperative interactions among the technical partners of this team, especially on design and modeling of the cryogenic vessels and insulation requirements. The NASA/KSC testing program is being provided suitable and representative materials and prototype vessels from the partnering commercial vendors. Presumably feedback from the thermal modeling simulations and laboratory tests is being provided in return. However, there seems to have been little or no direct contact with several outside organizations (i.e., the relevant research groups at Lawrence Livermore National Laboratory [LLNL], Argonne National Laboratory, and BMW) that have been heavily involved in cryo-compressed hydrogen prototypes.
- The project collaboration among the partners is good, although the project would benefit from collaborating with institutions involved in developing cryo-compressed systems, such as BMW and LLNL.
- The project needs to collaborate more with cryogenic tank and balance-of-plant equipment manufacturers to find out where heat losses need to be further reduced.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.2** for its relevance/potential impact.

- Very high thermal isolation of the cryo-compressed or cryo-adsorbed hydrogen contained within storage vessels is crucial for extending dormancy and overall efficiency of these tanks. Performance levels are improved by using insulators with very small thermal conductivities, as well as minimal outgassing that would reduce vacuum levels that lead to thermal shorts. Highly insulating materials that are also inexpensive would enhance volumetric and gravimetric densities and lower total system costs.
- The project addresses a highly relevant topic related to vacuum stability, which is needed to advance the feasibility and robustness of a cryo-compressed hydrogen tank concept. This project should keep focused on the key barrier of vacuum stability and provide solutions with this impact, rather than being distracted by other efforts.
- There is a significant need to validate the DOE technical targets relative to dormancy with cryogenic hydrogen storage. This work may be able either to confirm the validity of these targets or to guide DOE in the development of new, more reasonable targets.
- Improved thermal insulation under a rough vacuum is a key problem for cryogenic hydrogen storage. This is a problem in desperate need of a solution.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- The team provides a reasonable and realistic plan to assess some critical components via laboratory testing, along with completing a full-scale design with an optimized configuration that should minimize thermal leaks into the storage volume. Fabricating and testing a subscale prototype vessel designed with these features would be an excellent goal before the FY 2018 AMR. Detailed comparisons with the thermal modeling predictions for the specific prototype vessel will be especially important to validate whether practical cryogenic hydrogen storage can be achieved.
- The future work was well-planned and -articulated.
- The future work provides general tasks but could include specific steps toward improving the vacuum stability.
- It is not clear what components are going to be tested, other than insulations in the cryostats. It is unclear whether there are plans to select and evaluate structural components such as support rings and penetrations. The future plans should have been better described. There are also plans to update the system based on cost. It would seem that efforts should be made to achieve the required dormancy before ruling out components because of their cost. It would be beneficial to discuss how the model and experimental work will interact as part of the project's proposed future work.
- In slide 13, the authors marked a "sweet" region in pink where the thickness requirement can be met. However, for the expected vacuum quality (pressure >0.1 Torr), there is nothing that can deliver the necessary insulation power. When the presenter was asked about it, he said that the plan was to ask Aspen Aerogels to deliver an improved insulation that would meet the target at the necessary conditions. This is, however, a very difficult proposition since there are fundamental reasons why insulation performance decreases with vacuum. It seems, therefore, that the team is depending on Aspen Aerogels to deliver a miracle for this project to succeed.

Project strengths:

- The team assembled for this project brings diverse, high-quality expertise to bear on the thermal management issues for cryogenic hydrogen storage systems. The thermal design and modeling capabilities at SRNL continue efforts that were part of the recently finished Hydrogen Storage Engineering Center of Excellence (HSECoE) program, while NASA/KSC and Vencor provide the capability for intensive experimental testing of cryogenic components and prototypes. The commercial partners Aspen Aerogels

and Hexagon Lincoln manufacture appropriate cryogenic insulating materials and hydrogen storage tanks. Hence, separate skills and capabilities have been assembled for this project. This is a strong technical team to identify and evaluate better insulation materials and configurations for cryogenic hydrogen storage.
- The project strength is the access to NASA's previous material test information and cryogenic test equipment. The SRNL system modeling and previous experience as part of the HSECoE is also a strength.
- This work is definitely needed if DOE is to continue to consider cryogenic hydrogen storage as a viable alternative to pressurized gas storage.
- Project strengths include good methods of characterization of heat losses and good progress on milestones.
- This is a good team of insulation experts.

Project weaknesses:

- While the technical team is quite strong for investigating issues for the development of improved cryogenic containment systems, the inclusion of the organizations Energy Florida and IBT for commercialization and marketing activities seems premature at this stage. If there is a useful role for these organizations, it should be better explained.
- The project weakness is that this project does not have a clear concept to resolve the main barrier of vacuum stability. This project also has a weakness in the area of partners with direct experience with cryo-compressed tanks.
- It would help to break down the system sensitivity of each component. This project needs more collaboration with the end users.
- There is not a clear plan to address the outgassing of Type 3 or Type 4 tanks in an effort to maintain the required vacuum to achieve the low heat leakage.
- This project seems to depend on Aspen Aerogels' developing a whole new insulating material to meet this target. This seems very difficult and most unlikely.

Recommendations for additions/deletions to project scope:

- The team assembled for this project brings diverse, high-skill expertise to bear on the thermal management issues for cryogenic hydrogen storage systems. The thermal design and modeling capabilities at SRNL continue efforts that were part of the recently finished HSECoE program, while NASA/KSC and Vencor provide the capability for intensive experimental testing of cryogenic components and prototypes. The commercial partners Aspen Aerogels and Hexagon Lincoln manufacture appropriate cryogenic insulating materials and hydrogen storage tanks. Hence, separate skills and capabilities have been assembled for this project. This is a strong technical team to identify and evaluate better insulation materials and configurations for cryogenic hydrogen storage.
- The project should make connections with organizations that have cryo-compressed tank experience to gain lessons learned rather than conducting their own characterization. The analysis of dormancy in the past has shown that physical insulation is unable to meet the dormancy and volumetric density targets. Therefore, this project should acknowledge this past analysis and focus on vacuum insulation rather than physical insulation. The recommended target insulation thickness of 23 mm should be reduced since it is significantly higher than existing cryo-compressed demonstration systems.
- It seems that the modeling is unnecessary. The effort should be focused 100% on finding the magical material that falls within the pink zone of Figure 13.
- The project should use its system to analyze different cryogenic systems and work with DOE laboratories that are doing plenty of analysis in this area.

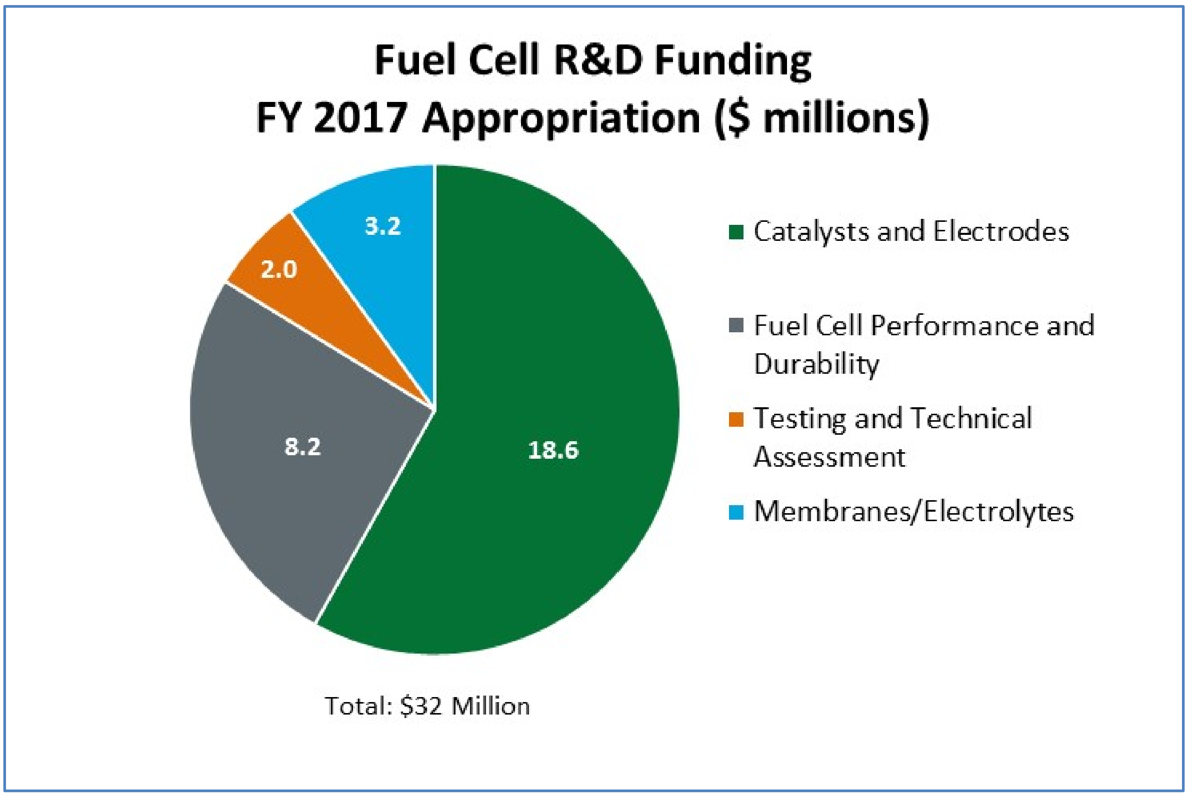
2017 – Fuel Cells
Summary of Annual Merit Review of the Fuel Cells Sub-Program

Summary of Reviewer Comments on the Fuel Cells Sub-Program:

Reviewers commented that there was a good balance between near-, mid-, and long-term research and development (R&D) in the Fuel Cells sub-program, and they agreed that cost and durability are the major technical challenges. Reviewers praised the sub-program's approach to identifying and addressing these issues and noted its well-structured, collaborative, and well-managed projects as a strength. In particular, the consortia established by the sub-program, the Fuel Cell Consortium for Performance and Durability (FC-PAD) and the Electrocatalysis Consortium (ElectroCat), were lauded for their potential to transform fuel cell technology. Key recommendations included (1) increasing focus on technologies that will build on progress achieved thus far, particularly in fuel cell performance; (2) conducting more scaled-up analysis of performance and durability at the stack and fuel cell levels; (3) developing better transport properties for platinum-group-metal (PGM)-free catalysts and a better understanding and characterization of novel membranes; and (4) establishing clear and ambitious go/no-go criteria to enable ending projects that do not meet these criteria. Several reviewers encouraged continued and increased collaboration with relevant consortia and key industry partners such as 3M, General Motors, and others.

Fuel Cells Funding:

The sub-program received $32 million in fiscal year (FY) 2017. The sub-program focuses on reducing fuel cell costs and improving durability. Efforts included approaches that will achieve increased activity and utilization of low-PGM catalysts, PGM-free catalysts for long-term applications, ion exchange membranes with enhanced performance and stability at reduced cost, improved integration of catalysts and membranes into membrane electrode assemblies (MEAs), and advanced fuel cell performance and durability. There was no funding in FY 2017 for balance-of-plant (BOP) component projects.



Majority of Reviewer Comments and Recommendations:

At this year's review, 39 projects funded by the Fuel Cells sub-program were presented, and 35 were reviewed. Projects were reviewed by between four and eight reviewers, with a median of six experts reviewing each project. Reviewer scores for these projects ranged from 2.5 to 3.5, with an average score of 3.1.

Catalysts and Electrodes: The scores for the 12 catalyst projects ranged from 2.5 to 3.5, with an average of 3.1. Reviewers praised the highest-rated project for its progress on improving the lifetime durability of PGM-free catalysts and the strength of its collaborations with university and industry partners. Reviewers recommended that the project increase its focus on longer-term durability testing of new catalysts. For the lowest-scoring project, reviewers noted fundamental flaws in the approach used to characterize the support stability of the platinum catalysts, citing a need for better understanding. Reviewers also expressed doubts over the project's overall relevance to meeting U.S. Department of Energy (DOE) fuel cell targets.

Fuel Cell Performance and Durability: The seven projects reviewed in this area are all part of FC-PAD, including the consortium overview. All projects scored above 3.0, with a range from 3.1 to 3.4 and an average of 3.3. Reviewers praised the highest-rated projects for their focus on component degradation characterization and electrode optimization, the strength of the teams and their access to a large number of characterization tools, and the design of their approaches. However, reviewers noted that the projects will face challenges if they do not foster stronger collaborations with suppliers, other DOE-funded projects, and original equipment manufacturers. Reviewers felt that the lower-scoring projects demonstrated strong project teams and that their approaches were reasonable, but identified the need to transfer rotating disc electrode findings to useful results at the MEA level.

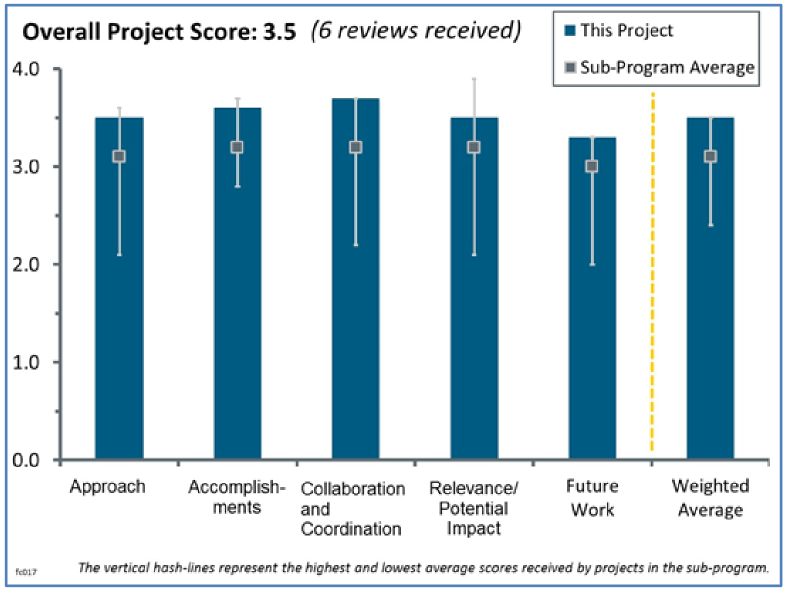
MEAs, Cells, and Other Stack Components: Two projects were reviewed in this area, with one project receiving a score of 3.1 and the other receiving a score of 3.2. Reviewers felt the highest-rated project, which focused on novel bipolar plate development, utilized a sound cost-analysis-based approach and effective partnerships to achieve targets. However, reviewers expressed some concerns over the scalability of spray-coating for pre-stamped plates and suggested future work focus on analysis of a fully scaled-up system. For the second project, associated with dimethyl ether (DME) fuel cells, reviewers found the approach to be sound but noted that the project lacked a demonstration of the PtRuPd catalyst and remained short of stated targets. It was noted that the potential applications of high-temperature DME cells could help meet DOE's strategic goals but do not support specific polymer electrolyte membrane fuel cell development targets.

Membranes/Electrolytes: The four membrane projects reviewed received scores between 3.0 and 3.4, with an average score of 3.2. The highest-rated project, focused on developing improved anion-exchange membranes (AEMs) and MEAs, was one of the highest-rated in the sub-program, and reviewers commended the innovative approach to studying alkaline membranes, recognizing real progress in in situ testing. They suggested that future work focus on PGM-free rather than low-PGM catalysts. The other alkaline membrane fuel cell project also received praise from reviewers for producing stable membranes by eliminating sulfonamide linkages. It was suggested that the project place more focus on cost and performance. For the lower-rated project, focused on AEMs for high-voltage redox-flow batteries, reviewers found the project's approach reasonable and noted improvements in stability and progress toward other targets. Reviewers were uncertain about the project's relevance to Fuel Cell sub-program goals, given its focus on redox flow batteries, but noted that it could yield benefits in advancing hydroxide membrane technology. Recommendations included focusing future work on testing and improvements in high-temperature fuel cells.

Testing and Technical Assessment: Four projects were reviewed in this area and received scores between 3.0 and 3.4, with an average score of 3.3. Reviewers lauded both of the highest-rated projects for the variety of interesting and helpful findings that can help set realistic DOE cost targets and goals. Both projects were urged to continue work in analysis at the fuel cell system level. Reviewers commented that the lower-rated project was reporting impressive imaging advancements, but the improvements had not been directly linked to specific DOE goals and targets.

Project #FC-017: Fuel Cell System Modeling and Analysis

Rajesh Ahluwalia; Argonne National Laboratory



Brief Summary of Project:

The overall objective of this project is to develop a validated system model and use it to assess design-point, part-load, and dynamic performance of automotive and stationary fuel cell systems. Argonne National Laboratory (ANL) will support the U.S. Department of Energy (DOE) in (1) setting technical targets and directing component development, (2) establishing metrics for gauging progress of research and development projects, and (3) providing data and specifications to DOE projects on high-volume manufacturing cost estimation.

Question 1: Approach to performing the work

This project was rated **3.5** for its approach.

- This project is certainly valuable to DOE and to Strategic Analysis, Inc. (SA) in helping to evaluate the impact of various cell materials and design options. It is unlikely that any fuel cell OEM is actually interested in these results, since OEMs have their own models that enable them to do this type of analysis. However, it is very important for the entire fuel cell community to be aware of system-level implications of various design/material options, so this project is certainly worth the modest budget.
- ANL employs a sound approach in developing and validating robust models for system design and analysis, which are predictive in nature and made available to the greater community.
- The team has developed a validated systems model that is essential to allowing DOE to guide component targets and project success and allows for high-volume manufacturing costs to be estimated.
    - The approach used in this project is relevant and ambitious. The developed model at the system level is able to achieve cost and durability projections, even if more degradation mechanisms and their impacts on durability should be studied and taken into account in the model.
    - A very good point of the developed tool is that different electrode structures and different catalysts have already been evaluated. Among them are recent developments and collaborations with other ongoing projects. This shows the ability of the developed tool to be updated and refined by integrating recent achievements, even if it does not prove the tool's versatility.
    - ANL does not address some aspects such as the validity of the passage from small-size cells to the expanded polarization and the applicability of results outside of the operating conditions and configurations used in the differential cell. This is important to address because the entire tool relies on this model. The investigators may also address the question of how to validate the durability projections at the system level when only individual components are optimized, and when system designs, architectures, and control are different from one original equipment manufacturer (OEM) to another. There is a lack of real validation with real systems.
- The goal of this task appears to be a detailed fuel cell system model to assess the effects of changing certain design parameters such as catalyst type, catalyst loading, membrane thickness, etc. If this assessment is accurate, then the effort is worthwhile.
- Received performance data are clearly analyzed, and the existing model parameters are fitted accordingly, thus enabling performance forecasts when altering operating conditions—it is not always clear whether these projections have been validated as well.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.6** for its accomplishments and progress.

- ANL reported on an impressive range of achievements that include predicting stack performance of de-alloyed PtNi/C, analyzing conditions under which humidification could be eliminated, exploring the application of pulse ejection, and evaluating the impact of increased stack inlet pressures. These results were much broader in nature than last year's scope and show great progress toward providing both specific predictions and suggestions for improvements in stack efficiency and cost.
- This is an excellent study of catalyst systems in the stack in collaboration with industry stakeholders and national laboratories. The partners are continuing to look at air, water, heat, and fuel management in the system to improve efficiency and cost.
- Several accomplishments were in line with the fiscal year 2017 planning. The comparative performance study of different state-of-the-art membrane electrode assemblies (MEAs) with Pt, Pt-alloy, and de-alloyed Pt-alloy catalysts provides valuable input to the industry. Good performance and cost targets were shown for the de-alloyed PtNi/C. However, investigation of the impact of the Ni loss degradation mechanism on not only performance but also long-term operation durability is very relevant and must be integrated in the model.
- The results of the performance degradation study help in understanding the breakdown of the contributions to the voltage loss. This is a good step; however, this part must be continued by including all the aspects and issues linked to the system (degradation mechanisms at stack level resulting from balance-of-plant [BOP] components, interaction between these mechanisms, and varying operating conditions/load profile).
- Many interesting results were generated over the past year, and the principal investigator is clearly responsive to suggestions. The emphasis on low-volume cost is very good.
- There has been clear progress toward comparative performance evaluation between four state-of-the-art MEAs with different catalysts. There is additional emphasis on the influence on operational conditions but no work mentioned (yet) on the updated projected durability relative to the life target of 5000 hours in the submitted version of this presentation (April 2017).
- The model is impressive, and some of the results given are interesting, such as the catalyst cost and degradation estimates. Other results are more confusing. For example, UTC Power was fielding hardware with anode recycle blowers in 1998 and pulse-width-modulated fuel injection circa 2010.
- It appears that the model results are being benchmarked, but this is unclear.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.7** for its collaboration and coordination.

- The collaboration and coordination with other institutions are excellent and well balanced. The collaboration includes industry (component suppliers and OEMs), laboratories, and other consortia. The component suppliers and OEMs provide data to continuously refine the developed tool and to validate it. They also provide guidance/feedback to be continuously in line with the industry needs. Having different suppliers helps the versatility of the developed tool. The collaboration and involvement in other consortia allow use of the tool in the most recent component optimization.
- ANL continues with its impressive list of collaborations, engaging with various Fuel Cell Technologies Office (FCTO)-sponsored partners and other industrial collaborators. The nature of the engagement between this project and the Fuel Cell Consortium for Performance and Durability (FC-PAD) could be more clearly defined.
- There is a large number of collaborators including component suppliers, OEMs, universities, and national laboratories.
- There was excellent collaboration with multiple partners, especially SA. However, more collaborations with OEMs to obtain stack and/or system data could be very beneficial.
- The level of collaboration and coordination appears appropriate for this type of project.
- The information provided was not made public for all partners separately but appears to be fully integrated in the model. Comments or feedback on the fit between model and original data would be appreciated.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.5** for its relevance/potential impact.

- A generic (versatile) multi-scale model for assessing the impact of component change at the system level that allows fuel cell system performance, cost, and durability assessment is a powerful tool for industry, laboratories, and the DOE Hydrogen and Fuel Cells Program (the Program). This model allows evaluation of performance, durability, and cost for new materials, components, architecture, and operating conditions for a fuel cell system at low cost, without running long-term testing. It is also a good tool to guide the industry's technical choices regarding the cost/performance and durability targets. The tool is not complete, and its validation is not achieved. Calibration is needed upon each new component assessment.
    - The project results are key inputs for the Program. Evaluating performance, durability, and cost for fuel cells will allow DOE to assess the advancement of the technologies and correlate their current status with the set of objectives and the means to achieve them (funding). Knowing this, DOE can update its objectives and targets more precisely and efficiently.
- The project is relevant in its role of predicting and directing stack development and DOE targets. Further validation or adoption of the various system-level predictions made in the presentation will solidify the relevance of the modeling work by ANL.
- The major impact here is on helping DOE and the entire fuel cell community understand the cost status (with SA), which is very important. The impact would be higher if ANL could show that their models have been validated at a stack and/or system level since there is always a large degree of skepticism with an unvalidated model.
- This project addresses multiple barriers including cost, performance, thermal and water systems management, air management, and start up/shut down. As such with a validated system model, its impact across the FCTO Multi-Year Research, Development, and Demonstration Plan is very high and is an essential component.
- Performance boosting and problem solving could be made more insightful when such a model is made accessible to the wider community.
- The project appears to be relevant, although this type of work is usually done by the fuel cell developer and not a national laboratory.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- ANL proposes to continue the excellent work that has been started. It is very nice to see that more durability will be included in the future.
- The proposed future work listed by the project team is in line with the results shown.
- The proposed future work is almost verbatim from the previous year's presentation; more thought should be invested here. Validation against a full stack system might be a good addition. Future plans should also include the ongoing development and dissemination of the ANL General Computational toolkit (GCTool) software package, which is a key component of the project approach.
- This future work is good, but ANL should add model validation at stack and/or system level.
- ANL provided a comprehensive list to achieve maximum performance, seemingly not considering stability issues.
- The future work appears to be appropriate.

Project strengths:

- The proposed tool is powerful for assessing the fuel cell system performance, durability, and cost for different components at the stack or system level. It should be applicable independently of the component, the application, the operation condition, or the system architecture and design (versatile). Another strength is that the good communication and different collaborations allow the tool to integrate large data sets and

feedback from different technology suppliers and users. Strong communication with other ongoing DOE projects allow refining of the model with the most recent developments (materials) and achievements (modeling).
- ANL continues to be engaged in very strong collaborations involving topics highly relevant to the Fuel Cells sub-program.
- The transparency of system-level performance and cost implications of various materials and design options is a project strength.
- A strength of the validated system model is that it can be applied from component, modeling analysis, stack, and system levels.
- The skills of the national laboratory have shown themselves to be a project strength.
- This model is solid, based on data.

Project weaknesses:

- The following are project weaknesses:
    - One weakness is the wide range of explored topics and the difficulty in assessing the final objective (fuel cell system performance), taking into account the interactions between individual components as they are optimized.
    - The project relies entirely on the developed model. Therefore, the validity of the passage from small cell operating condition to extended polarization should be addressed.
    - The model should include the degradation and aging mechanisms at the stack and system levels.
    - There is a lack of validation on real systems.
- It is not clear why a national laboratory is developing a fuel cell system and design tools. This is normally intellectual property (IP) for an OEM. It is unclear who has direct access to the results and whether they are considered IP.
- This work includes a system-level model that has not been validated at a system level, or even at stack level.
- Areas of uncertainty are not obvious.

Recommendations for additions/deletions to project scope:

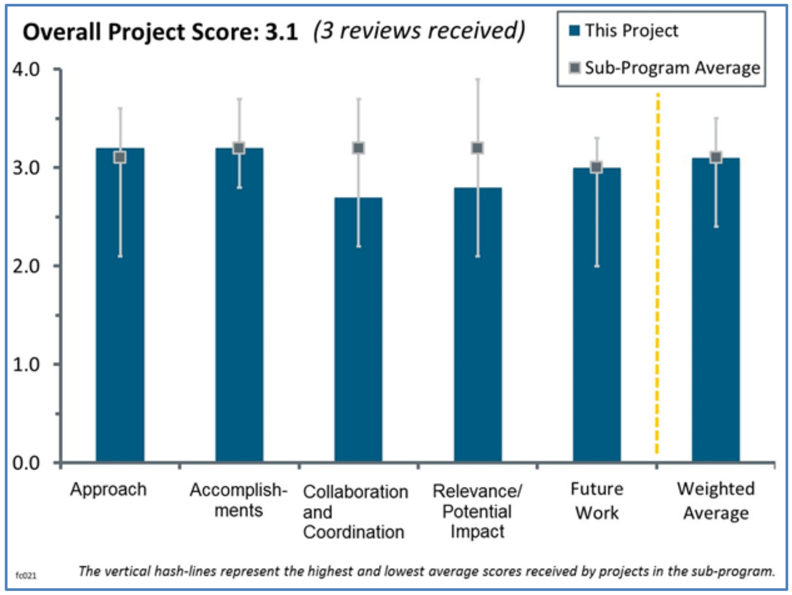
- The project team should keep the driving objectives at the system level. That will help to lower the number of possibilities and save time and effort in exhaustive component evaluation. Durability studies must be continued and completed with degradation mechanisms, impacts on performance, and aging. Including new stack and BOP component suppliers is relevant.
- General Motors should be persuaded to share stack or system data (which could be done under a non-disclosure agreement) to validate ANL's model under at least a few key operating conditions with at least one system-level configuration.
- The project team should rethink how to protect the laboratory from perceived threats from the marketplace.
- Projections toward lifetime vs. performance would help highlight the best mode of operation.

Project #FC-021: Neutron Imaging Study of the Water Transport in Operating Fuel Cells

David Jacobson; National Institute of Standards and Technology

Brief Summary of Project:

The objectives of this project are to (1) study water transport in single cells and stacks, (2) enable the fuel cell community to study water transport phenomena using state-of-the-art neutron imaging, (3) tailor neutron imaging to the needs of the fuel cell community, and (4) improve the spatial resolution to provide more detail of the water content in commercial membrane electrode assemblies.



Question 1: Approach to performing the work

This project was rated **3.2** for its approach.

- The National Institute of Standards and Technology (NIST) maintains a national user facility for neutron imaging of water transport in operating fuel cells. NIST pursues facility improvements through collaboration and feedback with testing partners and the fuel cell community. NIST provides free access for open research or fee-based access for proprietary research. NIST operates the neutron imaging facility and test stands in a user-friendly environment.
- The work that the project team is doing is fantastic, but as the team members admit, they are nuclear physicists looking at fuel cells. As such, it is ever more important that they have close ties and connections with those doing the work in fuel cells, particularly the original equipment manufacturers, but these interactions seem weak at best. It is hard to know the problem that they are solving. In that regard, they are doing brilliant work to improve resolution, but it is not at all clear what that increased resolution will buy the fuel cell community or the problem that it is trying to solve. Karren More's work would provide the obvious blueprint for their interaction, but there must be just as much of a call for this resource.
- Intention and implementation is clearly focused on providing the best tool for imaging in situ fuel cell conditions, moving beyond current limitations and incorporating backup plans.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.2** for its accomplishments and progress.

- The work the project team is doing is excellent. The progress toward project targets is good but is very loosely linked to DOE goals. The potential certainly seems to be there, and the investigators cite the work with General Motors to shed light on cell corrosion as a good example of how it could work.
    - There was really nothing here except a demonstration of what the technology can do using baseline materials.
- Despite some delay in the work as explained by the team, the presenter clearly presented how progress was made on centroids and why this was important, and advances in further improving timescale of measurement.

Question 3: Collaboration and coordination with other institutions

This project was rated **2.7** for its collaboration and coordination.

- NIST listed a number of partners, users, and collaborators from academia, national laboratories, and industry. The last call for proposals received six new submissions for fuel-cell-related projects.
- There is a clear focus on the needs of the community.
- This is the weakest part of the project. Normally there is not as much weight placed on the collaboration rating, but this project can have an impact only if there is strong collaboration. It is hard to see where collaboration exists here, especially outside of the national laboratory community.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **2.8** for its relevance/potential impact.

- This project is actively engaged in developing state-of-the-art neutron imaging capability for fuel cells and making it available to the community of fuel cell researchers and developers. The latest call for proposals received six new submissions. Experiments planned for summer 2017 will investigate electrolysis, solid oxide fuel cell, alkaline electrolyte fuel cell, and polymer electrolyte membrane contaminants.
- A highly specialized tool has been developed, enabling users to visualize the situation at hand in great detail. It could gain further value by providing insight into off-spec conditions that may occur and cross-correlate these with other characterization measurements such as electrochemical impedance spectroscopy so that researchers can identify, recognize, and visualize problems without being in the beamline themselves.
- The investigators need to work harder to make their work relevant. Having a stronger interaction with someone whose main focus is fuel cell performance would be a big improvement. It would be better if the project was led by someone in the fuel cell community.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- Enhanced resolution in experiments taking less time is welcome, as are more measurements to ensure reproducibility under fuel cell operating conditions.
- The main focus is on further increasing resolution, but the rationale for why this is important has not been presented. The investigators mention that there will be more demand if they improve the resolution or decrease the sample time, but it is not clear why. For example, with 2 µm resolution on a 5-s time scale, we could observe water formation and release from the catalyst layer and determine the time and length scale on which this occurs. NIST needs a compelling reason to further improve the technique; otherwise, efforts should be more focused on outreach and using current tools.
- Owing to unexpected delays at NASA, the target completion dates in the ongoing project on the neutron microscope to reduce the image acquisition time to 10 s for 20 mm spatial resolution and to improve the spatial resolution to 1 mm with 10-minute acquisition time have been postponed to 2020 and 2021, respectively.

Project strengths:

- NIST has fantastic imaging capability. There is great work on the physics and improving characterization capabilities.
- NIST has a unique facility, staff capabilities, and experience.
- NIST provides a unique facility that is open to the entire community, encouraging learning from the field.

Project weaknesses:

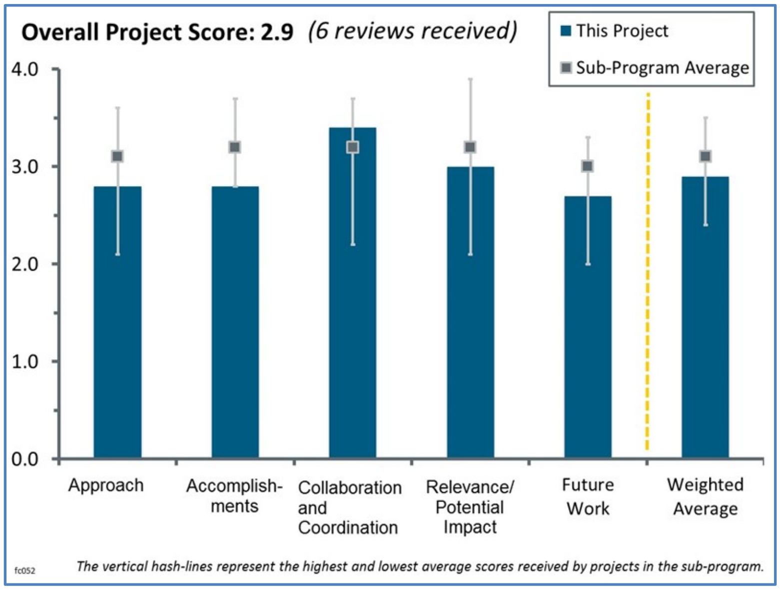
- Collaboration needs improvement. This project works only if the researchers are intimate with the challenges and problems in the fuel cell community and how the researchers can help.
- The localized analysis needs to be representative for a situation under evaluation, which is always a question.

Recommendations for additions/deletions to project scope:

- The team should not focus on continual improvement of the device, but should work with those in the fuel cell arena to ensure that the team's work is relevant.
- The vast number of achievements and results need to be easily accessible to educate and inspire users to submit more compelling proposals.

Project #FC-052: Technical Assistance to Developers

Tommy Rockward; Los Alamos National Laboratory



Brief Summary of Project:

Los Alamos National Laboratory (LANL) will test catalyst materials and participate in the further development and validation of single-cell design and test protocols. LANL will also provide technical assistance to working groups, the U.S. Council for Automotive Research (USCAR), and the USCAR/U.S. DRIVE Partnership Fuel Cell Technical Team.

Question 1: Approach to performing the work

This project was rated **2.8** for its approach.

- The aim of the project is for the LANL group to provide technical assistance to the testing and validation of materials, to validate single-cell test protocols, to assist durability working groups, and to make technical expertise available to the U. S. Department of Energy (DOE) and the Fuel Cell Technical Team. The proposed approach is rational but requires improvement.
    - The strength of this project is the utilization of a combination of sputtering systems, which, in combination with physical vapor deposition (PVD), provides sufficient knowledge to create unconventional classes of coatings with desired thicknesses and other properties.
    - The approach to characterizing low-platinum-group-metal (PGM) catalysts should be improved. Simple testing provides no information on the interesting activity and stability of these materials. Furthermore, the proposed approach for probing the "mechanism" that governs the activity of non-PGM materials is insufficient for such an ambitious task.
    - It will be very important to expand this project to provide concrete information about the differences and similarities between rotating disk electrode (RDE) performance and performance in real fuel cells, which is a subject about which the fuel cell community has still not found any final answers. The principal investigators (PIs) should consider pulling together experts in both RDE and fuel cell testing to address this important issue.
    - Given that the project deals with the stability of both the active and supporting materials, the PIs should consider utilizing inductively coupled plasma-mass spectrometry methods to quantify the dissolution rates of their materials.
- LANL does careful work, primarily in response to fuel cell community requests filtered through DOE and to address important controversial questions, such as whether oxygen reduction reaction (ORR) activity of non-Pt catalysts correlates with the reduction–oxidation reaction (redox) potential.
- The potential overall impact of this kind of service project is less than that of more tightly focused laboratory projects properly coordinated with industry. The PVD efforts and the fuel cell/catalyst work are so different that they should be undertaken under separate projects to allow for improved direction and review.
- The approach for this project is not leveraging the resources and technical know-how of the national laboratories but is instead acting as a service provider for technical developers. There is no transparency in which projects/topics get selected. This project should be ended in fiscal year 2017. A completely alternate approach to the developer can be established by:
    - Creating an online portal for accepting incoming requests from developers
    - Understanding how the developer is willing to pay for using the national laboratory resources
    - Identifying the technical benefit of the project to DOE goals

- Overall, the approach is to help those in the field to access capabilities that they do not have. However, the selection process was not clear, nor was whether the work provided is addressing critical barriers. It would be good to see how many new projects and carryover projects there are per year, including those that were not selected.
- It is not really clear how this work necessarily makes significant contributions to key barriers, nor how what is done is decided (besides the statement that assistance is “as directed by DOE”).

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **2.8** for its accomplishments and progress.

- The work showing a lack of correlation between redox potential and ORR activity of non-Pt catalysts is an important contribution to fuel cell development, addressing recent data from a reputable group that claimed such a correlation despite earlier work that found no such correlation. The new data should prevent developers from following a false pathway toward improvement of non-Pt catalysts.
- The University of California, Los Angeles, shape-controlled catalysts show unusually low initial activities for catalysts of this type but have shown unusually good stability, at least in RDE testing. It is not clear that one should expend effort on complex catalysts with little improvement in activity versus standard Pt/C.
- The PVD work on catalysts and bipolar plate (BPP) coatings was sufficiently encouraging to serve as seed data for more detailed projects on these topics.
- Overall, there has been progress, and the project has helped academia and industry. However, it is not clear how much of the activities address the DOE goals. The selected highlights were interesting and wide in scope, so it is hard to see cohesiveness. The selection of projects is a bit confusing, and it would be good to understand if there is a priority based on DOE goals.
- The PIs presented testing of Pt_3Ni catalysts doped with Mo. To be able to compare the activity and stability of these materials, the obtained results should be compared with the state-of-the-art PtNi and/or PtCo catalysts. It is also very important to acquire information about the particle size and shape before and after testing. An independent RDE measurement is also required to confirm that addition of Mo indeed affects the stability of the catalysts. Without such a comparison, it is very difficult to evaluate the Pt_3Ni/Mo system.
- The PIs have also shown results for the ORR on Fe-N-C catalysts in two electrolytes. It is puzzling why the diffusion currents are different in perchloric and sulfuric acids, while in the kinetic region the activities are the same. For the next review, the PIs should establish a much better protocol for exploring electrochemistry in the RDE configuration. It would be highly desirable to simultaneously assess the stability and activity of the catalysts. Furthermore, although it is very important to establish correlations between the redox potential of cations and the onset of the ORR, it is not clear that the proposed experiments will resolve this issue. In situ spectroscopy(s) is (are) required to gain insights into such complex relationships.
- The examples provided clearly yielded useful results for those who received assistance, but it is not clear that these results yielded significant progress toward key DOE goals.
- The support of the working groups, as well as the Fuel Cell Short Course, is arguably the most beneficial work here, since this work obviously has impacts on a much broader group than simply working on the needs of individual customers. Assistance to a Canadian company (Blue-O Technology) is also a questionable use of U.S. taxpayer support in this manner.
- Since this project does not generate any ideas or intellectual property on its own, the accomplishment needs to be measured on how efficient the service request system is working. No metrics were provided on the total number of requests or the percentage of projects that were completed on time. There is no definition of measurement of metrics.
- In addition to the evaluation and assistance to the developers, the project should include benchmark data for a standard or best-of-class material so that the developers could understand the level of achievement.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.4** for its collaboration and coordination.

- This project provides facilities and expertise that allows collaborators with less complete fuel cell facilities to make meaningful contributions to the field of fuel cell development.
- The PIs have established excellent collaboration with many partners who are part of this project.
- There are obviously a number of collaborations here since this is a necessary part of this sort of work. A potential improvement would be if the results of these collaborations were disseminated more broadly. For example, it might be a requirement that any work done on this project should be published so that others can potentially benefit from the results (e.g., use the National Institute of Standards and Technology model for free use of government assets).
- It is a highly collaborative project. It would be good to coordinate perhaps with other laboratories or capabilities as needed. There is a question about how much of the work is just data-gathering versus truly collaborative and jointly performed research.
- The project would benefit from listing all of its competencies so other developers can relate.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.0** for its relevance/potential impact.

- This project is highly relevant with a potentially high impact on the DOE Hydrogen and Fuel Cells Program. Note: If the investigators are able to fully integrate fuel cell testing with fundamental science, then the project will contribute significantly to DOE efforts for full implementation of electric cars.
    - The project provides an important service to the community. This provides impact, assuming that the correct and higher-valued projects are chosen.
    - It is not clear whether this is duplicative to other efforts such as Small Business Vouchers, ElectroCat, the Fuel Cell Consortium for Performance and Durability (FC-PAD), cooperative research and development agreements, etc.
- Since this is primarily a service project, the relevance and potential impact are dependent on the importance of questions brought into play by the collaborators. The current case is a mixed bag of good and mediocre subprojects.
- LANL worked on multilayer coatings for BPPs, which could be an extremely expensive approach, and it is unclear how this will reduce BPP costs. Other projects also did not show any significant progress toward meeting DOE goals since the PIs did not report any metrics toward the Pt utilization in grams of Pt per kilowatt.
- The project has a minor impact toward overall goals.

Question 5: Proposed future work

This project was rated **2.7** for its proposed future work.

- In general, the proposed future work is reasonably well organized. One direction that needs to be improved is developing methods that are capable of resolving the issues of catalyst stability and a strategy to provide fundamental reasoning for why Mo improves the stability of PtNi alloy catalysts. Further development is also needed on a strategy for optimizing the physicochemical properties of nanoparticles to improve the activity and stability of these catalysts.
- Testing stability in real fuel cells is an important step in the evaluation of cathode materials. However, without having a reliable balance with the fundamental understanding of the driving forces that control catalyst activity and stability, it will be impossible to know what types of materials we should synthesize.
- It was hard to judge the future work, as it depends on the projects being added. The existing collaborations and continuing projects seem adequate in terms of making progress.

- The project's potential impact could be significantly improved by requiring that companies that request assistance must agree to publication of at least some of the key results.
- The planned future work seems to be just completing present activities and responding to questions that arise in the future. This service project does not seem to initiate activities on its own.
- It is not clear why the researchers are working on durability of materials that do not show promising beginning-of-life results.

Project strengths:

- The leading PIs have proven in the past that they are able to develop and execute similar projects. The methodology is rather well developed.
    - A big strength of the project is the utilization of many tools that can explore the feasibility of implementing various types of noble and non-noble catalysts in polymer electrolyte membrane fuel cells.
- This project leverages core expertise, provides critical help and service, and is making technical progress on the issues presented and requested.
- There are good collaborations with multiple parties.
    - National laboratory resources are used to help multiple customers.
    - This project supports DOE working groups.
    - This project contributes to the Fuel Cell Short Course.
- The resources, technical personnel, and national laboratory know-how are strengths.
- The project makes catalyst testing and PVD available to the fuel cell community.

Project weaknesses:

- One key weakness is the lack of a clear path toward understanding and minimizing the dissolution of catalyst components during fuel cell operation. For non-noble materials, there is no alternative direction if the proposed systems do not work as planned, and it does not seem likely that these materials will work.
- It appears that this work may duplicate other efforts and mechanisms. Justification for choosing projects is needed, and it is unclear if cost share is provided and if it should be. It is unclear if there is a priority for industry versus academia or U.S. versus non-U.S. projects.
- There is limited impact on major barriers, limited dissemination of results, and a generally small impact on the broader fuel cell community.
- The project responds to limited-scale requests from the community rather than pursuing a coherent set of ideas toward the improvement of fuel cells. There is a lack of approach and leverage.

Recommendations for additions/deletions to project scope:

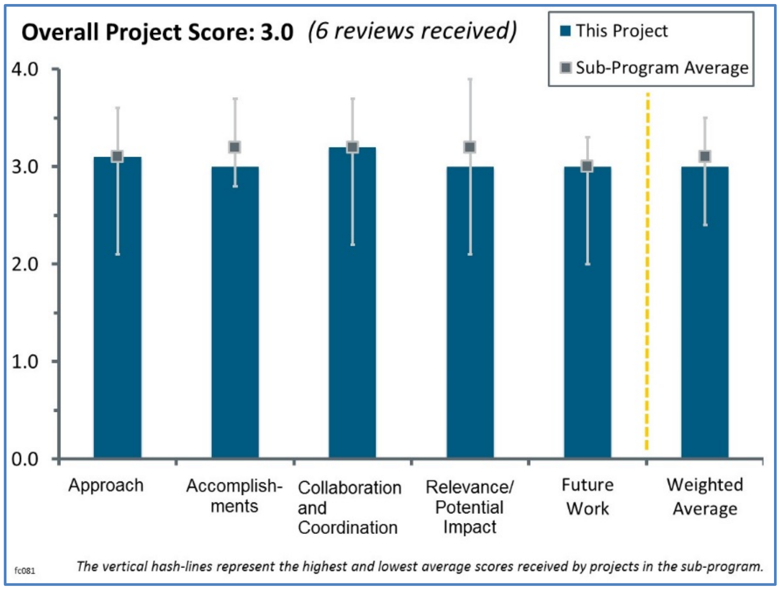
- Overall, with some tweaks, this project can be enhanced. This is a great project for the community and should perhaps be expanded to other national laboratories.
- One suggested addition would be a clearer connection between single-cell testing and fundamental understanding of the processes.
- More dissemination of key results should be required when individual companies are provided with assistance (e.g., publication in technical journals).
- It would be better to use the funds and facilities currently dedicated to this project for projects with clearly defined goals rather than for loosely defined service to the field. It might be good to dedicate such a service project specifically to support projects funded by the Small Business Innovation Research program rather than making it available also to organizations with their own extensive facilities and capabilities.
- The whole project should be terminated. However, if the DOE Fuel Cell Technologies Office decides to keep the project, then the high-value addition would be an online portal wherein any developer can request testing with some additional details on what the cash contribution would be.

Project #FC-081: Fuel Cell Technology Status: Degradation

Jennifer Kurtz; National Renewable Energy Laboratory

Brief Summary of Project:

The fiscal year 2017 objectives of this project are to (1) receive and analyze new laboratory durability data, (2) update and publish the durability results, and (3) include electrolysis data. The National Renewable Energy Laboratory (NREL) will (1) develop a snapshot of the state-of-the-art fuel cell durability, (2) uniformly apply analysis methods to developers' voluntarily supplied data from laboratory testing, and (3) provide an independent assessment and status of state-of-the-art fuel cell technology.



Question 1: Approach to performing the work

This project was rated **3.1** for its approach.

- The approach being used by the project team is sensible given the nature of the data being collected. The National Renewable Energy Laboratory (NREL) team has a solid track record with this sort of data collection and aggregation, and the summaries are appropriate. Presumably, the full composite data product (CDP) report contains more views of the data that might help the broader community understand trends in fuel cell durability.
- The project aims to gather durability data (mostly from industry), analyze that data, and produce detailed data products (DDPs) and CDPs. The amount of data gathered, submitted voluntarily by suppliers, increases over the years despite the difficulties associated with data protection and the required 1,000-hour minimum operation condition, which demonstrates the efficiency of the approach (receiving DDPs is a good return on investment for data suppliers). The approach used is a statistical analysis that processes a large number of data with plenty of heterogeneities (different technologies, suppliers, operating conditions, testing protocols, operating ranges, etc.), which do not allow for fine analysis. The degradation fitting is based on a segment linear fitting, which is one simple option, but other fittings could be tested. Voluntary data collection can be limiting when data supplied is incomplete, as it was for fiscal year 2017 (numbers related to backup power and bus analysis were the same as in 2016 because of a lack of 2017 data). The use of a 10% threshold for power degradation for all applications is still questionable (metrics used in the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan [MYRDDP] are 20% for backup power and for stationary applications [1–10 kW]).
- It would be more informative if the request for information (of course on a voluntary basis) also included durability testing conditions and temperature.
- The approach is limited by the data suppliers are willing to share. Given this, the project team has systematically improved their data collection and analysis.
- The data collection method is limited because NREL does not have leverage with U.S. companies and most companies consider data intellectual property. A nicely phrased request would help to some extent. A demonstration in how this might be in the individual company's best interest (a "carrot") might work better. Small companies often have limited test budgets. If NREL can assist a company with either test support or test funding, the company may share the data under a non-disclosure agreement in which release of data requires the company's approval.
- Many of the voltage degradation trend data products represent an averaging of steady, duty-cycle, and accelerated data. For some applications, particularly automotive, this averaging will put the application in a

fairly poor light. System mitigations for stack failure modes are commonly implemented for automotive operation so that averaging data from accelerated testing of stack components with system or vehicle-level lifetimes will certainly lower lifetime estimations. Accelerated tests exist for the purpose of understanding failure modes, not for providing a representation of component lifetime in a vehicle setting. The approach does not address how information such as current density and Pt loading bins might be used to understand emerging technology trends. It would be interesting to see voltage degradation as a function of either current density or Pt loading. Current density and Pt loading should be compared to each other as well to see whether particular applications have been more adept at making the most of low Pt loading. Perhaps there are lessons learned that other applications could derive. As in years past, the voluntary data inputs severely restrict the meaningfulness of the data. Given the impossibility of any other route, the practicality of this project is questionable.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.0** for its accomplishments and progress.

- The results are interesting. A voltage–current plot is useful to the researcher; however, a voltage–current plot at times requires perspective of the relevant task. A loss of 70 mV may or may not be germane, and a loss of 25% of the available power resulting in only 50 mV/cell margin on the power electronics might also be useful to the researcher. Depending on the context, a fuel cell with given performance might still generate power but may fail to run a vehicle. Current density might not be a good metric. For example, a PAFC unit might operate at 300 mA/cm^2, but last with negligible performance degradation for 80,000 hours. An alkaline fuel cell on the other hand might operate at 10,000 mA/cm^2, but last with negligible performance degradation for only 200 hours. It is not clear which is better. The project team should be careful when mixing data from different applications and technologies. A cross-plot of current (I)–voltage (V) curves (i.e., changes in voltage as a function of fixed current density and time) can be useful, and derivative plots can help detect internal (decay) and external (step change) issues.
- There is appreciable difficulty in harmonizing test data in multiple formats from multiple sources. It is a credit to the NREL team that they continue to get data from manufacturers. It is good that the team used the limited set of more recent results, although it would have been good to see the early results compared directly to later results. Given the patchy nature of the data, perhaps a rolling three- or four-year window should be used.
- Although it is good to see that some information is coming back with respect to the current density and Pt loading bins, the project has not been able to derive much that is useful so far from either, with the possible exception of the current density versus application plot. The Pt loading versus year trend is not likely to reflect the overall industry trend, which is unfortunate. It can be seen that automotive applications use the highest current density, followed by materials handling vehicles, but these trends were fairly well known within the community. The challenge for this project is to go into greater technical depth with the small amount of information gathered. The short stack and full stack plots for automotive operating hours are interesting for status reporting to the public, but being removed from operating and materials context (e.g., power density, operating conditions, Pt content, and membrane thickness), this data does not allow the development of any deep understanding as to how durability is being achieved. Because of this, the project team cannot say that it is assisting in overcoming the barriers that developers face.
- The project does not address any objectives set in the MYRDDP, but it is meant to provide an assessment of the status of fuel cell and electrolyzer durability and cost. It is, however, a valuable tool for DOE to follow the evolution of the technology regarding the targets, even if it is difficult to draw fine conclusions regarding durability since the analyzed groups do not distinguish between various fuel cell technologies or designs. Durability assessment depends also on the fuel cell utilization (control strategies, hybridization, etc.) that is not taken into account. Stationary application analysis is achieved independently of the range, while DOE's targets address residential applications (1–10 kW) and distributed generation (100 kW–3 MW) differently.
- The project is doing about as well as expected given the limitations of the data gathering (i.e., dependent on supplier willingness to disclose information). In addition, progress was shown in presenting the current density and cathode platinum group metal (PGM) loading segmentations, as requested in previous project reviews.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.2** for its collaboration and coordination.

- The project team has been very successful in convincing several data providers to share data. However, the issue remains that this data is provided on a voluntary basis, and that makes the project very dependent on the goodwill of data suppliers to provide quality data, complete information about the testing conditions, testing history, and so on. That can lead to unreliable conclusions despite the team's sound analysis. The number of supplied data sets have increased over the years (50 datasets since May 2016), and the same partners have provided data over several successive years, which means they are satisfied with the resulting analysis quality of the CDPs and DDPs. The project team has excellent collaboration with other partners, given the facts cited above. The collaboration and the coordination seem to be good.
- The project team is canvassing as many suppliers/developers/stakeholders as it can. The response rate is outside of the team's control but appears to be decent. One can always hope for more thorough responses, but at least the project team is trying to get the information and has been responsive to adding extra categories (cathode PGM loading, max current density) with at least some supplier response.
- NREL is the only funded participant on this project. Although there is an impressive list of participants among fuel cell manufacturers, this group is not collaborating among themselves. Nevertheless, given that the data collected is not pre-competitive, this is an appropriate level of interaction, so no change from current levels is recommended.
- Given the reluctance of most organizations to provide data, it is commendable that 23 developers were willing to provide data. Furthermore, it is understandable that identification of developers cannot be provided. Collaboration could be enhanced by working more closely with developers than through just an email with an attached spreadsheet. The project team should think more about what developers could derive from the information while still maintaining the confidential boundaries crucial to enticing data sharing. If there are data products available only to those that share and those data products contain technical depth, the sharing of data might become even more widespread.
- Additional collaboration may be needed to advance this project. NREL should start thinking about "carrots."

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.0** for its relevance/potential impact.

- The data being collected is extremely useful in gauging the progress of the fuel cell and electrolyzer industry toward DOE's durability goals for various applications. The project should include graphs or tables that can get at trends over time, perhaps with a sliding three-year average of results. The project should also evaluate how the main project deliverable, the CDP, is being publicized so that people in the industry can find it. Also, perhaps there are venues other than the Annual Merit Review and the U.S. DRIVE Partnership's Fuel Cell Technical Team meetings at which this project's results can be presented.
- There is potential to both understand the operation of the fuel cell and help some of the struggling companies out there.
- The analysis has an impact because it allows DOE to track the trends of durability and cost evolutions, to assess technology advancements, and to correlate their status with set objectives and means to achieve them. The analysis would have a greater impact with more relevant information (separate analyses for different fuel cell technologies, proposition of durability values based on different thresholds, etc.).
- As it is, the project does not advance progress toward the goals and objectives of the Fuel Cells program. The best results from the project still confirm only the widespread opinions that exist within the fuel cell community. While the project has progressed in terms of obtaining current density and precious metal loading information, the information is still not being used in a way to clearly show technical trends. Even at its best, if the project completed all of its objectives, the results might be only a very good status report. However, the project would not be able either to provide direction with respect to closing gaps or to advise

why gaps have been closed. The best the project can do is indicate where there is no longer a technology gap.
- The project has relevance to the Hydrogen and Fuel Cells Program, as it gives a durability assessment that is at least data-driven. It is, however, of virtually no relevance to developers without much higher contextual data (all of the information pertaining to loading, electrode type, generation, membrane characteristics, detailed cycle data, acceleration factors, temperatures, pressures, relative humidity, voltage cycling, etc.). This is not a criticism of the project team but of the project goal.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The plan for future work is more of the same, which is perfect. The project should keep up the good work.
- The proposed future work listed by the project team is expected and in line with the results shown.
- It is agreed that the project should try to better characterize the acceleration factors. However, unless given very detailed time histories (including cycle data, voltage, temperature, relative humidity, and pressure vs. time), the project may have to rely on the supplier estimates of the acceleration factor. The principal investigator is encouraged to add "estimated acceleration factor" to the data request to get that information. The supplier estimate of the technology readiness level (TRL) value should also be added. In addition, if possible, the project should ask for suppliers to test to an agreed-upon durability test profile (e.g., Fuel Cell Technical Team durability test) to provide a consistent baseline.
- The project team acknowledges that it could do more work in trying to understand relationships between cost (or PGM loading) and durability, which are important. The project team should seek to explore even more technical relationships from the data it has. The relationship of current density and cost to operating conditions is probably fertile ground for trying to understand technology trends. Categorization of accelerated tests is mentioned in the future work and is very much needed to have any hope of making these data meaningful. However, the project must decouple accelerated stress test data from stack duty cycle data. Greater emphasis needs to be placed on interactions with developers. The project team needs to brainstorm how the process could be made more valuable for developers so that more developers contribute data.
- The proposed future work appears rational. The project needs to find "carrots" to get the original equipment manufacturers to play.

Project strengths:

- This project offers an independent and uniform analysis of data from key stakeholders involved in fuel cell technology development. This is an important tool for DOE in estimating the progress of current technologies regarding the objectives set in the MYRDDP and the involved funding, and for data suppliers to assess objectively the evolution of their technologies (DDPs). The analysis provides a general overview and trends of the evolution of the durability and cost values from different applications. Based on the analysis, targets for electrolyzer technology could be defined.
- This project brings together and synthesizes data from multiple sources, covering several manufacturers, technologies, and applications. The project team does a good job of synthesizing the information received into summary reports that support the DOE Fuel Cell Technologies Office's mission.
- There is access to data from many prior years as well as access to considerable fuel cell expertise at NREL. The project has demonstrated the ability to collect data from numerous developers.
- This project offers the ability to share the data on a publicly accessible website and to leverage DOE to be able to gather the data.
- The dedication of the researchers (performance engineers) is a project strength.

Project weaknesses:

- The data analysis is applied uniformly, and different fuel cell technologies/ranges are analyzed within the same classification. Sometimes, in the same class (automotive, for instance), different balance-of-plant designs and architectures, hybridization, and control strategies could be applied, and the operation objective could require a unique trade-off between performance, efficiency, and durability, which makes the fuel cell durability completely different. In the current analysis, the projected value for backup and stationary (1–10 kW) applications seems to be underestimated: a value of 20% voltage degradation seems to be a more adapted metric to assess voltage degradation (MYRDDP). (In general, durability could be given as a function of different metrics values.) A key point in durability studies is linked to the operating conditions (cycling, load profiles, etc.) and the past fault and the exposure time, etc. This kind of information is difficult to obtain (even with the goodwill of suppliers) and to correlate with the durability projections.

- Confidentiality boundaries prevent the project from providing deep technical insight to show relationships between degradation and operating conditions or materials. Continued mixing of accelerated data with stack duty cycle and steady-state data convolute the results shown by application. Application durability should be reflected by the mode of operation most likely to be observed in the field. The encouragement of developers to submit data is still not strong enough. The project team must consider what rewards could be made available to developers that share data. The results of the project, even if fulfilling objectives, may provide only a good status report. The results do not contribute to overcoming technology barriers.
- The main weakness is that the data shared are those volunteered by the participants. Thus, they may not be the most representative results for the state of the art in industry. Also, while there are reasons for using cell data, it would be helpful to correlate these test results to full fuel cell system durability results.
- The project is limited by supplier willingness to disclose detailed information required to develop a better understanding of durability status and degradation mechanisms.
- There is a lack of leverage to access more data.

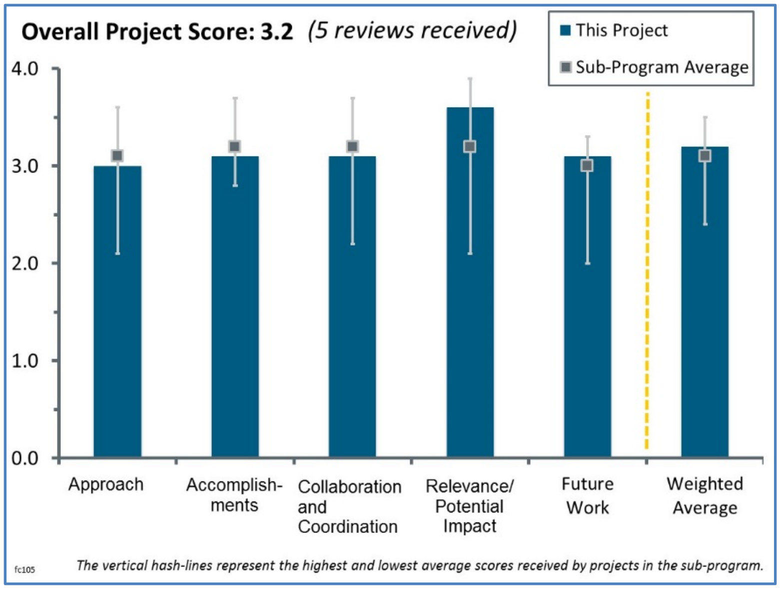
Recommendations for additions/deletions to project scope:

- No changes are recommended.
- The use of Pt loading bins and current density bins for the different technologies being surveyed represents an improvement over prior years. It would be interesting to compare the Pt loading bins versus the current density bins for like datasets to see whether there is a trend. There could be approximate “gram-per-kilowatt” bins derived from there that would begin to show the different levels of technology are being used. The information supplier should be asked to specify TRL. This would help to distinguish results that are more experimental from those that are already incorporated into a product. The project team needs to break out accelerated tests into various categories or by acceleration factor. Some operating conditions data (e.g., temperature) would benefit the analysis.
- The data should be analyzed by technology and by application for fuel cells and electrolyzers and to assess the durability with different metrics (from 10% to 20% is more compatible with backup/stationary applications [MYRDDP]). DOE-funded projects could be highly encouraged to share their generated data with the project team. Degradation, fault, and failure history should be included in the metadata template. The project should elaborate on fitting approaches other than linear.
- The project team is encouraged to include the acceleration factor in the data request. The team is also encouraged to request that suppliers supply data to a fixed durability cycle. The project might require a new project structure to enhance the data collection quality needed for true durability/degradation analysis. Such a project may require supplier compensation and involvement of the Fuel Cell Consortium for Performance and Durability for both project scope/management and analysis.
- Particularly for durability data, there should be a clear distinction between laboratory results and fleet results. Laboratory testing is commonly done in a more aggressive manner with both materials and test conditions.
- The project should work on “carrots,” perhaps offering to test or reduce data with various companies.

Project #FC-105: Novel Structured Metal Bipolar Plates for Low-Cost Manufacturing

C. H. Wang; TreadStone Technologies, Inc.

Brief Summary of Project:



Bipolar plate (BPP) cost is a major portion of total fuel cell stack cost. The project's goal is to develop low-cost metal bipolar plates to meet U.S. Department of Energy performance and cost targets, specifically a cost of <\$3/kW, corrosion of $<1\times10^{-6}$ A/cm^2, and resistivity of <10 mΩ·cm^2. The approach is to coat a stainless steel bipolar plate substrate with semiconductive doped titanium oxide (TiO_x). The project is addressing titanium oxide's challenges to increase the conductivity, increase the bonding strength to the substrate, and increase the coating composition uniformity. The project is also developing a large-scale manufacturing process for the coating technology. In addition, the project is investigating the relationship between the processing conditions and the doped titanium oxide properties for production quality control system development.

Question 1: Approach to performing the work

This project was rated **3.0** for its approach.

- The approach encompasses deposition and fabrication of BPPs, along with characterization at Oak Ridge National Laboratory. The work continues from previous Small Business Innovation Research (SBIR) efforts growing doped TiO_x interlayers for BPPs using a multi-step sputtering and oxidizing batch process. The difference here is that the project will evaluate alloy compositions using a new approach. The team starts with a cost analysis performed with a partner.
- The approach is technically sound and should provide a coating with the desired properties. High-volume manufacturing is still in question, but no showstoppers are evident.
- This project is a continuing effort of a previous project (FC-105), so the team has a good understanding of the barriers: high manufacture cost and missing of dopants (high resistance) on the surface of TiO_x-coated-metal BPPs. The work also proposes a feasible and integrated plan on fabrications, characterizations, and performance tests. A better fundamental understanding of the dopants (Ta, Nb) on the surface of TiO_x with surrounding electrolytes might better guide the experiments. Also, some modeling work should be included on the design of the "Mosaic" target for the desired atomic mixing, based on the dimension of each strip of the "Mosaic," the distance between the target and the substrate, etc.
- The project is new, and future work identifies approaches to meeting the cost barrier. The project established cost analysis values and addressed resistivity issues.
- The approach of doing a physical vapor deposition (PVD) coating of the titanium barrier layer and TiO_x sprayed coating on a pre-stamped plate may not be a solution capable of reaching high production volumes.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.1** for its accomplishments and progress.

- The team has been making nice progress in modifying the deposition process and bringing the dopant to the TiO_x surface to reduce the surface resistance. The proposed milestone has been reached as planned. The report also shows high-resolution images of the thickness and roughness of the surface layer, which is very important to understanding the microstructures and properties of the coating.
- For the startup of the project, good progress has been made in cost analysis, and previous SBIR work provides a pathway to superior corrosion resistance. The modified process suggests improved distribution of Ta and Ti can be achieved.
- The basic concept has been proven. Low contact resistance and superior corrosion have been achieved. Excellent adhesion of the coating on the substrate is anticipated. Projected high-volume manufacturing cost is lower than that of competing technologies.
- The project started six months ago but only got under contract recently. It is unclear what the full assumptions were that went into fabrication cost analysis. Number, type, and throughput of sputter system(s) would be required to get to volume to bring costs down to below targets.
- Compared to previous year results, the new accomplishment seems to be optimizing the layer composition and cost analysis. It is unclear if any of these deliverables are proportional to the amount of funding.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.1** for its collaboration and coordination.

- It looks like the researchers have a good plan with Hawaii Natural Energy Institute (HNEI) for testing once they have a prototype.
- The team has set up effective collaborations on cost analysis, film depositions, microstructural characterizations, and performance tests. Some collaborative work is suggested on the modeling of the deposition and fundamental understandings of the materials, if the team does not have such expertise.
- Partners are adequate for this phase of the development and include Strategic Analysis (SA) for cost analysis. A stack integrator would certainly be beneficial in terms of BPP insight and in-cell testing.
- Researchers report results of work with SA. There is testing at HNEI to be initiated.
- The project is collaborating on a “what must get done” basis. However, the project could use some external help with the correct analysis techniques and leveraging existing national laboratory capability to do the analysis with higher accuracy (e.g., copper metal detected during the x-ray photoelectron spectroscopy depth profile on slide # 9).

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.6** for its relevance/potential impact.

- The cost of a BPP is a significant portion of fuel cell cost. The project aims to develop highly conductive and stable BPPs and manufacture the product at a low cost. Therefore, the project is closely relevant to the Hydrogen and Fuel Cells Program goals.
- Reducing the overall cost of the BPPs is highly relevant to meeting DOE project objectives. The potential impact of this project is high, provided that the goal is reached and the cost analysis done correctly. It looks like the cost analysis is either optimistic overall or missing the cost of the PVD titanium protective layer.
- The cost of the BPP is one of the main contributors to the overall stack cost. This project seeks to develop a coating that mitigates corrosion at an acceptable cost.
- If successful, this project could resolve corrosion issues and fuel cell poisoning by corrosion products from BPPs.

- If costs can be realized and technical targets met, there is potential in this BPP technology, although it is difficult to get low-cost coatings with a line-of-sight batch-type process.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- Proposed future work looks fine, given the scope and funding for this project.
- Future work logically follows progress to date: process development, coating characterization, and durability evaluation. Pre-forming coating will be evaluated.
- The proposed work is mostly well planned and achievable. However, the plan does not provide a target number for the performance. There is little risk analysis. Some modeling on the deposition and a better understanding of dopant segregation on the TiO_x surface should be included so that the proposed work can be carried out more efficiently.
- The approach uses the PVD process, which is slow compared to production requirements for BPPs for automotive fuel cells. The project should evaluate the throughput of PVD process and determine whether it will meet required production rates/costs for 500,000 fuel cell systems per year.
- The patterned sputtering approach suffers from getting away from the type of deposition that will eventually be used (alloy sputter target). The issue is that the alloy target has preferential sputtering of Nb versus Ta, which the researchers have seen in the past. This will also happen inside the chamber unevenly as many BPP assemblies are placed, leading to different compositions and morphologies on the surface. The approach does not address this issue and works only on optimizing an unachievable at-scale "optimal" composition.

Project strengths:

- The project aims at an important component for fuel cells, BPPs. The project is based on the product of a previous SBIR project, so the team has a good starting point and clear understanding of the challenges, such as high manufacturing cost and low conductivity on the surface of TiO_x coating. The team has proposed the approaches to overcome the challenges and provided some initial results to demonstrate the feasibility. The team also has established collaborations on depositions, characterizations, and durability tests.
- A primary project strength is the innovative coating on stainless steel plates and the concept developed by TreadStone.
- The approach has the proven capability to meet technical targets at low volume.
- A creative, technical person is the principal investigator.
- It is an innovative concept.

Project weaknesses:

- There is a lack of discussion on a fundamental understanding of the surface solubility and segregation of dopants (Nb, Ta) in TiO_x. The computational effort on achieving an optimized "Mosaic" target is not presented either. No risk analysis is provided.
- Processing using PVD may be too slow for automotive applications. Multiple PVD units may turn out to be too expensive. This needs to be evaluated by SA.
- It is unclear if there is any serious thought on durability and stampability of this coating to enable a pre-coated strip approach.
- The high-volume capability to achieve cost and compositional (performance) targets is questionable.
- The lack of participation of a stack integrator is a project weakness.

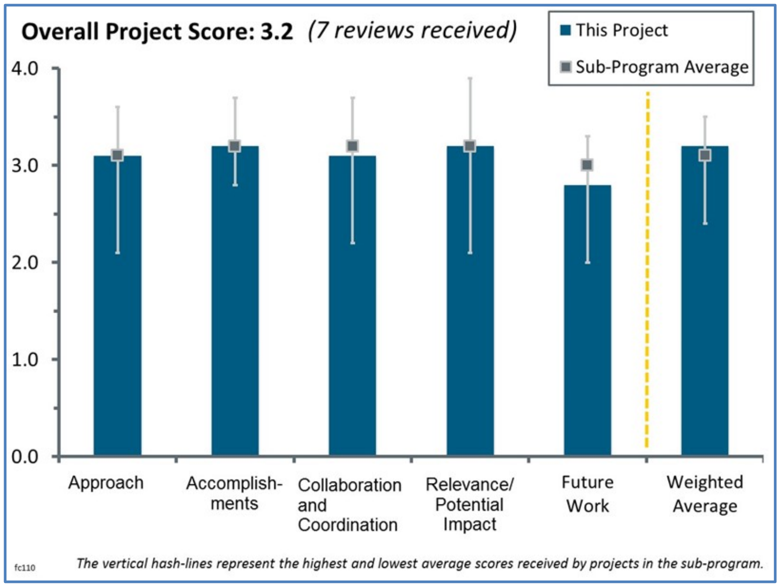
Recommendations for additions/deletions to project scope:

- A more fundamental understanding is recommended on the design principle of the coating, such as the segregation of dopants on the surface and bulk of TiO_x. Also, the development of targets for depositions can be expedited with the aid of computation.

- The project should clarify cost analysis and evaluate capability to achieve compositional targets at volume across the deposition space of a scaled-up deposition system.
- Adding a good analytical characterization technique of the fresh and aged samples of this coating is recommended.
- The project team should consider other coating compositions based on theoretical assessment.
- The project timeline is too short and should be extended by six months.

Project #FC-110: Advanced Hybrid Membranes for Next-Generation Polymer Electrolyte Membrane Fuel Cell Automotive Applications

Andrew Herring; Colorado School of Mines



Brief Summary of Project:

The overall objective of this project is to demonstrate a low-cost hybrid inorganic/ polymer from superacidic inorganic functionalized monomers with (1) area-specific resistance (ASR) <0.02 Ω cm^2 at operating temperature of an automotive fuel cell stack (95°C–120°C) at low inlet relative humidity (RH) (<50%) and (2) 50 cm^2 membrane electrode assembly (MEA) with desired mechanical properties and durability. The current-year objective is to incorporate the best hybrid polymer system into an MEA and deliver a 50 cm2 MEA with all desired properties for third-party testing.

Question 1: Approach to performing the work

This project was rated **3.1** for its approach.

- This work continues a long line of investigation from the principal investigator (PI) on the use of heteropolyacids (HPAs) in polymers as proton conductors. The work for this review period settled on a specific fluoroelastomer system and HPAs, which the project team used to create membranes that were tested in the team's laboratory for conductivity and by a partner (Nissan) as MEAs. A key advance is the ability to make membranes that are thin, strong, and flexible. Conductivity values are very impressive at high humidity; work at higher temperatures (above 100°C) and lower humidities is needed in general and to address one of the milestones. The researchers say this work is planned with the National Renewable Energy Laboratory (NREL). MEA studies used conventional gas-diffusion-electrode-based electrodes sandwiching their membranes. Performance was very good and tracked with expectations for the membrane conductivity and thickness.
- The approach involves design of an improved polymer electrolyte membrane (PEM) through tethering of an HPA to a fluorinated backbone polymer. The fluorinated backbone should provide good chemical stability and gas transport, while the HPA should provide high conductivity even at low RH. This approach has been pursued by the PI and team for many years now, but it remains promising. The team is also working on integrating the new membrane into MEAs, which is appropriate at this stage of membrane development.
- The approach initially focused on addressing the performance, and indirectly the cost barriers, by attempting to prepare membranes that can operate at high temperatures under low RH. Earlier work indicated good conductivity for the Generation 1 polymers under hot and dry conditions, which could help reduce system costs. Recent work has not shown conductivity or ASR data for the new fluorocarbon-based HPA membranes under hot and dry conditions, but has focused on high RH conditions. It is not clear that these membranes will be less expensive than current perfluorosulfonic acid (PFSA)-type membranes, as the Colorado School of Mines (CSM) membranes rely on fluorocarbon polymers as well and are likely to have costs similar to other fluoropolymers. Advantages for this type of membrane are expected to come from the ability to operate under low RH. Performance under these conditions needs to be demonstrated.
- The scientific method includes appropriate controls. From the presentation, this seemed to be consistently lacking. For example, the PI cannot compare water transport of different thicknesses. Also, during the presentation, the Nafion™ sample was referred to as 2 million, but the label indicated 1 million. This made

it unclear (1) whether it was even known what control sample was tested and (2) whether anyone took the time to actually put a micrometer to it to verify. The PI could easily make the novel membranes the same thickness as the control. Not all data slides specified the type of control. The project team should be specific and reference accordingly. There are many different types of Nafion: standard, high, and low equivalent weight, as well as solvent-cast and melt-extruded films. All of these variables have impacts on fuel cell performance. Regarding the cost barrier, it is certainly understandable how $3 million would be secretive; however, the PI certainly could add rationale. For example, it is unclear what the cost and source of the inorganic active group are, what the resin cost of a "standard" fluoroelastomer is, and what the range of costs for all fluoroelastomers is. The Synquest prices and logic through benefit of scaling should be shown. It is assumed that the cost of the polymer is the largest component; however, do not underestimate the cost of converting into a film. It is unclear what the incremental estimates via the different methods are. A cost of $\$20/m^2$ is an extremely low amount. Additionally, thickness is a critical factor. The work is feasible and integrated, and this is a good project—this criticism applies to the design.

- The approach follows mature chemistry modified for film-making capability, conductivity, and crossover properties, even at 120°C. The approach includes testing against U.S. Department of Energy protocols and 50 cm^2 cell testing. The project should be careful about drawing conclusions based on 80 µm films.
- The approach is challenging since this is such a new materials development project. There needs to be a good balance with actual fuel cell testing/demonstration versus material fundamentals understanding.
- The overall approach is feasible, but the plan for thinner membrane fabrication is not clear.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.2** for its accomplishments and progress.

- After a rocky start to the project, the team has been making good progress since last year. The work so far has indicated that HPA content needs to be kept below a threshold level to maintain good mechanical properties. Also, the mechanical properties are highly sensitive to the membrane processing conditions, with the only membrane showing good mechanical properties having been pressed at 180°C and 6000 psi for five minutes. It seems likely that the optimal pressing time would be different for different HPA contents. Therefore, it might be useful to further explore this space by constructing a plot of mechanical properties versus HPA content on one axis and pressing time on the other axis. The chemical durability and gas crossover results shown are misleading because they compare a thick HPA-based membrane (80 µm) with a much thinner Nafion 211 membrane. This sort of comparison should never be done unless the membrane thickness is the same. The PI indicated plans to repeat these tests with a thinner HPA membrane. The PI also indicated that 3M will examine degradation products to look for evidence of degradation modes that may harm performance without strongly affecting the open circuit voltage. These are crucial tests to run, and it is good that the PI seems committed to running them. The MEA results presented from Nissan are very encouraging. Considering the struggles the project experienced in earlier years, the level of achievement at this point is quite impressive. The H_2/O_2 performance looks especially good, whereas the H_2/air performance is good at low current but shows mass transfer limitations at high current. For some reason, the testing used extremely high flow rates of 2.0 and 4.0 liters per minute for anode and cathode, respectively. These flow rates are quite a bit higher than what is needed for normal differential testing and likely caused significant pressure drop. The team should check the pressure drop under these conditions and report the actual cell pressure, which is probably quite a bit higher than the claimed 0 kPa_g. Furthermore, fuel cell pressures should always be reported as absolute pressures, not gauge pressures, especially since two of the partners on this project are located at high altitude. Also, the testing should be repeated with lower cathode loadings. The use of an unusually high cathode Pt loading prompts questions about whether there may be issues at more normal loadings. Considering the high loading, the performance of the baseline N211 MEA looks a little low.
- Progress toward conductivity and crossover targets is excellent. Crossover prevention is particularly good with these materials, which may ultimately be one of their greatest strengths. Durability is also good, which the PI attributes to the fact that HPAs catalyze peroxide decomposition.

- The project has managed to make perfluoro-HPA membranes with very good conductivity under high RH conditions and has been developing processing techniques to repeatedly make good membranes. The project has not shown progress toward the DOE target of achieving an ASR of <0.02 Ωcm^2 at 120°C and water partial pressure of 40 kPa, which is lower RH than the project target of 50% RH. The progress toward durability and permeability targets is not convincing when using an 80 µm thick film (that had an order of magnitude higher ASR than the target), as the thickness has a large impact on both permeability and durability.
- Accomplishments are very good, but some of the data seem to be from 80 µm films (usually <25 µm), so caution must be exercised when making conclusions. The process has been scaled from 10- to 100-gram batches. The process steps were reduced from seven to three. Stability at open circuit voltage is excellent. Cell performance is very encouraging for the unoptimized MEA (slide 18). Research and development on the electrode ionomer compatibility with the CSM membrane is needed. All project targets have been met but not simultaneously.
- Fundamental materials property advancements are hard to judge since they compare to a much thinner NR-211 membrane. A better comparison to a Nafion benchmark should have been done. Last year's reviewer comments were to compare to NR-212, which has similar thickness, rather than the much thinner NR-211. That comment did not appear to take since this year there are still plenty of NR-211 comparisons in which the difference in thickness confuses the comparison.
- There is good progress on concept demonstration. Cost needs more attention. Durability was addressed, but it is well known that the molecular junctions of dissimilar materials are the weak links. More attention to durability (in the holistic sense) could be beneficial.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.1** for its collaboration and coordination.

- Coordination in this evaluation period with Nissan Technical Center North America (Nissan) has been very strong and was responsible for nearly all MEA results. Collaboration with 3M helped the PI work through selecting and using fluoropolymers. Collaboration with NREL was not much emphasized this period but was useful in earlier project phases and in other joint projects.
- Nissan and 3M bring substantial knowledge and expertise to the project, as do NREL and Hamrock. Cooperation is excellent.
- Collaboration with Nissan for in situ MEA testing is good.
- Collaboration between CSM and 3M appears to be working well, and 3M's participation has been beneficial in improving the film processing. Collaboration with Nissan seems to be working satisfactorily and should increase as MEA testing gets in full swing. The collaboration with NREL is not so clear, and it is not clear what NREL has contributed to date, and what NREL's future role is. Membrane testing results, especially under hot and dry conditions, were not shown. Testing shown appears to have all been done at Nissan and CSM, and future work is detailed at CSM and Nissan with no mention of NREL.
- The interaction with Nissan is valuable for MEA testing. The described role of NREL in Year 3 seems almost identical to that of Nissan. NREL could offer increased value to the project through the national laboratory's transport diagnostics capability, especially given the high apparent mass transport losses exhibited in the hydrogen/air MEA performance.
- Better collaboration with the Fuel Cell Consortium for Performance and Durability (FC-PAD) characterization techniques could have been done. Many questions remain about the MEA performance issues being attributed to the Nafion used in the catalyst layer; however, the newly developed polymer would be a worse candidate for the catalyst layer since the oxygen transport is much lower for the new polymer. This is a good property for the membrane but not so good a property for the catalyst layer.
- It is not clear why 3M was not participating/giving consultation more. 3M should have been able to provide valuable insight that could have made the project more efficient and robust. There are many Nafion fuel cell experts (ex-DuPont) that are happy to consult. The PI should consider adding them to the team as both chemical and application inputs. A film manufacturer would be a good addition.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.2** for its relevance/potential impact.

- The project is highly relevant. Development of improved membranes is one of the most relevant things a project can do.
- Efforts to develop a membrane with the desired properties at high temperature and low RH are wholly consistent with DOE goals, objectives, and targets.
- If the approach can meet the cost target, $20/m^2, the project well supports the Fuel Cells sub-program goal.
- The concept is good, and the practical progression is pleasantly anticipated.
- The project is relevant and has potential to provide an alternative type of proton-conducting membrane for polymer electrolyte membrane fuel cells (PEMFCs). The potential will depend on the cost and any potential performance advantages versus PFSA membranes. There appear to be conductivity advantages in the membrane, but durability and performance with membranes with relevant thicknesses at high and low RH conditions still needs to be demonstrated. Low RH conditions at high temperature are of particular interest, as performance there could enable lower-cost systems.
- The PI's approach is unlike any other being pursued for PEMFC electrolyte materials. There are still issues to be resolved (e.g., his materials are so far not suited for use in electrodes, and little is known about how they might interact with catalysts), but there is no reason to think that the issues will not be addressed with further work. Cost is likely to be reasonable, and performance and durability of membranes appear excellent. This work provides an imaginative and potentially very attractive alternative to PFSA and related materials.
- Although the material appears to be promising at the outset, many trade-offs in performance creep in on the way to making an MEA, and at the end of the day, the overall performance remains on par with Nafion, which greatly diminishes the impact on the DOE goals.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- The future work is focused on testing these membranes in MEAs and determining MEA performance. Ex situ testing of the membranes should also be done, and testing should be to the DOE targets, including 120°C and water partial pressure of 40 kPa, not just to 80 kPa or 50% RH.
- Future work is focused on defining chemistries, structures, and processing conditions to meet all technical targets simultaneously in a single membrane.
- The future work for CSM and Nissan looks reasonable, though there should be more of an emphasis on low-humidity testing. No future work was shown for NREL.
- The future plans sound good. How cleanly it will be carried out is questionable, considering the current state of reporting. More and different accelerated degradation testing should be conducted. A plausible plan on combining different (desirable) attributes that will pass all of the hurdles should be developed. Cost was not addressed at all; the presenter indicated that "3M says it's okay," but costs for post-polymerization are unclear.
- The project has essentially ended (July 2017).
- The project ends very soon, and proposed future work is appropriate.
- It is not clear how to fabricate thinner membranes with good mechanical stability.

Project strengths:

- The project has developed an innovative membrane system that relies on a different proton conductor from previous PFSA or hydrocarbon systems and should provide different transport and physical properties. Along with providing membranes with different properties, this could offer potential to change ionomer–catalyst interactions and reduce the negative impact of ionomer adsorption on the oxygen reduction reaction catalyst.

- Materials have good properties as membranes (high conductivity, apparent good mechanical properties, and good durability) and are able to be used in MEA fabrication and testing. MEA behavior is as expected for a membrane having the ASR of these materials.
- The team has amassed considerable experience in tethered HPA systems. The recent progress in incorporating HPA membranes into MEAs with reasonable performance is encouraging.
- The project did make a lot of progress toward the development of a new PEM polymer and even demonstrated it in an operating fuel cell.
- Mature/scalable chemistry for the membrane fabrication can be attractive to industries. There is strong collaboration with Nissan and NREL.
- A strength is the concept of highly functional components being combined to provide new capabilities.
- The project team is very good.

Project weaknesses:

- Progress has been made in preparing membranes that can be incorporated into a functional MEA, but the membranes seem finicky compared to conventional Nafion, requiring very specific processing within a narrow range of conditions to yield acceptable mechanical qualities.
- So many properties of a good PEM membrane need to be realized at the same time, so it is difficult to achieve them all. For example, we can have all the greatest properties of the membrane, but if the costs of manufacture are much too high, then no significant advancement is made toward the DOE goals.
- More work is needed to understand how to process materials to make strong and flexible membranes. More parameter space on processing, coupled with more careful mechanical studies, should be informative. Integration of the membranes with electrodes, either with the project's ionomers or other ionomers, was beyond the scope of this project but should be addressed going forward.
- The project has had delays and has not provided data on the current membranes at high-temperature, low-RH conditions. The project does not appear to be targeting the DOE target of 120°C with water partial pressure of 40 kPa.
- Study and optimization of the interface between Nafion in the electrode and the CSM membrane is needed but not in scope.
- There is a sloppy scientific method (at least as presented—perhaps the work has been done but was just not shown).
- Plans for thinner membrane fabrications and how to meet the cost target are not clear.

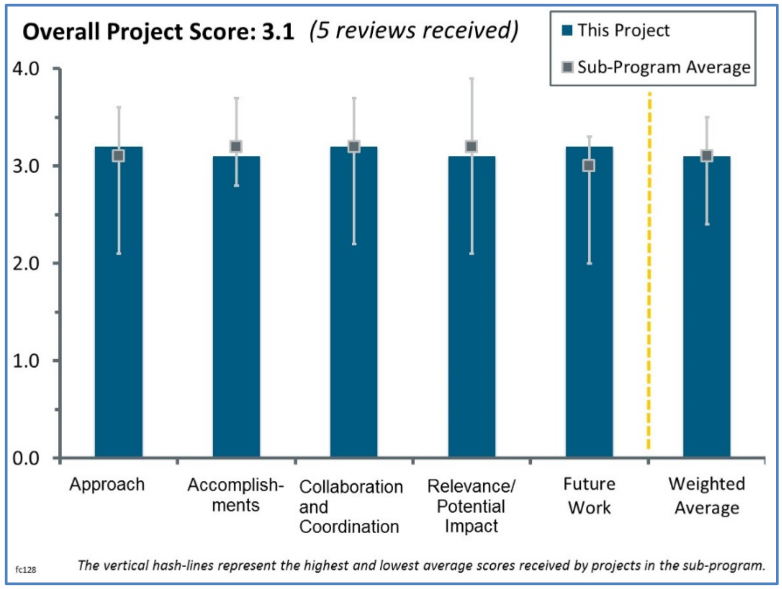
Recommendations for additions/deletions to project scope:

- The project should include testing over the whole range indicated in the DOE target table, including at 120°C with water partial pressure down to 40 kPa.
- There is a lack of real cost evaluation or at least comparisons/approximations. These should be added. The effect of film formation techniques (processing) on performance should be added. Forethought and probing on molecular degradation should be considered. There should be more accelerated degradation testing; for example, it is not clear what happens with freeze-thaw cycles or with mechanical stressing of the film.
- The project team should review the test conditions on slide 25.

Project #FC-128: Facilitated Direct Liquid Fuel Cells with High-Temperature Membrane Electrode Assemblies

Emory DeCastro; Advent Technologies, Inc.

Brief Summary of Project:



Direct dimethyl ether (DME) is a carbon-neutral hydrogen carrier that can be used both for internal combustion and as cost-effective fuel for auxiliary fuel cell power systems in automotive transportation. This project will demonstrate direct DME oxidation with high-temperature membrane electrode assemblies (MEAs) and a Los Alamos National Laboratory (LANL) catalyst. DME is expected to significantly outperform state-of-the-art direct methanol fuel cells (DMFCs). The project will incorporate the new ternary anode catalyst in gas diffusion electrodes designed for high-temperature MEAs, evaluate performance with two different high-temperature membranes (polybenzimidazole [PBI] and tetrapyridine sulfones [TPS]), and optimize structures and reaction conditions.

Question 1: Approach to performing the work

This project was rated **3.2** for its approach.

- The project addresses durability, cost, and performance barriers for portable power, direct liquid-fueled systems. The project is well designed to address issues with DMFCs by looking at an alternative direct DME fuel cell utilizing high-temperature polymer electrolyte membrane technology. This technology can take advantage of the higher temperature, lower crossover of DME fuel cells in high-temperature polymer electrolyte membranes and higher volumetric energy density of DME. Part of the approach is based on potential advantages of utilizing Pd to break C-C bonds, but the majority of the work to date appears to be focused on PtRu anodes and not the PtRuPd catalyst. The approach to prove the concept for direct DME by optimizing the PtRu anode and then develop the PtRuPd catalyst and anode seems to require additional effort than if the project would prove advantages of PtRuPd first and optimize the anode only once.
- The project team has spent a considerable amount of time doing baseline testing and quantification with traditional catalyst and membrane materials. This effort will be invaluable in the assessment of new MEA components and is something that is often lacking when addressing unfamiliar systems including unique fuels. A very systematic approach is used to assess the impact of a range of operational conditions and material properties. The project team may want to consider a more combinatorial approach to determine if there are parameters that interact to yield a certain outcome. It may help to more quickly isolate the optimal operational conditions and material properties. More fundamental insight into the mechanism by which the ternary catalyst selectively drives the C-O bond breaking will either aid its implementation into the fuel cell or point to other catalytic materials that may have enhanced DME oxidation performance. Overall, the desired outcomes and barriers are well detailed, and the plan appears to be feasible. With baseline testing complete, the hope is that progress will be accelerated during the next few quarters.
- The approach taken seems to logically progress from DMFCs to DME-operated high-temperature fuel cells on PBI membranes, incorporating new catalysts. The project addresses a unique case competing with DMFC with greater potential power density at lower loading and lower crossover.
- The CO poisoning from the DME oxidation is shifted from high temperature. Perhaps it would be possible to include a calculation to show what the up limit of temperature to completely eliminate the CO poisoning

will be. Also, perhaps the operating temperature can be further increased (i.e., beyond 200°C) to improve the performance. Finally, using an additive to improve the DME solubility in DME is a good approach, but the team needs to be more specific on the working principle and the expected results.
- It is difficult to determine whether the work is addressing all of the key barriers to commercialization of the technology, as the end-use application is not well defined. Certainly though, crossover, power density, and catalyst cost would be important for most applications.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.1** for its accomplishments and progress.

- Accomplishments related to performance benchmarking and operational parameter analysis have been satisfactorily completed. Some performance metrics have been met, specifically with the PtRu/C catalyst. Sufficient progress has been made to this point, and with the down-selection of materials, attaining the other performance metrics is in sight. PtRuPd/C was identified as an ideal catalyst early on in the project. However, it appears that little success has been achieved with this material, potentially because of a lack of insight into the properties of the ideal active site or ensemble for DME electro-oxidation.
- The results to date are encouraging, and with better catalyst layer development incorporating the Pd-containing catalysts, the performance targets should be achievable.
- The project is clearly pushing the state-of-the-art performance and understanding for this novel technology. The only weakness is the uncertainty regarding whether the technology really applies to DOE goals.
- The project has made significant improvements in the anode activity over the past year, increasing the activity of the PtRu anode by approximately 15 A/mg_{PGM} at 0.5 V, and matching anode activity of DMFC with 1 M MeOH. The project is still short of the target 75 A/g_{PGM} at 0.5 V by a substantial amount. The project has not demonstrated the advantages of adding Pd and that it increases C-C bond splitting in the direct DMEs over PtRu.
- The project is still about 60 mV from the Fuel Cells sub-program target. The project team should further improve the PtRuPd catalysts and optimize the corresponding electrode structure to achieve the target.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.2** for its collaboration and coordination.

- The project makes great use of national laboratory resources and other collaborators.
- This is a good complementary team. The project team should emphasize the effort from the University of Connecticut.
- The collaborations are appropriate for this phase, but establishing strong collaboration with a system integrator/commercialization partner needs to be accomplished to ensure the technology progresses beyond this funding.
- It is not clear how much LANL is contributing to the project other than contributing PtRuPd catalyst material. The results from LANL indicating efficiency of the PtRuPd catalyst to split C-C bonds or convert DME to CO_2 are lacking. The project could potentially benefit from some imaging experiments (possibly in situ x-ray imaging or neutron imaging), which could provide information on the phosphoric acid penetration into the anode.
- There should be greater interaction between collaborators or further evidence showing interactions in the presentation, for example, a task breakdown, Gantt chart, or work breakdown structure.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.1** for its relevance/potential impact.

- Expanding fuel cells to a range of other fuels is key to their adaptability to a range of applications including backup power, large-scale storage, and transportation/portable power. The proposed work fits well within the Fuel Cell Technologies Office (FCTO) Multi-Year Research, Development, and Demonstration Plan.
- The use of the liquid fuel is always a good approach for polymer electrolyte membrane fuel cell (PEMFC) applications on transportation. Keeping this exploratory effort is one of the options for liquid fuel for future PEMFCs in vehicle applications.
- The technology could be a potential enabler for phosphoric acid fuel cells (PAFCs) operating on DME, which may have niche market applications.
- The project partially aligns with the FCTO goals. It does not align with goals to aid development of PEMFCs. High-temperature, direct DME fuel cell development does not help with hydrogen PEMFC development, help develop the market, or help increase PEMFC production, supply stream, or hydrogen infrastructure.
- The project seems appropriate for incubator funding, but the potential commercial applications for the technology do not seem to fit the large-scale impact that DOE typically funds.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- The future work addresses the appropriate issues: activity of PtRuPd and integrating it into an MEA.
- The project has appropriate milestones and risk mitigation.
- The proposed future work is appropriate.
- Proposed future work focuses on MEA scale-up and use of additives to manipulate catalyst layer hydrophobicity and DME solubility. There needs to be a risk mitigation strategy for the PtRuPd/C catalyst, as its initial performance is low, and there are concerns related to the phase and segregation stability of this ternary alloy at elevated temperature, low pH operational conditions. Future effort should also consider other types of carbons, assessing them for their impact on transport and catalyst layer stability.
- More details on future work would be beneficial to reviewers.

Project strengths:

- The project is advancing the state of the art and the understanding of a novel DME fuel cell technology. The fuel is interesting because of its high energy density and means to reduce CO_2 emissions. This technology could ultimately find use in applications with weight sensitivity. A strong team is working on important barriers for this technology.
- The use of a high-temperature membrane is an effective way to deal with CO poisoning in hydrogen fuel, which is a very much less emphasized topic in the current Fuel Cells sub-program portfolio. For future fuel cell vehicle applications, the CO poisoning is still an issue that needed to be addressed. This project is a good exploration of the CO poisoning issue.
- There was a well-defined baseline performance for traditional materials. This project attained relatively high activity for DME in comparison to DMFC. The project used a systematic approach to understanding and optimizing the impact of operational parameters.
- The project provides a direct liquid-fueled fuel cell with potential advantages in power density over DMFC and reformed methanol fuel cells.
- This project has good partners and an approach to demonstrating PAFCs operating at intermediate temperatures on DME.

Project weaknesses:

- This project needs a risk mitigation strategy for PtRuPd/C catalysts. More fundamental insight into the performance and use of half-cell electrochemistry of catalysts could help to optimize their composition and morphology. This would also be helpful in assessing the properties of any new catalyst to determine what parameters, such as type of carbon, need to be changed to get efficient integration of the material into the catalyst layer.
- The project needs more fundamental aspects on the catalyst development. More characterization of the PtRuPd catalyst is encouraged to build the property–structure–performance relationship to better guide project development.
- The pathway for DME looks like a long shot compared with hydrogen and battery electric vehicles for transportation applications. Maybe this could work in limited markets. Catalyst loadings, power density, temperature, and cost are high compared to commercial low-temperature fuel cells.
- It is not clear whether this technology will ever have large-scale impact. The cells still require relatively high precious metal loading. Additionally, it is not clear how complex the system will be for this technology.
- The project addresses a smaller market, which does not help develop hydrogen-based PEMFCs and diverts resources from that goal.

Recommendations for additions/deletions to project scope:

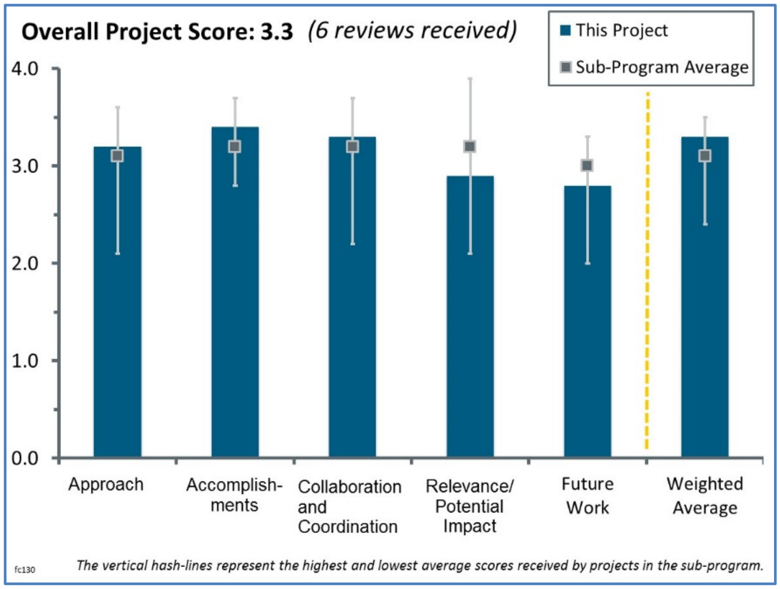
- The team should add some initial system design and report on the expected complexity and cost. This will help determine how competitive the technology can be with competing technologies and where future work should be focused. Determining the likely applications that would first adopt the technology would be beneficial to better define the barriers that need to be addressed.
- Characterization of the PtRuPd catalyst using transmission electron microscopy (TEM), x-ray diffraction (XRD), and rotating disk electrode (RDE) methods is highly recommended. Measurement of H^+ conductivity within the gas diffusion electrode is highly recommended as well to guide the use of the additives.
- More fundamental assessment of DME electro-oxidation on PtRuPd/C and half-cell analysis are recommended.

Project #FC-130: Development of Platinum-Group-Metal-Free Catalysts for Hydrogen Oxidation Reaction in Alkaline Media

Alexey Serov; University of New Mexico

Brief Summary of Project:

This project will enable integration of platinum-group-metal (PGM)-free anode materials into an optimized membrane electrode assembly (MEA) structure. The resulting PGM-free-based anion-exchange membrane fuel cell (AEMFC) is expected to demonstrate significantly improved peak power density (up to 250 mW/cm^2). Objectives include developing PGM-free electrocatalysts for hydrogen oxidation reactions (HORs) in alkaline media, scaling up the catalysts to 50 g batches, synthesizing a new type of ionomer for the AEMFC, and fully integrating the PGM-free catalyst with the ionomer into the MEA.



Question 1: Approach to performing the work

This project was rated **3.2** for its approach.

- The project is well focused on technology barriers for AEMFCs, particularly on replacing PGMs. The project was well planned using promising non-PGM HOR anode catalysts with a small amount of work on novel alkaline ionomers. HOR work showed promising results in both rotating disk electrodes in microelectrode experiments. A significant finding is that the ionomers appear to poison catalysts over time, which presumably will have a negative impact on fuel cell performance. MEA fabrication went very well, and MEA performance showed rapid and significant improvements to meet milestones. MEA tests showed an unusually large effect of temperature (e.g., in one case, peak power increased by nearly five times between 60°C and 80°C). The cause of this large change is not well understood, but it seems likely that it is not due simply to activation-energy-related effects. Overall, the final project results are quite strong for a cell with a PGM-free anode.
- There is a good materials design approach to meet unique project objectives (e.g., a PGM-free anode in an AEMFC). This project has met project objectives for peak power density. As pointed out by a number of audience members, this is a significant achievement.
- The team adopted a bimetallic nickel alloy supported over high-surface-area carbon. The new approach made significant progress over last year.
- This project is within three months of completion. The principal investigator's (PI's) approach is sound and well formulated. Project targets have been generally met or exceeded, most importantly including the second go/no-go design point of 250 mW/cm^2. Questions remain, for example, as to why there is such a large increase in power density with temperature for an MEA with NiCu/KB. It was surprising that there was no obvious mass transfer resistance/limitation for an anode 80–100 µm thick.
- The approach is fine, but the PI did not seem to really follow it. Instead, it appears that a myriad of materials and combinations of materials were tested, such as (1) commercial AEMs and ionomers, as well as ionomers provided by Los Alamos National Laboratory (LANL), and 2) both non-PGM catalysts and PGM catalysts. Additionally, there did not really appear to be any rationale to the combinations integrated into MEAs. For example, slide 8 claims certain combinations of ionomer and catalysts work well together, and then only one of these combinations is presented as an MEA.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.4** for its accomplishments and progress.

- Progress toward milestones and DOE goals appears to be excellent. All milestones were met, some by large margins.
- The project made significant strides this year and met a second go/no-go decision point.
- The approach demonstrated all project objectives with the possibility of a no-cost extension.
- The project team has met the project goals. The project had an end date of 5/31/2017, but the PI has requested a no-cost extension to 8/31/2017. The project goals have already been met, according to the AMR presentation. New project goals for the no-cost extension have not been identified. A "Future Activity" slide was included in the AMR presentation, with general research topics listed, but new MEA performance/durability targets were not identified.
- Although there has been some good technical progress, overall performance is still very poor. The milestones are really not compelling. There is no testing of MEAs on air—not simulated air or actual air (with CO_2).
- The project meets its own target, but the target is very low from a practical standpoint.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.3** for its collaboration and coordination.

- It appears that there has been good collaboration with the team members, and new participants have been added as well.
- Good collaboration was demonstrated with all team members.
- Coordination with Pajarito Powder and EWII Group appears to have been very well coordinated and essential to achieving milestones. LANL work on HOR diagnostics was valuable for a semi-quantitative examination of HOR kinetics. LANL ionomer participation appears to have been relatively minor, with nearly all results reported for Tokuyama ionomers. The project reported some promising results for one LANL ionomer but did not follow up on them. Tufts work on water imaging is impressive, though not so well integrated. Overall, the effort did well in meeting milestones, though the fundamentals behind why improved performance was obtained were a bit lacking.
- Collaborations with LANL, EWII Group, and Pajarito Powder were described. It appears that ionomers developed at LANL were not incorporated into MEAs, so this collaboration is weakly tied to the project goals/accomplishments. There was little or no information/discussion on Pajarito Powder's scale-up efforts.
- The project team consists of multiple partners from universities, national laboratories, and industry.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program (the Program) goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **2.9** for its relevance/potential impact.

- This achievement has significant impact. It opens the door on future studies in other alloy systems. In the NiMo and ternary systems examined, the project goals were met. Durability studies to determine long-term chemical stability are warranted.
- The project does a nice job toward advancing the goals and objectives of the Program.
- Alkaline fuel cell research represents one of the Fuel Cell Technologies Office's (FCTO's) long-term research and development focuses.
- Demonstration of MEA-level performance using a non-PGM anode is important and potentially transformative. More knowledge is needed about the mechanism and rate of HOR reactions and the role of ionomer poisoning, which apparently can be significant. Closer attention to water management will also be needed.

- Unless the more serious issues with AEMFCs are resolved, such as sensitivity to CO_2 and membrane stability, work on HOR catalysts will have no use.
- It is not clear that this work will have any real-world impact unless some future breakthroughs arise.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- Optimizing the carbon-supported NiCu alloy should be continued. It represents a good choice in finishing the project with the remaining time.
- There appears to be more future work listed than is likely to actually be achieved in the time/budget remaining. The plans are good but should probably be prioritized.

Project strengths:

- The project strengths are as follows: (1) the PI and project team have developed/tested a Pt-free high-activity anode for an AEMFC, which is a significant breakthrough, and (2) the project team has met all of the milestones and go/no-go design points.
- This is a high-risk project. It is good to have some in the FCTO portfolio, although it may be less important with the Advanced Research Projects Agency–Energy. This project has made good progress and has a good approach/plan.
- A non-PGM anode was demonstrated in an AEM fuel cell.
- The team achieved the second go/no-go target with promising performance.
- The project used a novel approach and delivered on project milestones.

Project weaknesses:

- Project weaknesses include the following: (1) the MEA power densities are not yet competitive with those obtained with Pt-based or PGM-free polymer electrolyte membrane fuel cells, so it is not exactly clear whether there is a pathway for commercializing this technology, and (2) fuel cell performance data with a NiCu/KB MEA and air were not presented.
- Mechanistic details regarding how HOR occurs and how ionomer can poison the catalyst are lacking. A very strong link between cell temperature and MEA performance is important but unexpected and is not yet understood.
- The project does not appear to follow the plan. Performance is too poor to make an impact.

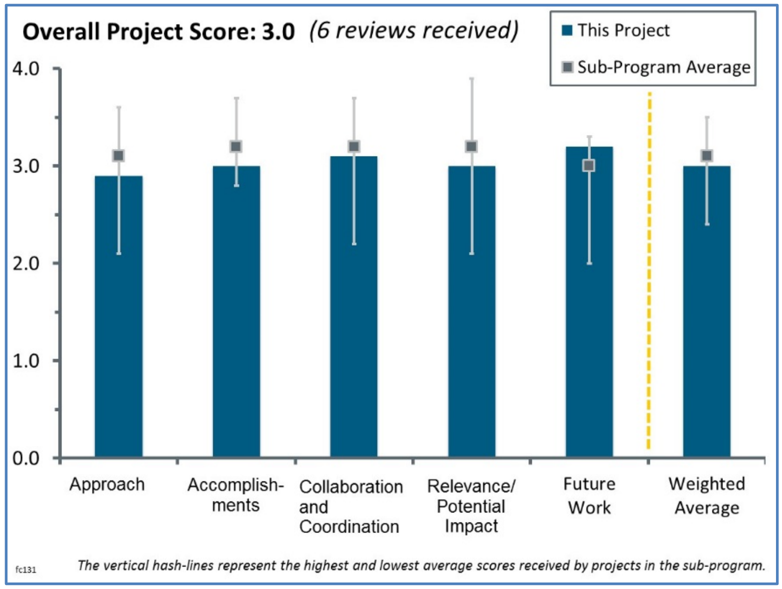
Recommendations for additions/deletions to project scope:

- Presumably, testing on “non-simulated air” means testing on actual air (with CO_2). If so, this should be the highest priority with the best MEA, to date, to see whether there are unique issues with these catalysts and ionomers in the presence of carbonates. This should be done before more optimization.
- This project will end in three months. There is no need for additions/deletions to the project scope.

Project #FC-131: Highly Stable Anion-Exchange Membranes for High-Voltage Redox-Flow Batteries

Yushan Yan; University of Delaware

Brief Summary of Project:



This project aims to develop a class of anion-exchange membranes (AEMs) with very high oxidation resistance for high-voltage cerium redox flow batteries (RFBs) and other alkaline-membrane-based electrochemical devices, such as fuel cells and electrolyzers. Cerium RFBs show potential to offer high-performance and low-cost electricity storage solutions for renewable energy, and stable AEMs are the key missing element in making cerium RFBs a viable technology. Stable AEMs can also be used for hydroxide-exchange membrane fuel cells, for improving cell durability and performance, and for highly durable AEM electrolyzers, lowering hydrogen production costs. This project will contribute to knowledge of polymer chemistry and membrane technology that will help advance the design and development of polymer electrolytes for electrochemical devices.

Question 1: Approach to performing the work

This project was rated **2.9** for its approach.

- The approach is to work on an RFB with high potential and low capital costs. This is an excellent choice, as making an AEM work in this environment will rapidly get the technology leveraged. This is a logical polymer development project that starts with gaining chemical stability, followed by mechanical strength, and finishes by demonstrating some modest scale-up capability.
- The project seeks to develop a stable alkaline membrane for use in RFBs, enabling the development of a double-membrane flow battery as demonstrated in a separate Advanced Research Projects Agency-Energy (ARPA-E) project. The approach of combining a stable cation with a stable backbone to achieve high membrane durability for RFBs is reasonable.
- The approach is effective and comprehensive, and the methods are sound in terms of membrane characterization and synthesis.
- The approach for membrane fabrication was well designed and reasonable. The project was integrated with the National Renewable Energy Laboratory (NREL) testing system.
- This project is focused on the development of a membrane for flow batteries. Although some of the fundamental properties of new materials can be used in both applications, targets for this work are not clearly defined. For example, the project's reported membrane conductivity of about 5 millisiemens/centimeter (mS/cm) is much too low for any meaningful automotive fuel cell application, for which typical polymer electrolyte membrane conductivity is more than 100 mS/cm. Furthermore, 5 mS/cm is not an adequate conductivity for flow batteries. Nonetheless, no target for membrane conductivity was given.
- The approach to making an alkaline membrane, using 9MeOTTP-PBI and oxygenated (methoxyphenyl) tetra substituted phosphorous cations in polybenzimidazole (PBI), is reasonable. However, the rest of the approach to the work is rather poorly designed. Using a liquid acid and base solution separated by a neutral salt solution for the RFB is impractical. These liquids will never be separable in a practical device, let alone by a Donnan electrostatic barrier. The conductivity is mostly liquid and not membrane conductivity, and it

is not so high. The authors should try to test the 9MeOTTP-PBI in pure water to see what the anion conduction is.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.0** for its accomplishments and progress.

- The project overcame initial stability issues with the first polymer system by switching to a PBI backbone. This improved polymer system demonstrated adequate stability. Building membrane electrode assemblies (MEAs) was delayed, as first materials were not suitable for testing. It is to be hoped that MEA testing will now be accomplished with the more stable materials.
- The team transitioned away from polysulfone backbones over the past year, finding that PBI-based backbones should have better oxidative stability. The strategy for ionic tethering also changed, with an iodobutyl linker replacing the bromomethyl group used previously. The new linking strategy appears to successfully avoid the crosslinking issue that arose with the earlier linking strategy. Changes to the cation itself, which involved replacing methyl groups with methoxy groups, were also made in an effort to improve the conductivity. Still, the conductivity of this ionomer seems rather low compared to other alkaline ionomers, and far lower than acidic ionomers. It is difficult to determine whether this should be considered a successful material since no targets exist for alkaline ionomers and the project milestones do not indicate a target conductivity. The new ionomer material passed the specified chemical durability test with less than 20% loss of conductivity, but it appears that the chemical stability of this ionomer is still insufficient. Significant conductivity loss occurred, and chemical changes are apparent in the nuclear magnetic resonance spectra. Further work is needed to understand and prevent the degradation. Since DOE does not have any published goals or targets for this application, it is not possible to assess progress toward DOE goals.
- This project is a low-technology-readiness-level (TRL) project. The principal investigator (PI) has finished most of the milestones successfully.
- The PI emphasizes that this is an AEM project and not a fuel cell/flow battery project. Even so, showing the performance in relevant applications (either flow battery or fuel cell) would provide the additional information. The stability of the “traditional” AEM was limited to 40 hours, and this work demonstrates stability in solution tests for 100 hours. It is unclear whether this test would hold in any operating cell.
- The conductivity is for mixed liquid and membrane electrolytes and is low, on the order of millisiemens. This work may have started with a good idea, but execution has been poor. The team should concentrate on optimizing the performance of the 9MeOTTP-PBI polymer and membrane in water.
- Conductivity and stability goals should be defined so that one can gauge the progress toward the goals. It is very difficult to see whether any actual progress has been made.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.1** for its collaboration and coordination.

- The addition of Giner Inc. and Xergy as team members that can help with reinforced membrane fabrication strengthens the project. Overall, it looks like a good and appropriate mix of capabilities within the team.
- The collaboration is very good. The PI from the same institute was involved. The formal PI kept contributing and even changed job duties. The collaboration with the NREL is excellent.
- The Delaware team needed help and seems to be getting it from membrane optimization. It is admirable to seek help when needed, but this may be too little, too late, to get useful results (a high-conductivity hydroxide-conducting membrane).
- There is collaboration with a national laboratory to build MEAs and with industrial partners to fabricate the reinforced membranes. The project needs collaboration with a national laboratory or university to study the in-depth physical chemistry and mechanics of materials so that they can be improved from a scientific basis. Also needed is collaboration with a redox flow company or potential original equipment manufacturers.

- Not much cost-sharing collaboration was seen. It makes more sense to collaborate on fundamental material measurements rather than fuel cell testing at this point in this project.
- The work includes partners at NREL, Giner Inc., and Xergy. However, it is unclear where they were involved and to what extent.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.0** for its relevance/potential impact.

- DOE needs to invest in AEMs, as they have potential to be game changers in polymer-electrolyte-based technologies. This project is an excellent example of building a membrane for a device that needs an AEM to be functional.
- This is a relevant project and will contribute greatly to the Hydrogen and Fuel Cells Program (the Program).
- Improvements in AEM are of importance to many electrochemical flow systems, and the project demonstrates that its polymer membrane is resistant to oxidative resistance and shows significant improvements in comparison to the state of the art. However, the scalability of this material is in question.
- The project seeks to advance RFB technology, which is mentioned in the Program's Multi-Year Research, Development, and Demonstration Plan but does not represent a major part of the Program. Since the Program has not established specific goals or milestones for RFBs, it is difficult to assess the likelihood that the project can contribute to meeting the Program's goals. Since flow batteries represent a secondary area for the Program, the relevance of this project to Program goals is limited. However, the membranes being developed may also be relevant for hydroxide exchange membrane fuel cells, which adds to the relevance of this project.
- The making of a hydroxide-conducting membrane gives relevance to the Program. The authors did well to try phosphorous cations and have evolved this class of AEM, but the results are still not clear, such as determining the conductivity of the best 9MeOTTP-PBI membrane in pure water. The redox flow aspect was a diverging distraction.
- Membrane conductivity needs to improve by a significant amount before any meaningful relevance/impact toward the Program goals can be realized.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- The four proposed future work areas as given by authors are:
    - 9MeOTTP-PBI polymer synthesis
        - Investigate conditions for large batch production of 9MeOTTP-PBI polymers
    - 9MeOTTP-PBI [polytetrafluoroethylene (PTFE)]-reinforced membrane preparation
        - Improve thickness uniformity of 9MeOTTP-PBI PTFE-reinforced membrane
        - Work with Xergy to prepare PTFE-reinforced membranes
        - Work with Giner Inc. to prepare electrolyzers
    - 9MeOTTP-PBI PTFE-reinforced membrane characterization
        - More comprehensive tests of reinforced membranes, including oxidation stability, conductivity, [ion-exchange capacities], water uptake, and mechanical properties
    - RFB/fuel cell test
        - PBI PTFE-reinforced membrane in cerium RFBs and fuel cells

  The first three work areas are fine, but the fourth should be dropped. Under proposed research work area 2, the work on electrolyzers should be dropped. The project should just characterize the best 9MeOTTP-PBI membrane in water to get the maximal useful result from this project. Phosphate cations are interesting; it would be good to see what the project has in this respect.
- The future work looks reasonable. Improved understanding of the degradation mechanism and the development of pathways toward improved conductivity should be emphasized.

- The project is close to completion and has been able to meet its proposed targets and milestones.
- The proposed future work is very feasible and meaningful.
- Future work focuses on modest scale-up, quality assurance and quality control issues, and reinforcement of material in membranes. It does not appear that the material is ready yet for device testing.
- The project has essentially ended (end date of August 2017).

Project strengths:

- The project has met its proposed targets on time (except for the one-month delay on the fourth-quarter milestone) and has successfully synthesized an ionomer that appears to have improved properties over the incumbent technology.
- This project developed a new type of highly stable AEM. Stability and conductivity were improved compared to the other membranes. This provides a new electrolyte film for both fuel cells and RFBs.
- The project builds off of earlier work performed by the PI in an ARPA-E project and successfully leverages that earlier work. The project benefits from the fact that the membrane under development could be useful in multiple applications, including the flow batteries as well as hydroxide-exchange membrane fuel cells.
- The project has the wide scope of work to innovate new materials.
- The approach to use immobile cations for a hydroxide-conducting membrane is novel.
- New AEMs are a strength.

Project weaknesses:

- A lack of targets or guidance from DOE makes it difficult to determine what this project should be shooting for. While progress and achievement of milestones is being demonstrated, the membrane conductivity is rather low and may be insufficient for commercial applications.
- The weaknesses of the project are the low transport properties, the synthesis yield, the limited direct collaborations (no data was presented in the presentation), and the limited applied results under electrochemical operating conditions.
- Because this membrane will also be used for fuel cells, the stability at higher temperature should be improved, and the property and performance at higher temperature should be given.
- The work was poorly executed. The best part was the evolving membrane, but to date, even this has not been brought to any tangible clear conclusion for conductivity in pure water and stability.
- Very little progress was made on materials with good conductivity.
- It is not clear that this technology can be scaled.

Recommendations for additions/deletions to project scope:

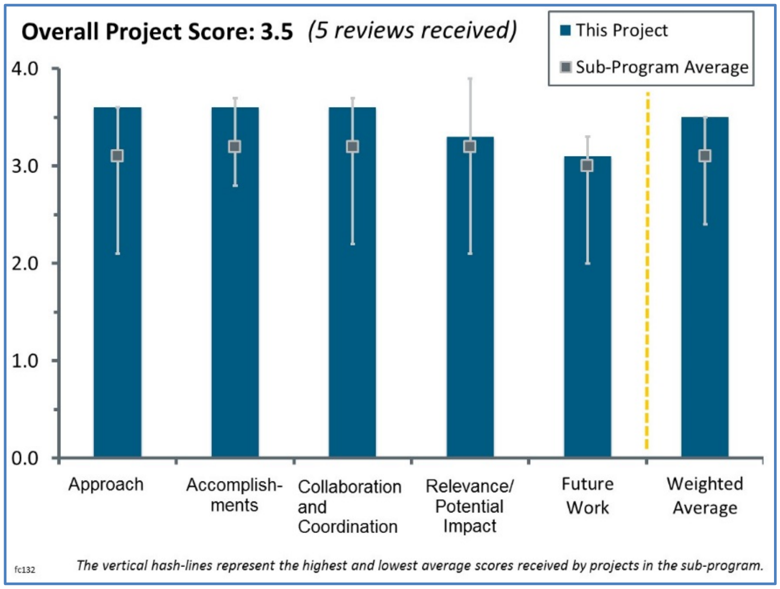
- The project should compare results versus commercial membranes as a reality check that the phosphonium-based membrane is on track to be competitive. This was shown for oxidative stability but not for other relevant metrics such as conductivity.
- The project should delete everything except optimizing the proposed research work areas 1, 2, and 3, which are fine. Work area 4 should be dropped, and the electrolyzer work under proposed research work area 2 should be dropped. The project should just characterize the best 9MeOTTP-PBI membrane in pure water for conductivity and stability to make clear conclusions.
- Electrochemical experiments would provide complementary information for assessing the true performance and value of this membrane.
- The project should improve high-temperature stability and test high-temperature properties and performance for this new type of AEM.
- More polymer science and device integration, maybe beyond the flow battery, are recommended.
- As the project has essentially ended, this question is not applicable.

Project #FC-132: Innovative Non-Platinum-Group-Metal Catalysts for High-Temperature Polymer Electrolyte Membrane Fuel Cells

Sanjeev Mukerjee; Northeastern University

Brief Summary of Project:

This project is investigating the use and development of platinum-group-metal (PGM)-free electrocatalysts that would allow for high performance in high-temperature (HT) polymer electrolyte membrane fuel cells (PEMFCs) based on polybenzimidazole (PBI)-type membranes. A successful outcome will enable HT polymer electrolyte membrane (PEM) technology to be less dependent on Pt resource availability and lower membrane electrode assembly (MEA) costs by at least 50%. Benefits include increased energy efficiency and improved U.S. energy security.



Question 1: Approach to performing the work

This project was rated **3.6** for its approach.

- This work builds upon prior work from the principal investigator (PI) on non-PGM oxygen reduction reaction (ORR) catalysts in other cells (e.g., at lower temperature). Multiple Fe-N-C catalysts were made and tested by rotating disk electrode voltammetry, showing reasonable ORR kinetics, though significantly less than Pt/C. Fuel cell measurements with PBI MEAs at NEU and the University of South Carolina show good behavior at high gas pressures. Transport limitations in the electrodes appear to be important and are under study but were not finished in time for this presentation. Overall, very good performance is achieved with non-PGM cathodes. Durability studies showed very good results, which is perhaps the reason that alternate supports (e.g., tantalum and tungsten carbides that were proposed initially for consideration) were not studied.
- This project is pursuing a promising approach to develop PGM-free catalysts for HT-PEMFCs. The use of PGM-free catalysts enables elimination of a high-cost component while also potentially avoiding the phosphate anion poisoning issue that has limited performance of previous phosphoric acid fuel cells (PAFCs). By further developing several related PGM-free catalysts based on carbon and nitrogen-coordinated iron centers developed for low-temperature PEMFCs in a previous effort, this project is leveraging previous work toward a new application.
- The project approach in developing metal–organic framework catalysts (Northeastern University [NEU]) and Fe-based catalysts prepared using silica template (University of New Mexico [UNM]) is promising and shows good activity and durability. The catalysts studied in this project have shown encouraging results for the mitigation of phosphate anion adsorption.
- This is a well-thought-out and well-planned approach. The non-PGM catalyst for a HT fuel cell is an innovative approach. The use of a PBI membrane is an effective and valid approach.
- The project applied several previously U.S. Department of Energy-funded PGM-free catalyst syntheses and achieved reasonable performance. It would be more desirable if the PI could elaborate the design principle in applying these PGM-free catalysts under HT operation.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.6** for its accomplishments and progress.

- Performance levels are not yet matching performance of conventional PAFCs, but significant cost reduction, through the elimination of Pt from the cathode, has been achieved. The project has met targets for MEA performance using an Advent North America (ANA) anode catalyst and a Pajarito Powder cathode catalyst. NEU/UNM cathode catalysts seem to be slightly behind the Pajarito catalyst. The project is close to meeting final performance goals. The durability results are encouraging, but the improvement in performance during the 48-hour hold makes it difficult to interpret. The MEA should have been fully conditioned to reach its maximum performance prior to the start of the durability testing. Since it was not fully conditioned, the simultaneous conditioning and degradation make it impossible to say how much degradation occurred. Last year, the PI showed results from a voltage loss breakdown analysis. This year, the PI did not show such results, though he indicated that such analyses are still being performed. It is okay to show results from previous years where needed, but these should be clearly labeled as such. Several slides from this year contain the same data as presented last year, with no labeling.
- Multiple synthesis techniques were applied to address the catalyst performance. Advanced characterization techniques were used to understand the catalytic active site and influence (or non-influence) by phosphate adsorption. The project made good progress in catalyst/MEA performance.
- All milestones were met with a non-PGM cathode, which is impressive. Durability tests in particular showed very good results.
- This project has produced a significant number of results, and most or all of the project milestones have been achieved.
- All major targets have been met, and the project successfully passed all go/no-go points.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.6** for its collaboration and coordination.

- NEU and UNM have had a good collaboration on PGM-free catalysts for several years now. The inclusion of Pajarito and ANA in this project is clearly critical since they are providing the anode and cathode, respectively, that enabled meeting performance milestones.
- This project has an impressive collaboration with a non-PGM catalyst manufacturer, membrane developers (both university and industry), and academic institutions. The contributions from different collaborators are very significant.
- Collaboration was important to the project, with catalysts coming from two partners (NEU and UNM), scale-up being accomplished by another partner, and assistance with fuel cell testing being provided by another partner (University of South Carolina). This report showed ANA as providing materials only. The degree of collaboration is reasonable relative to the project scope and goals.
- This is a very complementary team. From the presentation, all parties work effectively, and the project is well coordinated.
- The team has multiple partners, including universities and small companies.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.3** for its relevance/potential impact.

- The project is highly relevant to the Hydrogen and Fuel Cells Program (the Program), as it is following a promising pathway to improved performance and decreased cost of HT-PEMFCs. Furthermore, advancements in PGM-free catalysts developed through this project may prove helpful in developing PGM-free catalysts for low-temperature PEMFCs as well. If successful, the project could have a large impact in accelerating commercialization of stationary fuel cell technology. The idea that this technology will help

enable flare gas utilization seems improbable. Flare gas is currently vented or flared because it is uneconomical to capture and use. There is no chance that flare gas would be converted to electrical power for transmission since it would be easier and cheaper to transport the flare gas than to build electrical transmission lines. Similarly, there is little chance that it would be used to power local operations using a fuel cell since this can already be done more cheaply using combustion.
- This project can effectively reduce the cost and durability of the HT PAFC and improve the overall efficiency of the PAFC system. Non-PGM catalysts also help with CO tolerance.
- This project addresses HT-PEM cathode catalyst development and is well-aligned with the Program goals for combined heat and power (CHP) systems.
- Achievement of targets with a non-PGM cathode is impressive and potentially important.
- This project is aligned with the mission of the DOE Fuel Cell Technologies Office.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- Future work was well planned.
- The PI indicated plans to continue efforts to achieve higher performance with both UNM and Pajarito catalysts. Further durability testing will also be performed including some temperature cycling testing. The possibility of scaling up to the 100 cm^2 level was also mentioned, which seems to be a necessity to meet the Quarter 8 milestone.
- Focus on transport limits will be important going forward. The low volumetric active site density in these types of catalysts is a limiting factor, and transport studies will help to reveal how much these limits affect overall performance.
- The team has proposed performing a list of future work, including catalyst down-selection to achieve better hydrogen–air fuel cell performance, durability studies, and MEA scale-up, until the end of the project period.
- More aggressive and longer durability/corrosion tests should be included, given that high stability was found in the short-term test.

Project strengths:

- This project is well planned, well organized, and well executed. The project team is a supplementary and comprehensive team with well-balanced expertise and capabilities. The project is well coordinated and well managed to achieve all project targets and pass all milestones.
- Demonstration of strong performance of a non-PGM cathode in this fuel cell format is impressive and a project strength.
- The project has a well-defined approach and strong collaboration with industry and universities.
- The project met several milestones. Promising durability at MEA level was demonstrated.

Project weaknesses:

- There is no obvious weakness in this project.
- The durability test should be carried out for significantly longer than 48 hours, particularly when initial promising stability was found. The presentation should be laser-focused on the major achievement, since this project is approaching its end. With this high funding level and limited presentation time, topics such as the need for Pt replacement, the market on micro-CHP, and review of others' work should be significantly minimized or removed.
- This catalyst class suffers from transport limitations due to the low volumetric density of active sites. This is not a weakness of this PI or his ideas but of these catalysts in general. It will be valuable to the field as a whole if solutions to this problem can be found.
- While significant progress is being made, the challenge of making a business case for this technology remains substantial. Significant additional progress would be required to enable a cost-competitive product.

Recommendations for additions/deletions to project scope:

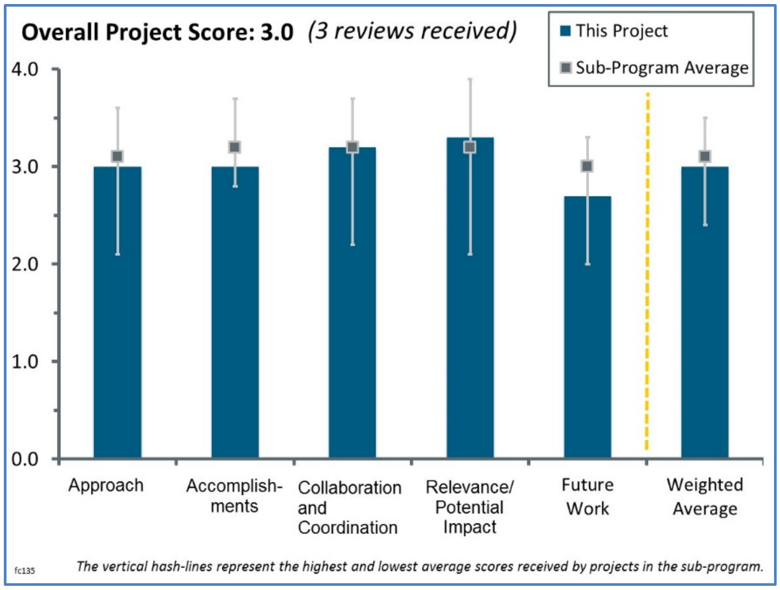
- Longer durability testing should be added to the project. The PI indicated plans to do so, but it is not clear how long they plan to test the durability. Addition of accelerating stressors, such as more thermal cycling (greater than the planned 50 cycles), and inclusion of inlet water vapor should also be used to look for durability issues.
- The only question is for the durability of the chronopotentiometric testing results, as there was no performance loss after 48 hours. After carefully looking over the data, the performance after 48 hours was slightly increased. The team may need to explain this phenomenon.
- Demonstration of durability for durations longer than 48 hours and a corrosion test for more than 3 hours would be a path forward for successful PGM-free HT-PEM technology.

Project #FC-135: FC-PAD: Fuel Cell Consortium for Performance and Durability

Rod Borup; Los Alamos National Laboratory

Brief Summary of Project:

The Fuel Cell Consortium for Performance and Durability (FC-PAD) coordinates activities related to the denoted development areas and supports industrial and academic developers. This effort aims to advance performance and durability of polymer electrolyte membrane fuel cells (PEMFCs). Researchers will develop the knowledge base and optimize structures for more durable and high-performance PEMFC components; improve high-current-density performance at low Pt loadings; improve component durability; and develop new diagnostics, characterization tools, and models.



Question 1: Approach to performing the work

This project was rated **3.0** for its approach.

- The approach of coordinating the investigation of the performance and durability of fuel cells through a consortium composed of the best available experts of national laboratories in a five-year project is excellent. It allows for a deep understanding of the different mechanisms involved and the impact of novel materials or structures and ensures a long-term continuity of the knowledge. The addition of complementary projects with new industry and academic partners completes this approach in a very efficient way. The addressed barriers are well-defined and -structured.
- The aligned approach of the FC-PAD consortium will have pros and cons, but on the whole, should provide more effective leveraging of the individual capabilities of the national laboratories involved. As a result, the overall advancement of fuel cell performance and durability should be accelerated.
  - The plan to include industry through four funded projects and with 30% support of the national laboratories' activities will provide an effective means of ensuring that the industry is engaged, that a reasonable portion of the national laboratories' work is relevant to industry, and that the work is well integrated with a broad range of activities.
  - On the cons side, care will need to be taken that administration of the consortium does not outweigh the benefits of coordination. Not all test plans and approaches should be decided by consensus, and the national laboratories should use their expertise to provide guidance and help set priorities.
  - The six component and cross-cutting thrusts have been well chosen to contribute to required fuel cell membrane electrode assembly (MEA) advancements.
  - The focus on pre-competitive-level activities is appropriate and will provide significant support to industry, whereas the competitive-level work is appropriately carried out by industry-led projects.
  - The technical work shown on the Ce migration appears well developed, with behavior of the Ce characterized through a number of methods that are providing a consistent picture and quantified parameters, which will be useful to others.
  - While the objective of evaluating/benchmarking different materials is useful and appropriate, it is not clear how the results shown (i.e., for the perfluoroimide acid [PFIA] versus perfluorosulfonic acid [PFSA] membrane) are different from what the supplier would also be doing and has shared

via U.S. Department of Energy- (DOE)-funded work. This type of work may be more useful if conducted on a broader range of materials.

- The main objectives of this work are to improve component stability, durability, and cell performance with optimized transport. Surely degradation analysis to couple experimental observation with modeling is conducted, but there is no indication of countermeasures on how to make these improvements. On top of that, it would be better to show a quantitative impact on the performance and durability.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.0** for its accomplishments and progress.

- The project's accomplishments and progress are effective. The project clearly addresses the DOE targets in terms of performance and durability of MEAs and the associated components. The main focus this year was on membrane additive migration, PFIA water uptake and conductivity, and microelectrode studies.
    - The high number of results is reflected in the numerous publications and presentations, which makes the results accessible to the whole scientific community.
    - Different effects of contamination have been presented. It might be interesting to try to better link the evolution with a quantitative impact on the performance/lifetime in a real PEMFC.
    - Moreover, it is not clear whether the contamination of the membrane can be differentiated from that of the ionomer in the active layer.
- It is relatively early in the project, about 1.5 years into the consortium, and it is difficult to assess effectiveness against overcoming barriers. In addition, the consortium is focused on increased understanding, and the objectives of the project are high-level in nature, without clear milestones. It is also not clear how much of the progress has been made under this project, as opposed to follow-on from previous work. In terms of accomplishments, the Cerium migration and modeling has shown clear and valuable progress. The work on cation effects on conductivity is showing useful information, the membrane conductivity ionomer model is a valuable approach, and the effect of sulfate contamination is relevant.
- Degradation analysis became better than the previous project and has been conducted well because not only experimental observation, but also modeling, are well coupled.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.2** for its collaboration and coordination.

- Collaboration between the different partners appears to be well structured, well managed, and very efficient, even if the material transfer agreements (MTAs) or intellectual property management plans (IPMPs) are still in progress. New collaborations were also started with DOE-awarded FC-PAD projects (under Funding Opportunity Announcement [FOA] DE-FOA-001412), including industrial partners 3M, General Motors, and the United Technologies Research Center, as well as with numerous non-FOA activities supplying materials or performing specific analysis.
- The very nature of the consortium and the interactions established through the FOA ensure that collaboration is an essential part of the work. It appears that the national laboratories are well coordinated. The interactions with the industry partners are just beginning, and how effective this will be will require proper assessment next year.
- Surely some collaboration exists; however, how to correlate one another organically is not well visualized to finally achieve the goal.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.3** for its relevance/potential impact.

- The FC-PAD consortium and project is, as Electrocat, crucial for the Fuel Cell Technologies Office and represents a very high potential to significantly advance DOE in achieving Multi-Year Research, Development, and Demonstration Plan targets. The main targets are improving fuel cell durability and performance while decreasing the cost through a better understanding of the mechanisms involved, leading to a better mitigation solution. The high number of publications and presentations allows a very good diffusion of the knowledge learned to the fuel cell community.
- Performance and durability of the MEA are critical to meeting the long-term targets of fuel cell commercialization. These must be met at low cost. While the industry will focus on designing to appropriate trade-offs with cost, FC-PAD is focused on those activities that will enhance the understanding and provide the input to the industry to do so.
- Current activities should focus on indicating countermeasure/direction of the improvement, as well as the degradation analysis to finally achieve the goal.

Question 5: Proposed future work

This project was rated **2.7** for its proposed future work.

- The future work proposed is in accordance with the results already obtained and aligned to achieve DOE goals.
- The activities outlined under future work are relevant and appropriate. However, in terms of milestones, only three near-term joint milestones were selected, and these are insufficient to understand the timelines and scope of the work to be accomplished. The stratified electrode layers are of questionable manufacturability, and it is unclear if this work is of any value.
- More effort on how to improve the performance and durability should be made with quantitative impact to meet the final target.

Project strengths:

- Extensive national laboratory capabilities will be coordinated and applied in a synergistic manner toward polymer electrolyte membrane issues affecting durability and performance. The multiple principal investigators are all of excellent caliber with many years of experience. The work is generally conducted in a systematic manner, with extensive characterization to support hypothesis and models. The use of models is routinely used to help support understanding, and development of appropriate parameters will help others for use in industry models. The interactions with industry are expected to be positive, will help to guide the work, and will allow industry to access the very extensive national laboratory capabilities.
- FC-PAD gathers the national laboratories' core competencies and the associated considerable amount of equipment to achieve the DOE goals. This project seems to be further improving collaboration between the national laboratories. Organization of the project into six thrust areas appears to be very relevant to cover all the required fields to advance fuel cell technology. The high number of publications and presentations allows a strong and quick communication to the fuel cell community.
- There are excellent human resources from various national laboratories.

Project weaknesses:

- No specific weakness was identified. A difficulty may be to finalize the IPMPs and MTAs, in particular for the state-of-the-art materials from industry.
- The large amount of administration and coordination is likely to take some focus away from the technical work and management. Is it unlikely that FC-PAD will truly get state-of-the-art materials, though the

researchers will likely get materials which are adequately close. The electrode structures to be studied are of uncertain relevance. Model predictions of the structures should be conducted as a first step.
- It was unclear how to link each analysis to finally indicate quantitative performance gain. Currently, it seems that only material-based analysis has been conducted. To communicate further with partners/ manufacturers, how to improve performance as a device, and not only the material itself, is preferred.

Recommendations for additions/deletions to project scope:

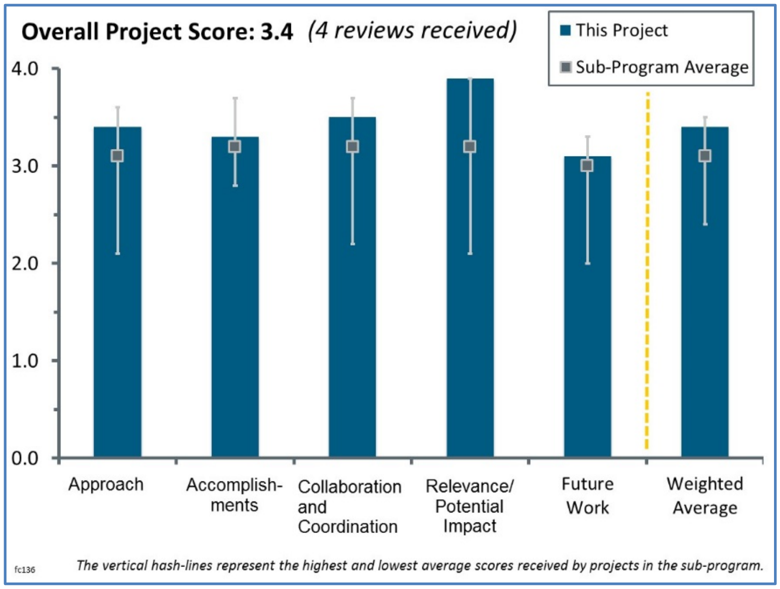
- FC-PAD is focused on MEA components. Quantification, the link of these results to single-cell and even to stack performance evolution, should be taken into account. When considering a stack, bipolar plates also have an impact on its performance and durability through the aging of the bipolar plate itself or through contaminating the MEA, even with the presence of a coating. This may be added in the FC-PAD investigations. Differential cells use a serpentine design, which is not used in the current stacks. It has to be ensured that extrapolation of FC-PAD results remains valid in these new stack designs.
- It is better to apply a typical performance model consisting of measurable parameters to predict performance gain based on the individual excellent degradation analysis.
- Timelines and the description of milestones should be improved.

Project #FC-136: FC-PAD: Fuel Cell Consortium for Performance and Durability – Components and Characterization

Karren More; Oak Ridge National Laboratory

Brief Summary of Project:

The Fuel Cell Consortium for Performance and Durability (FC-PAD) coordinates activities that advance performance and durability of polymer electrolyte membrane fuel cells (PEMFCs). FC-PAD efforts include six complementary thrust areas, including one on electrocatalysts and supports. This thrust area aims to realize the oxygen reduction reaction (ORR) mass activity benefits of advanced platinum-based cathode electrocatalysts in high current density, with air performance for over 5,000 operating hours, and with low-platinum-group-metal (PGM) loading.



Question 1: Approach to performing the work

This project was rated **3.4** for its approach.

- The approach of coordinating the investigation of the performance and the durability of fuel cells through a consortium composed of the best available experts of national laboratories in a five-year project is excellent. It allows a deep understanding of the different mechanisms involved and the impact of novel materials or structures, and it ensures a long-term continuity of the knowledge. The addition of complementary projects with new industry and academic partners completes this approach in a very efficient way. The addressed barriers are well defined and well structured. This is a thrust area of FC-PAD, and the objectives and approach are very clear.
- Development of a new, faster accelerated stress test (AST) is a very positive development and was strongly needed, as the old protocol took too long to complete. It was not mentioned, but one assumes this is still under nitrogen, which may not be representative of duty-cycle degradation. A comparison of the failure fingerprint to Pt dissolution under actual operation is required for validation of the protocol. Results will differ as a result of cathode catalyst layer (CCL) water generation when cycled under air.
    - The AST does appear to be independent of carbon type, but it is unclear whether the Pt particles were all the same size as well. If not, then it would not be expected to see overlapping electrochemical surface area versus cycle number results for all three catalysts. It is unclear whether any catalysts have been screened that do not overlay on top of the three shown.
    - The study of PtCo catalysts is well designed and highly relevant. The Pt and Co dissolution rate measurements as a function of potentials and operating conditions, under inductively coupled plasma mass spectrometry (ICP-MS) and microscopy characterization, provide valuable information to characterize degradation rates and to compare catalysts. Going forward, it may be important to understand in which acid these tests were performed. The use of H_2SO_4 will delay oxide formation (versus in $HClO_4$), but binding with bisulfate will enhance chemical dissolution, so it is not clear which acid will result in faster dissolution.
    - The different membranes used make it harder to directly compare catalyst results. This is likely one failing of the approach of testing "state-of-the-art (SOA)" materials supplied by partners in that it will be more difficult to draw understanding and make correlations, as opposed to systematic studies. Additionally, it seems that there is incomplete information on some of the materials, which will also make it harder to draw conclusions. There is characterization and

specification to be done within the project (e.g., x-ray diffraction [XRD], Co composition, and high-surface-area carbon) that will mitigate this, but only partially.
  - Regarding the question raised on how much Co remains within the ionomer in CCL: when load is applied, Co from the membrane will transport to the CCL (migration). Thus, evaluation/ calculation of Co in the CCL will be greatly underestimated if values of Co are used based purely on the ex situ (scanning tunneling electrochemical microscopy [STEM]/energy dispersive x-ray spectroscopy [EDS]) analysis.
  - Standardized rotating disk electrode (RDE) protocols are important to enabling cross-laboratory comparisons, and the understanding of the ionomer effect on ORR kinetics is important to interpreting data.
  - Presently, many national laboratories do not use Nafion™ in their RDE inks. It appears that the recommendation on slide 21 is to start using Nafion. It is unclear whether this indicates that the national laboratories will all be switching back to using Nafion. The optimal RDE ink seems to depend on the goal of the researcher. It is not clear whether the U.S. Department of Energy is interested in having RDE mass activities that match membrane electrode assemblies (MEAs) (the ink should contain ionomer), or activities that represent “intrinsic” values (no ionomer). The presence (or absence) of ionomer in the RDE ink is a major cause of discrepancy between the literature-reported values for mass activity.
  - It is not clear what the statement regarding the i_k>2 is referring to, since the data shown are for lower values. Perhaps this is referring to Pt/C powders.
- Since the recent introduction of the FC-PAD consortium, the concept of “Approach” has changed somewhat from a well-designed project with milestones and goals to a more community-wide collaboration, and this project becomes one with more of a supporting role rather than a leading role. Furthermore, this project combines and reports on the efforts of several laboratories.
- By applying SOA characterization techniques, it is expected that the bottleneck can be revealed gradually.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.3** for its accomplishments and progress.

- Significant progress has been made, and the accomplishment is solid and well coordinated.
  - AST development and refinement is interesting, with an acceleration of a factor of 5 in the testing duration. The effect of the water in the dissolution of nanoparticles has been demonstrated. It was not clear whether the test could be further accelerated by increasing the relative humidity.
  - Regarding electron spectroscopy for chemical analysis (ESCA) measurements and the Pt and Co dissolution measurements, it would be interesting to establish a quantified correlation between them.
  - The results of quantifying Co loss are interesting, but the remaining question now is how much Co remains within the ionomer in CCL and how it will be measured.
- Key parameters, such as Co dissolution amount and ratio of nanoparticles of inside/outside carbon support, have been quantified by SOA techniques, which can help in analyzing and improving performance by communicating with performance and modeling teams.
- Progress looks good, and relevant activities are underway. However, it is early in the project, and it is difficult to assess how much was done in this project and how much is building on previous work. This project also suffers from a lack of clear milestones. The objectives, while appropriate, are fairly high-level in nature, and it is difficult to assess the overall test plan. The identified activities are important and will provide valuable input to the overall DOE objectives.
- The project is more of a support role, so the responsibility to meet the goals has been somewhat diminished since it is a shared responsibility across FC-PAD. Sometimes innovation is required to advance the SOA toward the goals. However, sometimes good, shared information on the properties and characterization of the SOA allows others to provide innovation. Thus, more characterization of the SOA components should be included in this project.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.5** for its collaboration and coordination.

- There is excellent collaboration with other institutions to evaluate their SOA MEAs. Industry partners that receive DOE support should be required to have the FC-PAD team evaluate their components.
- Collaboration between the different partners appears well structured, well managed, and very efficient, even if the material transfer agreements or intellectual property management plans are still in progress.
- According to the representative partners' opinion, characterization by the latest technique at Oak Ridge National Laboratory is quite powerful and can act as a hub of the analysis with exceptional techniques and equipment.
- The very nature of the consortium and the interactions established through the funding opportunity announcement (FOA) ensures that collaboration is an essential part of the work. It appears that the national laboratories are well coordinated. The interactions with the industry partners are just beginning, and how effective this will be will require proper assessment next year.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.9** for its relevance/potential impact.

- The FC-PAD consortium and project is, as Electrocat, crucial for the Fuel Cell Technologies Office and represents a very high potential to significantly advance DOE in achieving the Multi-Year Research, Development, and Demonstration Plan targets. The main targets are improving fuel cell durability and performance while decreasing the cost by developing a better understanding of the mechanisms involved, leading to a better mitigation solution. The high number of publications and presentations allows for a very good diffusion of the knowledge learned to the fuel cell community.
- Advanced characterization techniques and AST development are critical to supporting the fundamental understanding of performance- and durability-related processes occurring in PEMFCs. This information will feed into the supply chain and fuel cell designers to advance the materials and designs used to meet the long-term objectives of the industry.
- Characterization results here can find the root cause of the degradation and quantify key parameters that can predict the performance gain. Therefore, whether the target is achieved can finally be transparent.
- This type of project, one with a common set of characterization and evaluation techniques of industry-wide fuel cell components, is critical to advancing technology toward the goals.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- This project includes world-class characterization techniques and technique development. The extensive national laboratories' capabilities will be coordinated and applied in a synergistic manner toward polymer electrolyte membrane issues affecting durability and performance. The extensive characterization provides significant understanding to experimental studies and will support model development. The interactions with industry are expected to be positive and will help to guide the work. They will allow industry to access the very extensive characterization capabilities.
- FC-PAD gathers the national laboratories' core competencies and the associated considerable amount of equipment to achieve the DOE goals. This project seems to be further improving collaboration between the national laboratories. Investigation of industrial SOA catalysts is a strength. The high number of publications and presentations allows for strong and quick communication to the fuel cell community.
- Some future work would be for the FC-PAD team to develop new characterization tools. This would be an excellent utilization of the innovative resources at the FC-PAD laboratories.
- The future work proposed is in accordance with the results already obtained and aligned to achieve DOE goals.

- The proposed future work is relevant and necessary. However, there is some concern with how the FOA partners' samples will align with a preferred systematic study approach and how much information will be shared to allow mechanistic understanding to be developed. There are neither timelines nor milestones provided for the future work. The use of a very small cell for a durability test may result in significant variability because of the small sample size under study.
- It is quite important to reveal the bottlenecks. It is necessary to feed the characterization results back to the performance analysis and to find the essential countermeasure and finally predict the gain.

Project strengths:

- The common characterization techniques applied to different SOA MEAs are an excellent strength of this project. The development of these outstanding techniques does not need to be duplicated industry-wide, and having them in a common shared national laboratory resource is a great asset to the industry.
- The project strengths include SOA characterization techniques and facilities with excellent researchers.

Project weaknesses:

- No specific weakness was identified.
- The characterization work will be dependent on samples received, and it is not clear how coordinated the work will be with all of the FOA support work. It is likely that some of the samples will have proprietary restrictions. The many variations in the FOA samples will make it difficult to draw direct conclusions (e.g., the MEA samples had both different membranes and different catalysts).
- The project has weaknesses in having fuel cell industry-wide participation in the characterization efforts.
- More quantification and linkage to the performance prediction/modeling are needed.

Recommendations for additions/deletions to project scope:

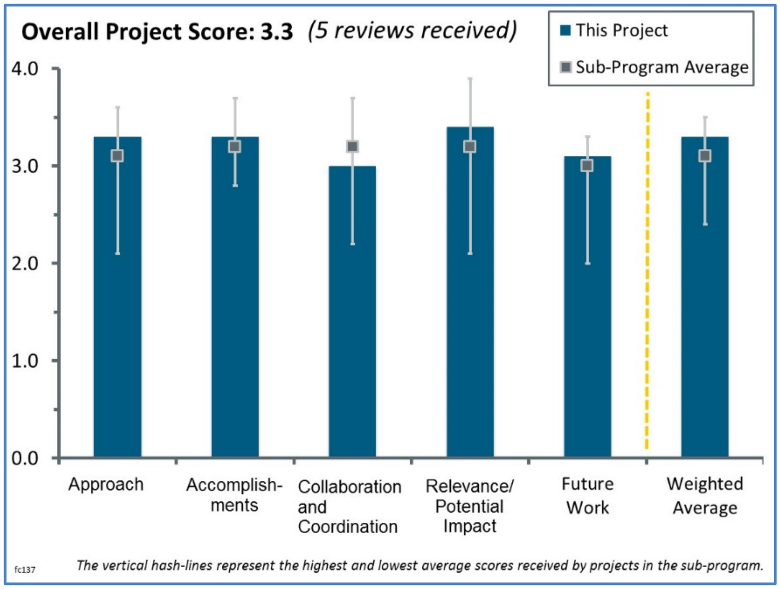
- The project scope could be expanded to include the development of new innovative characterization tools.
- The project is expected to characterize and quantify other key parameters that are controllable and critical for performance.

Project #FC-137: FC-PAD: Fuel Cell Consortium for Performance and Durability – Electrode Layers and Optimization

Adam Weber; Lawrence Berkeley National Laboratory

Brief Summary of Project:

The Fuel Cell Consortium for Performance and Durability (FC-PAD) coordinates activities that advance performance and durability of polymer electrolyte membrane fuel cells. FC-PAD efforts include six complementary thrust areas, all of which contribute to the electrode layer integration studies. Optimizing electrode layers and mitigating transport issues are vital to meeting U.S. Department of Energy targets. This project is identifying state-of-the-art catalysts; optimizing the catalyst layers; developing diagnostics to help resolve problems with high current density and low loading; and mitigating the problems through the use of novel electrode design, components, and diagnostic techniques.



Question 1: Approach to performing the work

This project was rated **3.3** for its approach.

- The overall approach is comprehensive. It is important that all the information feed into microstructural and molecular dynamics modeling. There is a broad range of activities, which are potentially too many. The highest-priority work should be the thin-film understanding, microstructural modeling, local resistance analysis, and ink model studies. Conditioning effects are also important. The characterization of ink structures helps to understand the ionomer structure. The electrode microstructure analysis via detailed characterization provides significant model input. The influence of the environment on the ionomer thin film is providing some interesting results. In terms of the electrode structures, there are some very interesting structures being developed. The use of model structures and understanding transport effects should provide good data for model validation, and the ability to control structures and confirm intended transport effects will provide good insight. However, it should not be expected that these structures can be manufactured as commercial structures, at least in the short term. The hydrophilic microporous layers (MPLs) using carbon nanotubes are also providing some interesting results. Overall, the combination of unique structures (catalyst layer [CL] and MPL) and enhanced characterization techniques will significantly advance understanding and eventually lead to the ability to tailor designs.
- The approach is excellent: coordinating the investigation of the performance and the durability of fuel cells through a consortium composed of the best available experts of the national laboratories in a five-year project. It is allowing a deep understanding of the different mechanisms involved and the impact of novel materials or structures, and ensuring a long-term continuity of the knowledge. The addition of complementary projects with new industry and academic partners completes this approach in a very efficient way. The addressed barriers are well defined and well structured. This is a thrust area of FC-PAD, and the objectives and approach are very clear. In particular, using a synergistic combination of modeling and experiments is very relevant.
- This FC-PAD project should use and report on commercially available materials and components. Detailed studies on new structures that are not commercially available or easily made are less valuable. For example, the stability study on the catalyst ink is a result that can be well related to industry efforts, whereas the

wettability study of a special carbon nanotube MPL, from a grade of SGL Group carbon material that is not available, is of less help. However, in general, nearly all of the work helps the industry as a whole with understanding the electrode performance; thus, the score was an "Excellent."

- Because the CL is a key component governing the performance, where both electrochemical reaction and mass transport occur simultaneously, modeling is quite helpful to understand phenomena there and finally find key parameters in terms of performance/degradation.
- This is a very mixed approach, as there are too many disconnected projects that have a small likelihood of success compared to a concerted effort. Additionally, much of the effort is spent on ionomer layer resistance for low loading. The work seems very good, but it does not correlate well with what General Motors (GM) is seeing (ability to have very low loadings with no additional mass transfer losses). Much of this work will be very catalyst/ionomer dependent, and the researchers need to be very selective about what they look at. It is unclear why they have added the patterned catalyst layers, as this certainly has a long history, and it is not obvious that anyone is interested in it. A better understanding and some guidelines for ink/slurry stability and formation would certainly be helpful.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.3** for its accomplishments and progress.

- Significant progress has been made, and the accomplishments are solid and well coordinated. Main accomplishments concern the development of new catalyst-layer architectures, unraveling the origin of local resistance, and the exploration of the ink stability, dispersions, and fabrication methods.
- Accomplishments and progress toward a specific goal are difficult to measure in this project since it is more of a fundamental understanding/supporting role. This should be considered a good feature of the project, so perhaps DOE should consider modifying this question a bit to better reflect the mission of the FC-PAD laboratory team members.
- It is relatively early in the project, about 1.5 years into the consortium, and it is difficult to assess effectiveness against overcoming barriers. In terms of accomplishments, there has been excellent development of techniques and the ability to link a suite of characterization and diagnostics methods to investigate phenomena. In addition, a number of interesting structures have been made.
- As much of the project goals are "a better understanding," this is difficult to judge. Along those lines, the work on better understanding of the ionomer resistance at low loadings is very important, but here coordination with other groups becomes very important. The investigator needs to ensure that what the project is measuring is relevant (i.e., whether these are the same catalyst/ionomer structures that are being used). When the data/conclusions differ, the team needs to actively work together or repeat the work of others to see what the bottom of the differences is.
- A catalyst ink study is needed from the industry aspect to finally guarantee the performance by process. A transport study is also helpful to find the bottleneck and finally improve hydrogen contaminant detector performance.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- Collaboration between the different partners appears well structured and well managed. New collaborations also started with DOE-awarded FC-PAD projects (Funding Opportunity Announcement [FOA] 1412) that includes industrials such as 3M, GM, and the United Technologies Research Center (UTRC), as well as with numerous non-FOA activities supplying state-of-the-art (SOA) materials.
- The very nature of the consortium and the interactions established through the FOA ensure that collaboration is an essential part of the work. It appears that the national laboratories are well coordinated. The interactions with the industry partners are just beginning, and how effective these will be will require proper assessment next year.

- Collaborations with other institutions should be expanded. Reporting on industry components provides the best utilization of efforts by the laboratories. Industry partners that do not allow sharing of this type of analytical work with the community as a whole should not be supported by DOE.
- Most of the collaboration is with other national laboratories. There is really good work being done outside of the laboratories. This seems to be partially corrected, moving forward.
- More collaboration with the electrocatalyst/kinetic team, performance team, and/or original equipment manufacturers is desired in terms of dominant factors and design of the performance.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.4** for its relevance/potential impact.

- The FC-PAD consortium and project are, as is the ElectroCat (Electrocatalysis Consortium), crucial for the Fuel Cell Technologies Office and offer a very high potential to significantly advance DOE in achieving Multi-Year Research, Development, and Demonstration Plan targets. The main targets are improving fuel cell durability and performance while decreasing the cost through a better understanding of the mechanisms involved, leading to a better mitigation solution. The high number of publications and presentations allows a very good diffusion of the knowledge learned to the fuel cell community.
- This project has very direct and significant relevance to electrode performance. Focus should continue to be on the SOA industry-supplied materials and components. Divergence from these sets of materials for the purpose of understanding is also very relevant. Therefore, this project has a high level of relevance.
- The investigation into the thin-film losses, the catalyst ionomer interactions, the ionomer morphology, and the impact of the conditions on the ionomer structure is critical to achieving commercial fuel cell targets. The focus is currently on beginning-of-life structures. It is anticipated that at some point these techniques and understanding will also be applied to understanding degraded structures.
- The work seems to be a step behind the researchers working to develop the catalysts. That is, they look at a problem facing catalyst developers and try to find the root cause, but by that time, developers have already moved on. For the work to have real impact, it needs to develop a fundamental understanding that could *lead* to catalyst development. If there were a catalyst/ionomer structure like this, then that could be achieved. If they can do this, it will truly help the developers.
- This activity is focusing on part of dominant factors governing the performance, which can finally clarify how to achieve the goals.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- The activities outlined under future work are relevant and appropriate. However, no timelines or milestones are presented.
- The work on the catalyst ink could be expanded to give more understanding as to how ink properties relate to resulting electrode structures and ultimately fuel cell performance levels. There is a large degree of interaction in these materials and the processing steps that is not well understood by the industry. Industry is mostly working on this as an “art form” rather than a fundamental understanding. This FC-PAD project could help all industry with more work in this area.
- The future work proposed is in accordance with the results already obtained and aligned to achieve DOE goals. However, regarding the exploration of different CL structures, there are so many routes that choices will have to be made and explained at the next review.
- Adding 3M and GM as collaborative partners is a big improvement and will hopefully guide the work. In so doing, the team will likely find little interest in patterned CLs. This is not really a section to address this issue, but having ~ten laboratories work separately on different issues and then trying to tie them together is an incredibly ineffective/inefficient way to fund research. A concerted effort at one location, or possibly two, would be much more effective. It will be interesting to hear more about their work on the inks, as this is a little-studied area. Much of the other areas seem as if little has changed over the past years.

- Catalyst ink should be addressed more to control CL microstructure. In addition, ionomer network and coverage on the electrocatalyst can be studied further, which can govern the performance as well. Therefore, to understand the phenomena around Pt/ionomer, it is important to quantify the microstructure and properties affecting performance.

Project strengths:

- The focus on the understanding of the electrode layers for low catalyst loadings is likely the most important area to achieve low-cost electrode structures. The principal investigator is a leader in this field, and the continued support to focus in this area is expected to drive significant progress. The collaboration and coordination between the national laboratories and the FOA partners will result in the most comprehensive approach possible to study the critical phenomena. The combination of the characterization, experimental studies, and incorporation into models is likely the greatest strength of the project.
- The strength of this project is for the FC-PAD team to have access to a wide variety of SOA materials and components. This access should be able to give the team a deep understanding of the fundamentals of the mechanisms that dominate the electrode performance.
- FC-PAD gathers the national laboratories' core competencies and the associated considerable amount of equipment to achieve DOE goals. Investigation of industrial SOA materials is a strength. The high number of publications and presentations allows for a strong and quick communication to the fuel cell community.
- This project has exceptional modeling capability with coupling SOA characterization.
- This project has a truly talented group of researchers.

Project weaknesses:

- It is not clear how coordinated the FOA support work will be. If this results in non-systematic studies or incomplete studies because of proprietary information, this may delay progress.
- There is a lack of focus, both in goals the team is looking to achieve and in the team itself. It is extremely difficult, if not impossible, to get so many disparate pieces to work together.
- There is a challenge with open exchange of information that one hopes can be overcome with DOE help.
- This project needs further interaction with the kinetic team and performance/degradation team (FC-135).

Recommendations for additions/deletions to project scope:

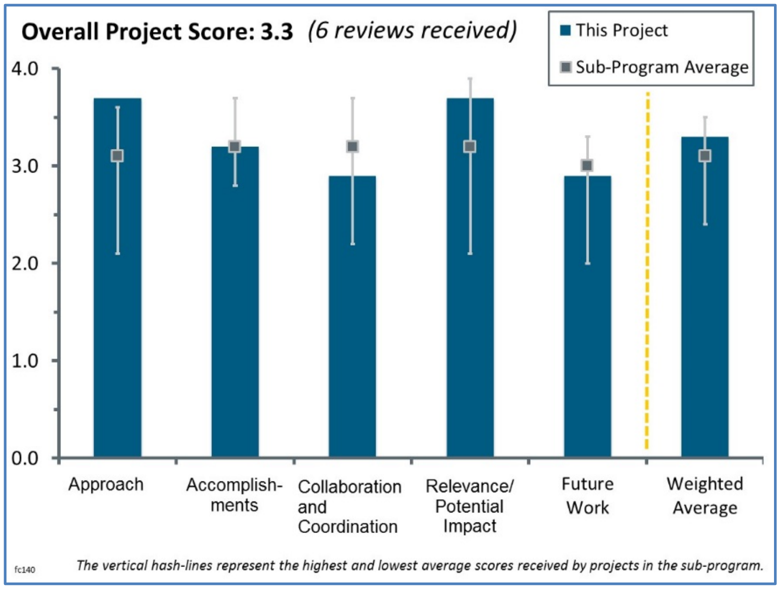
- It will be effective to consolidate some of the functions and roles between FC-135 and FC-137 in FC-PAD regarding performance analysis/prediction. Also, more communication with GM and UTRC is preferable for improving the performance in terms of design and prediction.
- Segmented catalysts should be deleted. Understanding why GM's new structures and, one could say, 3M's old structures do not see the mass transfer limitations that the team is trying to understand should be a big part of the work.
- There is no mention of how durability will be studied as part of this project.

Project #FC-140: Tailored High-Performance Low-Platinum-Group-Metal Alloy Cathode Catalysts

Vojislav Stamenkovic; Argonne National Laboratory

Brief Summary of Project:

A primary focus of the U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program (the Program) is development of highly efficient and durable Pt alloy catalysts for oxygen reduction reactions (ORRs) with low Pt content. This project will go from fundamentals to real-world materials to achieve rational design and synthesis of advanced materials with a low content of precious metals. Researchers are taking a materials-by-design approach to design, characterize, understand, synthesize/ fabricate, test, and develop tailored high-performance low-Pt-alloy nanoscale catalysts.



Question 1: Approach to performing the work

This project was rated **3.7** for its approach.

- The overall approach is excellent. The principal investigator (PI) and team are applying strong fundamental understanding and state-of-the-art methods to develop and characterize novel catalysts. Increased focus is recommended on membrane electrode assembly (MEA)-level testing for activity and durability to help understand the large gap in mass activity between the rotating disk electrode (RDE) (e.g., 4 A/mg) and MEA (e.g., 0.5 A/mg).
- The approach from fundamentals to real-world materials is the only way to tailor the structure/composition in order to optimize durability/performance in Pt alloys for the cathode. This materials-by-design approach, by a better understanding of limitation, will secure the ability to industrialize new compositions aiming at the DOE target. Very good work has been performed since 2016.
- These are clearly unique catalyst structures, and the authors have well represented why they believe they may have higher specific activity while achieving high current density. Additionally, they have demonstrated scalability with no exotic steps.
- The approach of this project to prepare nanoscale Pt-alloy catalysts is unique and fascinating. Changing the size, shape, and composition of alloy particle morphology should have substantial impact on ORR catalytic activity and electrode performance.
- The approach is both aggressive (multiple tasks in parallel) and well designed, since it strives to address many potential risks (in a highly complex system) at early stages.
- The project team uses world-leading resources and capabilities to design catalysts from a fundamental point of view.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.2** for its accomplishments and progress.

- This project had impressive results in the past year in all key areas. (1) Fundamentals: The previous development of the RDE-inductively coupled plasma mass spectrometry (ICP-MS) was a great contribution, and it is great to see the group using this tool effectively on these new catalysts, with interesting results. (2) Synthesis: The core team has continued to make excellent progress in developing new nanostructures. (3) Scale-up: The progress here is especially impressive. It is unclear whether this new one-pot process can be used to make nanoframes as well as nanoparticles. (4) MEA performance: It is also great to see MEA results, which are impressive when one considers how challenging it is to make a good MEA with a new catalyst.

- The work is progressing well toward scale-up synthesis reproducibility and 5 cm^2 MEA testing for demonstrating a real capability to reach the DOE target and reduce the cost.
- The team has made excellent progress in several areas. Use of electrochemical (EC)-ICP-MS is a very novel approach toward understanding the intrinsic stability of various catalysts, including different structures, compositions, and use of Au for stabilization. A new nanocage structure yields very high activity in RDEs, several times higher than the DOE target. It is unclear if the new structure is stable. Work toward scale-up of nanoframes, including development of a one-pot synthesis, is noteworthy. Additional work should focus on activity improvement in MEAs and durability assessment.
- Excellent mass and specific activities of the nano Pt-alloy catalyst have been demonstrated for fiscal year (FY) 2016. No further improvement has been reported in FY 2017. Some additional progress on characterization, particularly on transmission electron microscopy at Oak Ridge National Laboratory (ORNL), has been made. Scaling up and property validation of the catalysts are not trivial tasks; the team has good efforts on those tasks. However, fuel cell performance evaluation with the catalyst has seen very little progress, which is somewhat disappointing. The DOE target for the project is to use 0.125 mg platinum group metal (PGM)/cm^2 for an MEA. It is not clear how 0.04 mg PGM/cm^2 cathode loading can show an equivalent performance with the current state-of-the-art higher-loading (0.1 mg PGM/cm^2) Pt-based electrode. The team should have made more effort to improve fuel cell performance in addition to the RDE measurement. Also, durability of the catalyst in MEAs is missing.
- It is good to see increased focus on catalyst stability in the catalyst design, as EC-ICP could become a powerful tool. However, most work is still on the RDE level, a very slow transition from RDE to any demonstration in an MEA. The only scale-up and MEA evaluation was with spherical PtNi catalysts that were similar but inferior (activity and stability) to existing alloy catalysts. It is unclear what the project milestones and go/no-go criteria are.
- Progress in the past year has been slow. Compared to where the researchers were last year, not much more has been accomplished. A year ago, they had many of these amazing catalysts, had demonstrated their potential in RDE, but had miserable fuel cell performance. A year later, they have even more new catalysts, more evidence of their potential, and more poor fuel cell performance. More effort should have been put into demonstrating that RDE results can translate into MEA results, and if not, why not.

Question 3: Collaboration and coordination with other institutions

This project was rated **2.9** for its collaboration and coordination.

- This project has excellent collaborations with team members (with others at Argonne National Laboratory [ANL] and with partners at national laboratories). The collaboration with the Fuel Cell Consortium for Performance and Durability to obtain the MEA results is especially commendable.
    - The catalyst community position should simply be that RDE is a good screening tool and that they would welcome improved methods to translate this into MEA performance projections by those who can contribute to this challenging task.
- The level of collaboration is generally good. Work with electrode development/MEA integration partners should have higher focus.
- The collaborative work with ORNL is excellent. The interactions with Lawrence Berkeley National Laboratory (LBNL) and Los Alamos National Laboratory (LANL) are moderate. No interaction with original equipment manufacturer industries is a concern. Difficulty (or slow progress) with scale-up does not give much room for further evaluation at the industrial sector.
- The proposed approach needs a good coordination between the different institutions involved (LBNL, LANL, ORNL) for tailoring the composition based on design, characterization, understanding, and synthesizing end tests. Some international collaboration may also progress the work toward disruptive technology.

- On national laboratory projects, it would be preferable to see a centralized effort rather than work distributed to six different laboratories. This is not efficient. An industry partner would be a great help, especially in the fuel cell development area and to make sure that the work is relevant.
- ANL needs to get catalyst samples to other laboratories for evaluation. Inclusion of industrial partners would increase credibility. The project should avoid excessive delays in technology transfer.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.7** for its relevance/potential impact.

- The project aligns well with the Program and research, development, and demonstration objectives. The project has the potential to advance progress if the MEA using the developed catalysts shows good mass transfer properties.
- This project is focused on a key barrier (catalyst cost), and the focus on maximizing the full potential of PGMs makes it a highly promising route to having real-world impact.
- If activity in MEAs can be improved and sufficient durability is demonstrated, the project has the potential to significantly reduce costs of polymer electrolyte membrane fuel cells (PEMFCs).
- This project supports and advances progress toward the Program’s critical goals regarding the cost.
- ORR catalyst activity and stability remains the highest priority of PEMFC research and development.
- The authors have well documented the potential of these materials to make the relevant targets. However, unless some evidence can be given that these catalysts can be incorporated into catalyst structures, they cannot have an impact and will not gain anything but an academic interest.

Question 5: Proposed future work

This project was rated **2.9** for its proposed future work.

- The future work appears to be outstanding.
- Future work shown in slide 27 is a repeat for current activities. No specific or focused work has been addressed, even though the PI indicated some remaining challenges on Slide 27.
- International collaboration could benefit future work with alternative approaches.
- There is too much “stay the course.” The researchers have an obvious, huge problem in that their fuel cell performance looks worse than a non-PGM. Most of their future work is concentrated on new and modified catalysts, optimization, scaling, and characterization. After two years of very poor MEA results, it is very clear to an outsider where the effort should be.
- It is unclear if this was effectively planned (difficult to assess with limited slides).

Project strengths:

- The strength of the project is the PI, who is knowledgeable on nanoparticle preparation. The team also has a good background on electrochemistry and a good track record on advanced catalyst development. The approach of this project toward lowering PGM catalyst loading is unique and intriguing. Having good catalytic activities for the alloy catalysts in RDE experiments is outstanding.
- The project has wonderful new catalysts with a logical rationale as to why they will be stable, active, and able to achieve low loadings. This project has great characterization methods.
- The team has shown excellent progress in the scale-up of a high-activity catalyst. The use of tools (e.g., EC-ICP-MS) to understand durability brings excellent insight.
- The approach, overall quality, quantity of results, and scale-up were all project strengths.
- The materials-by-design approach was a project strength.

Project weaknesses:

- Scale-up of the nanoframe catalysts may be more difficult than for other advanced catalysts, which hampers other evaluation/validation processes of the catalysts. There is no clear pathway to improve high-current-density MEA performance using this type of catalyst.
- The researchers need to keep their eyes on the prize; the entire point is fuel cell performance, so they need to establish why RDE results are not translating. If there is a fundamental reason why these catalysts do not work in MEAs, then the researchers are wasting a lot of time, money, and resources.
- Activity of the catalyst in MEAs is approximately 10 times below RDE activity. Apparently, there is limited work on MEA-level testing and characterization.
- MEA testing was a project weakness.

Recommendations for additions/deletions to project scope:

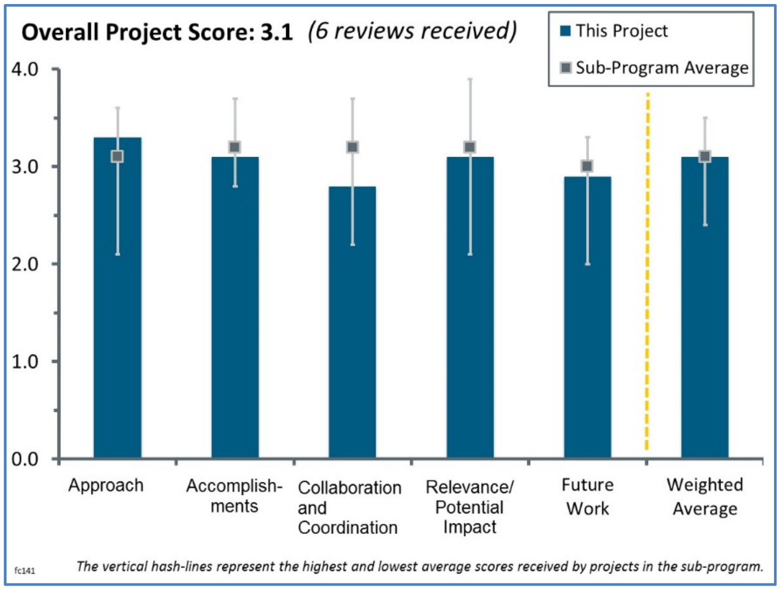
- No additions/deletions are needed. However, more MEA work should be planned. The notable inconsistency in MEA performance between ANL and the National Renewable Energy Laboratory evaluation suggests that the work for synthesis of low-PGM materials with alternative supports and their effects on MEA performance may be more weighted.
- The project should decrease focus on new nanocages until the activity of a nanoframe catalyst in an MEA is improved and MEA-level durability is understood.
- The project should reduce effort on new catalysts and catalyst scaling and increase effort on MEA development.
- The project should look for new collaboration at the international level.

Project #FC-141: Platinum Monolayer Electrocatalysts

Radoslav Adzic; Brookhaven National Laboratory

Brief Summary of Project:

This project aims to synthesize high-performance platinum monolayer (ML) electrocatalysts for the oxygen reduction reaction consisting of a platinum ML shell on stable, inexpensive metal, alloy, metal oxide, nitride, or carbide nanoparticle cores. Three low-platinum catalysts will be developed that will meet the U.S. Department of Energy (DOE) technical targets for 2020.



Question 1: Approach to performing the work

This project was rated **3.3** for its approach.

- The overall approach is good.
  The use of membrane electrode assembly (MEA)-level testing appears to be significantly increased over previous years, a key positive step. Development of non-platinum-group-metal (PGM) cores is key to the viability of this approach, and this activity level appears moderate.
- The selected approach addresses the main barriers related to both activity and durability of the electrocatalyst. The modification of the C support with oxides seems to be a very promising strategy.
- The approach is a good one that has a good balance of fundamental studies of catalysts manufactured and actual fuel cell performance.
- Many different technical concepts have been implemented and executed to a satisfactory standard to enable preliminary conclusions, falling just short of a ranking to indicate the most promising direction to achieve goals.
- The approach by Brookhaven National Laboratory (BNL) is to synthesize and screen Pt ML catalysts on inexpensive cores that enhance stability and activity while lowering cost. Nitriding to improve stability of non-noble metal cores, doping of Pt ML shells for improved stability and activity, and new catalyst supports are also being explored in this project. However, reported efforts spent on catalysts with expensive Pd-rich cores conflict with the defined approach.
- The team has studied a wide range of PGM and low-cost cores as support for platinum, and the researchers continue to develop highly active catalysts. However, focusing on one catalyst's material to pass all DOE-suggested accelerated stress tests on an MEA might help with understanding the limitations of this material group.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.1** for its accomplishments and progress.

- MEA testing of nitride-stabilized Pt/PdNiN/C was an important achievement of the project. It appears that additional effort is needed in electrode layer optimization to achieve the full potential of the catalysts. Characterization of the changes to the catalysts after MEA assembly and testing was very limited and would provide some critical insight into the structural and compositional changes that are limiting performance in the MEA. Progress made on the NbO_2-doped carbon black supports was promising and should be explored in more detail. Work on Au- and Pd-coated metallic W cores did not seem to directly relate to this project. The Pd-rich Ni aerogels, while an interesting concept, do not seem to offer much cost savings because of the high cost of Pd.

- Progress is as follows:
  - MEA tests of nitride-stabilized Pt/PdNiN/C systems show lower MEA performance than expected. The principal investigators (PIs) state that the performance would be improved with a "single membrane to be used next." However, no information about that membrane is provided in this report.
  - Stability tests of this membrane show low stability, and the PIs argue that this is due to C corrosion and a decrease of the electrochemical surface area, possibly due to Ostwald ripening. Thus, MEA implementation is still a challenge.
  - Introduction of new nitride cores containing refractory metals is shown to be a promising avenue.
  - Gold-doped Pt MLs are demonstrated to increase activity and stability. However, cost might be an issue.
  - Ir-doped cores showed very good stability during cycles. The results at 10,000 cycles are weird and not explained.
  - Doping of the C support with Nb oxides appears as the best result.
  - Synthesis of W-based cores is also shown as a very interesting approach, although some challenges point to the synthesis and electronic effects. How to overcome these challenges is not discussed in this report.
- Technical progress shows promise to meet the milestone requirements when considering the catalyst (stability) improvement in ex situ experiments; however, demonstration at the MEA level may provide practical difficulty, as experience with the aerogel support structures indicates. If, indeed, some innovative solutions cannot be validated during the project, a key should be used that correlates ex situ and in situ performance results to predict expected progress against milestones.
- The degree of MEA-level testing of catalysts has improved and is key for truly characterizing system-relevant activity and durability. Development at MEA level is needed. A large amount of work incorporates PGM-containing cores. It is unclear how much PGM is contained. More work on cores with substantially reduced PGM or PGM-free cores is needed.
- Catalysts showing high activity have been developed (e.g., the Pt monolayer on a $Pd_{20}Au$ aerogel). However, there might have been some trouble with the high activity on an MEA.
- It appears from the fuel cell performance curves that progress toward DOE goals is not as good as one would expect from the approach in this project. For example, the ML of Pt on a non-PGM core should yield a large improvement of Pt utilization: kilowatts per gram Pt. However, the comparisons at low current densities appear to have roughly similar Pt utilizations. At higher current densities, the utilizations are better than the benchmark commercial Pt/C-based gas diffusion electrodes. The validity of the comparisons to the benchmark being attributed entirely to the catalyst, and perhaps not somewhat to the electrode structure differences, is questionable.

Question 3: Collaboration and coordination with other institutions

This project was rated **2.8** for its collaboration and coordination.

- The PI collaborates with Los Alamos National Laboratory (LANL) researchers and with a number of industries and academic institutions. However, it is not clear whether Dr. Zelenay, the co-PI, reports separately. There is no discussion regarding his participation and no publications with his name.
- There is a clearly engaged collaboration on material synthesis and characterization, but cell testing and interpretation could receive more emphasis to validate results against milestones by solving stability issues.
- The project is able to leverage a good cross-functional team. It is unclear whether the licensing agreements for four patents are under this project or under some previously funded DOE projects.
- The degree of contributions from collaborators is unclear. The collaboration team appears well suited for work.
- Collaboration with LANL was mentioned, but it was not clear what parts were from LANL.
- BNL could do much better in highlighting the role and contribution of their collaborators. MEA testing was performed in this year's project but, little was said about the efforts of collaborators on this front.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.1** for its relevance/potential impact.

- It is good to see innovative catalyst materials and support structures being realized and prepared in "scale-up" 0.5 g batches. The overall impact could be further increased if such materials could be evaluated by relevant stakeholders apart from direct project partners to confirm findings and gain involvement.
- The project is perfectly aligned with the Hydrogen and Fuel Cells Program goals and objectives.
- This project has a high potential to improve power density and durability.
- The project is directly addressing key activity and durability barriers for polymer electrolyte membrane fuel cells. The potential impact is unclear. The cost of catalysts with multiple interlayers deposited on PGM-containing cores is a concern; multiple wet-chemistry steps with yield losses are likely.
- This project has potential to significantly increase Pt utilization in fuel cells, but the fuel cell test results do not appear to show this.
- The preliminary results of the MEA testing were rather disappointing. It seems much more effort is needed here to understand the factors limiting the realization of the high catalyst activity in an MEA.

Question 5: Proposed future work

This project was rated **2.9** for its proposed future work.

- The proposed plan follows the approaches discussed in this report. Most ideas look promising and feasible. Possibly the largest challenges are related to the synthesis. It would be good to factor the cost into the potential solutions being tested.
- Many different pathways that could work are suggested, but a fast method for screening performance is recommended (as mentioned in the 2016 presentation) to speed up iterations and recognize (lack of) progress faster.
- Future work should include a scale-up of some promising materials to the 10 to 100 g scale. Then, it is recommended that the project share these materials with commercial MEA manufacturers or Fuel Cell Consortium for Performance and Durability (FC-PAD) laboratories that can make MEAs with identical techniques to the baseline Pt/C catalyst materials. FC-PAD should be more integrated into this effort.
- Future work should largely focus on bringing PGM-free cores to technological maturity and fully evaluating MEA-level tests for activity and durability. Understanding of Cu contamination (slide 7) is needed.
- Additional advanced physical characterization of the MEA-tested catalysts is sorely needed and should be an emphasis of the future work.
- Proposed future work seems quite ambitious in developing various catalysts.

Project strengths:

- The great experience and knowledge of the PI and his team are project strengths. Since the PI is retiring, it is expected that the team will continue with his line of work. The great instrumentation existent at the national laboratories is also a strength. The collaborations with industrial partners are a project strength.
- This team has a high level of skill and execution regarding materials synthesis and characterization. BNL has great experience and knowledge on the subject.
- The project is developing catalysts that, conceptually, could greatly reduce the PGM content of fuel cell electrodes.
- The project has a good approach, and good techniques for understanding analytical and fundamental catalytic activity have been developed.
- The team is highly competent in imagining and synthesizing new catalyst concepts with high performance in rotating disk electrodes.
- This project has an excellent team and very innovative synthesis.

Project weaknesses:

- The project seems to be moving in too many different directions. The continued work on Pd-rich cores seems to contradict the project objective to utilize inexpensive core materials.
- While improved over the past, additional work on MEA-level performance and durability is needed, especially with PGM-free cores.
- Poor collaboration leaves the results and progress limited and in question.
- There are too many catalyst options, and none have shown better hydrogen–air performance at MEA level.
- Individual approaches appear disjointed in this presentation.

Recommendations for additions/deletions to project scope:

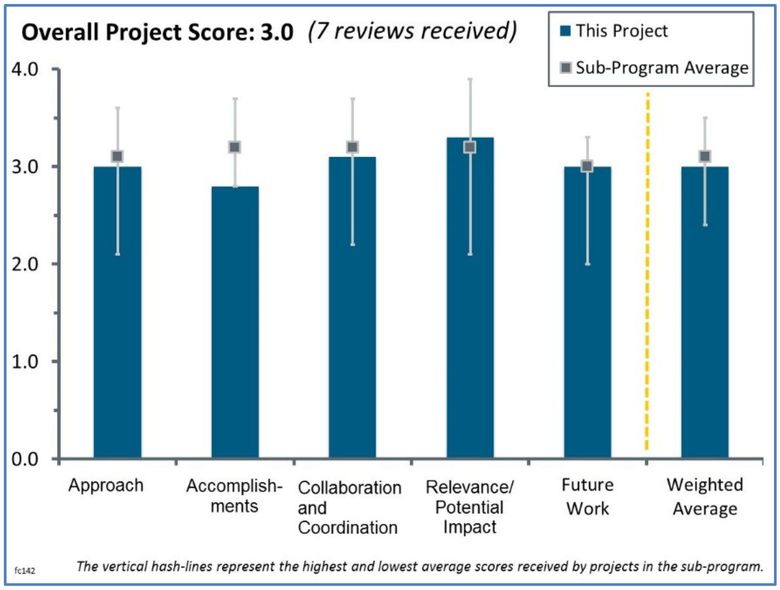
- Further integration of theoretical studies (possibly with existing or new collaborations) would be very helpful to understand the successes and improve the designs.
- Performance milestones appear to turn into stability requirements in attempts to maintain high activity of the MLs, and as a suggestion, the milestones should be defined as such.
- The cost of complex/multilayered structures needs to be understood. MEA-level durability testing is needed.
- A scale-up of the material synthesis and teaming with FC-PAD is recommended.
- MEA testing with 5–10 g scale batch catalysts is recommended.

Project #FC-142: Extended-Surface Electrocatalyst Development

Bryan Pivovar; National Renewable Energy Laboratory

Brief Summary of Project:

Platinum catalysis remains a primary limitation for fuel cell commercialization. This project is developing durable, high-mass-activity, extended-surface platinum-based catalysts for decreased fuel cell cost, improved performance, and increased durability. Researchers are focusing on novel extended thin-film electrocatalyst structures (ETFECSs), a particularly promising approach. Parallel efforts include novel extended nanotemplates; atomic layer deposition (ALD) synthesis of platinum–nickel nanowires; and membrane electrode assembly (MEA) optimization and testing including multiple architectures, compositions, and operating conditions.



Question 1: Approach to performing the work

This project was rated **3.0** for its approach.

- The project team has accomplished the proposed work with a well-defined, systematic approach assessing the impact of synthesis conditions on material properties and their impact on device performance. The feasibility of the project is not in question, as many of the early targets related to material development and synthesis have been met. However, the performance of the extended catalysts is still significantly lower than the target, and significant effort will be needed to bring the performance up.
- The approach of synthesis of ETFECSs for meeting the U.S. Department of Energy's 2020 objectives of improved cost, performance, and durability is very relevant. Low-platinum-group-metal (PGM) loading in ETFECSs has the potential to overcome the cost barrier of fuel cell implementation. The team has demonstrated that the use of nano-structured Ni template as a platinum deposition substrate has the potential to meet the low-PGM loading objectives.
- Using Pt-Ni nanowires with ALD Pt coatings is a novel approach for synthesizing fuel cell oxygen reduction reaction (ORR) catalysts. The project researchers correctly recognized that spontaneous galvanic displacement would not work, so they moved in a different direction, with ALD coating of nanowires. The ALD results look promising.
- The overall project approach is good. The utilization of PGM-free nanowires as substrates has great potential for the development of active and stable thin-film electrocatalysts.
- The nanowire approach is a good one for developing highly active platinum sites. However, the basic flaw with this approach is that there is either too much transition metal or the electrochemical surface area (ECSA) is low. It looks like the project is trying to optimize between these two tough trade-offs.
- It is expected the project will investigate the mechanism of each method (catalyst fabrication) and how it works, or does not work, rather than try to fill out the development gaps (gap to target value). For example, if hydrogen annealing shows better specific activity, it is expected to investigate why.
- This project continues to work on ALD synthesis of Pt-Ni nanowires to achieve the project milestones.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **2.8** for its accomplishments and progress.

- Significant progress has been made in the area of materials synthesis. Cost-effective scale-up of both the sacrificial nanowire growth and ALD deposition of Pt has been demonstrated. Sufficient operation has been demonstrated at low ionomer contents. The close match in performance metrics between rotating disk electrodes (RDEs) and MEAs is very promising, as this is not often the case with other types of electrocatalyst form factors. The dramatic improvement in activity with acid leaching of the core Ni metal is a significant accomplishment. However, developing a protocol for this that is amenable to industrial manufacturing scale-up is complicated. The mechanical stability of the catalyst layer against compression resulting in transport resistances must be addressed. Long-term durability of the catalyst must also be addressed. Strategies for improving the ECSA must be developed.
- Progress is as follows:
    - The team's decision to use a commercial source of Ni nanowire for making Pt-Ni nanowires helped the team accelerate ALD activities. Study and down-selection of Type 4 Ni nanowire among four different types of nanowires supplied by the vendor is good progress. The team has also optimized the oxygen treatment and hydrogen annealing steps for ALD-deposited Pt-Ni nanowires.
    - From the presentation, it seems that the team has done a significant amount of work with Pt-Ni made using spontaneous galvanic displacement (SGD) and compared the product with Pt-Ni made using ALD. As fabrication of Pt-Ni, SGD is not economically viable, and it is not clear why the team is devoting so much effort to it. Understandably, Pt-Ni (SGD) shows better oxygen transport resistance and better low relative humidity performance, most likely a result of the absence of Ni, as compared to the Pt-Ni (ALD) MEA. The focus of the work is Pt-Ni (ALD), and the overall cell performance of MEAs containing Pt-Ni (SGD) and Pt-Ni (ALD) are almost identical. Therefore, the team needs to focus more on the method of Ni removal from Pi-Ni (ALD) MEAs.
    - From slide 19, it seems that low Nafion® content (2%) is providing a higher ECSA for ALD-synthesized Pt-Ni MEA. This shows that the ALD-synthesized Pt-Ni is doable if the team finds out an efficient method of Ni removal.
- There is good progress toward identifying and apparently resolving Ni nanowire supply issues. There is good progress on ALD development. Reasonably high activities have been demonstrated (but perhaps not as high as previous galvanic displacement). While some progress on de-alloying has been made, it is unclear whether this has translated into substantial improvement in MEA performance under hydrogen–air; all data presented were under oxygen. This is the key first technical challenge this project needs to address, with MEA-level durability next. It is unclear whether the Ni dissolution issue can be sufficiently resolved. MEA activity is relatively poorer than RDE. Little evident work has been conducted toward understanding the gap.
- Accomplishments and progress for the past year has been adequate. Hydrogen annealing of ALD-coated nanowires appears to be an effective approach to achieving high ECSA and specific activity. The performance of catalyst nanowires prepared by SGD was not particularly impressive. Some contradictory results were present.
- Hydrogen annealing and acid leaching seem to have helped these catalyst types achieve satisfactory polarization curves. Bigger batch sizes is also a good accomplishment. Low ECSA (<40 at beginning of life) is causing some concerns.
- A significant amount of research such as batch scale-up, hydrogen annealing, and MEA studies has been carried out in the second year.
- Hydrogen-annealed ALD shows higher activity, and an explanation of how it works was expected. Durability and stability of acid leaching to remove Ni core nanowire to make hollow tubes is still in question.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.1** for its collaboration and coordination.

- The collaborations and coordination with other institutions such as the University of Colorado Boulder, the Colorado School of Mines, and ALD Nanosolutions seem to be very effective. The synthesized material from ALD Nanosolutions is post-processing and characterized by other institutions, which is going on well. There is no necessity to further coordinate with the University of Delaware, as that collaboration has ended. Overall, the task coordination and data flow between the collaborators seem to be moving well.
- Collaborative research tasks are well integrated into the overall project work plan.
- The project makes good use of national laboratory and university partners and resources.
- The project has established good collaboration with three universities and an industry.
- Collaboration exists; however, it is hard to see how much work and catalyst fabrication approaches are discussed in the team.
- The principal investigator (PI) should be conducting discussions with catalyst suppliers (e.g., Johnson Matthey or N.E. ChemCat Corporation) to figure out whether this solution is truly scalable.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.3** for its relevance/potential impact.

- The project is very relevant to DOE's Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan. The project goals are aligned with DOE's 2020 target of achieving 0.125 g/kW combined PGM content in both electrodes. The success of this project will have great impact in bringing down the overall MEA and hence fuel cell stack cost, which will increase its commercial feasibility.
- Moving away from traditional carbon-supported materials can lead to dramatic improvements in the operational lifetime of polymer electrolyte membrane fuel cells (PEMFCs). Extended surfaces can also be tuned to yield improved activity of nanoparticle-based catalysts. Almost as important as the material development is the ability of the team to nearly match MEA performance metrics with RDE values. This is notoriously difficult to do, but it is an important step in the development of this and other next-generation catalytic materials.
- There is a need for high-performance (high-activity) and durable ORR catalysts for fuel cells.
- The project objectives are relevant to DOE's catalyst activity and cost targets.
- There is good relevance to the DOE target, mass activity, and catalyst durability.
- The project addresses key commercialization barriers for PEMFCs. The ultimate potential impact is unclear unless Ni dissolution issues can be demonstrably resolved.
- RDE-level activities are now being translated and matched at MEA level. While this is promising, there is not a single hydrogen–air pol curve. Therefore, it is not clear how this can be translated to the Fuel Cell Technologies Office Program goals of < 0.125 g Pt/kW.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The proposed future work, namely ALD scale-up to prepare 10 g batches and fuel cell performance improvement, is very relevant to achieving the project goals.
- The proposed future work is well-thought-out and is aligned with the project goal. The team has appropriately focused on optimization of hydrogen annealing and acid leaching, which is needed for scale-up work. Co-deposition of Pt with Ni/Co to further enhance ECSA and specific activity may be a good avenue to explore, given the data from last year that showed some promise as a Pt-Co catalyst. The proposed "nanotemplate" work cited on slide 22 indicates that the critical-to-quality (CTQ) characteristics of Type 4 nanotemplates from the supplier do not meet the commercial specifications and need to be validated by the team. If so, the team needs to be upfront with the supplier and should try to "fix" the

nanotemplate specification as soon as possible. Any uncertainty in nanotemplate CTQ may delay the upstream activities for the team and delay the progress of the project.
- Reasonable future works are defined to the project goal. It will be important to identify critical characteristics for catalyst layer structure optimization for ALD catalysts for the fuel cell test rather than just engineering optimized catalyst layer fabrication.
- The mass activity of the extended materials is still considerably below the target. There does not appear to be a clear plan to address this other than further optimization of synthesis and leaching conditions. The project team should consider looking into the possibility of increasing porosity to enhance the ECSA and mass activity. The mechanical integrity of the catalyst layer, especially for the hollow structures, needs to be addressed.
- Project work should focus on the development and demonstration of catalysts in the MEA toward some reasonable measure of DOE activity and hydrogen–air performance targets. It is possible/likely that a large effort will be needed toward the development of sufficient de-alloying methods or a new, stable nanowire core. ALD scale-up is premature in light of technical issues.
- The team should be accelerating this work and conducting a factorial design of experiments to include catalyst preparation (e.g., annealing H_2 vs CO, acid leaching, and a few other factors) and testing these catalysts at an MEA level to understand the impact of these factors on activity, hydrogen–air performance, and accelerated stress test durability. The amount of future work proposed does not seem proportional to the funding level.
- Future work will focus on improving the mass activity from the current level of 240 mA/mg to 440 mA/mg at 0.9 V. The required increase in activity, which is to be achieved in just a few months (by 9/30/2017), appears to be a sizeable task. Future work should also focus on catalyst durability; the PI did not address the durability milestone (<40% loss in mass activity after 30,000 voltage cycles) in his listing of future work tasks.

Project strengths:

- The following are project strengths:
    - The scaled-up process for making ALD-coated nanowires is a project strength.
    - This project demonstrated the ability to run with low ionomer content in the catalyst layer.
    - MEA performance matches RDE performance.
    - There was high activity without carbon in the catalyst layer.
    - Leached material is active and minimizes Ni contamination of the MEA, or at least significantly decreases it from the previous case.
    - Technoeconomic analysis supports the viability of the ALD process at a large scale.
- Project strengths including the following:
    - There is a need for new, high-performance ORR fuel cell catalysts, and the PI’s approach is novel and potentially significant.
    - The experiments have been carefully carried out, and progress has been made by switching from an SGD to an ALD approach.
    - The project team members are well qualified, and the work shows a nice level of collaboration.
- The team is well composed of qualified scientists and a PI who are capable of conducting the research and development work. ALD Nanosolutions has technology required to use different deposition substrates to make Pt-M-type nanowire and hence create a non-morphology of Pt catalyst that possesses high ECSA and specific activity.
- The project conceptually has the capability of generating substantially active catalysts. Very high mass activities in RDE have been demonstrated previously.
- The project has so far showed an ALD Pt-Ni nanowire catalyst with significantly high specific activity.
- The project has various methods to fabricate the low-loaded catalysts to be tested.
- This is a good fundamental concept and a very innovative team.

Project weaknesses:

- The team needs to come up with an effective post-processing step, especially the acid-leaching step to make the MEA fabrication process viable. Any leftover of Ni in the electrode will diminish the cell

performance and affect its durability. The team also needs to ensure a supply of nanotemplates with consistent quality for this project. Any variability in nanotemplate quality may slow down the progress of the project.
- The following are weaknesses: durability is still a question, the pathway to higher mass activity is still unclear, mechanical stability of the catalyst layer needs to be addressed, and process development for the scale-up of the leaching process is needed. The project could consult 3M for its expertise.
- The following are project weaknesses: (1) it is questionable whether the project team will achieve its go/no-go decision metric of 440 mA/mg at 0.9 V by 9/30/2017, and (2) in addition to the mass activity metric, it is not clear whether the catalyst will exhibit the required durability after a metal dissolution accelerated stress test.
- The project does not have capable analytical methods to investigate how a fabricated catalyst works or does not work. For example, hydrogen annealing on an ALD catalyst shows higher specific activity, but not enough investigation was pursued to find how it works.
- Much too little progress toward resolving Ni dissolution is evident.
- The mass activity target is yet to be achieved.
- There is a lack of focus and traditional catalyst supplier collaboration.

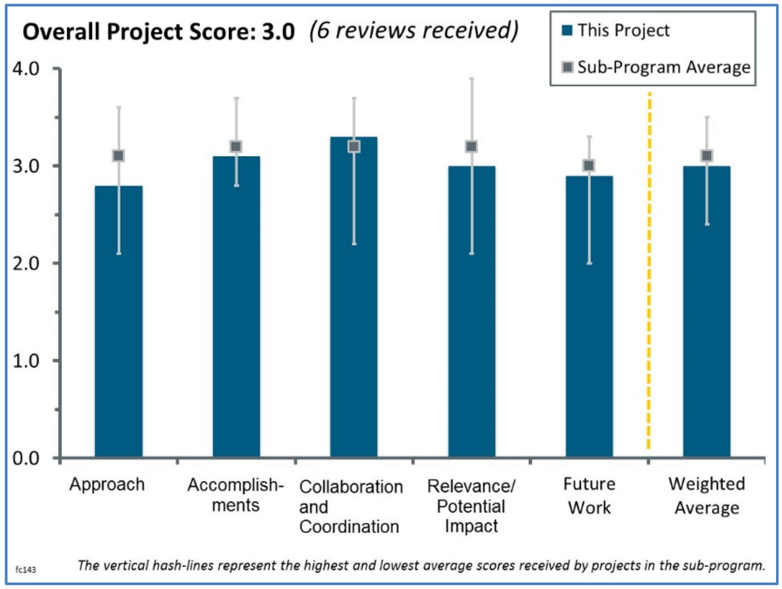
Recommendations for additions/deletions to project scope:

- The project should focus on approaches to fill the knowledge gap rather than the developmental gap or performance gap to the target. The project is expected to investigate how the hydrogen annealing can work for an ALD catalyst as a knowledge base that may be applicable for other materials.
- The project team should focus on ALD-coated nanowires. The mass activity go/no-go decision point (440 mA/mg) may need to be pushed back to a later point in time. Durability is an important issue; residual Ni in the nanowires may be an issue.
- For durability testing, the project should (1) assess mechanical properties of formed catalyst layers for solid and hollow nanofiber electrodes and (2) consider creating nanoporosity to improve ECSA and, consequently, mass activity.
- The project should predominantly focus on working toward Ni dissolution minimization to levels that will allow for acceptable MEA-level performance.
- A factorial design of experiments on how to optimize the catalyst is recommended.

Project #FC-143: Highly Active, Durable, and Ultra-Low-Platinum-Group-Metal Nanostructured Thin-Film Oxygen Reduction Reaction Catalysts and Supports

Andrew Steinbach; 3M

Brief Summary of Project:



This project is developing thin film oxygen reduction reaction electrocatalysts on nanostructured thin-film (NSTF) supports developed by 3M. The aim is to exceed all U.S. Department of Energy (DOE) 2020 cost, performance, and durability targets through developing two different NSTF-based structures, nanoporous thin film (NPTF) and ultrathin film (UTF) catalysts. The electrocatalysts will be compatible with scalable, low-cost fabrication processes. The project will integrate the catalysts into advanced electrodes and membrane electrode assemblies (MEAs) that address traditional NSTF challenges, which include operational robustness, contaminant sensitivity, and break-in conditioning.

Question 1: Approach to performing the work

This project was rated **2.8** for its approach.

- The approach taken addresses performance barriers and mitigates risk by tackling two different NSTF-based structures, an NPTF and a UTF approach, both showing potential to meet DOE and project targets. One of the structures will be down-selected for further work toward completing the project. Both structures can be combined into the dispersed NSTF-structured MEAs developed under a different project and thus address the flooding issue with the NSTF structure.
- The approach to performing the work involves adapting the long-standing 3M NSTF technology to produce two relatively new variations: UTF and NPTF catalysts. The materials are being tailored through investigation of different compositions and treatment methods, leading to different structures, and a variety of characterization techniques and computational methods are being used to interpret results. Overall, this seems like a reasonable approach to developing a better catalyst. However, the main issue with NSTF continues to be its integration into effective electrodes. 3M has made progress in this area recently, but until the problem is fully solved, the approach of investing in further development of NSTF catalysis is highly risky.
- The project has good focus on key targets including specific platinum-group-metal (PGM) activity and durability. The dual approaches (UTF and NPTF) with multiple alloys provide good options, but NPTF is clearly superior at this point. However, if loss of efficiency at rated power is important, as is stated repeatedly, then this should be added to the targets on slide 7, probably to replace "Loss in performance at 1.5 A/cm^2." Also, better integration of modeling and high-temperature (HT) work with main catalyst development is expected in the future.
- The project keeps two approaches in terms of fabrication processes, NPTF and UTF. There is no clear explanation about the relationship between the two approaches. They seem to be independent. If so, it is unclear why two approaches are necessary. If they are related, it is unclear how outcomes from each process can be used.
- The work involves an extension and continuation of previous NSTF work funded by DOE. Although the surface area is increased by one of two methods, it is unlikely to be sufficient to result in improvements or

resolution of the fundamental issues with the NSTF that have led to its failure to be applied to automotive stacks. The fundamental problem is that the catalyst layer is thin and the surface area is low. The combination of the two issues leads to high mass transport electrodes and, consequently, poor high-current-density performance under real automotive operating conditions as well as an increase of Rlocal (impact/loss of local transport retention after electrocatalyst accelerated stress testing) at low electrochemical areas. The catalyst has high specific activity, but the catalyst layer on the cathode will not meet real targets under real operating conditions, as attested by most auto companies in the past.

- The project approach is sound, with the development/examination of two types of thin-film cathode electrocatalysts, NPTFs and UTFs. The project includes both experimental and theoretical tasks. The connection and usefulness of the theory in directing experimental catalyst development was not well established.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.1** for its accomplishments and progress.

- Over the course of a year, the duration of the project, progress has been made toward reaching DOE targets, and feasibility has been shown for meeting more aggressive 3M project targets using both the UTF and NPTF approaches. Plenty of data are presented, which speaks to the breadth of work being undertaken. Multiple alloys have been tested (some not disclosed), and in a unique application, Ir is used to suppress Pt dissolution of alloy structures.
- 3M has done an admirable job of testing a large number of candidate materials in this project. Progress has been made on improving the activity and the MEA performance of NSTF. It looks like 3M is closing in on some compositions and structures that may be able to simultaneously meet mass activity, power density, and durability targets. Progress has been made on high-current performance, but much of the MEA data fails to show the low-current region. When the low-current region is shown, performance is sometimes quite low, with extremely low open circuit voltages of less than 0.9 V. On slide 13, a value of “NA” is shown for performance at 0.8 V. Based on the shape of a typical polarization curve, it appears that this catalyst may have had near-zero performance at this voltage. While the project does a decent job of addressing high-current H_2/air performance and low-current H_2/O_2 mass activity, more attention to low-current H_2/air performance seems warranted. Data shown for UTF catalysts looked promising in terms of mass activity, but the high-current performance suffered from the extremely low cathode loadings used. Based on the presentation, some technical challenges remain related to limited surface area supports limiting the cathode loading, but the nature of this challenge remains unclear.
- The project has made good progress in its first year. The effect of Ir on durability represents an important contribution, multiple alloys being assessed, HT characterization being established, and computational approaches producing results. It would have been good to see more discussion on HT fabrication and its integration into the main catalyst development process. It is unclear what the process is: deposition, de-alloying, or annealing. It is unclear how repeatable the process is and how it compares to batch fabrication. For this project to cover the planned broad design space, harnessing of the HT approach needs to happen very quickly.
- There was significant progress on the project over the past year. Both NPTF and UTF cathode catalysts appear to work well at ultra-low-Pt loadings. Pt alloys, PtNi and PtNiIr, appear to work best. Many project targets have already been met. Although the mass activity of NPTF and UTF cathodes was very high, Pt alloy loading was insufficient to reach a power density of 1 W/cm^2. Also, it is unclear how the modeling results were used to eliminate unnecessary experiments and streamline the project work plan.
- NPTF shows good progress and is close to the 2020 targets for mass activity (low current) and rated power (high current). There is still a question about robustness, particularly sensitivity with relative humidity and hydration of the catalyst layer. That is a generic issue of an ionomer-free catalyst layer.
- Meeting the target of 440 mA/mg Pt is not sufficient and has already been met by most previous NSTF catalysts. The specific activity of commercial Pt/C is about 300 mA/mg Pt. The initial activity of PtCo/C catalysts varies from 400–800 mA/mg Pt at beginning of life, as seen in the literature and presentations from previous years. This should be clearly stated in the presentation for an unbiased look at the current state-of-the-art materials. Density functional theory and other modeling have never succeeded in the past in

predicting an ideal composition for a high-activity catalyst. It is not clear that work has value except to show that modeling has been combined with experimental efforts.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.3** for its collaboration and coordination.

- Most of the key work is being done by 3M, but the principal investigator (PI) has assembled a good support team, with the characterization capabilities provided by Argonne National Laboratory (ANL) and Oak Ridge National Laboratory (ORNL) being particularly valuable.
- There is more than sufficient collaboration on modeling and other areas.
- Plenty of relevant work is being performed at multiple subcontracted institutions and was well represented in the slides. The interaction and leadership between the lead and subs appears to be well executed.
- 3M appears to be doing all of the main catalyst development in-house, with only ex situ characterization by ANL and ORNL and modeling by Johns Hopkins University (JHU) and Purdue University. It would help to clearly demonstrate the impact of external collaboration on progress in budget period 2. For example, on slide 14, it appears from the model that current densities are predicted to be significantly higher for UTF skin thicknesses of one to two monolayers and drop off substantially at three monolayers. It is strongly recommended that this prediction be tested experimentally.
- The collaborative aspects of the project were not explained well. There was some discussion of modeling work. The importance/need for some collaborations was not fully justified, especially for tasks during the upcoming year. For example, it is unclear how the HT development at JHU was coupled with a similar task at ANL.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.0** for its relevance/potential impact.

- The project directly addresses the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan targets and tries to exceed them. The project has shown progress in both approaches taken to achieve the DOE goals, while only one will be selected to meet the final project goals.
- This project directly addresses and supports the Hydrogen and Fuel Cells Program's (the Program's) goals and objectives.
- Developing improved catalysts is one of the most relevant things that a project can do for the Program. However, the relevance of this project is limited by the robustness issues that continue to face NSTF. While the use of electrode interlayers has helped with this issue, the durability of these interlayers and their ability to provide robust operation throughout the life of the stack still need to be demonstrated.
- As a catalyst development project, this approach seems very effective and can be envisioned to translate well to other architectures. However, in the context of NSTF MEA development, it is not clear whether this project addresses the key issues facing this technology (e.g., membrane degradation).
- Development of a lower-PGM catalyst is effective to the cost reduction if it can improve mass activity (low current) and area-specific power density (high current).
- The goals are relevant but are unlikely to be achieved by these modified electrodes.

Question 5: Proposed future work

This project was rated **2.9** for its proposed future work.

- The project has been planned for and is being executed effectively. Go/no-go milestones and key decision points are clearly laid out and presented and appear to lead to logical progression toward the final project targets.
- The proposed future work involves further development of both UTF and NPTF catalysts, which is reasonable and appropriate.

- Overall, future work is relevant to the project goals. The approach for the operational robustness (sensitivity with relative humidity and hydration of catalyst layer) is expected.
- The future plans flow logically from recent progress. However, it is not clear how HT development will be integrated with NPTF and UTF projects. The mention of other high-area supports, as an alternative for UTF, was surprising and would benefit from more detail.
- A complete change in direction that has been requested by reviewers for many years is necessary. The catalyst layer needs to be modified so that its mass transport is improved—it has got to be thicker, be porous, and have characteristics that are comparable to traditional Pt/C electrodes. Continuing in the current direction will not lead to achievement of the targets in a similar manner to traditional NSTF catalysts that have been studied for almost 15 years and are still not implemented in real automotive stacks successfully. At times, the investigators use English units such as “psig,” terms such as “AtmA” (atmosphere units of air pressure), and other such units that are jarring to the eye and outdated. Pressure should be presented with units of kPa or MPa. SI units are always absolute units by definition. The authors should not fill the slides with excessive data that muddles things up.
- Future work must focus on down-selecting either an NPTF or UTF cathode morphology. There is no mention of down-selecting on the “Future Work” slide. The criteria for making the selection do not appear to be well defined. It is not clear why further modeling studies are needed. The modeling work should help direct future experiments. A major effort must be directed to increasing the catalyst loading to achieve a power density of 1 W/cm^2. The issue of cathode flooding and the need to move away from ultra-thin cathode structures was not properly addressed. Many of the project’s cathode performance targets have been met, but future work should be better focused.

Project strengths:

- The team has demonstrated good early progress in the development of catalysts, with large design space yet to be explored. Modeling and characterization infrastructure appear to be in place. 3M has chosen good collaborators that can provide scientific insight into structure–function relationships.
- The project team has made two cathode layers with excellent mass activity and durability. Many project goals have already been meet. Experimental data collection has been extensive. The project is on target to meet all project milestones and go/no-go decisions.
- The team is doing an excellent job of leaving no stone unturned in the search for compositions and structures that could further improve the activity and MEA performance of NSTF. Several candidate materials and structures are meeting or approaching multiple, relevant DOE targets.
- This project utilizes two unique approaches to decreasing PGM loading while increasing durability through alloying. Both approaches seem to work well, while Ir incorporation into the catalyst structure leads to stabilization.
- The project is yielding a high-performance catalyst with NSTF approaches.
- The highly active catalyst is a project strength.

Project weaknesses:

- It is not yet clear how high throughput will be harnessed to address the large design space. Regarding slide 9, hiding the iridium content is not appropriate for precompetitive, federally funded research. The same could be said for the identities of the various alloys. This is especially true if no intellectual property is claimed (slide 31). This project, while valuable, does not appear to directly address major issues with NSTF technology. So far, there have been relatively few scientific contributions via papers, presentations, and patents.
- (1) There must be a down-selection process during the next year, after which the project team will focus on only NPTF or UTF. (2) The need for modeling work next year has not been established. (3) The issue of cathode flooding and the use of very thin cathode layers were not adequately addressed.
- No matter how successful the team is at developing improved NSTF catalysts, operational robustness issues will continue to undermine the relevance of this approach to oxygen reduction reaction catalysis.
- It is unclear how segmented cells, strain measurements, and various modeling efforts help in resolving the ultimate barriers within this system to achieve the Program targets.

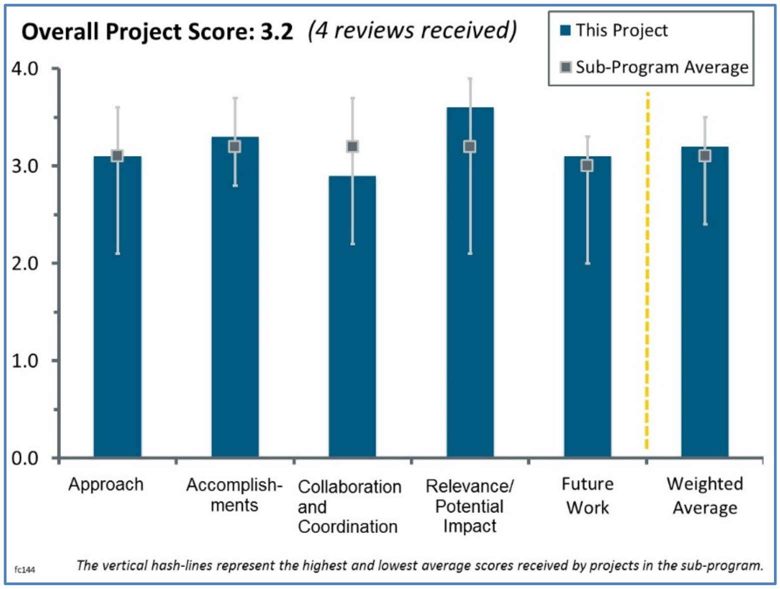
- The project has a weakness in its investigation for characteristics of an ionomer-free catalyst layer, particularly operational robustness.
- This project has a poor catalyst layer.

Recommendations for additions/deletions to project scope:

- The PI should down-select one of the two cathode morphologies. Modeling and experimental work should then be focused on this one structure. There should be better justification and integration of the experiments and theoretical work. The modeling work should help drive/direct experiments. Also, flooding issues need to be addressed.
- Very often the discussion revolves around small differences. Measurement and repeatability studies are encouraged to ensure that small differences are not significant. (A good example is in slide 8, on the bottom right.) A direct comparison with powdered NSTF and carbon-supported alloy catalysts would be valuable.
- While both UTF and NPTF approaches have merits, the project scope should be limited to NPTF unless methods of effectively incorporating UTF with good performance at reasonable loadings can be demonstrated.
- The project is yielding a high-performance catalyst with NSTF approaches. The project is expected to investigate characteristics of an ionomer-free catalyst layer, particularly operational robustness.
- Both approaches should be tested in dispersed electrodes prior to down-selecting to ensure that both can be incorporated into more conventional thick catalyst films.
- The project should focus on the catalyst layer and limit current studies that address the high-current-density performance.

Project #FC-144: Highly Accessible Catalysts for Durable High-Power Performance

Anu Kongkanand; General Motors



Brief Summary of Project:

This project aims to reduce overall stack cost by improving high-current-density performance in hydrogen/air fuel cells that meet U.S. Department of Energy (DOE) heat rejection and Pt-loading targets. Investigators will maintain high kinetic mass activities and mitigate catalyst degradation by using supports with more corrosion resistance than the current high-surface-area carbon (HSAC). The project takes a four-pronged approach: (1) improve oxygen transport with new carbon support, (2) reduce electrolyte–Pt interaction, (3) enhance dispersion and stability of Pt–Co particles, and (4) improve understanding and control of leached Co^{2+}.

Question 1: Approach to performing the work

This project was rated **3.1** for its approach.

- The project's approach is focused on overcoming barriers for polymer electrolyte membrane fuel cell (PEMFC) performance at high current densities. The project is well designed and addresses multiple causes of performance degradation at high current densities.
- The approach is well structured and stems from recent literature that clearly indicates that there are non-Fickian mass transport losses that present themselves as unexpected voltage losses at low-Pt loading. Three of the four different approaches correspond to the hypotheses that could be given for why these losses exist: (1) Pt buried in the primary carbon particle, (2) poor Pt–ionomer interactions, and (3) influence of leached Co or base metals from the alloy catalyst. Further details regarding the ionic liquid strategy would be useful. It would be good to understand how ionic liquids are selected and how they are incorporated into the electrode. The approach to situate Pt on the exterior of carbon primary particles has already reaped benefits that speak for themselves. However, it may have been good to report on the stability of PtCo/HSAC-e or PtCo/HSAC-f before declaring victory.
- The project has four distinct approaches that seem mostly unassociated with the others. This project was awarded under a catalyst section of a funding opportunity announcement. It is unclear why the project has such a large portion of electrode development. Apparently, multiple reviewers commented on this last year. The response seems overly simplistic and does not address the topic in which the project was awarded. Only one portion of the project seems to be relevant to a catalyst project.
- The project's approach is designed to address the relevant barriers. It is a little difficult to follow the approach because so much is going on in parallel on this project. There is concern as to whether Co dissolution can really be addressed with the proposed approach.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.3** for its accomplishments and progress.

- Significant progress has been made toward understanding the role of support porosity on Pt utilization in the oxygen reduction reaction.
  - The method development for evaluation of internal and external Pt nanoparticles on the support represents a significant accomplishment.
  - The DOE 2020 high-power target (8 kW/g_{PGM}) is exceeded using PtCo on a new HSAC.
  - On the other hand, the DOE 2020 target was exceeded on the HSAC that failed the accelerated durability test.
- A dramatic increase in specific power (kW/g) was shown due to reduction of interior Pt on an HSAC and through the use of PtCo. This is not just an empirical observation but is also justified by theories that suggest local mass transport resistances decrease when oxygen does not have access to Pt within a carbon particle. However, the PtCo is now in greater proximity to the ionomer, which could have implications for durability.
  - There was a good result on the finding that the carbon type has little influence on Pt being deposited in the membrane. However, it may be difficult to get from these results to a statement about the lesser role of coalescence, since coalescence would not be expected to contribute to a Pt-in-the-membrane band.
  - The project should quantify the ionic liquids in electrodes, as well as to see if ionic liquids are being lost from fuel cell operation.
  - New PtCo/C catalysts should also be tested for low-temperature performance.
  - The development of the CO stripping technique to quantify surface Pt may turn out to be one of the best outcomes from this project. This could be useful for many developers.
- The power looks great for Pt/Co/HSAC; however, simultaneously achieving high power and durability with the low-Pt catalyst needs to be demonstrated. There are many other interesting results that improve understanding of support effects, Pt–electrolyte interactions, and degradation mechanisms. Since so much is going on in parallel, it is difficult to gauge the extent of the progress toward the final objectives. Showing that the knowledge/results from parallel approaches can be utilized, or combined, to achieve the objectives should be presented in future work.
- The project seems to be using oxygen-limiting currents and mass activity as a successful predictor of carbon support development.
  - There do not seem to be any new catalyst synthesis results.
  - It is curious that the principal investigator (PI) does not seem to support the catalyst support accelerated stress test (AST), as this was developed by the U.S. DRIVE Fuel Cell Technology Team, to which the project team's organization is a primary contributing member. As this AST was developed with their companies' input, it seems that discounting the results from this test is inconsistent with their own guidance to other developers.
  - The researchers are showing that ionic liquids can promote rotating disc electrode (RDE) oxygen reduction reaction mass activity. (This has been seen before, specifically in Argonne National Laboratory's [ANL's] nanoframe catalyst project). However, this does not transfer to membrane electrode activity (MEA). As the PI apparently does not believe RDE is a valuable tool to predict performance, it is unclear why it is used in this case to suggest increased activity.
  - There is a question about the stability of the ionic liquids and whether they will actually be chemically stable in the long term, whether they will remain within the catalyst layer or simply migrate out and/or react with the cations and anions that are present in the MEA.
  - It is odd to claim a new capability of preparing an MEA from milligrams of catalysts; others have been doing that for more than 20 years.

Question 3: Collaboration and coordination with other institutions

This project was rated **2.9** for its collaboration and coordination.

- General Motors (GM) is a very strong developer, so their need for collaboration is less than for other primary investigators. This is somewhat reflected in how the project seems to have gone very well despite some subcontracts not having been signed yet. Other collaborators contribute a very specific input (e.g., a characterization technique), but little else.
  - Although the major findings so far appear to be from GM, there are plans to significantly involve most partners. 3M Company and National Renewable Energy Laboratory (NREL) will be

    involved in ionomer screening. NREL, ANL, and Carnegie Mellon University will be involved in understanding cobalt dissolution.
    - It would be good to see more of the decision-making from Drexel University with regard to ionic liquid selection and how the ionic liquid is incorporated into the composite catalyst.
    - Cornell University collaboration is spread between both characterization and materials development, which creates an even stronger collaboration.
- Excellent collaboration is established between multiple partners, as is made evident by results provided by Drexel University, Cornell University, Pajarito Powder, and ANL.
- Project partners include 3M Company, Carnegie Mellon University, Cornell University, Drexel University, and NREL. Several are not yet under agreement. To date, the interactions seem to be limited to pre- and post-characterization of materials.
- This project includes the efforts of a large team of experts. Integration of those results needs to be explained.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.6** for its relevance/potential impact.

- Improving fuel cell performance at high current density is the most relevant aspect toward lowering the overall cost of fuel cell systems. Outcomes from this project have been introduced into the Strategic Analysis cost analysis, and this is exactly what has already happened.
    - The project seeks to improve the performance and durability of the cathode catalyst layer, which is the most relevant component toward improving cost and durability of the entire fuel cell system.
    - Of all projects in the Fuel Cells sub-program, this project is best situated to address the barriers to meeting the DOE targets.
- The potential for a large impact is built into the project plan. Fresh ideas/approaches for preventing the degradation of Pt/Co in an MEA are lacking; however, it is possible that improving the fundamental understanding of the degradation could produce fresh ideas.
- Higher-performing catalysts with improved durability at low Pt loadings are critical to the Hydrogen and Fuel Cells Program.
- The project directly addresses the DOE target to reduce PEMFC stack costs by reducing Pt loading, while maintaining high current density performance.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- Many aspects of the future work line up well with what could be expected: optimization of PtCo supported on HSACs, testing of ionic liquid stability, and exploration of Co stability during operation. The one difficulty with the future work is the prescription toward higher-activity oxygen reduction catalysts in spite of the work already done to achieve high current density performance with a very specific type of PtCo supported on HSAC. Perhaps the only design lever would be greater ordering inside the particle, such as has been proposed in this project for the collaboration with Cornell University. However, beyond atomic ordering, the options appear to be slim.
- The future work is well planned and focused on achieving understanding of PtCo degradation at high current densities, transport losses, and implementation of new ordered PtCo alloys. Development of catalyst support is not indicated as one of the priorities of the project.
- The only weakness with future plans is if the ionic liquid studies, as described, would really lead to a useful result in an MEA. It is not clear how the team will get ionic liquids to work in an MEA.
- The project looks to optimize PtCo on three different carbon supports. In the approach, ordered metallic alloys are proposed, but that does not seem to be present in the future work.

Project strengths:

- GM is significantly invested in fuel cell research and has a proven track record of fundamental studies in which performance or durability gaps are elegantly defined, followed by hypotheses and experiments to address the gaps. The primary investigator is well equipped to address barriers. The project has already delivered a catalyst concept shown to reduce the overall cost of a fuel cell stack. The project is delivering not only material concepts but also analytical techniques that can help other developers, such as the CO stripping method, for observing the percentage of Pt on the outside of primary carbon particles. In many cases, the collaborations are premised on both material and analytical inputs.
- The project addresses multiple aspects of high-current-density mass-transport losses (such as catalyst and support instability, and oxygen and proton transport through ionomer and carbon micropores) using both experimental and modeling approaches. This is a very well-coordinated effort between different team members, including industry, academia, and national laboratories.
- The project has a strong team, and the project goals are well aligned with DOE objectives. A wide array of approaches are being pursued to achieve those goals. Improvements in understanding catalyst supports and degradation mechanisms were provided.
- The project uses a good mix of characterization of in situ characterization to evaluate materials.

Project weaknesses:

- There do not seem to be any new catalyst synthesis results; these were proposed, but it is unclear when and how those are going to happen.
    - For a catalysis project, there seems to be little catalysis development; this seems to be an electrode development project.
    - There is no real indication that the ionic liquid RDE results will translate and/or be stable in an MEA. The PI does not believe in RDE results, yet he presents those to indicate the promise of ionic liquids.
    - There are inconsistencies with what this project presents and the guidance that the lead organization is giving other organizations.
- The exact method for producing the catalyst that has resulted in estimations of lower-cost stacks is still unknown.
    - The project has shown considerable success for high current density performance without evaluating durability.
    - The project has come to the conclusion that further mass transport losses (beyond those already addressed through placing Pt on the outside of carbon particles) are not worth addressing. Between this conclusion and the limited options for improving PtCo supported on HSAC, the project almost unnecessarily constrains the future prospects for improving fuel cell performance further.
    - Further details are needed in the ionic liquid study with respect to integration of ionic liquids into the catalyst.
- It seems like a path to a durable support that would maintain a sufficient amount of mesopores is not very clear, as the HSAC that performs best in catalyst tests fails in accelerated support tests.
- It is a little difficult to follow how all of the approaches being pursued on this project will be tied together. The approach for exactly how Pt/Co alloys will be made stable in an MEA was not clear. The approach for exactly how ionic liquids will be made stable in an MEA was not clear.

Recommendations for additions/deletions to project scope:

- The team should either show improvement and stability of ionic liquids in an MEA or eliminate that from the project scope. The team should compare this project with the GM Fuel Cell Performance and Durability (FC-PAD) consortium project and eliminate overlap between the two projects. There seems to be significant overlap. Perhaps this, as a catalysis project, should concentrate on developing new catalysts.
- The project is already well scoped. However, further details regarding the methods for making the PtCo on HSAC would be useful to developers. It might be good to have specific go/no-go decision points for the ordered intermetallic alloys from Cornell University and the ionic liquid catalyst composites from Drexel

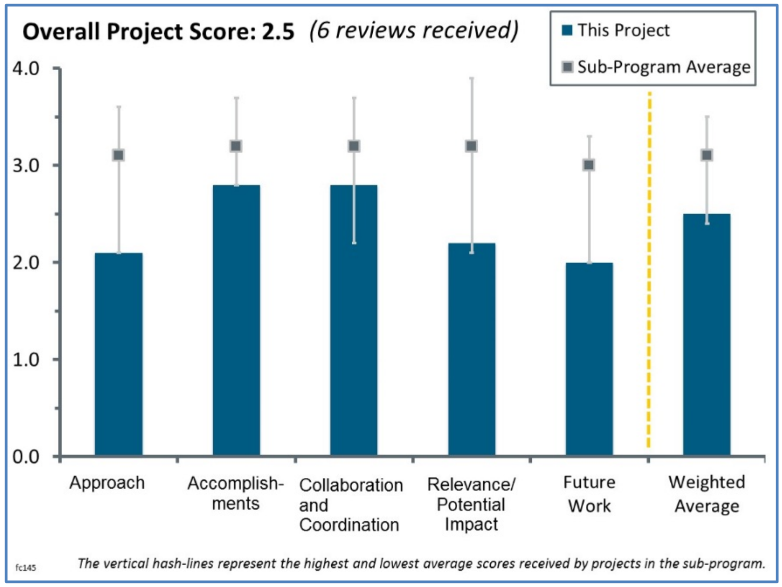
University. It would be preferred for the project to provide some understanding of how the PtCo on the HSAC catalyst is suitable for scale-up.

- The project may benefit from down-selecting approaches that are yielding promising results and focusing on those areas. A plan to address Pt/Co stability in an MEA should be presented. A plan to address ionic liquid use in an MEA should be presented.
- Support development should be more emphasized in the future work.

Project #FC-145: Corrosion-Resistant Non-Carbon Electrocatalyst Supports for Proton Exchange Fuel Cells

Vijay Ramani; Washington University in St. Louis

Brief Summary of Project:



Carbon's high electrical conductivity and low cost make it an excellent electrocatalyst support, but corrosion leads to kinetic, ohmic, and mass transport losses. This project is synthesizing doped non-platinum-group-metal (PGM) metal oxides as non-carbon alternatives. Along with being corrosion-resistant, the project supports would have high surface area, exhibit strong metal-support interaction with Pt, and demonstrate high electrocatalyst performance.

Question 1: Approach to performing the work

This project was rated **2.1** for its approach.

- Improving on carbon for fuel cell support materials remains a target that offers potential advantages for performance and durability. The material set chosen for investigation is very reasonable, and the application of multiple synthesis routes offers some opportunities for variability in structure and performance. The value of density functional theory (DFT) calculations is unclear.
- This work is very important in that both metal and support stability are key metrics to achieve commercialization. At this point, the reviewer has witnessed the talk, reviewed the 2016 and 2017 presentations, and reviewed some previous work on titanium dioxide–ruthenium dioxide (RTO) back to 2013. Perhaps there is more detail in the proposal, but it would be good to see more on the following:
    - It would be good to see data showing how much support electrical conductivity is enough to achieve performance targets. The project has materials from low to high conductivity and previous efforts on RTO. Perhaps there is a chart showing infrared or similar resistance losses in-cell versus support type. This would clarify an appropriate support conductivity target and give confidence to achieving 1.5 A/cm^2 targets.
    - The team's current activity is 0.05 A/mg$_{PGM}$. The project target is 0.30. There was not a clear path to achieve this in the 2017 presentation.
    - As electrode high current (1.5 A/cm^2) is part of the team's targets, future presentations must address water management issues of a hydrophilic support such as doped metal oxides.
- This project looks at doped non-carbon metal oxides using a combination of DFT and experiment synthesis to develop new corrosion-resistant supports. There are few projects in this area at present.
- The Brunauer–Emett–Teller (BET) target surface areas are the first indication that the project will probably not be able to make a practical fuel cell catalyst. Fuel cell catalysts made with supports that have >500 m^2/g BET surface area often still have difficulty achieving at least 50 m^2/g electrochemical surface area (ECSA) because of limitations of the triple-phase boundary, catalyst processing, and ink processing. The possibility of a 30 m^2/g BET surface area support being able to achieve exactly 30 m^2/g ECSA in order to obtain a roughness factor of at least 50 cm$^2_{Pt}$/cm^2 at a cathode loading of 0.167 mg/cm^2 (which is higher than the DOE target for total loading) is extremely remote. The DFT calculations were performed to detect electrical conductivity for the supports. However, the porosity of the support materials may compromise the conductivity, especially for an oxide made as an aerogel. Given past experiences with platinized metal

oxides being shown to be stable in a glass electrochemical cell, but then being shown to be unstable in a fuel cell, a better approach would seek to analyze stability directly in the context of a fuel cell.

- One of the critical problems of the previous project was the catalyst performance and dispersion of catalyst particles on the surface of the metal oxide support. This project tries to make higher physical surface area a target similar to a typical carbon support to be used for the polymer electrolyte membrane fuel cell (PEMFC) catalyst. However, there was no consideration as to whether the surface area of the metal oxide support has the critical characteristics for the catalyst dispersion. Toyota presented their metal oxide support materials at the 2017 Society of Automotive Engineers conference, and it achieved similar Pt dispersion to its high-surface-area carbon (acetylene black). Toyota showed good catalyst performance. This team needs to analyze why the previous project failed, and the approach should be developed based on that.
- This project is focusing on improving support stability while still using Pt as the catalyst. This is a fundamentally flawed approach because there is no indication that the learning from here could be translated to alloy catalysts.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **2.8** for its accomplishments and progress.

- The project has demonstrated the synthesis of a number of target supports and the ability to deposit Pt onto a number of these structures. Some of the properties reported, like ECSA at 75 m^2/g_{Pt} with durability toward potential cycling, seem to offer promise. The lack of any mass or specific activity data reported for these samples leads to concerns about the performance of these materials, as well as any potential advantages from strong metal support interactions as promoted as a motivation for investigating these specific families of materials. In past Annual Merit Review presentations by the project principal investigator (PI), novel supports often struggled to deliver reasonable mass/specific activity. Mass activity was called out as a target for these materials and needs to be reported with other relevant electrochemical measurements. Ta-doping for TiOx is shown to be best for stability, as it shows the lowest d-band center with Pt. However, Ta-TiOx was shown to be extremely low for BET surface area. Nb-doped TiOx appeared to have the best combination of surface area and conductivity. Surface area for Nb-TiOx was increased to 130 m^2/g, but the material has not yet been platinized, put in a fuel cell, or studied for durability. Sb-SnO_2 showed stability for rotating disk electrode (RDE) voltage cycling testing at 1.0–1.5 V. No fuel cell data were shown, although the project is still in its first year. BET surface area is extremely low for higher-conductivity Sb-SnO_2. Unless there is some way to increase BET surface area by at least one order of magnitude while still maintaining conductivity, the stability of the support will not matter since the required performance will not be obtained.
- The team has made significant progress in understanding the valence states and the critical factors in improving the conductivity of the metal oxide supports. It looks like there is only one metal oxide family than can meet both support surface area and conductivity targets. Beginning-of-life ECSA of 75 m^2/g_{Pt} in RDE looks quite promising.
- This project appears to be using DFT successfully to guide the synthesis approach and determine the level of dopants needed to get the appropriate conductivity. The project is in its early stages, but a number of relatively high-surface-area materials have been synthesized with good conductivities. Some metal oxide support materials have had Pt deposited on them; some are in process.
- The DFT calculation showed expected results for an electrically conductive doped metal oxide. For the material screenings, the usage environment should be considered. The PI mentioned that these metal oxide supports would be used for both the cathode and anode. Therefore, materials stability should be shown in the reduction environment (anode) and oxidation environment (cathode).
- It was understood from the talk that this work was only five months in at the time of slide submission. From the talk and slides, it is a bit unclear what milestones to evaluate against, as they start in Quarter 7 on the 2017 talk. It is unclear if the team was in Quarter 2 or Quarter 4 at the time of submission. There is some added clarity in the 2016 talk. It is exciting that there seems to be a possibility for >100 m^2/g supports, but again, information about the status and progress is a bit confusing.

Question 3: Collaboration and coordination with other institutions

This project was rated **2.8** for its collaboration and coordination.

- Collaborations appear to be limited to Nissan and the University of New Mexico (UNM). Nissan is essentially being used as a fuel cell testing partner, but it is unclear whether Nissan is providing the automotive perspective that clarifies whether the materials being developed are viable for meeting requirements. The low-BET surface areas would seem to be an obvious indication that some automotive requirements may not be met. UNM is providing the silica templating technique for making higher-surface-area supports, which is a material input, as well as DFT calculations that do not factor much into whether a material can be made at high surface area. What the project genuinely needs is a catalyst supplier to step in that can suggest scalable ways of producing high-surface-area supports, as well as an automaker (such as Nissan) to draw the line on which materials can possibly meet the requirements.
- The team is well-rounded, with the specific background relevant to the project. The PI was unable to attend, and the co-PI who presented was not fully aware of all the subtleties of the project (although this is not necessarily a surprise and is not fully required for successful project execution). The dynamic of assessing this specific aspect was slightly more challenging because of the PI's inability to participate directly.
- As UNM gave the presentation for the Washington University in St. Louis (WUSTL), the communication seems to be good. Both UNM and WUSTL have made progress. Incorporating Nissan appears to be a later date intention and mostly for evaluation/testing.
- There seems to be a good collection of partners for this work. The Nissan Technical Center North America should perhaps outline more of its path to electrode optimization, especially in achieving operational robustness.
- Collaboration is planned, but currently each group’s work is being individually pursued.
- The team needs to be collaborating with a traditional catalyst supplier (e.g., Johnson Matthey and/or Tanaka Kikinzoku Kogyo K.K.) to understand the feasibility of these proposed synthesis routes.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **2.2** for its relevance/potential impact.

- Supports that promote metal stability are likely more valuable than carbon stability. The possibility that this project might achieve both is quite exciting. Further, novel materials generation enhances overall industry understanding, leading to further progress.
- This project addresses the catalyst support durability target and thus the catalyst durability targets. It is unclear what the cost of these support materials will be and whether they will be able to address the cost targets. It will be critical to be able to support PtX alloys with high mass activity and achieve performance similar to carbon supports with improved durability.
- The development of improved materials relative to carbon as support materials is of clear relevance for performance and durability limitations of fuel cell systems. At this point in time, the state of this project does not suggest that a better material will be realized from these efforts.
- It is an industry consensus that the carbon corrosion problem is solved by a system solution rather than a materials solution. The system mitigation strategy is well developed and well implemented, although the DOE still keeps targets in this area. In other words, these system solutions enable the use of materials from a wider selection range and improve the performance and cost (less expensive materials might be used). Secondly, there is one industry project (no government funding) that already demonstrated good performance of a doped metal oxide support catalyst in a PEMFC. Pt dispersion on these metal oxide supports is similar to Pt dispersion on high-surface-area carbons. Optimized catalyst layers, such as ionomer dispersion, were achieved. This is a typical example of what the private sector can do. It is not clear why DOE should fund it.
- Thanks to system and seal mitigations for shutdown/startup operation, the prospect of a corrosion-resistant catalyst support providing benefits toward the Fuel Cells sub-program is practically zero. It may be good

for Strategic Analysis to find a way to estimate increased cost associated with (1) added system components for mitigation of high half-cell potentials on shutdown/startup, and (2) enhanced sealing materials associated with maintaining desired gas contents in the stack under vehicle soak conditions. If the increased cost is low or practically negligible, then it can be confidently said that the Fuel Cells sub-program should not be invested in projects such as this project.

- Very few automotive manufacturers need a stable support on the cathode side. Further, the project is reporting 0.4 mg/cm^2 loading as the state of the art; this is far from the DOE target of <0.125 g_{Pt}/kW. Therefore, it is unclear how this project, even if wildly successful, can reduce the cost and Pt loading of a stack.

Question 5: Proposed future work

This project was rated **2.0** for its proposed future work.

- The proposed future work seems to refer primarily to FY 2017; the overall strategy of using modeling to guide the dopants to achieve appropriate conductivity during the synthesis with final testing by a vehicle manufacturer (Nissan) appears to be a good strategy, and less of an Edisonian approach.
- There seem to be good work and potential paths toward support conductivity and surface area. The following need more clarity:
  - Paths toward achieving activity targets
  - Overall pairing of the catalyst to the support; for example, a higher percentage of metal on the support might enhance the conductivity
  - Nissan Technical Center North America optimization plans
- The plan for making both surface area and highly conductive Sb-SnO_2 needs to be clarified. Greater emphasis needs to be placed on fuel cell testing. The glass cell electrochemical evaluation could almost be skipped in favor of what will probably need to be many iterations of ink processing in order to understand how best to optimize a cathode–electrode for a platinized metal oxide. Even without an optimized cathode–electrode, though, an un-optimized electrode could be used to provide an early indication of catalyst durability in a fuel cell environment. The project's plan for future work needs to move faster toward fuel cell testing.
- To continue this low-relevance project, it should focus on tasks to fill the knowledge gap rather than developmental gap. DFT calculation and modeling should be focused for (1) materials stability for anodic and cathodic environments and (2) critical characteristics to synthesize the materials. It is still questionable if the BET surface area is a critical characteristic for catalyst Pt dispersion.
- The proposed work is a continuation of the work already underway, involving increased synthesis of materials, characterization, and DFT modeling. It is not clear what is systematically going to be probed or why improved performance over initial efforts should be expected.
- Shown at the membrane-electrode-assembly level, this catalyst can get close to the DOE targets for Pt loading of 0.125 g_{Pt}/kW. The project should be stopped if it cannot show <0.25 g_{Pt}/kW (double the Pt loading on the DOE 2020 targets).

Project strengths:

- The project demonstrated the ability to make Nb-doped TiOx with decent conductivity at 130 m^2/g. That provides some hope of an interesting material coming from the project. The project has an automaker (Nissan) as a partner, which should ideally provide a practical automotive perspective. Materials being used do not represent possible Fenton agents or other species that would be likely to cause quick membrane degradation or harm to other components.
- This project seems to be successfully coupling DFT with experimental synthesis to help guide the synthesis. Between WUSTL and UNM, the synthesis and electrochemical capabilities exist. Nissan appears to provide testing capabilities.
- Project strengths include DFT calculation, first principle modeling (UNM), and materials synthesis (doped metal oxide).
- Project strengths include the properties and potential of the support, as well as the team and expertise. The team achieved high metal surface areas.

- This is a relevant material set being investigated by a few select synthesis routes.
- The project has a good team and innovative scientists.

Project weaknesses:

- There is low activity at present and no clear plan to overcome it. This can be considered a support issue, as clearly different carbon supports enhance activity. There was no plan described for overcoming support hydrophilicity. There is a lot of data at present, and historical data from previous RTO efforts, but these are not organized into clear trends pointing toward long-term targets. It is understood that this is early in the project; however, such organization would be helpful.
- The relevance of the project is a weakness. First, industry consensus is that the system solution can work well for this carbon corrosion issue and enables wider selections of catalysts (with performance and cost improvement). Second, private sector studies already demonstrate good progress of doped metal oxide catalyst support for PEMFCs. (It is not clear why government funding is needed for a task that the private sector can do.)
- The project is working in an area that may have already been made obsolete because of system mitigations implemented in commercial fuel cell systems. The project is having difficulty obtaining high surface areas for all materials other than one particular form of Nb-TiOx. The project future work plan does not move fast enough toward fuel cell testing, especially for evaluating material durability.
- The value of DFT efforts has not been shown. The mass (and/or specific) activity of the synthesized materials has not been reported, even though other electrochemical data have been reported.
- There is not much thought to date, nor does the future work appear to address the cost of these materials.
- There is a lack of clear vision on how this project can reduce cost.

Recommendations for additions/deletions to project scope:

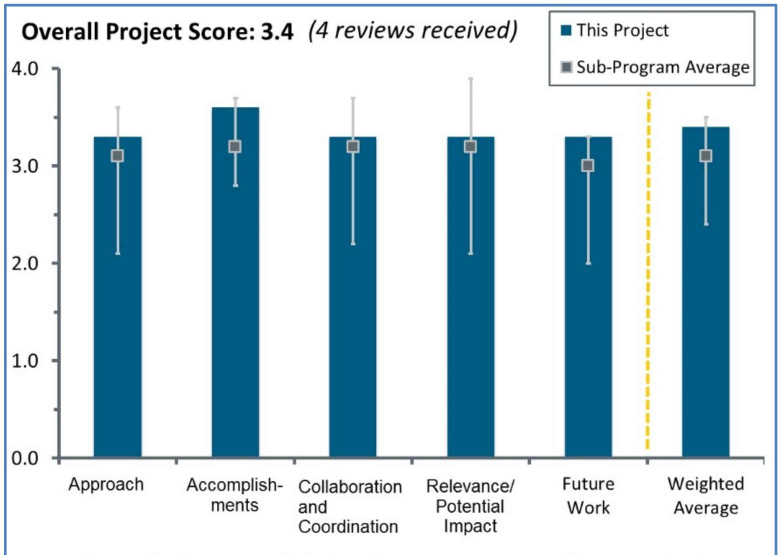
- It is highly recommended that the project funding be reconsidered based on the relevance. It is an industry consensus that the carbon corrosion problem is solved by system solutions rather than materials solutions. The system mitigation strategy is well developed and well implemented. Additionally, these system solutions enable the use of materials from a wider range of selections and improve the performance and cost (less expensive materials might be used). Secondly, there is one industry project (i.e., not government funded) that already demonstrated good performance of a doped metal oxide support catalyst in a PEMFC. Pt dispersion on these metal oxide supports is similar to Pt dispersion on high-surface-area carbons. This is a typical example of what the private sector can do, so it is unclear why DOE should fund this work. To continue this low-relevance project, it should focus on tasks to fill the knowledge gap rather than the developmental gap. DFT calculations and modeling should be focused on (1) materials stability for anodic and cathodic environments and (2) critical characteristics to synthesize the materials. These outcomes could be common knowledge and may be valuable for other areas such as metallic bipolar plates. It is still questionable whether the BET surface area is a critical characteristic for catalyst Pt dispersion. Optimization of the catalyst layer is necessary, but this is an engineering area.
- Fuel cell testing needs to be prioritized over glass cell electrochemical evaluations. In fact, it may be expedient to drop glass cell testing in the case of this project. Fuel cell testing should keep in mind low-temperature robustness. The hydrophilic electrodes may not perform well at temperatures experienced by a fuel cell stack warming up (e.g., 40°C). DFT calculations are not nearly as important as finding methods to deliver higher-surface-area supports. More effort needs to be shifted toward increasing surface area, or else the resulting fuel cell electrodes will not have high enough roughness factors at low Pt loading. The project targets should reflect DOE targets. There is no need to set the bar lower and expect a later project to resolve the gap.
- A small portion of the effort should be used to address the cost of materials and the cost of synthesis in comparison to more traditional carbon materials.
- The project should have intermediate activity targets (perhaps they are already there and were missed).
- The project should downscope the DFT studies to focus more on synthesis efforts.
- It is recommended that this project be deleted or refocused on developing an anode catalyst.

Project #FC-146: Advanced Materials for Fully Integrated Membrane Electrode Assemblies in Anion-Exchange Membrane Fuel Cells

Yu Seung Kim; Los Alamos National Laboratory

Brief Summary of Project:

This project is developing advanced materials for fully integrated membrane electrode assemblies (MEAs) in anion-exchange membrane fuel cells (AEMFCs), enabling fuel cell cost reduction without sacrificing performance. The improved anion-exchange membrane (AEM) materials are based on highly conductive and stable hydrocarbon polymers. The project also aims to address challenges with integrating catalysts and AEMs into high-performance MEAs. The approach involves (1) preparing AEMs without aryl-ether linkages in the polymer backbone and (2) developing different ionomeric binders for anode and cathode.



The vertical hash-lines represent the highest and lowest average scores received by projects in the sub-program.

Question 1: Approach to performing the work

This project was rated **3.3** for its approach.

- This is an innovative way to get to the conductivity and at least the intermediate stability of hydroxide-conducting membranes by “eliminating” weak points. This should provide membranes so that other properties, such as the hydroxide and carbonate ratio in a membrane, can be established. Their transference numbers can be established, and net membrane conductivity can be established, which are critical points to know in order to find out whether this “alkaline membrane” concept is practical.
- This is an excellent approach to study non-polar hydrocarbon polymers with resonance-stabilized actions and to develop hydrocarbon ionomers. Although it is understood why precious metal catalysts are being used in this primarily membrane and ionomer development project, the true potential of these materials will not be realized unless they work with non-precious metal catalysts. It may be that developing them with precious metals leads to developing materials not compatible with non-precious catalysts and so they are ultimately worthless.
- The work addresses the barriers of cost, durability, and performance. This work does a particularly good job of addressing durability issues with alkaline membranes and alkaline membrane fuel cells. The work is well designed and has demonstrated the feasibility of AEMFCs. It is well integrated with other efforts in the AEMFC field. If aromatic groups are detrimental, as recent results seem to suggest, this could have impacts on the applicability of all three classes of polymers being studied in this project, as the Rensselaer Polytechnic Institute styrene–ethylene–butane–styrene block copolymers, the Sandia National Laboratories Diels–Alder polyphenylenes, and the Los Alamos National Laboratory poly, di, and terphenylenes all have substantial aromatic content and would be expected to have some poisoning effect on the hydrogen oxidation reaction (HOR). The goal of the alkaline work is to enable lower costs by enabling platinum-group-metal (PGM)-free catalysts. In that vein, the effort spent developing PGM electrodes and looking at interactions and poisoning of PGM catalysts with the ionomers diverts resources from the ultimate goals of a PGM-free alkaline system.
- It is difficult to address all the barriers at the same time with such a new material set. When demonstrating in a fuel cell, it should be with all aspects of the approach. For example, when demonstrating AEM in a fuel cell, the project should use non-PGM electrodes, as it makes no sense to work on developing and

improving PGM-containing electrodes, since we will get no closer to cost goals as compared to the use of PGM electrodes, as in PEMs.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.6** for its accomplishments and progress.

- The team has demonstrated some very nice ex situ stability testing indicating these materials have much promise. The team is beginning to get an idea about carbonate/bicarbonate performance losses. There are interesting and insightful studies on HOR inhibition. Very impressive improvements in fuel cell performance have been achieved.
- There were good accomplishments on the fundamental material properties, such as conductivity and membrane film formation, and integration into fuel cells.
- This work is addressing the cost, electrode performance, and durability goals in a logical fashion with good progress.
- The project has made substantial progress in developing membranes stable under the basic conditions of AEMFCs. The project has made significant improvements in power density in H_2/O_2 conditions, achieving 1 W/cm^2 and surpassing the go/no-go metric for 2017 of 0.6 W/cm^2. The project has identified a new detrimental interaction between the catalyst and aromatic rings. However, in 2016, the researchers presented Fourier transform infrared spectroscopy (FTIR) data indicating alkyl ammonium groups adsorbing and interfering with HOR and guanidinium groups not adsorbing. The data they use to indicate poisoning by aromatic groups in 2017 uses benzyl trimethyl ammonium functionalized poly(phenylene) anion exchange membranes (ATM-PP) with a trimethyl ammonium cation, which they compare to a perfluorinated backbone with a guanidinium cation. Since the cation has been shown to adsorb previously, a better comparison to show the aromatic ring is affecting the HOR. It would compare the ATM-PP to the perfluoroalkyl backbone with the same cation functional group, and preferably a non-adsorbing functional group (i.e., with the guanidinium group on both the ATP and the perfluoroalkyl backbone). The project has slipped on the milestone to down-select an ionomer.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.3** for its collaboration and coordination.

- The collaboration within the project appears to be working well. The move away from studying perfluoro ionomers (being studied by the National Renewable Energy Laboratory [NREL]) suggests collaboration rather than competition there as well.
- All team members have well-defined goals. The work on non-Pt catalysts seems on hold. High-performance cells (conductive membrane with fairly stable membranes with catalyzed electrodes) have still been made.
- There is good collaboration with other national laboratories and universities. A number of collaborators are listed that could do device testing for fuel cells and the balance of plant, but it is not clear that materials have been exchanged with these partners, and no results were presented.
- Better collaboration should be done with other laboratories working on these AEM membrane materials. Materials should be exchanged with NREL since they are also working on AEM and common test methods could be used.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.3** for its relevance/potential impact.

- The project supports the goals and objectives of the DOE Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan. The work looking at performance and stability of the

alkaline membranes is well aligned with DOE goals. The work looking at interactions of the ionomer with PGM catalysts is less relevant, as PGM-free AEMFCs are the goal.
- This project is making progress toward DOE cost, performance, and durability goals. Some work should be on non-Pt catalysts and used in air at some point.
- DOE should absolutely study AEMs and the fuel cells derived from them. Major breakthroughs in this area will enable low cost and more versatile fuel cells, electrolyzers, and redox flow batteries. DOE needs to recognize that AEMFCs will take some time and investment to realize their potential, and the Department should not be too quick to cancel projects in this area. This project addresses many of the challenges in AEM development and cationic polymer development for ionomers in AEMFCs. That is critical if this technology is to get to the point at which it attracts much commercial interest.
- Since the progress on the materials is so pronounced, more effort should be placed on the non-PGM electrodes. If this is not undertaken, then the project is back to the same cost equation as PEMs, and not much relevance or potential impact can be realized.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- There is a very good plan to scale up polymers, down-select ionomers, and continue to study HOR degradation. Future work on MEA integration is much-needed, as is the fuel cell performance and degradation study.
- The proposed work does a good job of addressing membrane stability issues. The project should down-select to one membrane class to integrate into the MEA, but plans seem to continue with all three classes of membranes.
- The 2017 and 2018 work plans are reasonable. There is a good balance of needed fundamentals and useful, practical studies.
- The material is developed to the point that non-PGM electrodes should be developed for the full advantage of this new material to be realized for automotive fuel cell applications.

Project strengths:

- The project strength is the synthetic capabilities of the team and the focus on determining degradation points and chemical stability of the membranes.
- This is a good team generating good results and addressing DOE interests.
- New materials studies have potential for game-changing results.
- New AEMs are a strength.

Project weaknesses:

- The project needs to begin considering non-Pt catalysts and the effect of air at some point. It is logical that this has not been done yet, but this is needed if the “alkaline membrane” concept is going to be practical for automotive applications.
- Focus on the right issues needs to be shifted as progress is made in different areas.
- There is no non-precious metal catalyst work.

Recommendations for additions/deletions to project scope:

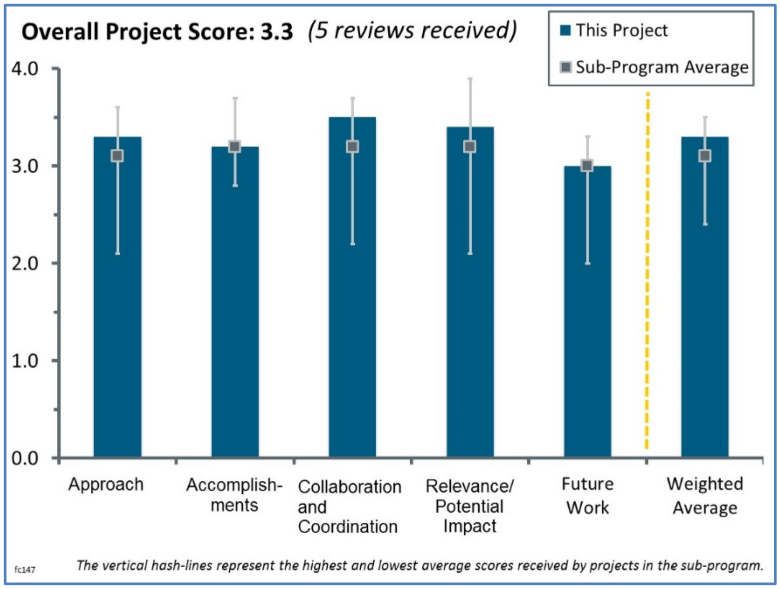
- Work on non-PGM catalyst electrodes should be added, even if the power density is not as good as in PGM catalysts.
- The project should start incorporating non-Pt catalyst studies in 2018, at least for comparison to Pt and Pt/Ru electrodes.
- This project should have less focus on PGM catalysts and interactions with/poisoning of PGM catalysts.
- Perfluorinated materials are already eliminated.

Project #FC-147: Advanced Ionomers and Membrane Electrode Assemblies for Alkaline Membrane Fuel Cells

Bryan Pivovar; National Renewable Energy Laboratory

Brief Summary of Project:

Alkaline membrane fuel cells (AMFCs) offer promise for improved performance and decreased cost. This project aims to develop novel perfluoro (PF) anion-exchange membranes (AEMs) with improved properties and stability, employ high-performance PF AEM materials in electrodes and as membranes in AMFCs, and apply models and diagnostics to AMFCs to determine and minimize losses (water management, electrocatalysis, and carbonate-related). Researchers will synthesize, characterize, and optimize alkaline-exchange membranes and fuel cells for performance and durability.



Question 1: Approach to performing the work

This project was rated **3.3** for its approach.

- The project addresses the barriers of cost, performance, and durability of alkaline fuel cells. The project focuses on alkaline membranes and alkaline membrane durability and performance. The approach of utilizing fluorinated backbones provides chemical stability of the backbone and advantages for forming a phase-separated structure, which has been found to be linked to good conductivity and mechanical properties. The approach of eliminating the sulfonamide linkage to increase stability is feasible and likely to be successful.
- The approach to developing an AEM is good, and the project is well designed and utilizes an effective teaming approach with modeling, industry, and academic team members.
- The approach of the project is well designed, integrating AMFC model development and diagnostics.
- This project is aimed at developing stable and conductive hydroxide-conducting membranes based on highly stable PF backbones. Oddly, short-term stability was found wanting, but the reason—namely, instability of the sulfimide linkage and short diamine linkages—appears to have been found and addressed. This is a work in progress.
- Had the proper chemists been involved, the design/progression of the tether could have been identified immediately to eliminate unnecessary work and be more efficient. The design was in series versus parallel and created plenty of work in which most people are not interested because they want to see a Generation 3 product. Both in the document and in the presentation, there seemed to be a lot of jumping back and forth on test subjects. Perhaps a Gantt chart in advance would help to streamline the work. It would be helpful if the project would verify that the chemical structures are correct for the PF tether versus the hydrocarbon tether; it became confusing to the outsider. Also, it is not clear where the composition details of the Tokuyama A201 and Tokuyama AS-4 were. It is also unclear which Nafion™ membrane was used. There are many different types. After a while, it almost seemed like the principal investigator (PI) was trying to impress by showing gobs of tests versus presenting a methodical analysis and evaluation. This can become baffling. As a side note, the reviewer has seen the flooding behavior/response in polymer electrolyte membranes (PEMs) before but, unfortunately, cannot remember the details.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.2** for its accomplishments and progress.

- The progress is excellent. Good film-forming capabilities have been demonstrated with the industry team member, 3M. The properties of the membrane look promising. Good power densities have been shown in operating fuel cells, although on oxygen only. Given the good progress on membranes and materials demonstrated by this project, future work should be shifted to using non-platinum-group-metal (PGM)-containing electrodes and operating the fuel cells on air.
- It was quite difficult and an excellent accomplishment to sort out stability of the ionic groups. Work is on track to use this knowledge to meet goals. The non-Pt catalyst and cell using air should be addressed at some point.
- Last year, membrane stability was significantly increased by extending the chain between the sulfonamide and the quaternary ammonium group. This year, the Generation 2 membranes met the midterm criteria of maintaining an area-specific resistance <0.1 Ω cm^2 (after correction for cell electronic losses) at 60°C for 500 hours during testing at 600 mA/cm^2. Degradation of the Generation 2 membrane at the sulfonamide site was determined to also be an issue. New chemistry looking at replacing the sulfonamide link to the backbone with aromatic linkages is being investigated, but results are not yet available. Membrane electrode assemblies (MEAs) prepared with Generation 2 membranes achieved power densities approaching 1 W/cm^2 in H_2/O_2.
- Cost has been ignored. Analogies, or at least attempts to compare and rationalize cost improvements, should be presented. Cost mock-up through film formation should be taken into account. Performance and durability should be more thoroughly addressed with the Generation 3 membrane. As with any new membrane structure, severe accelerated degradation and physical/mechanical/compositional analysis should be conducted to understand the most likely forms of degradation. This should include possible gasket/perimeter failures. It seemed that the PI was achieving the different goals using different membranes.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.5** for its collaboration and coordination.

- Collaborations outside of the project with other AEM fuel cell and AEM electrolyzer projects are apparent. Interactions with others outside the project have led to increased MEA performance by utilizing gas diffusion electrodes (GDEs) developed elsewhere. Collaborations within the project appear to be working.
- The National Renewable Energy Laboratory, Oak Ridge National Laboratory, Colorado School of Mines, and Lawrence Berkeley National Laboratory teams have well-defined roles for synthesis characterization and modeling of hydroxide-conducting membranes in different situations. Most work is in progress to address all issues.
- This project has demonstrated an excellent teaming approach with several small businesses, a large business, and academia, all bringing their own strengths to the project led by a national laboratory.
- It is clear that the PI is a networker. The only deficit: had a fuel cell fluoropolymer chemist(s) been involved, the compositional design/progression of the tether could have been identified immediately, and unnecessary work would have been eliminated. (Perhaps this was essential to aid in the modeling work, but it is doubtful.)

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.4** for its relevance/potential impact.

- Although excellent progress has been made and the goals and targets in the Fuel Cell Technologies Office (FCTO) Multi-Year Research, Development, and Demonstration Plan have been met, new targets need to be developed in order for the materials to begin to realize a more competitive approach as compared to the

conventional PEM fuel cell system. These targets should include the use of non-PGM catalysts and operating the fuel cells on air instead of pure oxygen.
- The project is relevant and aligns with the FCTO goals and objectives. AEM fuel cells could significantly reduce fuel cell costs by enabling PGM-free fuel cells, as alkaline membrane durability and availability have been issues. This project seeks to address these issues.
- This project has the potential to meet all requirements of an "alkaline membrane" to learn whether a practical hydroxide-conducting fuel cell for automotive applications can be made.
- The novel structure (and analysis thereof) is critical in understanding the potential for new membranes. It would be good to highlight the importance and benefit of this particular fuel cell technology and the conversion to this PF chemistry. The chemical durability aspect is understood, but it also seems cost is added. A cost-versus-benefit analysis could showcase rationale.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The reason behind the surprising increase in performance for the GDEs needs to be determined. The future work on the membranes is appropriate and focused on what appears to be the weak point now determining durability. The work on modeling and AMFC implementation is important for getting a working fuel cell.
- The focus on Generation 3 polymers is critical. It is good that there is intention to do hydroxide and carbonate transport studies, for a practical system in air depends on this. Modeling validated by experiment is also admirable. There is no non-Pt catalyst work planned, so this should be considered when stability problems are behind the team and a reasonable fuel cell activity is achieved with Pt group catalysts for comparison to non-Pt catalysts.
- The project should incorporate visuals such as Gantt charts, flow diagrams, etc. on decision points. The project should also work through risk mitigation and contingency planning. The whole electrode issue is a mess. The team should figure out a way to achieve the goals without electrode development.
- Future work should include more emphasis on the remaining limitations of AEM fuel cells from a system and cost perspective, such as operating on air, and the use of non-PGM catalysts.
- The plan for Generation 3 membrane development is not clear.

Project strengths:

- New materials allow for big opportunities to develop major advancements in fuel cells. A good teaming approach has been demonstrated in this project.
- The project had a well-designed approach to develop novel AEMs using model development methods, nuclear magnetic resonance studies, and performance tests.
- Collaborations and interactions with the AEM fuel cell community are a key strength of this project.
- This is a good team working at a reasonable pace to overcome formidable challenges.
- Modeling and testing are project strengths.

Project weaknesses:

- The project still utilizes PGM catalysts, while the raison d'etre for alkaline fuel cell work is the potential for PGM-free fuel cells. Alkaline fuel cell projects should move toward using PGM-free catalysts, or at least to loadings below PEM fuel cell anode loadings.
- The lack of a laser focus on only key materials and testing is a weakness. Cost rationale and estimates are a weakness. This project is susceptible to "not seeing the forest for the trees." Perhaps the PI does, but in conveying it, it becomes a bit of a random cluster.
- There is no plan for non-Pt group catalysts.

Recommendations for additions/deletions to project scope:

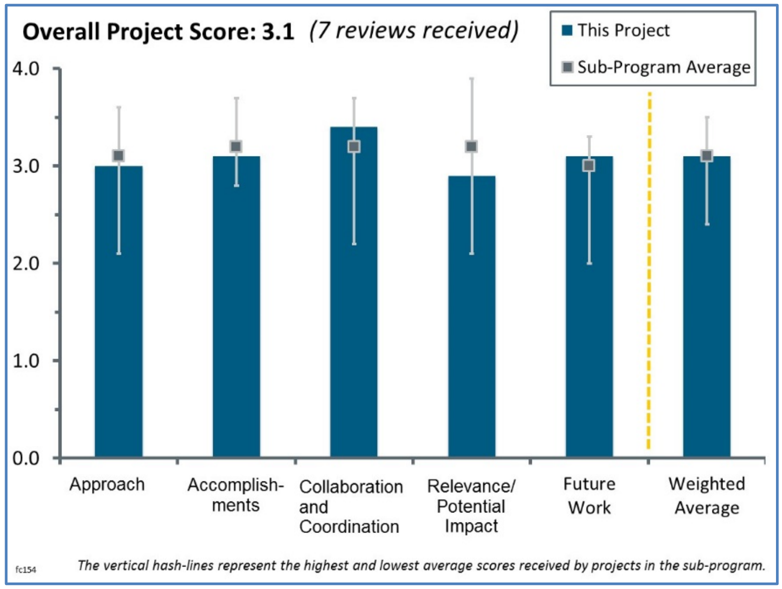
- Electrode development should be deleted. The project should use the best commercial performer it can find and go with that. Modeling work should be de-emphasized. The project should build in more analytical evaluations of the membrane before and after additional accelerated degradation (physical, mechanical, electrical, and application-developed).

- The project should focus on the big challenges for AEM fuel cell implementation, such as operating on air, and using non-PGM catalysts.
- The team should consider two things: studies in air and studies with non-Pt catalysts.

Project #FC-154: Regenerative Fuel Cell System (Small Business Innovation Research Phase II)

Paul Matter; pH Matter LLC

Brief Summary of Project:



Fuel cells operated in a reversible manner are a promising potential energy storage solution, but high system cost is a major barrier. Development of a low-cost reversible fuel cell would be a key breakthrough for energy storage. This project, which builds on an earlier Phase I Small Business Innovative Research effort in platinum-group-metal (PGM)-free catalysis, aims to develop and demonstrate a reversible anion-exchange membrane fuel cell (AEMFC) that incorporates membrane electrode assemblies as regenerative stacks. System durability over 1,000 cycles will be demonstrated, and economic analysis of the developed system for use as a grid energy storage technology will be performed.

Question 1: Approach to performing the work

This project was rated **3.0** for its approach.

- This project has a good overall approach. The principal investigator (PI) mentioned using the Steward et al. technical paper "Lifecycle Cost Analysis of Hydrogen Versus Other Technologies for Electrical Energy Storage" (November 2009, publication number NREL/TP-560-46719) guidelines in planning the work. The project demonstrated 360 cycles with a non-PGM cathode. The project also demonstrated a range of catalysts that perform well. The project appears on its way to a successful 1,000-cycle deliverable.
- The team is trying to make a reversible fuel cell based on anion exchange membranes (AEMs). The approach is innovative and timely. The project has the right team members, with the National Renewable Energy Laboratory (NREL) providing hydrogen oxidation reaction (HOR)/hydrogen evolution reaction (HOR) catalysts and Giner, Inc., providing cell and stack design.
- The project's approach is to utilize a carbon-based oxygen reduction reaction (ORR)/oxygen evolution reaction (OER) catalyst for a regenerative AEM-based fuel cell, and to show feasibility for a low- or non-PGM catalyst on the HER/HOR side of the cell. pH Matter LLC is collaborating with NREL and Giner, Inc., to integrate and demonstrate the performance of their catalyst. The project addresses a niche market where potentially low-cost regenerative systems may compete with batteries for energy storage. To date, the testing has largely been based on half-cell testing in concentrated electrolyte solutions. In pseudo-membrane-based cells operated under very short (one-minute) duty cycles, it makes it very hard to determine whether the project is feasible and whether the ultimate targets can be met.
- The project's round-trip goals and strategy make sense.
- No rational approach for the project is addressed in slide 6, although the benefits of using a regenerative fuel cell system are obvious.
- The project approach involves developing a proprietary CNxPy oxygen catalyst and integrating it into a reversible AEMFC. This is a very challenging system to develop, with the unitized nature, the use of alkaline media, and the use of a PGM-free oxygen electrode all adding barriers. The project's overall approach seems a bit too optimistic. At this point, it makes more sense for U.S. Department of Energy-funded projects to focus on just one grand challenge (such as reversible operation, or the use of alkaline

media), rather than trying to "shoot the moon" by incorporating so many high-risk aspects into a single project.

- The approach of this project did not give confidence that this work is very relevant. At a minimum, the project should do the following:
    - The data in slide 9 clearly shows Giner, Inc.'s baseline performance with previous metal cathodes. This project needs to compare its performance to this and clearly articulate the benefits, if any. For example, in slide 10, the voltage losses are significantly more when the PtIr catalyst is replaced with the COR-2 catalyst. It is unclear whether the cost of replacing the PtIr is enough to make up for this performance loss. If a system must be built that works at a particular efficiency at rated power, then the COR-2 catalyst system needs to be sized much larger, and it is not clear whether the cost saving from replacing the catalyst more than pays for this size increase.
    - It seems like the 42% efficiency target is not very high for an energy storage application. The PI needs to compare this to the performance of Vanadium flow batteries to at least make sure that this technology can compete with that on some basis.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.1** for its accomplishments and progress.

- The team has taken a catalyst developed in previous years and integrated it into a reversible membrane electrode assembly (MEA). The MEA is based on a commercial AEM (the manufacturer was not disclosed because of a non-disclosure agreement), a proprietary CNxPy oxygen catalyst developed by pH Matter LLC, and a commercial PtRu/C hydrogen catalyst. PtNi nanowire catalysts developed by NREL were also examined for use on the hydrogen electrode. The fuel cell and electrolyzer mode performance are both lower than dedicated fuel cells or electrolyzers, but considering the avant-garde nature of this system (unitized, alkaline, and PGM-free oxygen electrode), the performance looks reasonable. Still, considering how effective some other published PGM-free catalysts are for alkaline ORR, the fact that the fuel cell performance lags so far behind the PtIr baseline is not encouraging.
- Much progress was made in 2017. Slides 7 and 9 are from last year's accomplishments (the PI should have made this clear). The integration of the NREL work into the PI's work was not obvious. It is unclear what the point was for replacing the Pt/Ru with Pt/Ni. The HyRoc-1 catalyst seems to be PGM-free and has similar performance at the operating point (200 mA/cm^2) to the PtNi.
- The project has met its milestones; however, it is unclear why the targets have been set the way they are and what test hardware would be used to achieve them. For instance, the cells used to meet targets to date are operated under short duty cycles at 1:1 time duration, but the system will need to operate over longer timeframes to compete with batteries. If a 1:4 duty cycle is required, a discrete system makes more sense since the fuel cell and electrolyzer-active areas can be scaled separately to reduce the cost. Cost analysis should be expanded to compare discrete versions of the pH Matter LLC stack versus a fully polymer-electrolyte-membrane- (PEM)-based system operating at optimal current densities. It is also not clear based on a lack of catalyst composition or preparation description that the catalysts are indeed PGM-free, or how a carbon-based catalyst is stable at 1.6 V in potassium hydroxide.
- Some progress on measuring baseline catalyst performance was reported (slide 9). However, the slide does not contain much technical analysis. For example, it is hard to understand why the performance with gas diffusion electrodes is better than that with catalyst-coated membranes (CCMs). It is difficult to review without some information about the catalysts (e.g., COR-2 and HY-ROC). The justification to use Pt/Ni nanowire instead of Pt/Ru on the anode was not well rationalized. As the project is for developing non-PGM (or low-PGM) components, more efforts on COR catalysts, including comparison with other benchmark catalysts, should have been done.
- The overall performance goal is quite clear: 42% round-trip efficiency and >250 mA/cm^2 for fuel cells and >50 mA/cm^2 for electrolyzers. However, in a later section, it was not clear whether this target has been met or how much the gap is. The investigators claimed that the fuel cell met the goal, but it is hard to talk about fuel cells alone when the overall target is a round-trip efficiency. There is also confusion in the later slides, which refer to 200 mA/cm^2 for fuel cells, while the beginning of the presentation calls for 250 mA/cm^2.

- The current density for electrolysis mode is 40 mA/cm+, which makes the system cost very high for round-trip use. Cross-optimization is a significant challenge.
- The project is on cost and schedule.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.4** for its collaboration and coordination.

- It seems like most data in the presentation are outcomes of collaboration. In particular, the cycling durability test by Giner, Inc., is helpful for the project. More interactions with universities and other national laboratories may be beneficial to the project to get more benchmark materials for the test.
- Giner, Inc., is an excellent team member that can offer good feedback and guidance.
- The project collaborated well with Giner, Inc., in the CCM development and testing.
- There is good collaboration among the team members. NREL clearly has provided its PtNiNW catalysts, although the MEA results are not as good as the ones for RDE.
- The project's collaboration with Giner, Inc., looks very helpful. However, the value of the collaboration with NREL is questionable. The project should be focused on using reliable commercial hydrogen catalysts, rather than trying to use the experimental and unproven PtNi nanowire technology that is still being developed by NREL in a separate project. A better use of NREL would be to use their MEA diagnostic capabilities to help understand the voltage loss breakdown.
- The team has all of the necessary expertise.
- There appears to be limited interaction with subcontractors, which may be a problem for integration into a commercial system that operates differently from the current duty cycle, electrolyte feed, etc. It is not clear what the work breakdown structure is between partners or responsibilities.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **2.9** for its relevance/potential impact.

- This project contains both alkaline fuel cells and alkaline water electrolysis components. Therefore, it supports general goals and objectives of the Hydrogen and Fuel Cells Program. The product may still be far from the commercial product at the end of the project. Therefore, it may not help much on market penetration, but the potential impact still exists.
- This approach (i.e., of using a regenerative fuel cell for remote energy storage and power generation) is potentially much more cost-effective when compared to battery systems. The approach is very useful if deployed in island regions, wind turbine farms, etc.
- This is a project of strategic value, as AEM is the system in which completely PGM-free catalysts are possible.
- Relevance is not very high since there are no energy storage targets in the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan. However, the reviewer thinks this work is very relevant and should be continued *only* if it shows promise compared to other energy storage technologies.
- Unitized reversible fuel cells could have a big energy impact by helping enable intermittent renewables. However, the high cost, low performance, and low durability of the current technology means that a huge gap exists between current status and commercial requirements. The odds of this technology actually being deployed on a large scale seem small; therefore, the relevance is questionable.
- There is limited market and applicability of a regenerative fuel cell approach with the performance characteristics of an AEM. This is not only because of the low technology readiness level (TRL) of the individual components, such as the membrane and ionomer, but also because the economics do not work out. A PEM-based system, while still not ideal, would have a drastically lower cost, owing to the smaller cell size to achieve the same storage capacity. Cheaper still would be a discrete system.
- A 42% round-trip goal is too low to compete with batteries at 80%.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- The approach for the next budget period will aim to quickly transition the components from a dissimilar test cell and duty cycle to a commercial system that will struggle to operate under the required conditions for commercial applications, for example, having a potassium hydroxide feed to the membrane through wicking, and operating the anode on vapor during electrolysis operation. Before scale-up and five-cell testing, the targets should be met while operating the cell under the same conditions as the full-scale stack. As an aside, it does not make sense to utilize a carbon-based catalyst for the OER. Carbon oxidizes above 1.2 V, and it is unclear how it is stabilized by P and N. If this were true, the automotive fuel cell market would have switched to these as supports.
- The PI addressed the future work, which makes sense in light of the current project progress. However, no clear pathway is suggested to overcome the current system's low performance. It is questionable that the team can actually resolve those issues.
- Planning forward as described should enable the team to successfully demonstrate Phase II.
- In addition to what the investigators proposed, they should consider AEMs and ionomers with high-temperature stability so that they can raise the temperature and improve performance.
- The cell needs to be operated under more realistic conditions in terms of gases/humidity, potentials, and time period of charge (electrolyzer)/discharge (fuel cell) during the 1,000-hour durability test. A clear business case needs to be developed (e.g., a niche application) before the end of the project.
- It is unclear whether practical operating windows should have same current density for both modes. It is also unclear how to run this system in a real case.
- The future work is appropriate.

Project strengths:

- The PI has excellent expertise in PGM-free catalysts. The initial durability results look promising. Giner, Inc., offers great expertise in unitized reversible fuel cells.
- The team has good collaborations. The PGM-free catalysts developed from Phase I look promising. The project did a nice demonstration of excellent durability with the Pt-free electrode.
- The overall concept, when complete, will bring great benefit in remote regions.
- The demonstrated performance under the conditions used has allowed the project to meet targets.
- The team of Giner, Inc., and NREL is very good.
- This is a good project team that has made extensive progress.
- This is a good team on an excellent topic.

Project weaknesses:

- Regenerative AEM fuel cells do not make economic sense, and many of the components are at too low of a TRL to enable this technology, even if the concept was feasible. Carbon-based catalysts are fundamentally unstable and ill-advised for this application. Limiting the current of the electrolysis duty cycle coupled to wind that is variable also does not make sense; load following is one of the advantages of electrolyzers. The targets should be addressed at subscale, using realistic cell and operating conditions before scale-up to a five-cell stack that will inherently operate differently.
- The team should perform comparative cost–benefit analysis of non-PGM cathodes versus the potential performance enhancement that the Pt/Ni alloys, etc., can deliver. Then the team should perform measurements to substantiate the analysis results.
- The project is overly ambitious. It would be better to focus on one or two technological barriers, rather than try to develop a technology that faces so many challenges and is so far away from commercialization.
- The project provided very little information about the developed catalysts. If the structure of the catalysts is a trade secret, it should be a less favorable project, and DOE should reconsider supporting such a project.
- The project needs to have a clearer understanding of where the market is for this application, and what targets needs to be met in order to make this technology successful.
- The understanding of real-life dual-mode requirement is not clear.

- The project is likely in need of a better membrane and ionomer.

Recommendations for additions/deletions to project scope:

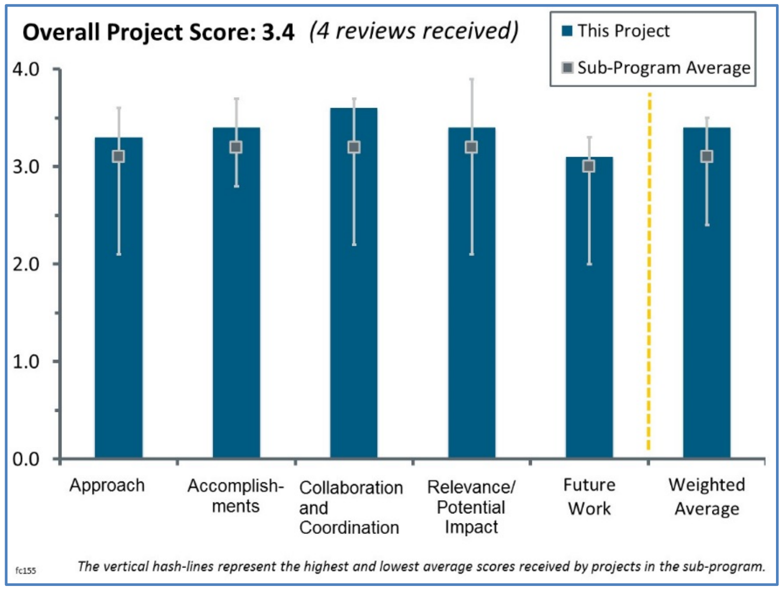
- The team should do a cost analysis comparing PEM-based discrete systems and a variety of operating duty cycles. The team should also do a long-term durability test in fuel cell and electrolysis mode at equivalent current densities. This would include catalyst characterization (pre- and post-mortem) to determine catalyst and support stability, and membrane short checks to determine whether the cell is shorting. The project should continue testing under relevant conditions, meaning relevant cell, materials, and flow rates, as will be used in the final device.
- The work with Pt-Ni nanowire for anode catalysts may be deleted, as the team has a Pt-Ru control catalyst, and the objective of the project is developing a non-PGM catalyst.
- New membranes and ionomers with higher temperature stability should be considered.
- It is necessary to match the current density 40 and 200 mA/cm^2.

Project #FC-155: Novel Ionomers and Electrode Structures for Improved Polymer Electrolyte Membrane Fuel Cell Electrode Performance at Low-Platinum-Group-Metal Loadings

Andrew Haug; 3M

Brief Summary of Project:

The objective of this project is to develop novel ionomers and electrode structures to improve polymer electrolyte membrane (PEM) fuel cell performance and durability. The focus of the ionomer development will be on combining high proton conductivity with improved oxygen transport. The project also seeks to understand and optimize novel cathodes that utilize nanostructured thin-film (NSTF) catalysts in powder form. These powder catalysts will be integrated with the ionomers to develop an advanced cathode of high activity and durability. State-of-the-art novel characterization and modeling techniques will be used to guide these development efforts.



Question 1: Approach to performing the work

This project was rated **3.3** for its approach.

- This is a well-thought-out approach with a good plan, milestones, and targets. The project mitigates risk by having two different strategies to minimize localized mass transport resistance in the cathode catalyst layer. Making powder out of NSTF is a new approach that is timely. The main issue (and potential strength) is that this results in completely different catalyst layers and interactions. It is unclear how much work will go into characterizing these structures, as opposed to figuring out if they help to improve localized mass transport.
- These NSTFs are a good approach to maximizing Pt utilization when the catalyst is decal-transferred, a path to minimizing the amount of Pt used in a fuel cell. It mostly addresses initial power density. It was not clear whether using powders derived from NSTFs would have some Pt “buried” by other Pt-coated whiskers overlapping another Pt whisker and another. It is also not clear whether the Pt would redistribute on a whisker. Maybe this was shown in the past, but this was not shown during this talk, so agglomeration of nanostructures on a whisker is one possible loss of Pt area per mass of Pt.
- Individual approaches are good, particularly ionomer characterization for the electrode. Powdered NSTF seems to be a developmental project and not suitable for the Fuel Cell Consortium for Performance and Durability (FC-PAD).
- Work on ionomers and NSTF represents strong technical contributions from 3M. However, there is not really a synergy between the two, and it seems almost like two separate projects: one on ionomers and one on NSTF dispersion. Exploring the ability of NSTF to be dispersed and incorporated into more traditional catalyst layers is of value, as is the work on novel ionomers (perfluoroimide acid [PFIA] and multi-acid side chain [MASC]). The ability of NSTF to break the trend for transport resistance losses at low surface enhancement factors may be due to the lack of ionomer in the electrode structure. More emphasis on local oxygen resistance and limiting current measurements would be useful to help elucidate the role of ionomers in these electrodes.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.4** for its accomplishments and progress.

- The team has a clear and effective plan and is following its design of experimenting and measuring the surface area and performance as a function of Pt mass in a cell. This will lead to a clear understanding, whether or not the approach completely succeeds.
- There are good outcomes from catalyst layer modeling utilizing a pore-network model to identify characteristics of oxygen permeability and proton conductivity, as well as their limitations.
- Good progress has been shown in a short time, including encouraging ionomer and catalyst layer activities.
- The project is in the early stages and has good results for such early efforts. The work in ionomers has shown the potential advantages of MASC over PFIA and perfluorosulfonic acid (PFSA). The work on NSTF does not seem to have particularly high cell performance and seems to be significantly lower than the standard NSTF membrane electrode assemblies (MEAs). More direct comparisons between the performance of dispersed electrodes and standard NSTF would be beneficial. Additionally, the highest-performing NSTF samples would be of greater interest, as those studied to date do not appear to be the highest performers.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.6** for its collaboration and coordination.

- The team led by 3M (M. Lindell, T. Matthews, J. Abulu, M. Yandrasits, A. Steinbach, M. Kurkowski, G. Weatherman, G. Thoma, I. Khan) has well-defined roles to address Pt dispersion, catalytic activity, and mass transport as a function of metal and polymer structures in the catalyst layer. Tufts University (Iryna V. Zenyuk, D. Sabarirajan, S. Normile) characterizes nano- and microstructure by direct imaging. Michigan Technological University (J. Allen, K. Tajiri, E. Medici, and team) is doing transport modeling. FC-PAD (Lawrence Berkeley National Laboratory [A. Weber, A. Kusoglu], National Renewable Energy Laboratory [KC Neyerlin], Oak Ridge National Laboratory [K. More], Los Alamos National Laboratory [R. Borup], and Argonne National Laboratory [D. Myers]) are helping with performance and durability validation. There is a challenge to correlating the nanostructure to modeling of transport when powders are used. The powders can bury some Pt by stacking the whiskers, and tomography and modeling will be needed to sort out whether this is a problem. FC-PAD will be needed to see whether Pt is redistributing in a whisker (as evidenced by loss of activity as Pt nanoparticles grow).
- Everything seems well organized, and there is good communication between the principal investigator, partners, and FC-PAD. The approach focusing on developing capabilities in budget period (BP) 1, and integration beginning in BP 2 is good.
- Good collaboration is pursued between industry and academia and also materials synthesis/empirical approaches and modeling.
- It is still early in the project, and it is not clear that Michigan Technological University had any specific contributions. This may be due to contracting delays. The project seems well coordinated with FC-PAD and can leverage efforts into this project.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.4** for its relevance/potential impact.

- The project looks to take on the key challenges of fuel cell cost, performance, and durability by creating high-performance, low-loaded electrodes. The team's work in both novel ionomers and catalysts is interesting and relevant.
- The project has relevance to the Multi-Year Research, Development, and Demonstration Plan fuel cell performance targets for 2020 and is very relevant to current performance-limiting issues.

- This is one straightforward way to test Pt dispersion and stability in well-defined structures initially, and as a function of usage and time for catalysts in hydrated PFSA ionomer catalyst layers.
- Overall tasks of the project are relevant to the FC-PAD objectives, characterization, and analysis, not new development. This means that the project should focus on tasks to fill out the knowledge gap rather than the developmental gap. It is not suitable to work only on materials development to meet the target. Investigating why it works (or does not work) is expected. Electrode ionomer characterization is good. Powdered NSTF should be reconsidered to make it more relevant to FC-PAD.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- The full work plan is clear and concise, with appropriate goals and go/no-go decisions divided by task and subtask. Proposed work progresses logically and brings in collaborators to work on key issues.
- The team is following its design of experiment. It should lead to good evidence to make sound conclusions. It would be good to see some consideration of Pt ripening per whisker and the effects of stacking of whiskers in the imaging/modeling. This should be correlated with the performance to see whether these issues are relevant.
- The general plan to further study 3M's novel polymers and catalysts is fine. However, the specifics of how the project will investigate these areas lacks clear direction or next steps. This statement reflects general trends from the presentation, in which acronyms are used often without definition, and the presentation has the feel of needing further revision and thought for both layout and content. The specifics for next steps have not been presented in a clear, concise manner, nor are the key variables or learnings from the next steps presented in a way to lend confidence in obtaining positive results.

Project strengths:

- This is a good approach to minimizing Pt usage by dispersing in thin films. The new approach of using different amounts of whiskers of different Pt loadings with different polymer loadings is a good way to expand the design of experiment for Pt activity and transport of protons, water, and oxygen at Pt in the catalyst layer. Imaging and modeling need to perform validating and predictive roles, respectively.
- 3M's capabilities in novel ionomers and catalysts (NSTF) are a strength. Exploring dispersed electrodes as a pathway to overcome current NSTF limitations is another strength.
- Materials synthesis and empirical approaches for ionomer and electrodes are a strength. Pore-network-model application to the catalyst layer is a strength.
- This is a great team, work plan, and approach.

Project weaknesses:

- The approach is very good. It would help strengthen the argument if there was some consideration of other possibilities besides those in the original design of the experiment—possibilities such as the effects of Pt active area lost by whisker stacking and Pt agglomerating within a whisker.
- A clearer experimental plan and next steps are needed. Why specific approaches are going to be undertaken and what is expected to be learned at each step need to be clarified.
- MEAs based on NSTF powder are new. There are plenty of variables, but the initial data look good.

Recommendations for additions/deletions to project scope:

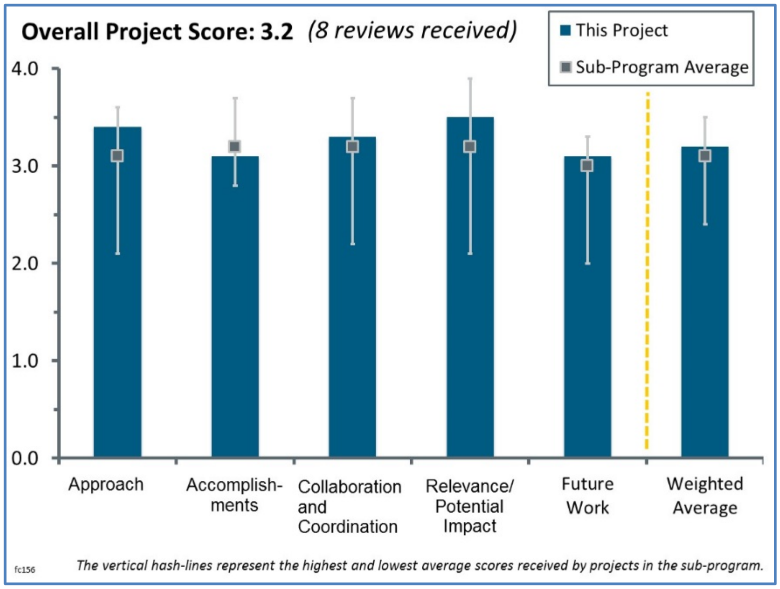
- It is suggested that the project reconsider its approaches to make them more relevant to the FC-PAD objectives of characterization and analysis, not new development. It is not suitable to evaluate the progress and go/no-go decisions based on the performance target. It should be evaluated based on the knowledge gained, such as characterization and why the technology works or does not work.
- This is actually two projects, and it would be preferable for the focus to be on dispersing NSTF rather than investigating multiple ionomers. Both approaches are important, but the more critical one is focus on dispersed NSTF, while other projects (perhaps within FC-PAD) focus on alternative ionomers.

- No real additions or deletions are needed, just some attention to detail—that is, the effect of whisker stacking and Pt redistributing on a whisker. Polymer addition and mixing are just fine.

Project #FC-156: Durable High-Power Membrane Electrode Assemblies with Low Platinum Loading

Swami Kumaraguru; General Motors

Brief Summary of Project:



This project seeks to improve the durability of a state-of-the-art (SOA) membrane electrode assembly (MEA) by identifying and reducing the stress factors affecting electrode and membrane life. Project tasks include (1) MEA optimization of a low-loaded electrode through down-selection and integration of MEA components, (2) durability studies of the developed MEA, and (3) development of a predictive model for degradation in different operating conditions.

Question 1: Approach to performing the work

This project was rated **3.4** for its approach.

- The approach for assessing electrode and membrane durability follows the standard DOE protocols. Nothing novel was demonstrated by the model approach, but it was nevertheless well defined. The Fuel Cell Consortium for Performance and Durability (FC-PAD) is well equipped and experienced to measure cerium ion migration in membranes, as the consortium published seminal work in that area. Segmented cells by their very design may introduce mechanical stresses within the catalyst-coated membranes that are not present in ordinary stacks.
- The project's work plan seems appropriate. The schedule looks to be based on three men for three years, plus operational cost and development hardware. The schedule looks aggressive, similar to an industry schedule, but obtainable.
- The project builds on good results from previous projects, projecting to have a SOA MEA within the first year after implementing a few iterations with select components. The only improvement could be to reserve time for optimization of this MEA so that it shows a stable performance at the targeted level as a whole.
- The project approach was well explained and logical and is integrated well with FC-PAD activities. The plan addresses relevant barriers.
- The focus on durability of SOA MEAs is clearly relevant. The approach is fairly comprehensive: first, screening potential SOA MEAs; then, focusing on a specific MEA for extensive durability studies; and finally, developing comprehensive models of the durability concerns. This is a reasonable approach, but one would expect General Motors (GM) to already have a SOA MEA, and much of the first-year optimization effort could likely have been avoided, and comprehensive durability studies could have started more quickly. More detail on model status and model development would have been beneficial, as it is not clear what the current status of the models are and how they will be further advanced.
- The project is to develop a SOA MEA, develop models for electrode and membrane durability, and determine benign operating conditions. Undoubtedly, there will be significant value in the work; however, there are a number of areas of potential concern.
    - It appears that the development of the SOA will be a benchmarking exercise. It does not appear that the design will be model-driven.
    - The electrode durability model does not appear to advance the SOA of modeling and will be based on empirical design of experimental data. The fuel cell industry should be moving beyond this type of approach and further build on the fundamental models based on mechanistic studies.

  - Based on the use of an empirical approach and the U.S. Department of Energy, the determination of benign operating conditions will be MEA-design- and test-set-up-dependent. Furthermore, the selection of operating conditions is very dependent on specific application and system design. It is not clear whether the peroxide vapor test is representative of in situ mechanisms; otherwise, the membrane degradation studies/modeling will provide valuable insight. It is important to include voltage effects in the membrane degradation model. The studies shown on slide 12 for budget period 1 will provide valuable insight; however, these do not seem to be represented in the milestones. If these are included, valuable insight will be gained. Further, this type of work is also described in FC-137, but it is not clear whether the approaches and models will be in common with Lawrence Berkeley National Laboratory (LBNL).
- The objective of this project is to improve durability of the SOA MEAs by identifying and reducing the stress factors affecting electrode and membrane life. The project's approach relies on developing an electrode durability model for the power degradation rate caused by voltage cycling and a membrane durability model combining mechanical and chemical degradation with Ce migration.
- The project is new but planned. Its approach appears well designed and feasible.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.1** for its accomplishments and progress.

- This is a new initiative awaiting the official start of technical activities. The principal investigator (PI) discussed the planned activities for SOA MEA selection, test matrices for electrode and membrane degradation, model development for performance and aging, model validation, and model application.
- Even though the project has just started, it shows the potential to accomplish the goals.
- This is not a relevant question, as the project was just funded. The collaborations between the parties are well mapped; therefore, the project should make progress within the first year. Not Applicable is really the correct answer for this question; however, the site does not accept that input.
- As the project is just starting, this review criteria is not particularly relevant, as no accomplishments have been achieved or presented.
- The project just started in January, so it is difficult to really measure progress. Consequently, this question received a neutral score.
- The project has not started past contract planning. The accomplishments are appropriate for this point in the project.
- The project is new; there are no results.
- The project has just started.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.3** for its collaboration and coordination.

- GM, as the prime contractor, has significant experience in this area. Both Giner and the University of Texas at Austin (UT) bring very specific, complementary competencies. The FC-PAD laboratories have complementary roles as well.
- It is early in the project to properly assess how effective the collaboration will be. Collaboration is likely to be good based on the FC-PAD/funding opportunity announcement structure, which has been designed to encourage collaboration.
- The project has Giner and UT as subcontractors. The project has significant contributions from the FC-PAD team.
- Considering the project objectives, there is a balanced consortium among the partners selected.
- The project's planned collaborations appear to be well suited for work to be done.
- The planned collaborations seem appropriate for the proposed scope of work.
- Project collaborations include the appropriate parties, with the exception of a tier-one membrane manufacturer.

- The project collaboration highly favors national laboratory researchers over academic or industry researchers. The universities have most of the same toys and can do the work for less expense and usually less time. Their undergrads are the next generation of electrochemists.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.5** for its relevance/potential impact.

- This project is designed to have a large potential impact on DOE's goals related to fuel cell cost, durability, and performance. Understanding degradation dependence on operating parameters and creating a model for this degradation set this project apart from other projects in this area.
- Improving durability of SOA, low-loaded electrodes is a key need for industry. Development of an understanding of operational stressors and means to minimize will be useful.
- The focus on SOA MEAs with improved durability is critical for the advancement of fuel cell applications, particularly in vehicles. The breadth of what is being attempted is commendable but also makes the project perhaps broader and less focused on the most critical aspects. The focus on alloy catalyst durability and electrodes has been highlighted as a major driver for this work, and seems to be the most critical part of the effort. Adding membrane degradation, including complex and/or difficult approaches such as specific shorting defects, will be a challenge to achieving meaningful advances and runs the risk of reducing the advances in the catalyst/electrode area.
- The outset is good to provide the pathway to meet the cost, performance, and durability targets, but eventually it may provide an overview of benign conditions for individual components that could be mutually conflicting, thus not clearly giving direction or a single failsafe solution. It is recommended that in addition to the map of "operational danger zones," the final outcome could advise how non-SOA components could also meet DOE targets.
- The access of GM to SOA materials will likely result in the study of very relevant MEAs. The association with FC-PAD will ensure detailed characterization and modeling studies. The membrane degradation model and associated studies have not been done in detail previously and will be highly relevant. However, the MEA performance degradation model does not appear novel, and the design of experiment approach may result in dependencies that limit the applicability of the model for other systems.
- This task is to develop a new generation of polymer electrolyte membrane fuel cell with a lower cost and higher performance, in a short length of time. It will be interesting if the national laboratories can step up to the pace.
- The project is aimed at demonstrating a pathway to cathode and membrane life of 5000 hours with existing non-proprietary materials by defining implementable benign operating conditions.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- The project's future work is well planned and is expected to produce reasonable progress toward DOE and project goals.
- The project has yet to start. The team's plan looks sound. It is a standard electrode development program.
- The PI defined the future activities related to developing fundamental models, formulating correlations, validating and fine-tuning models, and applying models.
- The project is well laid out, with appropriate milestones.
- The focus on electrode durability from both an experimental and modeling perspective is very strong and needed. The efforts in membrane durability are less focused, attempting to include both mechanical and chemical aspects.
- The project's future workplan is good; however, the weighting of the selection criteria for SOA is a bit vague.
- The project plan seems reasonable. It was somewhat unclear whether any catalyst development is planned beyond year one. It may be required based on durability results in year two.

- The validation of the project's models will show true value of the work and make it transferable.

Project strengths:

- The project is unique from the many other cathode-related projects because significant effort will be placed on studying correlations between operating conditions and degradation. This will help build a nice predictive model for how long electrodes will last in the actual application. The project also considers real-world issues related to membrane degradation that are overlooked in other projects.
- GM has demonstrated its ability to make high-performance, low-loaded MEAs. The project has access to SOA MEA materials. The coordination/collaboration with FC-PAD will ensure use of detailed diagnostics and will feed into mechanistic models. The project has a fairly comprehensive and novel approach to membrane durability studies.
- The team has a well-designed project plan. Access to SOA materials makes the project highly relevant. Project organization and collaborators are good.
- There is strong teaming, particularly in the durability testing and characterization aspects of the project.
- The project team is a strength. The team showed strength by focusing on the durability aspects of SOA MEAs, including alloy catalysts.
- The project has a good starting point by taking the best-known components and supplier to work with, giving the project a proper chance of success.
- GM's project experience is a strength.
- The project has a credible team and partners.

Project weaknesses:

- All of the MEA development is in year one, but it seems that the majority of degradation characterization will be performed in year two. Feedback from the work in year two to further optimize the MEA should be added.
- The objective of establishing benign operating conditions does not seem particularly valuable, as operating conditions are very application-, component-, and system-dependent. It is not clear how coordinated the electrode modeling and mechanistic studies will be. MEA design appears to be by benchmarking, rather than model-driven.
- It would have been good to have seen participation from Gore, 3M, Ballard, IRD Fuel Cells, or other MEA manufacturers.
- The breadth of the project will be a challenge. Membrane durability efforts are not as likely to result in meaningful advances.
- The individual component approach may not capture (reversible) effects observed in reality when exposing the MEA as a whole to continuous operation.
- It is unclear how well, if at all, project results will be translatable to the field as a whole if the project is using GM-proprietary materials exclusively.
- The project has a high reliance on national laboratories being on budget and schedule.

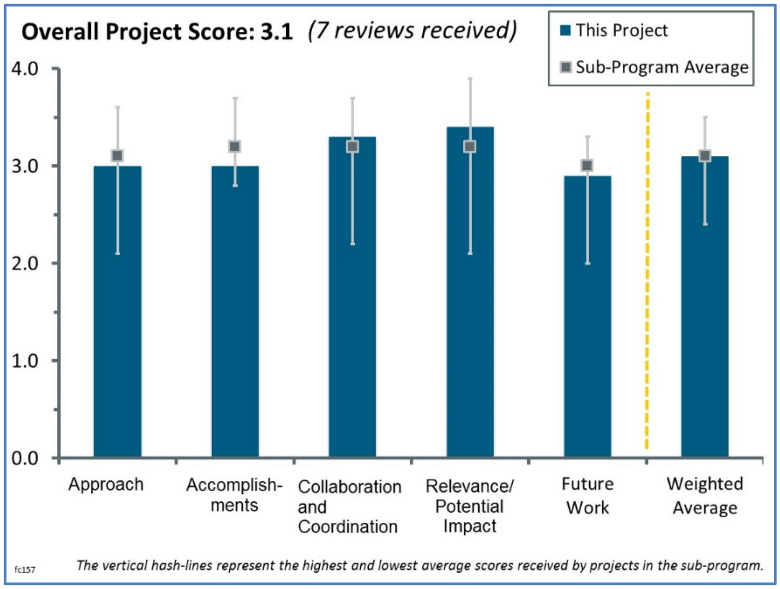
Recommendations for additions/deletions to project scope:

- The team should consider using lower-cost academics to meet budget and schedule. Clemson, Hawaii Natural Energy Institute, University of Connecticut, University of South Carolina, etc. have all demonstrated this ability in the fuel impurity testing. Additionally, universities are used to working under non-disclosure agreements.
- Definition of scope and experimental parameters may be needed when addressing the influence of mechanical stress together with chemical degradation.
- The project should consider focusing only on electrodes at the expense of membrane studies. For the level of funding, it is likely to have an increased impact and a clearer path to meaningful results.
- The team should ensure coordination with LBNL-led work on understanding thin-film losses and ionomer studies.
- Feedback from the work in year two to further optimize the MEA should be added.

Project #FC-157: High-Performance Polymer Electrolyte Fuel Cell Electrode Structures

Mike Perry; United Technologies Research Center

Brief Summary of Project:



The objective of this project is to improve the fundamental understanding of transport limitations in state-of-the-art (SOA) membrane electrode assemblies (MEAs) for polymer electrolyte membrane fuel cells and use this knowledge to develop and demonstrate high-performance MEAs with ultra-low catalyst loadings (ULCLs). Transport losses are a major barrier with ULCLs, but fundamental understanding of those losses is currently lacking. To gain better understanding of the nature of these losses in cathode catalyst layers, a detailed microstructure model of the cathode catalyst layer will be developed. This improved knowledge will then be utilized to develop improved MEAs that meet the U.S. Department of Energy's (DOE's) performance targets.

Question 1: Approach to performing the work

This project was rated **3.0** for its approach.

- The project is well aligned with DOE targets, as it addresses high-current-density performance losses for catalysts with ultra-low Pt loading. The project is well designed. It relies on a combination of SOA experimental work and modeling in order to clarify the origin of high-current performance losses. Although the focus is on catalyst structures, some of the proposed structures do not seem to be very relevant.
- Transport limitations at high current density and low loading remain as a barrier for the efficient deployment of fuel cell MEAs. The focus on Pt-only MEAs makes sense for focusing on local transport resistance but makes the tests less relevant for true SOA materials. Efforts along these lines have been common in the community lately, but the core team for this project has not been leading this area and does not have the strongest background to undertake these studies. The four simplified cases shown in slide 10 are key to connecting models to the experimental results obtained, and the complexity of the real system will result in significant challenges in connecting these efforts, with significant risk that little will be connected between the model and experimental results. No data have been presented yet to suggest that the models can be effectively applied to trends seen experimentally. There will be challenges in applying the model thin-film catalysts being developed to MEAs.
- The generic modeling approach (slide 10) seems to be good. The question is how to validate the model for each mass transport loss, total oxygen transport resistance, and local oxygen transport resistance. The project set go/no-go for this model validation. It is necessary to clarify the metric of the validation. It is also necessary to see effectiveness of operating conditions. Measurement of mass transport loss with the oxygen partial pressure method (various oxygen partial pressures) is not sufficient to distinguish total oxygen transport resistance from local oxygen transport resistance. Investigation of the novel thin-film catalyst later does not fit the Fuel Cell Performance and Durability (FC-PAD) consortium objective (characterization, not novel concept development).
- The project constitutes an effective combination of theoretical and experimental work to elucidate the causes of local transport losses in low Pt-loaded electrodes, a critical barrier to fuel cell commercialization, and to start on the road of mitigating these losses. The project seems to be overly

wedded to the idea that the local transport losses arise from details of aggregate structure, ignoring the possibility of losses right at the Pt–ionomer interface.

- The team has taken a good approach of understanding the fundamentals of transport limitations in SOA MEAs and then using the learnings to develop high-performing MEAs. Development of a microstructure model of cathode catalyst layer is expected to shed light on different modes of transport limitations. The project is new, and very little technical work has been done to assess the significance of the approach made by the team.
- The team has a good approach, but it might be helpful to add additional details on how the limiting case study MEAs are going to be fabricated.
- As the principal investigator (PI) noted, the project relies heavily on inventing methods to prepare electrodes with sufficient differentiation to identify model parameters. However, the PI did not share a clear plan to achieve these goals. The project team does not currently have that capability and likely will need to rely on FC-PAD to come up with a method. The characterization methods being used appear to be similar to previous projects. It is unclear what new insight the project will bring.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.0** for its accomplishments and progress.

- The results presented were reasonable for a project at the beginning stages. The most interesting/useful results to date were in the area of model development. Isolating four limiting cases based on agglomerate morphology can help to provide insight into the catalyst layer structure/performance relationships. MEAs were fabricated and tested but did not provide any new insight or results that were not expected, rather just verification of the ability to synthesize relevant materials. The work in the area of thin-film catalyst development was useful at a rotating disc electrode level but will have significant challenges in transferring to useful MEA results.
- The project is new; it started in January 2017. The accomplishments achieved by the team in three months, which are cited in the presentation, are good. The prime (United Technologies Research Center [UTRC]) has organized the team and gotten the contracts signed. The relationship and communication tools to run the project are in place. The project is in a very early stage, and not much time has been spent on the project. The team's progress is satisfactory within the given time they have been involved in the project.
- Although none of the DOE targets have been exceeded yet, progress has been made toward development of a microstructured model of the catalyst layer, fabrication of SOA MEAs, and evaluation of activities of thin-film catalysts with porosity gradient.
- The project is still in an early stage but is already showing some good results.
- Even considering that the project has just started, it is disturbing that the Ion Power, Inc. MEAs are still just trying to match the performance of SOA low-loaded MEAs, and that no start has yet been made on producing MEAs with the controlled structures shown on slide 10. It is not clear that estimates of aggregate diameters and ionomer film thicknesses necessary to generate the experimentally observed local transport resistances have yet been made for the cases shown on slide 10. Such estimates should have been compared to Oak Ridge National Laboratory's measurements of actual electrode structures prior to generation of the proposal, and they need to be done early in this project to minimize wasted effort.
- The project just started.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.3** for its collaboration and coordination.

- This project will likely be a showcase demonstrating the benefits of close coordination between industry projects and the characterization and theory capabilities of the national laboratories in the FC-PAD consortium. If Ion Power can actually control electrode structures to approach the limiting cases shown on slide 10, the collaborations in this project will be unusually fruitful. The presentation did not make it clear how the thin-film electrodes being made at the University of Arkansas at Little Rock will contribute to the understanding and mitigation of local transport resistances.

- The team comprises capable scientists and organizations to run the project. The team is in the early stage of coordination, and all collaborators in this project have past experience in working on a DOE project. As a part of FC-PAD, the team has access to the great resources from other FC-PAD member organizations and scientists involved in FC-PAD. If needed, the team can consult with other FC-PAD members.
- Although the project just started, there seems to be an excellent collaboration between Ion Power, UTRC, and the University of Arkansas.
- The project has reasonable collaborations with Ion Power to synthesize MEAs and a university collaborator to aid in catalyst synthesis. The project will have high dependence on FC-PAD core members. The connection with Lawrence Berkeley National Laboratory for modeling is one that will be particularly critical.
- The project has a good team and can leverage the national laboratories through FC-PAD further.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.4** for its relevance/potential impact.

- This project is tightly focused on the local transport resistances, which now constitute the major barrier to the commercial application of low-Pt-loaded cathode electrodes, which is the key to economic viability of fuel cells in most applications. This project should generate the fundamental understanding of the still-mysterious local transport resistances needed to enable design of MEAs fully meeting DOE's performance targets.
- The project is relevant to DOE's 2020 target. Proposed performance comparison of SOA and high-activity oxygen reduction reaction (ORR) catalyst MEAs to understand the mass transport limitations is needed before developing a ULCL or thin-film catalyst layer (TFCL) to reduce the catalyst loading. It will be good to know how the increase in fluctuation rate affects the catalyst sites and affects the transport rates in an MEA. The understanding of such mass transport loss may help in reducing the mass transport loss and hence improve the performance of the ULCL and TFCL.
- The project has the potential for significant impact on the DOE Hydrogen and Fuel Cells Program, as stack cost is one of the most important metrics for commercialization of polymer electrolyte membrane fuel cells.
- Increasing the high-current-density performance of fuel cells is clearly a primary challenge to decreasing cost and increasing performance of fuel cell systems. The improved understanding of the mechanisms of overpotential losses can aid in mitigation of these losses.
- Detailed characterization of the cathode catalyst layer for the mass transport losses is critical for MEA development (performance and cost).
- The project is highly relevant and could have a big impact if the team can gain understanding of the root cause of high-current-density performance loss.
- The project does not intend to address DOE targets directly but attempts to identify key limiting parameters of high-current-density performance.

Question 5: Proposed future work

This project was rated **2.9** for its proposed future work.

- As the project is very new, the proposed future work presents the details of the work proposed by the team in this project. The team has described the quarterly deliverables and the go/no-go stages for the duration of the first half of the project. The proposed future work for the duration of the first half of the project is aligned with the overall goal of the project.
- The project's proposed future work is well planned. It relies on a combination of modeling and experimental work to provide insights into the origin of transport losses at high current densities. There is no clear path to make outlined catalyst structures that are intended to be used for model validation.
- The question is how to validate the model for each mass transport loss, total oxygen transport resistance, and local oxygen transport resistance. The project set go/no-go for this model validation. It is necessary to clarify the metric of the validation. It is also necessary to see the effectiveness of operating conditions.

Investigation of the novel thin-film catalyst later does not fit the FC-PAD objective (characterization, not novel concept development). Measurement of mass transport loss with the oxygen partial pressure method (various oxygen partial pressures) is not sufficient to distinguish total oxygen transport resistance from local oxygen transport resistance.

- The proposed future work has a number of overlaps with existing results in the literature investigating high-current, low-loading operation, particularly work reported by General Motors. A major addition would be the ability to selectively create structures in the electrodes that approximate the structures in slide 10. At this point, it is not clear that the agglomerate structure can be controlled or influenced effectively through MEA fabrication modifications. For thin-film catalyst development, it is not clear that the thin films being developed can be transferred effectively to MEA incorporation.
- The project's proposed future work is sound; however, the team is heavily dependent on the ability to create and characterize the limit-case electrodes. Therefore, there needs to be some alternate factorial designs to improve the probability of success.
- The proposed work, if successful, should provide a clear test of the aggregate theory of local transport resistance. Insufficient information was provided to give any confidence that model electrodes distinguishing between the different transport modes as diagrammed on slide 10 can actually be grown. In the absence of such controlled electrodes, it is not clear that the project could generate clear conclusions about the true mechanisms of local transport.
- It is not clear what, how, or when tasks will be done, or by whom. The milestone criteria are also not specified.

Project strengths:

- The objective of attempting to understand the mass transport loss at the fundamental level is one of the important steps in the development of high-performing MEAs with ULCL- or TFCL-type low-catalyst-loaded electrodes/MEAs. The team consists of knowledgeable scientists and a knowledgeable PI, who are capable of conducting the proposed research. The team contains the FC-PAD consortium, allowing the FC-PAD team members to coordinate relevant information exchange with the project. This will help in the project's progress to maintain its direction as well as to input any relevant information that may come from other FC-PAD projects. The approach taken by the team is also a strength: working at the microstructure level to gather understanding of mass transport loss and to develop a model to direct future high-performing MEAs with ULCLs to meet DOE's 2020 target.
- Project members, in collaboration with the characterization capabilities of FC-PAD, are well situated to determine whether the local transport resistances observed for low-loaded cathodes arise from details of carbon and/or ionomer aggregates. The presentation evinced a good understanding of the complexities of local transport issues on the part of the PI.
- The major project strength is in applying unique UTRC expertise in modeling and diagnostics to elucidate the origin of high-current losses in the rationally designed catalyst layers.
- Quality experiment capability for MEA performance is a project strength, as is the modeling capability for mass transport losses.
- Modeling at the agglomerate scale is a good addition to the established fuel cell models.
- The project has a good team and approach.

Project weaknesses:

- Regarding Ion Power MEA, the initial result shown in slide 12 with the Ion Power-developed MEA (B1286) contains three times the Pt loading as the baseline SOA MEA (B1240), while it performs close to the SOA. As the team has identified, more work is needed to improve Ion Power's MEA performance to match the SOA MEA performance. It was not clear why the team chose the high-loading MEA from Ion Power, as it may be having conventional agglomeration issues leading to mass transport loss. In ULCL, the mass transport loss mechanisms could be different. There is another weakness regarding the density gradient electrode (DGE): in slide 13, the team has proposed the use of a gas diffusion layer (GDL) as the substrate. Using the membrane as the substrate will allow the porous top of the DGE to be against the GDL, and then the porous part of the electrode will allow better oxygen transport into the electrode to support the high kinetics of ORR. Using the GDL as the substrate will invert the configuration, and the porous part of

the DGE will be close to the GDL (i.e., away from the membrane, and the porous part of the electrode will be against the membrane), which will not allow better oxygen flow into the membrane–catalyst interface. The team needs to look into the configuration of the proposed DGE.
- It is not clear how the thin-film electrode work at the University of Arkansas contributes to the overall goals of the project. It is not clear how model electrodes with controlled aggregate forms and ionomer film thicknesses can be grown. The project apparently has not yet plugged the numbers into its math models to determine the sizes of aggregates and thicknesses of ionomer that would be required to give the experimentally observed local transport values. The estimated first-order dimensions may be large enough that the aggregates should be more obvious in microscopy than have been seen to date.
- The project weakness is in uncertainty with fabrication of catalyst layers with a given structure, both for carbon-supported and thin-film catalysts. Carbon support has not been given a proper consideration in the modeling and experimental work
- The project team is behind the SOA in the area of high current, low loading. The efforts in novel thin-film catalyst development are going to have significant challenges in extending to fuel cell tests.
- It is too early to say and unclear how they can help move the bar on the DOE 2020 goals.

Recommendations for additions/deletions to project scope:

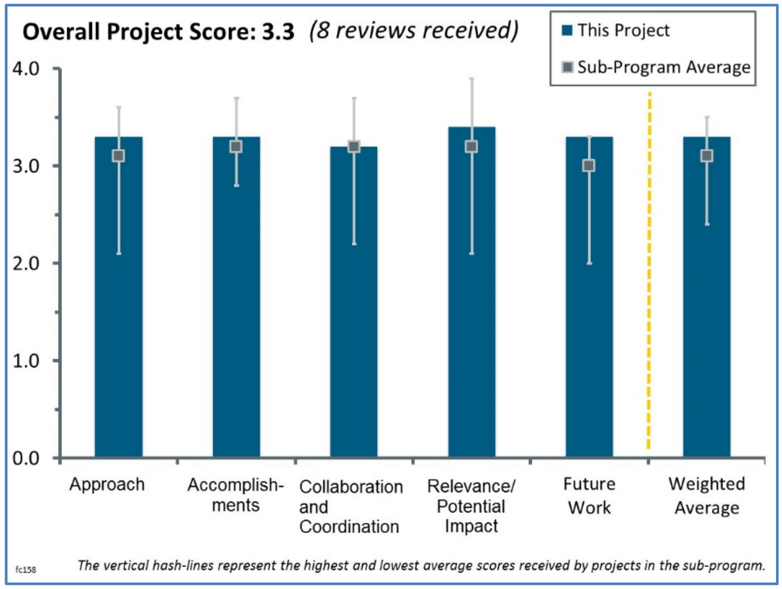
- It is suggested that the project clarify the metric of the validation of the mass transport losses model. The measurement of mass transport loss with the oxygen partial pressure method (various oxygen partial pressures) is not sufficient to distinguish the total oxygen transport resistance from local oxygen transport resistance. It is necessary to propose alternative methods (or additional measures). Investigation of the novel thin-film catalyst later should be reconsidered to make it fit with the FC-PAD objectives, which are focused on characterization rather than new concept development. The catalyst should be evaluated based on the knowledge gained, such as characterization and why it works or does not work.
- Novel catalyst synthesis seems to be of limited value. It would be better to reach out to others who have established thin-film catalysts to include such materials rather than develop them specifically within this project.
- It would be good to consider dropping the thin-film electrode work unless it can be logically connected to the rest of the project. The project should consider the possibility that the observed local transport losses arise not just from effects of aggregates but also from as-yet-inexplicable losses right at the Pt–ionomer interface.
- The team may consider including some low-Pt-loaded commercial cathode electrodes from other MEA suppliers for the study.
- Some pre-templated electrode structures should be added to enable limiting case electrodes.
- Carbon supports with different microstructures should be incorporated in both parts of the project.

Project #FC-158: Fuel Cell Membrane Electrode Assemblies with Ultra-Low-Platinum Nanofiber Electrodes

Peter Pintauro; Vanderbilt University

Brief Summary of Project:

Particle/polymer nanofiber mat electrodes are a promising alternative to conventional fuel cell electrode structures. This project seeks to better understand and further improve the performance and durability of low-platinum-loaded nanofiber mat fuel cell electrodes and membrane electrode assemblies (MEAs). Mat electrode MEAs with highly active oxygen reduction reaction catalysts for hydrogen/air fuel cells will be fabricated, characterized, and evaluated. The project will focus on nanofiber cathodes with commercial platinum–alloy catalysts and platinum–nickel octahedral catalysts containing various ionomer and blended polymer binders.



Question 1: Approach to performing the work

This project was rated **3.3** for its approach.

- This project looks to demonstrate a novel electrode architecture based on electrospun fibers. Based on initial results, this approach improves performance and stability because the electrospinning process results in excellent catalyst/binder mixing and forms a more porous morphology that is better for high-current-density operation.
- This is a novel approach to reducing Pt cost by dispersing Pt nanoparticles and polymer in nanodimensions on the active layer, catalyzing electrode reactions (mainly oxygen reduction in this presentation). There is a catalyst team (Georgia Institute of Technology [Georgia Tech]), an ionomer team (3M Company [3M]), a catalyst and polymer dispersing team (Vanderbilt University), and a performance validator (Nissan Technical Center North America [Nissan], with the help of the Fuel Cell Consortium for Performance and Durability [FC-PAD]). Therefore, the approach should be doable and checkable.
- Electrospun fiber electrodes are a new type of electrode structure that shows promise of good activity and improved and more durable high-current-density performance. This project's approach is appropriate for further developing this innovation and for understanding why the benefits occur.
- The electrospun nanofiber approach addresses the barriers of performance and durability. The project is well designed and feasible. It is well integrated with other efforts in FC-PAD.
- The approach of making nanofiber cathodes and MEAs is novel. This has demonstrated a significant performance and durability increase over conventional MEAs. The approach is also based on the principal investigator's (PI's) multiple years of experience in nanofiber development.
- The project approach of development of novel electrode structures directly addresses key DOE cost barriers.
- Nanofibers offer good opportunity. However, MEA is the key. The project has good collaborations.
- The PI and team are attempting to make high-performance MEAs based on electrospun carbon fibers. The premise of the concept is to provide a porous network for the electrocatalysts and a basis for evaluating more advanced electrocatalysts that other members of the team will provide. The approach is to make MEAs with the different catalysts and the ionomers and test them at standard conditions. There are several concerns:

- The researchers claim that the "electrode macroporosity, microporosity, and particle and binder interconnectivity become more critical when high-performance nanomaterial catalysts are used in fuel cell electrodes." However, there is little or minimal attempt to correlate these parameters to the electrochemical results.
- Another major concern is that the porous materials will flood if used in a stack at low temperatures and will never be able to reach full power as tested on single cells. The test plan needs to be expanded beyond testing at around 80°C, in an attempt to replicate cold start.
- It is unclear how water will be removed from the porous materials if the fuel cell stack is frozen.
- The gas diffusion media will likely play a large role in the performance of these materials, but there is little or no attention to this vital part of the MEA.
- The test cell for the MEAs should also be described, along with how the cells are compressed; cell compression is key to the performance of porous materials and might skew the results if it is not carefully tracked.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.3** for its accomplishments and progress.

- The project results are excellent for initial performance and mass activity (even though electrochemical surface area is low) to date, far exceeding conventional catalyst spray coating, which is a state-of-the-art way to disperse catalysts in a gas-fed porous fuel cell electrode active layer.
- The project has made good progress toward its goals. Initial electrode optimization work has yielded modest activity improvements, and results appear superior to conventional spray-coated electrodes. The nanofiber electrodes appear to yield substantially improved hydrogen/air performance retention (slide 13). Development of Georgia Tech's catalysts with high activity appears well underway and to be making good progress.
- The project has made good progress in the short time it has been active and since the non-disclosure agreements were signed. The project has prepared electrospun catalyst layers from commercial catalysts with improved performance over conventional sprayed or painted catalysts. The project has prepared shape-controlled PtNi and Pt-coated PtNi catalysts.
- The initial results with alloy catalysts are very encouraging. Rotating disc electrode results with the octahedral catalysts show unusually good durability for this class of materials, particularly with the added Pt overlayers. Activity is reasonable for this catalyst class.
- This project has progressed well in less than six months. The PtCo/C nanofiber cathode has demonstrated tremendous durability improvement. Shape-controlled Pt-Ni octahedral catalysts also show improved activity.
- The project had a delayed start, so the useful test data are limited. However, the results are very promising. The team has demonstrated good progress on electrode and MEA processes.
- Within the statement of work, the team has made progress. If possible, the researchers should carry out more in-depth physical characterization and have broader ranges for electrochemical evaluation.
- The project is mostly on track—just slightly behind on the full delivery of the catalyst.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.2** for its collaboration and coordination.

- The team—Vanderbilt University (prime), led by Professor Peter Pintauro for polymer and catalyst dispersion; Georgia Tech (sub), led by Professor Younan Xia (project co-PI) for catalyst-making; 3M (sub), led by Dr. Mike Yandrasits for ionomers; and Nissan (sub), led by Dr. Nilesh Dale (project co-PI) as performance evaluator with FC-PAD for validation—covers all bases for executing and validating this nano-spinning approach to high electrode catalyst active layer activity in a perfluosulfonic acid electrolyte membrane fuel cell.

- A good degree of collaboration is planned with Nissan, Georgia Tech, and the FC-PAD consortium. Advanced electrode structural characterization and modeling to help understand the apparent improved transport would be useful but does not appear to be part of the project.
- Collaboration and coordination with partners is in place. Coordination with the FC-PAD team is in place. Connections with the modeling efforts in FC-PAD are not yet apparent but could be beneficial to both FC-PAD and this project
- This project has a team with diversified experience. The collaboration of Vanderbilt University with Nissan, 3M, and Georgia Tech make this project team very strong.
- The project has a very good team; there are great collaborative efforts with 3M, Nissan, and Georgia Tech.
- The teaming with Nissan and other universities is good.
- The project is in too early of a stage to judge how well it will integrate with FC-PAD. The collaboration between synthesis and the testing centers seems to be working well.
- One expertise missing from the team is a partner who can perform electrode modeling. This would help to better understand the morphology effects at a fundamental level. Coordination with catalyst development projects may also prove useful as this project progresses.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.4** for its relevance/potential impact.

- Electrospun cathode layers are one of the few novel electrode structures that show good promise both in kinetic activity and in high-current-density performance. The high specific activity of octahedral catalysts would lead to crippling local transport losses at high current density in standard electrode structures. The improved high-current-density performance seen to date with electrospun electrodes using standard catalysts gives hope of mitigating local transport losses on octahedral catalysts, possibly allowing practical utilization of their high specific activity that could not be achieved with standard electrodes.
- The Vanderbilt University, Georgia Tech, 3M, and Nissan team are well positioned to find a better understanding and further improve the performance of low-platinum-loaded fuel cell electrodes and MEAs. It is not clear what the long-term durability of these electrodes is because of the presence of 20–30 wt.% of hydrocarbon carrier polymer. This is an important issue to keep aware of when developing this technology. This may be a top priority of FC-PAD and Nissan.
- This is a novel approach to making electrodes that is showing very interesting results in the initial tests. Other reviewers may question the scalability of electrospinning since it is relatively new to the fuel cell community; however, this process has been scaled up for other applications and should not be a concern.
- Goals toward lower Pt loadings and high performance are in alignment with DOE goals, and the project is also testing durability. The larger question is whether meeting the DOE goals at a narrow test condition (i.e., 80°C at pressure) will translate to success at the stack level.
- The project supports the goals and objectives of the Fuel Cells sub-program to decrease cost and improve durability. The project provides a unique electrode structure with the capabilities to vary parameters in different ways from what can be done with conventional electrode structures.
- The project is directly relevant to addressing the key barriers of performance, durability, and cost. With access to high-activity catalysts, the project has good prospects for achieving several DOE 2020 targets.
- This project is very relevant to the fuel cell goals delineated in the Multi-Year Research, Development, and Demonstration Plan. The project aims to enhance fuel cell MEA performance and durability.
- The cost of nanofiber-based electrodes and MEAs for the proposed process needs to be justified for ensuring a competitive cost; yields are very important.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- The proposed electrochemical characterization work is substantial and should be helpful to the project toward meeting its first-year milestones. The milestones (slide 20) are largely operational, rather than

metric-driven. Support accelerated stress testing (AST) should be done early to assess whether this is a key issue with electrospun nanofiber electrodes.
- The team's design of experiment is very good. The team plans to inspect other carrier polymers that are either very stable or completely removed. The activity is already high, and the plan to do a design of experiments to vary the catalyst and polymer ratios to improve performance is logical.
- The project plans are an effective combination of novel electrode preparation and testing. The roles of the FC-PAD laboratories should become clearer as the project moves forward.
- The project builds very well on the initial data and input from team member Nissan.
- The proposed future work is appropriate and should help elucidate the differences between electrospun catalyst layers and traditional layers, and determine the factors limiting performance.
- The plan is for Vanderbilt University to make materials and Nissan (and FC-PAD partners) to do testing. There does not seem to be a good plan for developing a matrix to answer the questions about what type of catalyst microstructure is important, and how the microstructure affects the performance of Pt and other catalysts. Overall, the process seems boilerplate and not poised to answer general scientific questions—rather, just whether the team's MEA works or not.
- The proposed future research is reasonable. However, the PI should focus to some degree on the nanofiber MEA characterizations to elucidate the microstructures using in situ and ex situ approaches. It is unclear why the nanofiber MEAs show performance superior to the conventional MEAs.
- A high-level Gantt chart beyond 2017 should have been presented.

Project strengths:

- The project further develops one of the few novel electrode structures that show promise at both low and high current densities. Better understanding of how electrospun electrodes work could also clarify how standard electrode structures could be improved. The octahedral catalysts in this work have shown better durability than most such shape-controlled catalysts, and facile synthesis methods have been developed. Electrospun electrodes are a plausible, though still poorly understood, way to prevent excessive high-current-density losses on octahedral electrodes giving very high local current densities.
- Electrospun structure provides unique electrode structure and flexibility to provide different structures (for example, using a second needle to add additional ionomer in an independent intersecting ionomer pathway). The project has access to high-activity shape-selective catalysts and Pt-coated shape-selected catalysts that show good durability.
- This project has demonstrated novel approaches using nanofiber cathodes and MEAs. The project has shown good progress in less than six months and has a strong team with diversified experience.
- Nanofiber electrodes appear to have some strong advantages over conventional electrodes in terms of beginning-of-life performance and hydrogen/air performance retention after the electrocatalyst AST. The project has a strong team.
- The strength of this project is that it is developing a novel approach for electrode preparation that improves catalyst/ionomer mixing and porosity. The approach, in initial testing, demonstrated interesting results for performance and durability.
- The catalyst layer microstructure is important to the function of MEAs. The team has a good means of making highly porous microstructures, and a plan to test out their electrochemical performance.
- This project offers a novel and effective method to intersperse catalyst *and* polymer for producing a catalyst active layer. This project is very creative.
- The team is very well-qualified and -coordinated. The laboratory, university, and industry combination is very good.

Project weaknesses:

- Electrode structural characterization (e.g., nanocomputed tomography and transport modeling) is absent from the project. Such work would be useful toward development of further-improved electrode structures. It is unclear whether stability of support will be sufficient against the support AST.
- The carrier polymer's being made of hydrocarbon opens up questions about chemical and physical stability—especially in the intermediate (1,000 hours) and long term (5,000–10,000 hours). Tracking this

carrier polymer should be a top priority, and changing it may be needed to optimize this method's effectiveness.
- The conventional electrodes being used as controls are fabricated by spraying rather than by more manufacturable slot-coating processes, and thus may not properly represent the true state of the art. The expected roles of the FC-PAD laboratories should be better defined.
- This is a work-intensive project that may not lead to any mechanistic insights and might produce MEAs that do not work in actual fuel cell stacks. More work should be done on understanding why porous fiber mats might lead to higher-performance systems, whether they flood, and what gas diffusion media are ideal for operation with porous fiber mats.
- The correlation between the improved electrode performance and the microstructure is not well understood. Therefore, the in situ and ex situ approaches should be used to characterize the electrode microstructures. The PI should also discuss the scalability of the nanofiber approach.
- The project plan did not convey plans to model and understand the reasons that the electrospinning approach would improve durability.
- Mechanistic understanding of performance improvement and stability should be characterized to greater depth.

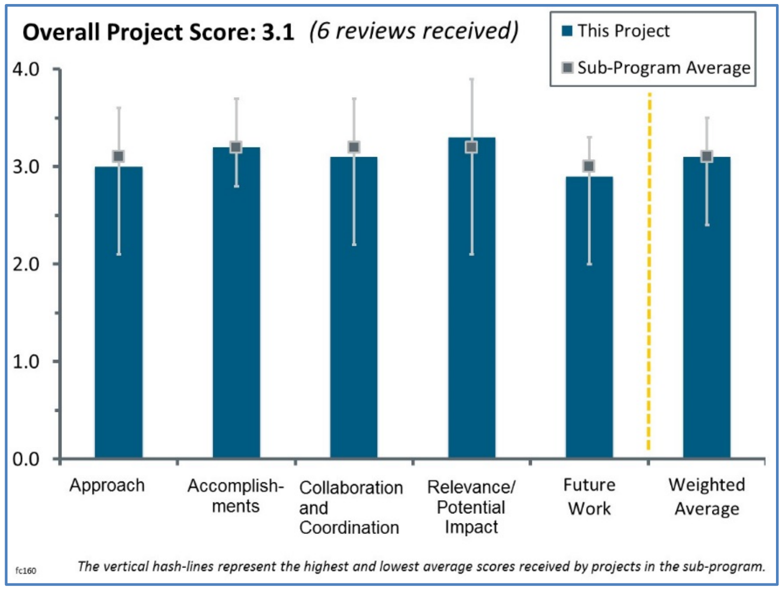
Recommendations for additions/deletions to project scope:

- Performance should be compared to state-of-the-art MEAs that were not made in-house. It is possible that the electrospun electrodes were better mixed because the team was not mixing the conventional electrodes well enough. Plans for modeling the electrode performance and degradation should be added to better explain what the new approach does at a fundamental level. The team should also consider coordinating with other projects/suppliers that are putting effort into optimizing catalysts, as collaboration with those entities could be mutually beneficial.
- FC-PAD has shown some advantages for electrode designs with varied Pt loading that the researchers believe leaves room for areas for water transport. Using dual electrospinning, this project could look at a more uniform way to provide a separate water transport path, or water highway, by electrospraying a second stream with just ionomer and mixing it with the stream with ionomer + catalyst + carbon, and reducing ionomer in the mixed stream to reduce ionomer adsorption on the catalyst.
- The project should set up long-term testing of any electrode using a hydrocarbon carrier polymer as soon as possible to see whether it degrades. Like they say, if it is too good to be true, it probably is not true.
- Plans on how to understand transport properties in electrospun electrodes should be fleshed out more. Consideration should also be given to later studying hybrid electrodes using electrospun fibers mixed with standard catalyst powders and ionomers.
- The researchers should carry out microcomputed tomography studies and/or porosity measurements to characterize the porosity. The team should add in a task for a freeze start test and look at different gas diffusion media materials. The researchers should also report out how cell compression affects the results.
- In situ and ex situ approaches should be used to characterize the electrode microstructures. The PI should also discuss the scalability of the nanofiber approach.
- The team should increase early focus on evaluation of electrodes for support stability. The team should also add some amount of electrode structure characterization to aid development.
- Scale-up impact on mechanistic understanding should be emphasized.

Project #FC-160: ElectroCat (Electrocatalysis Consortium)

Piotr Zelenay; Los Alamos National Laboratory

Brief Summary of Project:



ElectroCat was created as part of the Energy Materials Network in February 2016. The goal of the consortium is to accelerate the deployment of fuel cell systems by eliminating the use of platinum-group-metal (PGM) catalysts. ElectroCat and its member laboratories—Argonne National Laboratory (ANL), Los Alamos National Laboratory (LANL), National Renewable Energy Laboratory (NREL), and Oak Ridge National Laboratory—will develop and implement PGM-free catalysts and electrodes by streamlining access to unique synthesis and characterization tools across national laboratories, developing missing strategic capabilities, and curating a public database of information.

Question 1: Approach to performing the work

This project was rated **3.0** for its approach.

- The project has a well-defined approach. The key messages taken directly from the presentation are as follows:
  - Durability and cost are the primary challenges to fuel cell commercialization and must be met concurrently.
  - The project's goal is to accelerate the deployment of fuel cell systems by eliminating the use of PGM catalysts.
  - The project's mission is to develop and implement PGM-free catalysts and electrodes by streamlining access to unique synthesis and characterization tools across national laboratories.
  - Demonstrate improved feasibility of segmented cell system for combinatorial PGM-free samples (e.g., Fe-CM-PANI-C catalyst).
  - Extract values for the reaction order with respect to oxygen partial pressure and activation energy as a function of PGM-free catalyst type and/or electrode design.
  - Improved fuel cell performance in both kinetic and mass transport region reaching a current density of 120 mA/cm^2 at 0.8 V (iR-free).
  - Iron (Fe) dissolution rates for (AD)Fe-N-C are >10×lower than for (CM+PANI)-Fe-C(Zn).
  - Low fuel cell performance caused by dense packing of catalyst layer resulting in uneven ionomer distribution and low porosity.
  - Oxygen mass transport losses are dominated by flooded pores in thick electrodes and film resistance in thin electrodes.
  - High-current-density performance improved by decreasing electrode thickness, tortuosity (m), and size of micropores (rm), and increasing volume fraction (vf) of micropores.
  - Demonstrated hydrogen–air performance of 120 mA/cm^2 at 0.8 ViR-free with (CM+PANI)-Fe-C(Zn) cathode catalyst, a 25% improvement over the 2016 status.
  - Achieved half-wave potential (E½) of 0.83 V with (AD)Fe-N-C in rotating disk electrode (RDE) testing, an increase of 0.02 V over the 2016 status.
  - PGM-free catalyst activity in an MEA: 16 mA/cm^2 at 0.90 V iR-free and 0.044 A/cm^2 at 0.87 V.

- The approach being taken with ElectroCat is well designed to address the issues with PGM-free catalysts. It will be important to fundamentally understand the active sites in this class of materials, improve durability, and increase active site density. All of these things are addressed in the project approach. The only minor concern is that some of the initial focus seems to be on improving activity; however, until degradation is well understood, activity and durability should be examined in parallel to prevent development of really good catalysts that may never last more than 100 hours.
- The project should concentrate more on electrode modifications to get thick electrodes to work even in air at high current densities and concentrate less on increasing the volumetric number density of active sites. Extensive high-quality work in recent years appears not to have led to the significant improvement in active site density that is needed if 10-micron electrodes are to suffice. Less reliance should be placed on testing with RDEs and with RDE-similar flow cells; work should be done with membrane electrode assemblies (MEAs). Some of the non-Pt catalysts that have done best in fuel cells have given little or no activity when tested in RDEs. High-throughput methods of synthesis and testing are of questionable value for non-Pt catalysts, the performance of which depends less on chemical composition and more on details of processing. The physical vapor deposition (PVD) generation of thin-layer model catalyst systems is unlikely to be useful, as the methods are too far removed from the complex preparation methods that have given the best non-Pt catalysts, and the number of active sites, already low in high-surface-area catalysts, will likely be too low to give enough activity to allow meaningful mechanistic conclusions to be drawn.
- Comprehensive sets of advanced synthesis and characterization methods are brought to make carbon-based, PGM-free, fuel cell catalysts and MEAs and understand the material behavior. Emphasis on high-throughput approaches should be balanced by fundamental science efforts to address outstanding questions regarding oxygen reduction reaction (ORR) catalysis by PGM-free carbon.
- The project approach appears substantially focused on improving non-PGM catalyst activity and the electrode structure to enable high power capability. While very important, the project does not appear to have a strong apparent focus on addressing the key durability concerns with carbon-based structures.
- The project has a large and expansive approach but is also a highly funded ($3 million per year).

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.2** for its accomplishments and progress.

- The project has demonstrated very good technical progress by incorporating a Zn pore-former in the electrode (slide 13), allowing substantially improved hydrogen–air performance. Use of RDE-inductively coupled plasma mass spectrometry (ICP-MS) can allow for good early detection of stable catalysts and helps assess degradation mechanisms (slide 15). Systematic studies of performance versus electrode properties (thickness, tortuosity, etc., slide 23) appear well executed and should act as a good baseline dataset for the modeling work. Modeling of catalyst active-center durability (slides 24, 25) may be useful if results correlate with experiment. Some work should focus on stability of the catalysts against corrosion relatively early in the project.
- ORR activity of PGM-free ORR catalysts is in continued need of further improvement to reduce cathode thickness and to lower the cost of other stack components. Insufficient long-term stability and performance durability under steady-state and load-cycling conditions, a limited understanding of the ORR mechanism and the nature of the ORR active site, as well as the mechanism of catalyst degradation preventing the rational design of next-generation PGM-free catalysts, requires electrode design and component integration to provide adequate ionic, electronic, and mass transport to and from active sites. It also requires integration with existing automotive fuel cell stack and system technology. The stability of PGM-free catalysts is significantly affected by high-potential excursions (start–stop conditions).
- All aspects of the project appear to be on track. Promising, high-quality results have been generated. There has been good scientific output since the launch of ElectroCat. The atomic resolution and science, technology, engineering, and mathematics (STEM) work is excellent. The durability descriptor calculation based on e-beam damage is unconvincing because it does not reflect the electrochemical processes that occur in a polymer electrolyte membrane fuel cell (PEMFC) cathode.
- Given the size of the project, reasonable incremental improvement in fuel cell performance, mechanistic understanding in activity, and degradation of the catalysts have been demonstrated. All of the project work

is on Fe catalysts. The transition away from Fe is slow. New catalyst approaches are now focusing on a metal–organic framework approach. Fuel cell stability was not discussed in the presentation.
- Modest improvements in performance have been made in the last year. Fluoridation of catalysts (a good idea) has so far led to a loss of Fe and of performance. More work on this is needed to keep Fe levels adequate after fluoridation. While attempts to streamline the national laboratories' intellectual property (IP) procedures are needed, the current approach should be replaced by the labs seeking to get their developments into the public domain as rapidly as possible. The present emphasis on retaining IP for the labs is counterproductive to the goal of getting innovations into the American economy.
- The ElectroCat consortium is clearly off to a good start and making progress towards its planned goals, which are aligned with DOE goals.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.1** for its collaboration and coordination.

- The team of national laboratories under Zelenay, Myers, Dinh, and More is conducting an excellent project to develop PGM-free catalysts for low-temperature fuel cell applications. The researchers are showing significant progress, which they verify and report formally in a technically sound manner, and they utilize the latest state-of-the-art equipment and methods. They are studying some of the most advanced catalyst materials, and their work is at the leading edge of development for this technology. In addition, this technology is one of the most important for fuel cells at this time.
- ElectroCat appears to be collaborating well between the national laboratories involved. It was not clear if there are other institutions involved or if that will start after the related project awards. An explanation of how there will be industry collaboration would also be beneficial.
- LANL work seems to be rather well integrated into the project as a whole, though closer coordination with outside groups skilled in making high-performing MEAs would be useful. The ANL high-throughput efforts need better coordination with groups experienced in the development and testing of non-Pt catalysts. The NREL personnel planning to use PVD to grow thin-film model non-Pt catalysts should talk long and hard with experienced LANL personnel before committing much time to such an effort.
- The project appears to extensively utilize national laboratory consortia and has a large list of highly capable, no-cost collaborators.
- The project's scientific output so far has been dominated by the lead laboratory (LANL). Collaborative results among the four member laboratories appear to be in the pipeline. External collaborators are listed, but no concrete evidence of collaboration was presented.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.3** for its relevance/potential impact.

- If successful in developing durable, high-performing non-Pt catalysts, this project could revolutionize fuel cells. Full success in this project is highly unlikely. The most likely benefit from this project would be modest improvements in non-Pt catalyst durability, which would still leave such materials short of the requirements for commercial application.
- This consortium can clearly help achieve DOE goals for fuel cells and have a significant impact. The only uncertainty is whether it is necessary to pursue completely PGM-free catalysts. That may prove to be unnecessary from a cost perspective and technologically too challenging.
- The project aim to develop catalysts with improved activity and performance in electrodes directly addresses key barriers. However, the project does not address carbon durability, a key issue with carbon-based PGM-free electrocatalysts. Achievement of activity and performance parity with PGM catalysts will be for naught if durability cannot be substantially improved.
- Promising results based on completely PGM-free catalysts have been generated, which suggests the carbon-based approach has the potential to meet DOE targets.

- Reducing/removing PGM from a fuel cell is highly relevant. It is unclear how relevant the knowledge learned from the Fe catalyst will be.
- This report acknowledges, but possibly understates, the stability issue with non-PGM catalysts in an acid environment. While this team has shown significant performance improvement and will likely continue to do so, the dependence on RDE leaves the project exposed to some significant surprises. The PEM technical community recognizes RDE as the "baseline test method" for qualifying catalysts based on its proven performance on Pt/C catalysts. However, many publications have shown that there is a significant discrepancy between the stability of non-PGM catalysts as measured by RDE and as measured by subscale cell testing. If RDE is giving unreliable results, alternative methods should be used.

Question 5: Proposed future work

This project was rated **2.9** for its proposed future work.

- The planned work for 2017 is logical. A high-level Gantt chart beyond 2017 should be added to better understand the full plan. In addition, if the highly active sites being pursued now are inherently unstable, it was not clear how that would be mitigated.
- The project's future work is focused on development of improved activity catalysts and improved performance electrodes. The project appears to be on track toward these goals. Carbon stability does not appear to be substantially addressed; emphasis on this area should be increased.
- If the current non-PGM catalysts are totally unstable, as shown in the literature, this team has to modify its development plan to increase the focus on stability. Somebody needs to have a task either to modify the RDE test process so it gives valid results for stability or to develop a new, valid procedure for non-PGM catalyst stability testing.
- Long-term durability of the proposed carbon-based catalysts needs to be established. Computation and modeling are not integrated with the experimental efforts. Experimental efforts from catalyst activity improvement to active site identification can all benefit from appropriate modeling work.
- High-throughput methods are unlikely to be productive for these complex non-Pt catalyst systems. Testing should concentrate on single fuel cells and get away from RDE or flow cells as rapidly as possible.

Project strengths:

- The project has an excellent team and is already producing interesting results. The proposed approaches for understanding the active site and degradation mechanism are greatly needed for these materials. If successful, the consortium would enable technology that drastically reduces fuel cell cost at commercial scales.
- LANL experience with non-Pt cathode catalysts should serve to keep the rest of the project within realistic bounds. Consortium characterization skills could elucidate how non-Pt catalysts work and how they degrade, determine the number and location of active sites, and determine why they stop working. The Fuel Cell Consortium for Performance and Durability (FC-PAD) experience should be available for guidance on how to make thicker electrode layers with good performance.
- Most aspects of this project are thoughtfully planned, and the expertise and activities of the member laboratories are nicely interwoven. This project has the opportunity to address urgent scientific questions, including the exact nature of active sites in functionalized carbon cathodes.
- The project has a very strong technical team. Very good improvements in activity and hydrogen–air performance have been demonstrated. High throughput/combinatorial development will be very useful toward accelerating development if/when validated.
- The team provided data for MEAs. The project needs to conduct many more experiments in MEAs and address the ionomer glomeration after testing.

Project weaknesses:

- More emphasis should be placed on getting thick electrodes to work in air at high current density. More realism needs to be applied to the high-throughput effort. It is tough for any electrocatalyst, but very tough for non-Pt catalysts. It seems very strange to have a consortium entitled simply "ElectroCat" and have it

restricted to non-PGM catalysts because for the foreseeable future, practical PEMFC catalysts are likely to contain low levels of PGMs, and much work still needs to be done on PGM catalysts. More effort should be placed on methods of measuring the density of active sites in non-PGM catalysts.
- The consortium should place more emphasis on understanding degradation mechanisms for various possible active sites. Developing a highly active PGM-free catalyst will not be impactful if it is later found to be inherently unstable. Further, some justification for why only a completely PGM-free catalyst is necessary would be beneficial (versus the consortium considering a minimal Pt loading that could still meet long-term cost targets).
- Computation and theory could play a bigger role, but they are not. Catalyst development for ORR and hydrogen oxidation reaction in alkaline metal fuel cells seems to overlap with other projects funded by the Fuel Cells sub-program.
- The project has a small-area MEA. The project uses the anode with 0.3 mg/cm^2 pt. The compression must be applied, otherwise delamination will occur during the accelerated stress test. The project lacks an understanding of the stability of the catalyst clusters.
- The project's weakness is insufficient effort toward carbon durability.

Recommendations for additions/deletions to project scope:

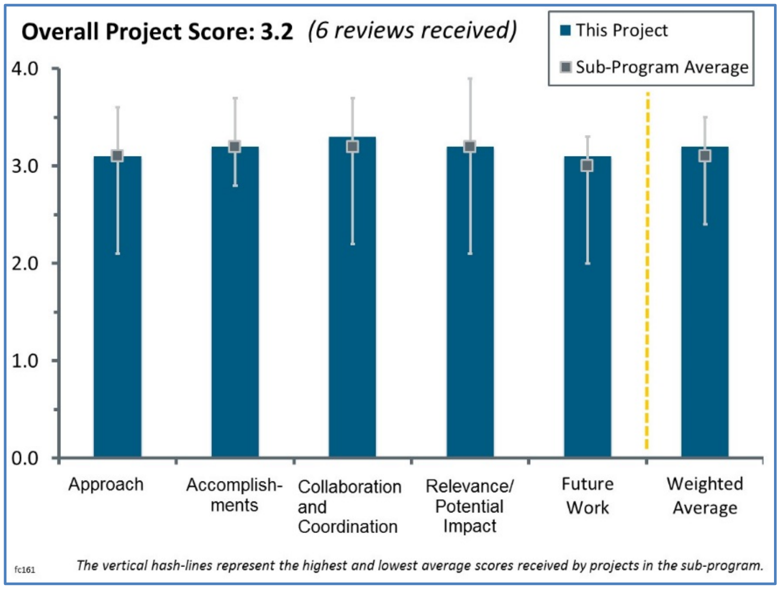
- The team should redirect a high-throughput effort to a more careful synthesis and fuel cell testing of single samples. Non-Pt catalysts are too complex for shortcut methods to be useful, and compositional variations are less important than details of processing. Non-Pt catalyst precursors are cheap (compared to Pt). Therefore, even initial synthetic work should be done at a scale giving at least 5 g of catalyst to allow testing in fuel cells, as RDE is particularly unreliable for non-Pt catalysts. Scale-up of non-Pt catalysts is also unusually difficult, so one should start as soon as possible with the manufacturability processes. Particular attention must be paid to giving powder surfaces adequate exposure to gases during heat treatments. The team should concentrate more on making thick electrodes work and less on another round of attempts to increase the density of active sites. The team should work harder to develop methods to quantify the number of active sites present in a given catalyst. It is unclear whether an appropriate adsorbate molecule can be found to use to titrate the number of active sites. The team should deemphasize efforts to replace iron, as iron loss does not appear to be the mechanism whereby non-Pt catalysts lose activity (active iron stays in the catalyst and does not hurt the membrane). The project should continue present efforts to remove non-active Fe from the catalyst precursors before MEAs are made.
- In next year's presentation, it would be beneficial to show an explanation for why only a completely PGM-free catalyst is being pursued, a greater emphasis on the degradation mechanisms in the most active catalysts, a high-level Gantt chart for the project, and results from probe molecule studies being conducted.
- The project should strongly accelerate assessment of carbon durability evaluation and, if needed, development of PGM-free catalysts based on more intrinsically stable materials.
- The project should deposit material on the carbon support in order to have a mechanical robustness.

Project #FC-161: Advanced Electrocatalysts through Crystallographic Enhancement

Jacob Spendelow; Los Alamos National Laboratory

Brief Summary of Project:

Los Alamos National Laboratory (LANL) seeks to design active and durable oxygen reduction reaction (ORR) catalysts based on fully ordered intermetallic alloys on highly graphitized nitrogen-doped carbon supports and demonstrate them in high-performance membrane electrode assemblies (MEAs). Synthetic work is guided by computational ORR kinetic studies, and each round of synthetic development is further guided by feedback from MEA testing and characterization studies.



Question 1: Approach to performing the work

This project was rated **3.1** for its approach.

- The project approach is multifaceted and well designed. Use of highly/fully ordered alloys to enable higher activity and electrocatalyst stability is a reasonably sound approach. The project is also addressing electrocatalyst support durability, another key barrier.
- The approach is appropriate: studying improvements of Pt alloys with Fe, Co, Ni, frequently studied catalysts, involving ordering of these alloys, ordering cores, and forming intermetallic compounds. It opens up the possibility to increase catalyst stability and activity. In particular, stability of the catalyst can be improved, given a better stability of ordered structures and intermetallics compared to alloys. The use of N-doped carbon supports is likely to provide additional improvements of durability and particle dispersion.
- This is a valid approach to addressing the major barrier of catalyst cost and durability. The approach would be enhanced if it was evident that the team has some good concepts to overcome the challenge of making fully ordered alloys without making unacceptably large particles (i.e., more than simply lowering the temperature).
- The approach is well thought out and communicated effectively. The principal investigator (PI) was very clear that the Pt/Fe system serves as a stepping stone to a more realistic alloy that exploits the properties observed in the Pt/Fe system.
- The faceted nanoparticle approach is not new. However, using the face-centered tetragonal (fct) structures may lead to higher activity and stability.
- The LANL-led team attempts to reconcile whether well-ordered nanoparticle alloys can indeed affect catalyst activity.
  - The goals of the project are reasonable, as they follow those crafted by the U.S. Department of Energy (DOE).
  - The approach stems from improving the activity of Pt/C by alloying. There is something wrong with the rotating disk electrode (RDE) results reported by Brown (slide 6), which serves as the unfortunate motivation for the work. The Pt/C standard is clearly low—none of the materials have the expected limiting current of -6 A/cm^2 at 1600 rpm (in fact, they have different limiting currents, most likely due to contamination). The results on slide 15 show an ineffective catalyst, if it is indeed measured at 1600 rpm—and a loading of 5–20 µg Pt/cm^2 should be used rather than 60 µg Pt/cm^2.

- The reporting of these results is quite surprising, as there are now numerous tutorials on how to measure the activity of Pt/C catalysts. Garsany et al. have published a tutorial and then reported the results from a round robin for RDE with the University of Hawaii in 2014 (*Journal of The Electrochemical Society*, 161 [5] F628-F640 [2014]). In this paper, the "benchmark" for Pt/C was moved from around 0.2 A/mg Pt at 0.9 V and 1600 rpm in 0.1 M $HClO_4$ to 0.4 A/mg Pt. The Japan Automobile Research Institute has also worked on benchmarking papers for Pt/C by RDE. If a laboratory cannot carry out careful measurements on Pt/C and repeat literature results, the results from their other electrocatalysts are also suspect.
- Reporting on mass activities of electrocatalysts in MEAs is likely to be another huge problem, and no clear benchmarks exist in this regime (other than the 2005 Gasteiger paper). Key issues are catalyst and ionomer dispersion in the ink method of making the catalyst-coated membrane, the gas diffusion media, and the cell compression, plus the usual parameters of relative humidity and backpressure. None of this key information is reported in the presentation, although it will have a large bearing on the electrochemical results.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.2** for its accomplishments and progress.

- The results obtained in the first year of this project are quite good. Improved stability of ordered intermetallics was verified. N-doped carbon supports also indicate improved durability. All catalyst characterizations using several techniques were performed with high skill.
- Accomplishments are reasonable, considering the short time that the project has been active. There was a very surprising result of increasing mass activity of fct-CoPt after 50,000 cycles at 60°C, a substantial loss of Co. While the compositional stability is not a target, the resultant activity gain is intriguing and should be assessed.
- The initial ORR intermediate adsorption strengths show compelling justification for this approach. Initial MEA cycling data show the potential for the desired catalyst stability. This is a good start for a project that is only a few quarters old.
- The project has been active for only a few months and has already shown some new catalysts and some H_2 –air performance.
- There were great initial results.
- It is difficult to fairly compare the results because of the issues with the electrochemical evaluation of the materials.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.3** for its collaboration and coordination.

- This project has excellent collaboration. Collaborators are well-selected experts in the collaboration subject. Coordination of the activities has been carried out very well.
- Collaboration team members provide most or all necessary capabilities to carry out the project work.
- The team appears to be the right mix of expertise in both theoretical and experimental capabilities.
- LANL has put together a strong team involving a wide range of skillsets.
- There are a lot of team members, including some no-cost participants, and all seem to be engaged. However, it is not clear what the University of Pennsylvania will really contribute here.
- LANL should provide more leadership in training its university affiliates in proper electrochemical methodology and reach out to other DOE laboratories for guidance if necessary.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.2** for its relevance/potential impact.

- The project directly addresses the DOE targets for catalysts. The results, confirming the usefulness of ordered nanoparticles and of intermetallic compounds as catalysts or cores, as well as the illustration of the effects of nitriding carbon supports, will have an impact on future work and the progress of the Hydrogen and Fuel Cells Program.
- The project is directly relevant to key DOE barriers of cost, performance, and durability. Inclusion of integration of the catalyst onto supports with increased durability is necessary to achieve project targets, and it appears that the project is emphasizing this appropriately.
- This project is certainly focused on key barriers. It is probably unlikely to result in a step change in performance improvement, but it could potentially result in substantially improved Pt alloy stability, which is definitely needed.
- This work has the potential to achieve the mass activity and durability targets and further advance the state of the art in low-loading catalysts.
- The potential impact is very good if the team is able to develop catalysts that are <5 nm and have good stability. Initial results of high stability are based on larger particles, hence the true impact cannot be estimated.
- The project could have impact if the researchers took a critical look at the thesis that an ordered nanocrystal is indeed more stable and active, but it is not clear why it should be, as the materials will reach equilibrium while under use and presumably go to a disordered state. The researchers should make sure that they challenge their assumptions carefully.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- The proposed future work is planned to complete some initially promising results, complete syntheses, scale up syntheses, and perform MEA tests, all of which is likely to lead to successfully addressing catalyst barriers.
- The proposed future work is generally appropriate. Per slide 20, it is unclear why the team will move away from fct-intermetallics if the DOE mass activity target is not met in MEAs. One year may not be sufficient time for development of new catalysts with high MEA activity. Few catalysts that yield high activity in RDE actually yield high MEA mass activity.
- Proposed future work is clearly laid out and follows a thoughtful plan. Work seems to rely heavily on the ability to substitute Co or Ni in place of the iron. If these metals do not exhibit the same activity or stability, then there may not be very much room to pursue this approach.
- The proposed future work is sound; however, there is no metric on catalyst particle size and MEA-level performance to show <0.125 g Pt/kW.
- This looks to be a good plan.
- The researchers need to rigorously characterize their electrocatalysts with RDE, once they have proven that they can meet the new standard results for Pt/C RDE. LANL should also carefully benchmark their Pt/C MEAs and provide leadership by fully discussing the parameters used in measurements. Without such careful work, the observations made on their well-alloyed electrocatalysts cannot be proven.

Project strengths:

- This team has identified an effect in Pt/Fe systems that has the potential to be exploited in other Pt metal alloys. The project has a good balance of theoretic and experimental approaches. In-cell testing and out-of-cell characterization methods are designed to understand the key variables and aid in the design of these catalysts. Collaborations seem to be well suited for the objectives of this project.

- The project takes a look at some well-loved theories in the U.S. fuel cell community regarding materials with improved d-band structures and well-ordered materials.
- This project has strong fundamentals with durable, high-activity electrocatalysts and integration with improved durability supports.
- There is a strong research team from LANL. Expert collaborators from national laboratories, universities, and industrial laboratories are project strengths.
- This project addresses major barriers. The approach is to maximize the full potential of platinum group metals (PGMs). There is a good potential risk–reward ratio with an excellent team.
- This is a good team and a sound project concept.

Project weaknesses:

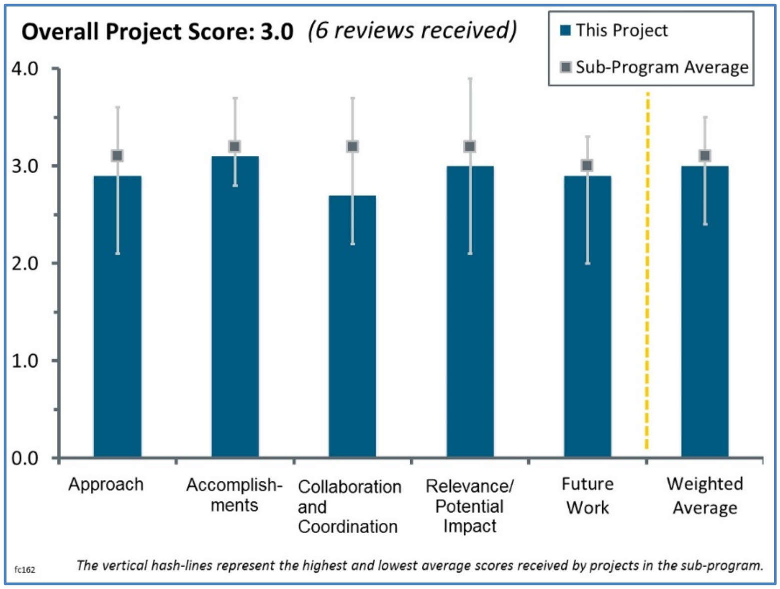
- The project appears to have limited options for substituting Fe in the Pt/Fe crystal structure. The balance between activity and durability, as it relates to particle size, may be technically challenging. This challenge was readily stipulated by the PI. Preliminary results show the potential for good stability after cycling in the Pt/Fe system; however, the last points show a large decline. It is unclear whether this is a reproducible effect or experimental error. Nonetheless, the stability as compared to a baseline will need to show regular progress as the project proceeds.
- The timeline to achieve 0.44 A/mg in an MEA within one year is likely too aggressive. It is unclear whether the reasonably high specific surface areas can be achieved. The achievement of high-MEA-rated power near the target PGM may not be feasible.
- Focusing exclusively on Fe, Co, Ni alloying components, even as intermetallic compounds, can dissolve and degrade catalysts' performance after extensive use. This may be a weakness of the project.
- The project is not on track to prove or disprove any electrocatalyst theories because of poor electrochemical methodology.
- It is unclear how the process can be controlled to a small and uniformly sized particle.

Recommendations for additions/deletions to project scope:

- Exploring surface segregation of intermetallics, dissolution of non-noble metal components at long time use, and the Kirkendall effect would address these important aspects of catalyst durability.
- A go/no-go decision should be added for delivering a catalyst that shows both improved activity and stability with particle size $\leq$4 nm.
- In future AMR presentations, it should be made clear what all of the team members are doing (including the University of Pennsylvania), especially the various team members doing catalysts synthesis (i.e., the presentation should explain what each of them does that is unique).
- The project has just started and appears to be off to a good start.
- LANL needs to straighten out its RDE and MEA methods and then start over. The researchers should also take a critical eye to the thesis of this project because having well-ordered nanocrystals in electrochemical cells under cycling loads seems unfeasible in the long term.

Project #FC-162: Vapor Deposition Process for Engineering of Dispersed Polymer Electrolyte Membrane Fuel Cell Oxygen Reduction Reaction Pt/NbOx/C Catalysts

Jim Waldecker; Ford Motor Company



Brief Summary of Project:

The objective of this project is to develop, integrate, and validate a new cathode catalyst material by developing and optimizing a vacuum powder coating physical vapor deposition (PVD) process. Project tasks include (1) development of a new cathode catalyst powder made of titanium, niobium oxide, and carbon; (2) improvement of the PVD process for the manufacture of the catalyst powder; (3) cost-effective scale-up of the PVD process; and (4) integration of the developed cathode catalyst powder into established fuel cell manufacturing processes.

Question 1: Approach to performing the work

This project was rated **2.9** for its approach.

- The PVD process as described in this project is an interesting process of making a Pt-supported oxygen reduction catalyst. Sputtering assisted vacuum deposition of dry catalysts has been practiced by 3M in its nanostructured thin film (NSTF) catalyst layer fabrication process. Unlike NSTF, which is a multiple-layer deposition process, the present approach is a single-layer deposition process that is expected to be faster. The advantages of a dry PVD process, as described in slide 5, are true. However, the catalyst will be subjected to a solvent-based ink-making process in which most of the solvent-related issues, such as incorporation of contaminants into the electrode layer, will take place. It is not going to have the advantages of the NSTF process, which directly forms the catalyst layer. From some of the early data that the team has presented, it seems that the approach is feasible. The goal of the project is to address the mass transport issue, an area in which Ford has good experience, as explained in the wire-wound bar method in slide 9. It will be interesting to see how the PVD-mediated catalyst gives similar results.
- The project's approach involves using PVD to form Pt/C electrocatalyst particles with niobia stabilizers. The approach is feasible and addresses U.S. Department of Energy (DOE) targets. The project involves a number of university and industry partners that are well placed to ensure success.
- In regard to cost and performance, the inclusion of niobia appears to allow better Pt dispersion and enables lower loadings of Pt without compromising cathode performance. Large-scale PVD on powder is a worthy goal and a promising production method that appears to be within reach. In regard to durability, insufficient information was provided. Establishing the stability of Pt/NbOx/C should have the highest priority.
- This project will develop a Pt/NbOx/C catalyst using a PVD process to overcome the catalyst activity and durability and support durability issues often faced when using conventional Pt/high-surface-area carbon (HSAC) catalysts. Proof of concept for the proposed approach is shown using square wave cycling between 0.1 and 1.05 V in rotating disc electrode (RDE) studies.
- The principal investigator (PI) presented a project on Pt on NbO_2.
  - The premise of the project is that NbO_2 is an electronic conductor and somehow adds to the activity of Pt. Such pursuits of "conductive" supports have never made sense, as an oxide conductor with a conductivity of 1 S cm^2 has electronic conductivity about four orders of magnitude lower than carbon. Additionally, for thin films and nanomaterials, electronic tunneling is likely, even through insulators. Furthermore, any oxide that contacts the acidic media in

polymer electrolyte membrane fuel cells (PEMFCs) will immediately convert to an insulating hydrous oxide. If there is one pinhole in the Pt skin, a hydrous oxide surface will break through.

- Supporting Pt on oxides and phosphates is a well-tread area, investigated by many over the last 10 years. Unfortunately, many of the publications on Pt on MOx-type compounds have not been useful because of poor RDE methodology.
- Unfortunately, the PI's team continues in this tradition of having poor RDE results. The PI quotes the project's RDE Pt/C activities at 0.2 A/cm^2—per Gasteiger's 2005 paper. Since then, Garsany et. al. (*Journal of The Electrochemical Society*, 161 (5) F628-F640 [2014]), with improved methodology, moved the benchmark from around 0.2 A/mg Pt at 0.9 V and 1600 rpm in 0.1 M $HClO_4$ to 0.4 A/mg Pt. The Japan Automobile Research Institute has also worked on benchmarking papers for Pt/C by RDE. Then DOE national laboratories (the National Renewable Energy Laboratory [NREL] and Argonne National Laboratory) teamed up to write another benchmarking paper on Pt/C this year, published in 2017 in *Electrocatalysis* ("Best Practices and Testing Protocols for Benchmarking [Oxygen Reduction Reaction (ORR)] Activities of Fuel Cell Electrocatalysts Using Rotating Disk Electrode," DOI: 10.1007/s12678-017-0378-6), and supports the Garsany work. The DOE sub-program manager (Papageorgopoulos) is a coauthor; therefore, DOE should be well aware of these results.
- Because the PI uses an outdated methodology for the Pt/C standard, their results for Pt/NbO_2 are likely skewed. The project's high-specific-activity results are also likely high because the electrochemical surface area of the Pt/NbO_2 is low, skewing the results. This should make more sense once the RDE is improved.
- The results for fuel cell testing in a membrane electrode assembly (MEA) are poor. The approach is to characterize mass transport losses in the catalyst-coated membranes (CCMs). It is more likely that the hydrophilic NbO_2 is causing water retention in the CCMs and flooding. Others (e.g., 3M) have seen this with oxides. This has also been observed on other Pt/MOx compounds. How to prevent such flooding is a huge problem and worthy of the team's full attention.
- The team needs to be realistic about their mechanisms first. The cited papers should be reviewed for accuracy before using them for reference. The PI might try making a Nb_2O_5 support for Pt and testing it to prove whether the premise of requiring an "electronic" NbO_2 support is required. It is not evident that this support is required, and Nb_2O_5 may work just fine.
- After the researchers have more convincing electrochemical results, they might consider scale-up.
- Lastly, the heating temperature of the materials may have a large impact on their performance, and this should be investigated at a small scale.

- The approach to performing the technical work is reasonable in terms of the outline suggested for synthesis and evaluation of MEA performance and durability. However, it lacks a solid foundation and baseline for the component materials and, in arguing the usefulness of Pt/NbOx/C materials, relies on literature data and baseline RDE results that are dubious because of their low values for Pt/C compared to DOE benchmark values. All RDE results presented are low and do not support the notion that the new materials will have higher ORR activity. No basic studies on components such as NbOx have been conducted to clearly and quantitatively verify that their electronic conductivity and corrosion resistance are better than conventional carbon supports used today. It is unclear what the electronic conductivity of NbOx is and by what factor its corrosion resistance is higher than conventional carbon blacks.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.1** for its accomplishments and progress.

- The project is new; it started earlier this year. Within this short period, the team has accomplished all the important elements of the project such as getting the contracts signed, generating some early results, etc. The team has conducted preliminary tasks related to the PVD coating, such as exploring the deposition conditions, sputtering system upgrades for large-batch catalyst production, small-scale PVD deposition at Oak Ridge National Laboratory (ORNL), and testing at the University of Michigan (U-M) and Ford. The team's accomplishments and progress meet the expectations at this point of the project.
- Considering the start date of the project, the accomplishments/initial results presented are impressive and encouraging, although the reason for high mass activity of Pt/NbOx/C catalysts is unknown.

- Small batch production, testing, and characterization of Pt/NbOx/C are all underway. The preliminary results are encouraging.
- The project just started; therefore, there are not too many results. Feasibility has been shown in forming conductive niobia and depositing Pt onto niobia-coated C. Further characterization should be performed to determine what the deposited Pt really is. It is unclear whether there is film formation, and it is unclear whether there is an oxide. It is also unclear whether the product is similar to a conventional Pt-supported C in terms of morphology and surface charge.
- Progress made is 0%. Therefore, it is hard to judge accomplishments. The survey of literature and preliminary RDE results presented are inconclusive and do not provide sufficient basis for optimism that the materials suggested have potential use in PEMFCs. Using RDE studies as a screening tool is not in the task list, and jumping to MEAs without any basic affirming studies is questionable. A critical review of literature studies is needed, with weaknesses in them clearly pointed out. Preliminary RDE studies need to be conducted on Pt/C to make sure they hit the DOE best practices and benchmarks reported after verification by several national laboratories.
- The RDE results all need to be improved and repeated. The researchers need to take a critical eye to the MEA results for flooding. Progress has been made on materials scale-up, but it is not clear that this is important yet.

Question 3: Collaboration and coordination with other institutions

This project was rated **2.7** for its collaboration and coordination.

- The prime (Ford) has arranged a good team of experienced scientists from reputable institutes/ organizations. As the project is very new, the team has not had much opportunity to collaborate; however, the early interactions and results show that the team has good coordination between the members. Work has already started at ORNL, U-M, and Exothermics and has generated some early results (which manifests a good coordination between the stakeholders in the team). Organizations such as Ford, U-M, and ORNL are well versed with DOE projects, and the prime (Ford) is well experienced in running the DOE programs. Overall, the team has shown good interaction and is expected to handle the project well.
- The project has initiated excellent collaboration with two other industrial partners, one national laboratory, and two universities.
- Collaboration and coordination is reasonable for the beginning of the project. Ford should consult with and work with other national laboratories to verify the properties of their novel materials as individual components for electronic conductivity and corrosion resistance. Ford's relationship with the chemical vapor deposition (CVD) company remains mysterious but will probably open up at a later stage in the project. Ford worked on this research for three to five years before this particular project began, and one would expect better control and relationships with collaborators by now.
- A large number of partners are included in the project. The project structure and work breakdown seem appropriate to ensure interaction between lead and subs.
- Partnering with a team to scale up seems premature considering the project is a long way from making a good CCM (and this may not be a solvable problem, per 3M's NSTF oxide-based electrocatalysts, which suffered from flooding). It might help to have NREL contribute to or advise about the RDE results and MEAs.
- There is no evidence of collaboration outside the six partners in this project. Perhaps this is not a fair question since the project has just begun and it should be up to the PIs to determine whether and what additional expertise will be needed for achieving the targets.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.0** for its relevance/potential impact.

- If indeed the Pt/NbOx/C has improved specific activity, performance, and durability over Pt/C or PtCo/C, it will benefit the Hydrogen and Fuel Cells Program (the Program) significantly. If the CVD manufacturing process is successful for producing large quantities of catalysts without the complications of wet chemistry, it will also be a great advantage and benefit commercialization of PEMFCs.
- The project is relevant to the Multi-Year Research, Development, and Demonstration Plan (MYRDDP). The team's goal is to develop a PVD catalyst, which is aligned with the 2020 technical targets for electrocatalysts and MEAs for transportation. The team is also working on a cost-effective manufacturing process for making such a PVD catalyst, which is aligned with the same 2020 objectives.
- If successful, the proposed research will meet all of the 2020 DOE technical targets for electrocatalyst and catalyst support.
- The project addresses MYRDDP targets and advances Program goals.
- This project will meet DOE needs if indeed the materials are high-performance, but it is hard to tell from the present work and approach.
- The team urgently needs to establish that actual PVD-made Pt/NbOx/C powders have sufficient durability that they can significantly outperform conventional Pt/C catalysts in cost per life cycle.

Question 5: Proposed future work

This project was rated **2.9** for its proposed future work.

- Future work, the work plan, and milestones are organized toward successfully achieving DOE targets.
- The project is new, and most of the tasks are still not being attempted. The proposed future work is well described and relevant to the project. The work described in slide 19 is logical and important. The team did not discuss possible barriers and relevant mitigation strategies, nor did they provide alternative pathways.
- Since the project is in its early stage, the project proposes to perform catalyst synthesis, characterization, and fuel cell testing, which are necessary to achieve the project goals. It is not clear how the project will achieve the mass activity requirements of a cathode catalyst without using a transition metal alloying element, as shown by most of the previous low-platinum-group-metal (PGM) catalyst development projects funded by the DOE Office of Energy Efficiency & Renewable Energy.
- The future work is consistent with the proposed milestones.
- Little progress has been made at this time, so all work is future work.
- The PI's team needs to be able to characterize Pt/C accurately to the 2014 Garsany *Journal of the Electrochemical Society* work or the 2017 Kocha *Electrocatalysis* work. The researchers will not be able to eliminate the role of mass transfer resistances until they understand the role of flooding. They should also report in detail the specifics for their MEAs, including gas diffusion media and cell compression.
- The fundamental properties of NbOx—as well as those of Pt/NbOx and Pt/NbOx/C—such as electronic conductivity and corrosion resistance are missing and not scheduled to be evaluated. In the team's proposed work, no clear plans are presented on RDE screening and obtaining reasonable baseline data to compare to the results of new materials.

Project strengths:

- The approach of making a PVD-mediated Pt/NbOx/C oxygen reduction catalyst is a somewhat different approach than the traditional wet chemistry method of making catalysts. 3M's NSTF, made by the sputtering process, has demonstrated very high activity and good performance while utilizing very low PGM loadings. The PVD process as proposed in this project has an advantage over the NSTF process since the PVD process is not a layer-by-layer sputtering process. The PVD process is expected to be capable of large-scale catalyst production. The team consists of qualified investigators and organizations with experience in the proposed technology pathways. Regarding technology feasibility, the feasibility of the

PVD process on a small scale has been demonstrated by the team. Therefore, the technical challenge lies in the scale-up, not in the manifestation of the process.

- The team has a good, practical idea, which is strongly focused on producing lower-cost PEMFC catalysts and appears to be achievable within a short timeframe, producing immediate impact on the market.
- There is a potential ease of integration of produced catalyst powders. It is a new approach that could result in a new stable and active catalyst system.
- Niobium oxide is a possible new deposition method for large-volume scale-up, possible higher specific activity, and durability.
- The project should be able to determine whether Pt supported on an oxide has higher activity and durability than standard Pt or Pt alloys on carbon.
- It is too early to make a judgment about the project strengths. Nevertheless, the project has a strong collaboration with two industries, two universities, and one national laboratory.

Project weaknesses:

- In regard to MEA fabrication, the team plans to make powdered catalysts using the PVD process and make MEAs using the wet ink process. However, the solvent-in-wet-ink process can introduce the impurities that the team was trying to avoid. The use of the wet ink process can also introduce catalyst agglomeration and hence lower catalyst activity. The catalyst deposition time, as shown in slide 17 by the small-batch sputtering system at ORNL, is very high. Exothermic's large-batch sputtering system may be more efficient; however, the team needs to address the deposition time of the catalyst.
- A go/no-go decision based on the long-term stability of the Pt/NbOx/C catalysts and cost savings versus existing Pt/C catalysts should be made in Budget Period 1, not later. No fundamental science on Pt-niobia or niobia-C interaction is planned, despite the project's having university partners.
- The project does not seem to have a backup plan in case any of the components fail, e.g., alternative support materials or alternative catalysts. It would be helpful to have a risk management plan.
- The project has demonstrated weak scientific background work on the evaluation of properties of suggested new materials, poor RDE results, and inconclusive evidence that new materials will be better than Pt/C.
- The premise of the project is questionable, considering the choice of materials is based on poor RDE results.
- It is too early to judge the project weaknesses.

Recommendations for additions/deletions to project scope:

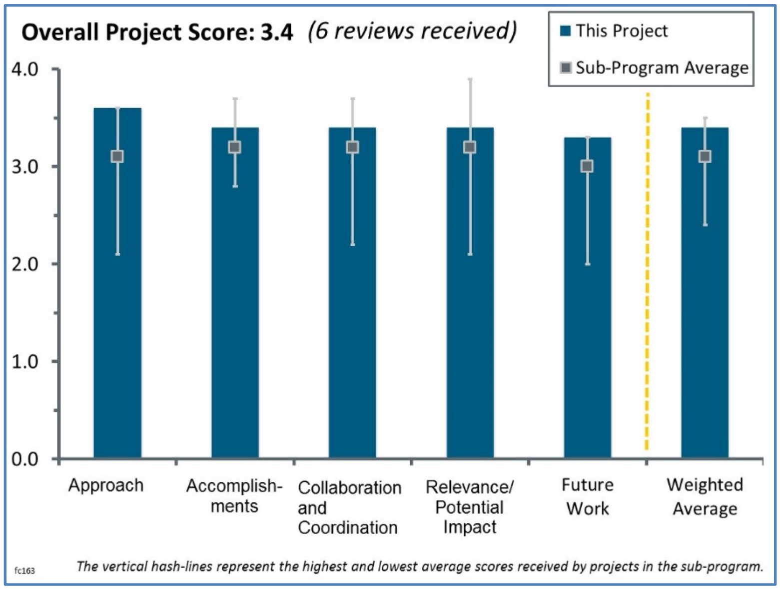
- The project should evaluate with the Brunauer, Emmet, and Teller mathematical modeling method (BET), CO chemisorption, transmission electron microscopy, and x-ray diffraction powder catalysts first, then screen using RDE (after establishing a solid baseline for Pt/C), then prepare MEAs proving that baseline performance has been established using Pt/HSAC, and finally work on catalyst layers with the new materials. If carefully conducted, RDE studies do not show that the new materials show improvement over Pt/C; there should be a go/no-go decision and no need for further studies on MEAs.
- There should be cost analysis to account for capital expenditures or operational expenditures of the sputter system at scale. There should also be greater in-depth characterization of the produced Pt structure and composition, as well as assessment of how it will influence ink integration, catalyst layer functionality, and localized mass transport resistance at high current. In other words, the project needs to determine whether this is a new particle morphology, whether the cathode layer structures are new, and whether they are more prone to mass transport issues.
- The PI's team members should straighten out their electrochemical methods to determine whether there is something special about Pt/NbO_2 (rather than Pt/Nb_2O_5). If they have promising results, perhaps then they should focus on scale-up.
- The team should add go/no-go stages, possible barriers, and mitigation strategies clearly in the project planning.

Project #FC-163: Fuel Cell Systems Analysis

Brian James; Strategic Analysis, Inc.

Brief Summary of Project:

This project seeks to estimate current and future costs (for years 2020 and 2025) of automotive, bus, and truck fuel cell systems at high manufacturing rates. Analysis projects the impact of technology improvements on system cost, identifies low-cost pathways to achieve U.S. Department of Energy (DOE) automotive fuel cell cost goals, benchmarks fuel cell systems against production vehicle power systems, and identifies fuel cell system cost drivers to help facilitate Fuel Cell Technologies Office programmatic decisions.



Question 1: Approach to performing the work

This project was rated **3.6** for its approach.

- The project did very well this year looking at higher-power density for automotive applications. Power densities near 700–800 mW/cm^2 at rated power no longer represent the state of the art. Even 1095 mW/cm^2 may be somewhat conservative. The cost decrease ($53/kW to $45/kW) was realistic to the extent that it was premised on the decreased power density. The project approach was also enhanced by assuming higher pressure and lower cathode stoichiometry at rated power. The added task to develop cost analyses for medium-duty and heavy-duty applications is consistent with the trend in the industry. As fuel cells show substantial weight advantages versus battery-only systems for these applications, cost analyses will need to be done. The analysis on metal plates went through an exhaustive number of options for forming and coating. However, given the amount of variability that could be caused by 100+ lines running, the approach must consider a constraint on the number of lines.
- The project uses a good approach to provide current and future cost of automotive, bus, and truck fuel cells at high manufacturing rates using the Design for Manufacture and Assembly (DFMA) method. The fact that the model integrates the latest technological advances, combined with the good contacts of Strategic Analysis (SA) with industry, will ensure the validity of the approach. The project aims to identify low-cost pathways to achieve DOE targets and, in general, identify fuel cell system cost drivers. Assessing the impact of technology improvement (e.g., catalysts, bipolar plates [BPPs], membrane electrode assembly, and balance of plant [BOP]) is a very valuable approach to that aim. The project will help DOE to set realistic cost targets. The approach consists of reconsidering different stack components (BPP forming, bipolar coating, and comparison of cathode catalysts) and assessing the impact on system cost. It is a valuable tool for DOE to demonstrate the impact of different technical achievements on the system cost.
- A DFMA approach is sound. The catalyst alloy selection might benefit from past phosphoric acid fuel cell (PAFC) research. PAFC stacks run at steady-state points have achieved over 80,000 hours in commercial service. Admittedly, the operating conditions are different: higher temperature, lower pressure, higher CO content, lower current density, etc. The team should also review what others have fielded. For example, United Technologies Corporation (UTC) fielded rotating component recycle designs starting in the 1990s and pulse width modulation fuel injection around 2010. US Hybrid is still active with pulse width modulated injectors.
- This project shows well-reasoned choices of topics for application of excellent cost-estimation methodologies.

- The project utilizes Toyota's information to verify the cost estimation method, which is a good approach. It is unclear how accurate and insightful the information obtained by Toyota will be. Adding fuel cell cost for heavy- and mid-duty vehicle applications is also relevant. Fuel cell system assumptions should be different from those for fuel cell systems for light-duty passenger vehicles. It is suggested that the project make the fuel cell system assumptions with original equipment manufacturers (OEMs) first.
- The ground-up DFMA approach used by the investigators is commendable. However, validation remains a consideration. For example, the Toyota Mirai analysis is presented as validation, but it is unclear what is being used as the basis for comparison for the model costs. Understandably, this will remain an issue because of OEM and supplier confidentiality. It is unclear whether the researchers can explain what actual methods they use to validate the cost numbers.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.4** for its accomplishments and progress.

- The clear flags placed this year on being able to meet DOE's cost goals for bipolar plates using SS316 are reasonable and should alter DOE's planning a bit. The project has aptly captured the significant cost benefits of the recent developments in catalysts and electrodes under DOE projects. The cost analysis of the Mirai adds an element of realism to the costing expertise and provides a useful check on costs of the current status at low volume.
- The project continues to achieve their annual work product targets. This reviewer appreciates the increased synchronization with the Argonne National Laboratory (ANL) system analysis project and the inclusion this year of a state-of-the-art, non-nanostructure-thin-film-based cathode electrode.
- Considerable progress has been made this year incorporating higher-power density with the higher-pressure and lower-cathode stoichiometry context.
    - The project has been able to deliver results with respect to many different coating options. While the number of lines remains an issue, it is good to see that metal oxide and carbon coatings have been considered.
    - Hydrogen blower calculations for the Mirai appear to contain some small mistakes. The cost per net power at 500,000 systems per year is higher than that at 100,000 systems per year.
    - The project does well to consider the Mirai example. However, there are many assumptions and technology parameters that require refinement and validation, which can be approached with further benchmarking.
- The comment on the change from stainless steel (SS) 316 to SS304 bringing a negligible change is to be expected; the nickel content is about the same, as is the usage. This is an interesting trade study.
    - If the bi-polar plate is being coated, it is unclear whether carbon steel can be used. This is an interesting trade study.
    - Gore's costs did not go down. It was unclear whether the performance increase allows savings on other components.
- The team used results data and feedback from several teams (ANL, Fuel Cell Tech Team, and General Motors [GM]) to reconsider the cathode catalyst choice.
- The project showed good progress by updating the fuel cell cost estimation with a Pt alloy catalyst.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.4** for its collaboration and coordination.

- The project makes skillful and creative use of information from a wide range of sources in order to give the most accurate cost estimates possible. Interactions with ANL, National Renewable Energy Laboratory (NREL), and the Fuel Cell Tech Team have improved the accuracy of cost predictions and have kept the status more representative of the state of the art than has been true in the past. The project now seems to be getting more complete information from fuel cell developers than has been true in the past.
- The project has good collaboration with ANL and NREL on the results of the Systems Analysis project. Data from GM for high-surface-area carbon Pt/Co has been used. In general, SA has good contacts with

partners in order to get knowledge and feedback and to apply the latest technological advances and system designs.

- SA has shown the ability to collaborate with many different technology partners for many different components.
    - The range of partnership could be expanded on catalyst-coated membrane suppliers beyond Gore. The same could be said for membranes, especially with respect to ionomer cost.
    - The project has expanded the range of supplier collaborations beyond the bounds of DOE-funded projects for metal plate forming and coating. The same level of outside collaborations should be applied for other components as well.
    - Expanding scope into medium- and heavy-duty vehicles will force collaborations with vehicle OEMs. While light-duty vehicles can be assumed to have a low degree of hybridization with battery systems, the same cannot be said for medium- and heavy-duty vehicles. Deeper collaborations will be needed to understand systems for higher-energy vehicles.
- The team's extensive list of collaborators is impressive, but collaborations may be lacking with Japanese companies, academic institutions, and national laboratories. The reviewer inquired as to whether there is any way this project can interact with similar efforts overseas (e.g., the Japan Automobile Research Institute [JARI] and the European Council for Automotive R&D [EUCAR]) to ensure the widest input possible.
- The partners listed have been involved in this work for a while. These partners are not likely to add additional insights. ANL may be of use in upgrading existing computer models. Newer collaborators might enhance thinking for outside the box, which might be helpful.
- The project has good collaboration with industry partners to obtain the materials/process information for cost estimation.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.4** for its relevance/potential impact.

- This project's relevance is high for DOE program management to present an overall status and indication of progress. The relevance is less so to developers, as they will have their own information to generate their internal assessments. However, having a publicly available project and annual report-out is of general benefit, and the reviewer would go as far as to call it necessary. The team's effort and results are appreciated.
- The project derives relevance based on how it is able to assist DOE in the department's decisions about funding opportunities and the research portfolio. The project does not directly help developers overcome barriers, although there are occasions in which component cost analyses are useful in understanding manufacturing costs for processes that do not presently exist at volume. The project helps to define new targets by exploring existing cost as well as what cost could be with technology advances. Keeping aligned with the system analysis project directions toward reduction or elimination of the humidifier, elimination of active hydrogen recirculation, and the exploration of higher-pressure operating conditions all helps to keep this project relevant.
- This project gives a very professional view of present and anticipated costs for fuel cell systems. Since cost, along with infrastructure, is now the major factor limiting the introduction of fuel cell vehicles, this project is critical to the development of the field.
- The project aims to identify low-cost pathways to achieving DOE targets and, in general, identify fuel cell system cost drivers to help DOE refine future research, development, and demonstration plans.
- The project is relevant if realistic goals and research paths are identified.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- The project properly plans to cost out fuel cell systems for a wider range of vehicle types.

  - Reduction in the uncertainty in ionomer cost is properly flagged for future study.
  - The planned further attention to Pt–alloy-catalyst synthesis costs is definitely needed, as the different experienced catalyst manufacturers differ widely in their estimates. Multiple scenarios of who owns the platinum group metal (PGM), and at what stage of the processing, should be explored, as the cost of the risk of holding a PGM inventory could make a significant difference in the estimate of the synthesis cost.
  - Planned further attention to the costs of roll-to-roll processing is sorely needed.
- The project is moving in many directions consistent with the needs of the Fuel Cells sub-program. The mainstream project continues the trend of performing side studies on alternative technologies before incorporating alternative technologies into the main cost analysis for light-duty vehicles. Analyses on medium-/heavy-duty vehicles are consistent with the industry trend because of the advantages fuel cells give these vehicles versus battery systems. Analysis on the Toyota Mirai provides a unique status benchmark.
  - The alternative technology side studies will continue to focus on hydrogen recirculation concepts still being studied in the systems analysis project, which is an appropriate direction. The project is also right to challenge its prior studies with respect to ionomer cost and to look at an alternative membrane reinforcement.
  - The project could use better definition in terms of how to approach cost analyses on medium-/ heavy-duty vehicles. Instead of assuming a fuel-cell-dominant system, it may be more interesting to take a few medium-/heavy-duty applications and plot the level of range or energy at which a fuel cell range extender becomes more cost-advantageous than a battery system.
- The reviewer agrees with the plan to perform a deeper dive on membranes and the ionomer, given the high-cost estimates reported here. It is understood that this project also supports various Hydrogen and Fuel Cells sub-programs in their cost study projects. Many projects, and even proposals, would benefit from some earlier technoeconomic studies to help guide their selection and go/no-go decisions. The project should put greater future focus on early support of fuel cell projects to help guide their direction and potential cost impact, if successful.
- In addition to the light-duty vehicle analysis, heavy- and medium-duty vehicle analysis is good, and expected outcomes are interesting.
- The proposed future work listed by the project team is as expected and in line with the results shown.
- Future work is appropriate. Room should be given to explore alternative paths.

Project strengths:

- The project uses a good approach to provide current and future costs of automotive, bus, and truck fuel cells at high manufacturing rates using the DFMA method. One strength is that the model integrated the latest technological advances, combined with the good contacts of SA with industry. The project aims to identify low-cost pathways to achieve DOE targets and, in general, identify fuel cell system cost drivers. Good contact with partners (laboratories and industry) will allow the team to gain knowledge and feedback and to apply the latest technological advances and system designs.
- The investigator has considerable experience in cost analyses over many years of DOE funding.
  - The use of DFMA enables cost analyses to be derived from knowledge of labor, energy, capital equipment, and materials inputs.
  - The project team is collaborating with ANL on system analysis to receive critical performance and BOP component inputs.
  - The project has experience collaborating with many suppliers for both stack and BOP components.
- The project has been creative and successful in gathering input data. The project uses consistent and appropriate costing methodologies. The project updates estimates as new information becomes available. The project flags the few DOE targets that are likely unrealistic. The bases of cost estimates are clearly communicated.
- The project has a strong DFMA background and strong collaborations. The project showed fast response to reviewer feedback, incorporating suggested work into future deliverables.
- Project strengths include a database of accumulated fuel cell materials/process information and the team's cost estimation. The team networks to obtain information from industry.

- The project has detailed cost accounting.

Project weaknesses:

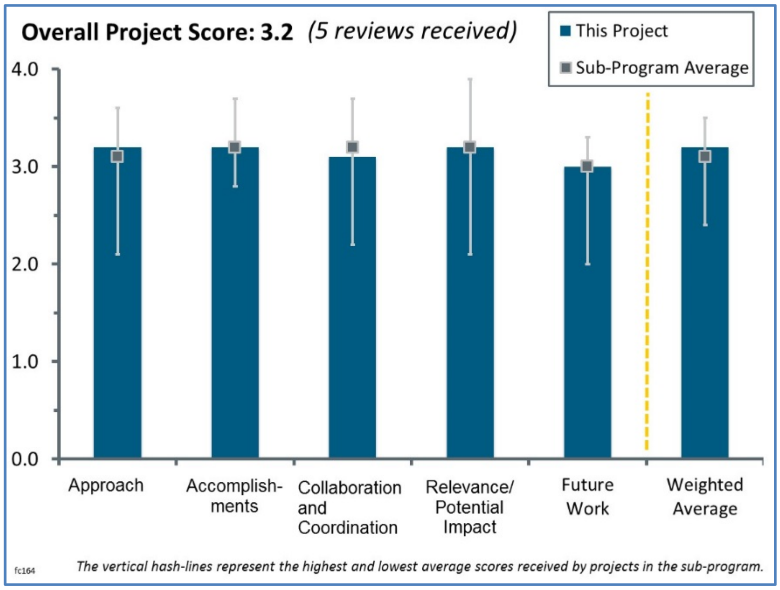
- The project has had difficulty over the years estimating ionomer costs. Project analysis of BPP cost usually can be found to have some unrealistic assumptions buried deep within the analysis. This year, the number of production lines is what appears to be unrealistic. The project sometimes limits itself to what is known through DOE-funded projects. The investigator should more aggressively seek out technology alternatives that are not already related to the Fuel Cells sub-program.
- Not all of the information necessary to accurately estimate costs is released by suppliers and developers, so the project is dependent on the (considerable) skill and (so far, apparently good) judgment of the investigators.
- Validation is always a question mark, but that is the nature of the beast.
- The project lacks validation of the developed model.
- The team needs more “new eyes” to explore less obvious options.

Recommendations for additions/deletions to project scope:

- More attention should be given to what constitutes a reasonable profit for each stage of manufacture. For example, some roll-to-roll processors are used to working with relatively inexpensive materials and expect a high percentage value added for their efforts. Since fuel cell materials are rather expensive, a lower percentage value added is needed, despite the additional costs of handling inventory of such expensive materials as PGMs. Some preliminary costing of non-Pt catalysts at scale might be useful, including such steps as precursor synthesis, pyrolysis, and treatment with hazardous gases (e.g., ammonia and high-energy ball-milling). While processing costs could be high, they likely would still be small versus the material costs of Pt-based catalysts, but this should be checked. Scale-up of non-Pt systems has proven particularly difficult (largely a matter of getting adequate exposure of a powder to gas during heat treatment). Some attention should be given to the costs of recycling PGMs during catalyst synthesis. This could be an unusually large factor in the costs of alternative synthesis techniques, such as physical vapor deposition and atomic-layer deposition. For example, in physical vapor deposition, one would need to recover Pt from non-noble-metal shields that catch Pt overspray.
- It would be good to see the Mirai compared to the SA baseline at 500,000 systems/year. If the study finds that higher ionomer cost is realistic, the higher ionomer cost could lead to a drive for thin membranes, which would compromise drive-cycle efficiency. The project should seek to leverage resources from ANL systems analysis to estimate the impact of lower-cost design choices on drive-cycle efficiency. The project could be used to estimate the “cost” of improved fuel economy. The project should expand its efforts on stack conditioning to determine the additional conditioning costs for catalyst systems (e.g., nanostructured thin films), which would require long conditioning time.
- The team should utilize Toyota’s information to verify that the cost estimation method is a good approach. It is suggested that the team talk with DOE to obtain accurate and insightful Toyota information. Adding fuel cell cost for heavy- and mid-duty vehicle applications is also relevant. Fuel cell system assumptions should be different from those for the fuel cell systems for light-duty passenger vehicles. It is suggested that the fuel cell system assumptions be made with OEMs first.
- It would be good to see an increased focus on supporting DOE fuel cell projects at the earliest stages to ensure that the individual project’s targets and approach, if successful, will result in marked progress on cost (where applicable). Specifically, there should be greater priority on performing cost analysis of DOE projects (even at the proposal stage, if at all feasible).
- The team should reach out to non-fuel-cell researchers for different views and suggestions. For materials, recommendations include organizations such as the American Petroleum Institute, ASME, and the National Association of Corrosion Engineers. For coatings, recommendations include organizations such as Sherwin Williams, 3M, Dow, and DuPont.

Project #FC-164: Development of Corrosion-Resistant Carbon Support for Ultra-Low-Platinum-Group-Metal Catalysts (Small Business Innovation Research Phase I)

Prabhu Ganesan; Greenway Energy, LLC



Brief Summary of Project:

This project seeks to demonstrate corrosion-resistant carbon (CRC) support stability in the presence of platinum or platinum-alloy nanoparticles under 1.0–1.5 V potential cycling condition to meet the DOE technical targets for catalyst support. The project will optimize CRC support physical properties, enhance catalyst–support interaction, synthesize platinum/CRC and platinum-alloy/CRC catalysts, and evaluate catalyst activity, support stability, and high-current-density performance.

Question 1: Approach to performing the work

This project was rated **3.2** for its approach.

- This project uses surface modification of a preexisting carbon to facilitate deposition of Pt with good dispersion. Next, the chemical modifications are largely removed by an annealing step prior to fabrication of the electrode layer. This is a rational approach to making good electrodes from base carbons that are intrinsically corrosion-resistant but, in unmodified form, do not allow proper dispersion of Pt. One can expect incremental improvements of catalyst durability under conditions of incomplete mitigation of start–stop and fuel starvation effects.
- The approach to utilize a functionalized corrosion-resistant carbon support is logical and feasible. The functionalization should increase Pt–support interactions and aid Pt dispersion. The approach addresses Fuel Cell Technologies Office (FCTO) barriers and uses appropriate milestones to guide the work. The work is integrated with other work and appears to build on previous work at the University of South Carolina.
- Carbon corrosion is an important issue that must be addressed. The project's approach supports identification of carbon supports. The company is focused on ease of tailoring surface area, porosity, pore-size distribution, and hydrophilic/hydrophobic properties. To address corrosion, the project will conduct optimization of metal–support interaction through surface functionalization. Johnson Matthey (JM) will do a stable Pt deposition with uniform particle distribution (3–6 nm).
- The project approach involves surface modification of commercial carbon supports to improve their platinum dispersion properties. The team did not indicate the type of commercial carbon used, but it appears to have a high degree of graphitization. Improving Pt dispersion on graphitized carbons is a good approach to developing better catalysts.
- The project's general approach is very straightforward and feasible. The description of the approach lacks detail, but this is not uncommon for industrial project teams. The performance metrics are outlined, but the specific steps to meeting those metrics are somewhat unclear.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.2** for its accomplishments and progress.

- X-ray photoelectron spectroscopy (XPS) results show the existence of surface oxygen functionalities. However, XPS of the precursor support should have been shown as well. Some of these surface oxygen species were probably already present in the precursor. The rotating disc electrode (RDE) durability study with cycling between 1 V and 1.6 V showed that most electrochemical surface area (ECSA) was retained, but the comparison vs. the Tanaka Kikinzoku Group (TKK) Pt/C apparently used an inherently unstable carbon. Many commercial carbons could pass this test with ECSA similar to or better than the GreenWay carbon. The membrane electrode assembly (MEA) results are actually much more impressive. The loss of only 23 mV at 1.5 A/cm^2 is a good result, and the overall MEA performance looks pretty good as well, assuming that the pressure given is absolute and not gauge. For future work, the team should use 150 kPa absolute since this is the specified pressure in DOE targets. The team should also show raw voltages and report high-frequency resistance, rather than iR-free voltages.
- The platinized supports have demonstrated good stability in support stability potential cycling tests in both RDE and MEAs. The data shown indicates the team can increase the micro porosity and surface area using surface modifications and increase Pt dispersion using surface functionalization.
- The project accomplishments to this point are impressive. The team has achieved good scale-up, catalyst-coated material shows significant improvement in durability, and MEA activity is promising.
- This project has started very recently and has made limited but satisfactory progress toward scale-up of the carbon production. The project will need 100 g batches for adequate testing in fuel cells. Preliminary durability testing on rotating disk and small MEAs has provided encouraging results, though comparing to standard Pt/high-surface-area carbon (HSC) cycling to 1.5 V or 1.6 V is like shooting fish in a barrel. Comparisons should also be drawn to the durability of unmodified graphitized carbons. As a durability project, this work should get past RDE studies to MEA studies as soon as possible.
- The presentation highlights include the following:
    - There was a fivefold increase in batch size (400 mg to 2.0 g). This is still a low amount for any industrial processes. The cost and volume that can be manufactured by this technology should be looked into.
    - Highly reproducible (yield, pore size, pore volume, and surface area) multiple 2 g batches are made.
    - The optimization of 5 g and 10 g batches is in progress.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.1** for its collaboration and coordination.

- Getting 100 g of the carbon to catalyst manufacturer JM should lead to a high-quality evaluation of the potential of the carbon supports generated under this project. It is of some concern that Savannah River National Laboratory (SRNL) reportedly saw little degradation of TKK Pt/HSC when cycled in RDE up to 1.5 V, leading to a change in upper potential limit to 1.6 V. One would expect rapid degradation of that baseline material when cycled to 1.5 V if the testing was working properly.
- The collaboration with JM and SRNL appears to complement the capabilities of GreenWay.
- The project's collaborations appear to be working well. Catalyst supports have already been scaled up to multigram quantity. The integration of JM into the project will be a big step forward.
- The project team makes good use of national laboratory and industrial partners and their resources.
- There is in-kind collaboration with JM.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.2** for its relevance/potential impact.

- Operational durability of polymer electrolyte membrane fuel cells is strongly related to the stability of the carbon support. Fuel cell development to this point has been optimized for carbon-supported materials. Integration of any other type of electrocatalyst has been proven to be difficult. Therefore, it would be optimal if a durable carbon support could be developed. In this regard, the current work strongly supports the goals of FCTO.
- Developing catalysts with improved performance and durability is arguably the most relevant thing a project can do. This project could be helpful in developing catalysts that can meet both activity and support durability targets.
- Improved catalyst supports can have a large impact on performance and durability. Recent improvements in high-current-density performance have been attributed to having the right pore size, volume, and distribution of Pt within the pores. Therefore, being able to adjust pore size and volume with the modifications proposed here could prove very beneficial.
- This project, if successful, could allow the use of carbon supports more resistant to degradation due to incompletely mitigated start–stop or fuel starvation effects. It is unlikely that any carbon could withstand completely unmitigated start–stop, and it is quite possible that even quite corrodible carbons can withstand operationally fully mitigated start–stop or fuel starvation.
- The project offers an important topic. However, the scale-up of carbon manufacturing is not there. Currently, the project team is focused on process optimization for 5 g and 10 g batch sizes.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The proposed future work addresses the appropriate issues of scale-up and MEA testing and, critically, brings in JM to do MEA testing and optimization. Future work should also look at the impact of pore size and porosity on high-power performance.
- The planned future work constitutes a logical progression of activities to properly evaluate the potential of the innovative modified carbons. Not enough activity, durability, and performance testing will have been completed under Phase I to allow the level of promise of these carbons to be determined. There should be as much MEA testing of durability and performance as possible brought forward in time to see whether further investment in a Phase II project would be justified.
- The proposed future work includes further scale-up, use of Pt-alloy catalysts, and work with industrial partner JM. The project's future work should also include a more fundamental analysis of the mechanism by which stability is enhanced. It is unclear whether the particles are located on the surface or in the interior of the porous carbons. Interior-located catalyst particles could help to limit particle agglomeration but could also result in transport losses.
- The project's future work is appropriate but should include running the DOE start-up/shutdown protocol on the most promising catalysts. While the support accelerated stress test is useful for screening, it does not fully replace actual start-up/shutdown testing.
- The presentation's future work bullets include:
    - Synthesis and performance evaluation of Pt-alloy/CRC catalysts
    - Evaluation of initial mass activities of PtCo/CRC catalyst in rotating ring-disk electrodes (RRDEs) and fuel cell MEAs
    - Support stability studies under accelerated stress test conditions in RRDE (1.0–1.6 V) and MEAs (1.0–1.5 V)
    - Support preparation for industrial partner
    - Agreed to send 100 g CRC support: 25 g support is ready for shipment; 75 g CRC support to be prepared and shipped to JM for Pt and Pt-alloy catalyst synthesis

Project strengths:

- The project has provided dramatic improvements in catalyst stability and the systematic development of all aspects of the formation and scale-up of catalyst-loaded carbon materials. Project collaboration with JM is a good test for the viability of their carbon materials.
- The project's approach is well-thought-out, and the progress so far is impressive.
- The project addresses an important issue, but it is not certain that this company will be able to address it alone. The team should work with companies that know how to scale up carbon production, e.g., Cabot Fuel Cells.
- The stability of the carbon supports being investigated and ability to get well-dispersed Pt on these stable supports are strengths of this project.
- The project gives a rational plan for development of incrementally more durable electrodes through modification of a preexisting carbon black, assuming that the initial carbon black does have significantly better corrosion properties than typical high-surface carbon blacks. The team's very preliminary testing shows somewhat promising results.

Project weaknesses:

- No carbon can withstand totally unmitigated start–stop, and it is not clear that a carbon of modestly improved corrosion resistance would provide significant benefits in a properly designed fuel cell system.
- The project needs to partner with a university for the evaluation of the carbon that the project produces. A larger team is necessary to make faster progress.
- Scale-up seems to be progressing slowly toward the 100 g batches needed to adequately test viability.
- The project should include more fundamental investigation into the mechanism of enhanced durability.

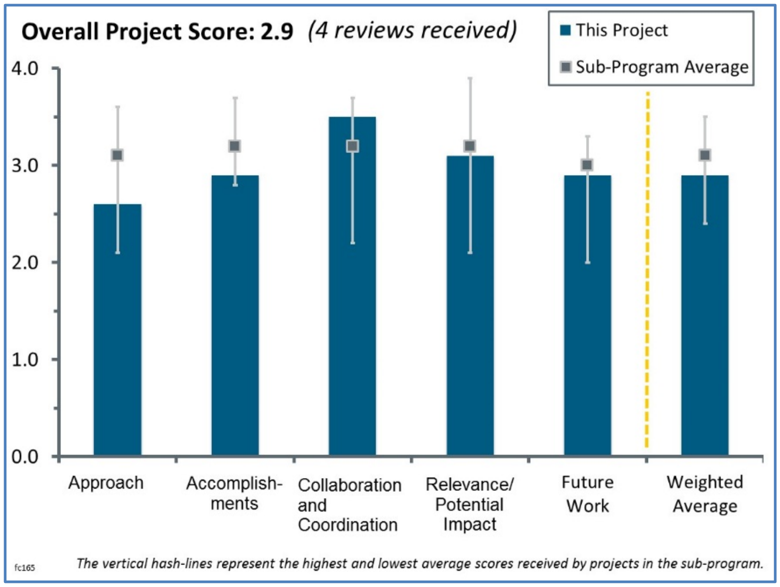
Recommendations for additions/deletions to project scope:

- RDE testing of durability is of questionable relevance to fuel cell operation. Therefore, testing should advance more quickly to MEAs. The feature catalysts should be compared to Pt on unmodified graphitized carbons as well as to Pt on high-surface carbons. The project should include clearer milestones for continuation to a Phase II project.
- The project should include a more fundamental investigation into the mechanism of enhanced durability. The team should perform mass spectrometry measurement of carbon dioxide evolution from fuel cells to quantify carbon corrosion during accelerated durability testing.
- The team should do additional work focusing on impact of the support on high-power performance, in particular, tailoring the support and support porosity to optimize high-power performance.
- The team should partner with others and demonstrate stability of the carbon.
- The project should add start-up/shutdown testing.

Project #FC-165: Mesoporous Non-Carbon Catalyst Supports of Polymer Electrolyte Membrane Fuel Cells (Small Business Innovation Research Phase I)

Jacob Coppage-Gross; Certaintech, Inc.

Brief Summary of Project:



The objective of this project is to improve the durability and cost efficiency of fuel cell performance through the development of a mesoporous platinum–metal carbide (Pt-MC) catalyst support material. Pt-MC offers improved corrosion resistance and lower platinum loading compared to traditional carbon-based catalyst supports. The project will synthesize and characterize high-surface-area Pt-MC nanocomposites, and the electrochemical performance of a membrane electrode assembly (MEA) incorporating Pt-MC will be demonstrated.

Question 1: Approach to performing the work

This project was rated **2.6** for its approach.

- MCs should provide good chemical stability, and the approach of using a sacrificial silica support to impart porosity and increase surface area is logical and feasible. An MC support could provide a corrosion-resistant support. The proposed work addresses the main problem others have had with this approach, obtaining high-surface-area MCs. It is not clear this will provide for lower Pt loadings, as there are currently mesoporous carbons available as supports and it is not clear how well Pt will disperse on these supports. The MCs and MC precursors to be investigated have not been identified, and it is unclear what the materials and processing costs for the support will be. It is unclear what process will be used to convert the precursors to carbides and how that will be done under conditions that retain the structure of the template (temperature is the main concern). There do not appear to be any milestones or targets regarding the MC support, such as a target surface area or electrical conductivity, prior to Pt deposition and testing in a rotating disk electrode (RDE).
- The project's approach is excellent. The plan is to synthesize supports, anchor Pt on them, prove stability and performance in an RDE, and then translate this to an MEA.
- The approach is somewhat novel, but the project team appears to have no idea if it will ever be economical or even if the substrates being proposed will eventually be stable. Removing the templates will require harsh chemicals (hydrofluoric acid solution [HF]), and not much is known about the cost of containing/recycling the HF. A full commercialization plan is not needed at this stage, but a primary effort is expected. The team has a long, hard path to success; the templates have to work, then the materials that the team is generating need to be shown to be stable, then those substrates have to be made catalytically active, and finally the team needs to work them into MEAs. The chances of each of these steps being successful is fairly small.
- The project's process and implementation milestones are well laid out. The project needs to increase focus on fundamental aspects of the supports, especially conductivity, but also including Brunauer–Emmett–Teller (BET) surface area measurement, pore size distribution, and porosity.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **2.9** for its accomplishments and progress.

- While the project has not been active for long, it appears to be behind schedule for completion of Phase I by November 2017. At this point, the team should have some supports made. However, no preliminary results for any supports were shown, just results showing the project has a pure precursor for the MC and results showing the team can make a mesoporous silica template. There are no results showing the project can make a mesoporous or high-surface-area MC yet.
- The accomplishments are few because the project started only at the end of February. However, this is only a nine-month Phase I project, and the authors have much to do in the remaining six months. The project is still in its first task and needs to actually make high-surface-area supports and functionalize them soon.
- The team is just beginning. The team has begun making templates and the substrates, which is appropriate.
- This project has recently started but has made progress toward first samples.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.5** for its collaboration and coordination.

- The team's working with Dr. Shimpalee is a good start, as he has much experience in MEA fabrication and characterization. Achieving mass activity loss of <40% for electrocatalyst support stability is a very large task, as catalyst activity in MEAs is a very large undertaking.
- Collaborations have been set up between the partners, and they appear to have the capabilities needed. It is early in the work, and they have not had material to test or characterize yet. Inclusion of a commercial catalyst or MEA manufacturer in Phase II would be beneficial.
- The project has excellent collaborators for electrochemical fabrication and testing.
- The project has good collaboration with two universities and one other company.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.1** for its relevance/potential impact.

- The project aligns with the Fuel Cell Technologies Office goals to improve the durability of polymer electrolyte membrane fuel cells and could decrease costs if durability is increased, allowing for lower initial Pt loadings.
- A successful project will have a significant impact by producing supports with a high-stability catalyst surface area and conductivity that can replace carbon in highly oxidizing environments.
- The project's topic is certainly relevant to DOE goals. The likelihood of success or even demonstrating feasibility in Phase I will be daunting. The team has not really given enough information about how it will stabilize the supports or why the supports are expected to be stable enough to judge.
- A novel support that can help meet DOE targets is valuable. The project needs to make sure it meets both performance and durability targets.

Question 5: Proposed future work

This project was rated **2.9** for its proposed future work.

- The project goals are quite ambitious for time and funding, but in general, the team is taking the correct approach. MEA testing should be put off until Phase II. It would be a successful Phase I if the researchers can demonstrate that they can make the substrates, they have the rheology the team is looking for, and the product is stable. Then catalyst generation and MEA fabrication could be the focus of Phase II.

- A good plan is in place for both Phase I and Phase II, but the project needs to directly measure conductivity, BET surface area measurement, etc.
- It is unclear what the Phase I target is. It is unclear what determines success (all project goals are very qualitative). The principal investigator just listed the DOE targets. There seem to be no targets associated with the Phase I and proposed Phase II of this project. There should be clearly defined mass activity, performance, and durability targets that should determine whether the project would go forward. For example, the end-of-life performance after one thousand 1 V to 1.5 V cycles should be better than an electrocatalyst-carbon-based Pt/C catalyst. This should not be too difficult to achieve and should set the stage for better balance-of-life performance in Phase II.
- The proposed future work addresses the broad areas of concern, but the plans are generic and do not address issues specific to the proposed MC-based supports.

Project strengths:

- This project has a good plan for material fabrication. This project has a good plan and collaborators for electrochemical fabrication and characterization.
- This project offers a different approach to try to obtain high-surface-area MCs to use as supports.
- This project has a good team with all relevant capabilities. This project is an interesting idea.
- This project has a proper approach, but it is difficult to gauge without knowing what the composition of the supports is.

Project weaknesses:

- The project lacks focus on important material properties of non-carbon supports: conductivity, BET surface area measurement, pore size distribution, and porosity.
- This project has many hurdles to success. There is uncertainty about whether the supports will be stable. Multiple steps will likely lead to an expensive catalyst.
- The project needs quantitative success/failure criteria for Phase I.
- There is a lack of information on MCs and precursors to be used.

Recommendations for additions/deletions to project scope:

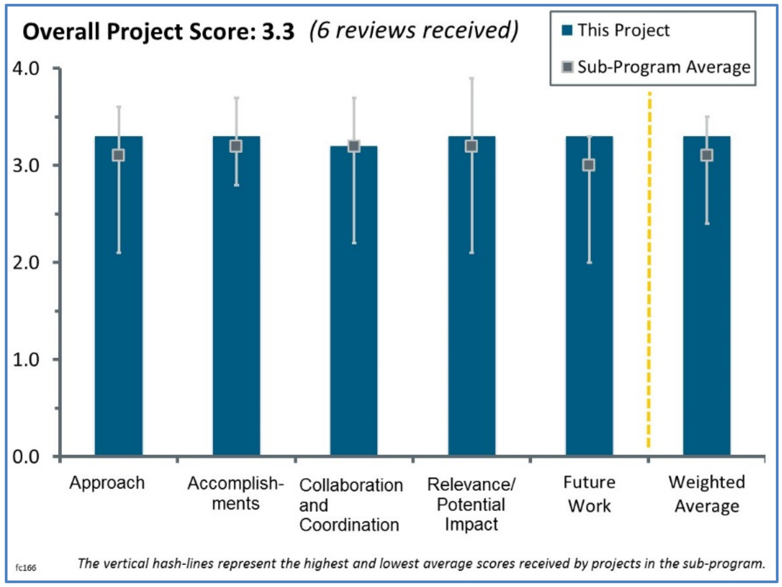
- Some milestones or targets for the MC support prior to Pt deposition and RDE testing may be useful. Minimum electrical conductivity and surface area targets for the support should be met before moving on to platinization and RDE testing.
- The project should focus just on the supports and demonstrating their stability and that they have the structure that the project is seeking in Phase I. If time permits, the team should add the catalyst to the surface, but MEA testing and fabrication should wait until Phase II.
- It is strongly recommended that the project include a detailed plan to assess MC properties.

Project #FC-166: Development of Durable Active Supports for Low-Platinum-Group-Metal Catalysts (Small Business Innovation Research Phase I)

Barr Halevi; Pajarito Powder

Brief Summary of Project:

To enhance the durability of fuel cell electrocatalysts and improve the economics of polymer electrolyte membrane fuel cells (PEMFCs), this project will further develop Pajarito Powder's durable active carbon supports (DACSs). This will be done by optimizing the DACS materials characteristics and platinum–support interactions, improving the corrosion resistance of support carbon, and increasing support–platinum activity and durability synergism. To validate DACS performance, platinum–DACSs will be deployed in membrane electrode assemblies (MEAs).



Question 1: Approach to performing the work

This project was rated **3.3** for its approach.

- The project's approach of utilizing different techniques and materials to prepare platinum-group-metal-free (PGM-free) catalysts to prepare active supports for low- Pt catalysts is feasible and addresses fuel cell barriers of cost, durability, and performance. The team has demonstrated good activity with PGM-free catalysts and also the ability to modify the morphology to improve transport and durability in these materials. In addition, N-doped carbons should provide better anchoring for Pt and improve dispersion. The Pt is likely to bond to the PGM-free active site, as the support will likely provide very little to no additional activity for the oxygen reduction reaction (ORR).
- The early application to MEAs and polarization curve testing to higher current densities at low (<=0.1 mg/cm^2) Pt loadings are appreciated. The project notes the use of iron in the support, an issue known to have negative impacts on PEMFCs. The team should either focus on removing and demonstrating retention of support activity, or demonstrate that the iron does not have a negative impact on performance over life (preferably, the former). Graphitization usually results in reduced surface area and high-current-density performance. While high surface area was mentioned, no data were shown. The project is asked to communicate the electrochemical surface area (ECSA). Tailored pore size is mentioned; it was unclear whether the project considered the findings from FC-144 in pore size impact.
- The team is trying to develop a new corrosion-resistant support for a cathode without PGMs. This is important for start–stop stability.
- This project applies the principal investigator's (PI's) previous experience in PGM-free catalyst development to low-Pt catalysts. The idea is generally good, although the justification on the support stability improvement is not clear.
- It is difficult to see how a combinational approach, non-PGM supporting PGM, is better than just one. Generally, one ends up doing all of the work. It is difficult to see that there will be a synergy between the catalysts. One might say that if the catalyst is going to be supported, why not make it an active support so it is worth pursuing.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.3** for its accomplishments and progress.

- This is very good progress for so early in the project. The early MEA fabrication and polarization curve testing to high current densities with low Pt loadings and cycling results are appreciated.
- The project has been active for only a short time but has already shown improvements in durability from ~80% loss at 0.6 V to ~40% loss at 0.6 V after a start–stop cycling test. However, losses are still much higher than for the DOE target of 30 mV loss at 1.5 A/cm^2 (data showed >150 mV losses at 1 A/m^2).
- Within a short time, the project has made excellent progress.
- It is difficult to rate this because the accomplishments that the project shows are exceptional but were clearly done outside of the project. The team has made many catalysts and tested them in MEAs with continued improved performance, yet the project has spent only $3,000. There is good improvement on the support durability. The team's assumptions behind the cost reductions with regard to Pt/C are unclear, especially through 2030.
- The project started only two months before the Annual Merit Review presentation was due. It is too early to assess the full accomplishment.
- The project has just started.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.2** for its collaboration and coordination.

- While Advent Technologies has experience in electrode development, the team may consider working with Los Alamos National Laboratory (LANL) and/or the Fuel Cell Consortium for Performance and Durability (FC-PAD) for MEA testing (and perhaps MEA development). The team could consider collaborating with Strategic Analysis to validate process costs and overall cost impact.
- The project has only Advent Technologies as a collaborator, which is not surprising for a Phase I effort. Adding Karen More at Idaho National Laboratory would be a good idea for visualizing these catalysts, especially after cycling.
- Collaboration between Advent Technologies and the PI appears to be good, and they have been collaborating successfully in other projects. Collaboration with others outside the project was not apparent.
- The project collaborates with another company for MEA and fuel cell research experience and testing capability.
- The project has just started, and it is hard to judge this aspect, but it does seem to have a good partner in Advent Technologies.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.3** for its relevance/potential impact.

- Since original equipment manufacturers (OEMs) will employ system mitigation strategies to reduce the impact of carbon-support corrosion, the relevance was rated only as "Good" instead of "High." As such, OEM focus has moved more to performance at high current densities (at low loadings) with corrosion resistance at low temperatures (relevant to startup) as a secondary priority.
- Lowering PGM loadings while improving support durability is still very relevant and necessary, and this is a viable approach.
- The project advances FCTO goals to reduce Pt loading and increase PEMFC durability. The project objectives are in line with DOE targets and goals.
- This project covers an important component of fuel cells.
- The project addresses fuel cell catalyst support durability, but tests so far were mainly on catalyst/MEA performance. Support-specific tests need to be carried out.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- The project focus on MEA development is appreciated. It would be good to see the future plan include:
    - Removal of iron
    - Testing ECSA, and a plan to increase high-surface-area carbon if less than state of the art
    - High-level cost analysis with Strategic Analysis

  The project might also consider testing at LANL, as well as collaboration with LANL/FC-PAD on electrode and MEA development.
- The project's proposed future work is appropriate and logical. The project has appropriate milestones and down-selection points.
- What the project team proposed at the presentation makes sense.
- The team's future focus should be improving support durability and switching to alloy catalysts.
- The Phase I plan is somewhat generic. There should be more specifics on support-stability-related activity.

Project strengths:

- The team and the team's experience with methods to provide porosity and high graphitic content are strengths of this project.
- The project is off to a good start. The team is very well aware of challenges and issues ahead of them and the relevant metrics and obstacles to achieve them.
- There is company-demonstrated capability to make active supports. The project team has an MEA partner for development experience.
- The project has a good team and approach.
- The project approach has a good initial start.

Project weaknesses:

- There must be some sacrifice in making a support active for the ORR, either in materials, cost, structure, or the performance of PGMs. The team will need to demonstrate that these sacrifices are worth it.
- Durability improvement on the catalyst support needs to be demonstrated to justify why the proposed doped materials should have better stability than carbon.
- The project could benefit from further collaborations on MEA development/test and cost analysis.
- The budget is modest; one hopes it is adequate.

Recommendations for additions/deletions to project scope:

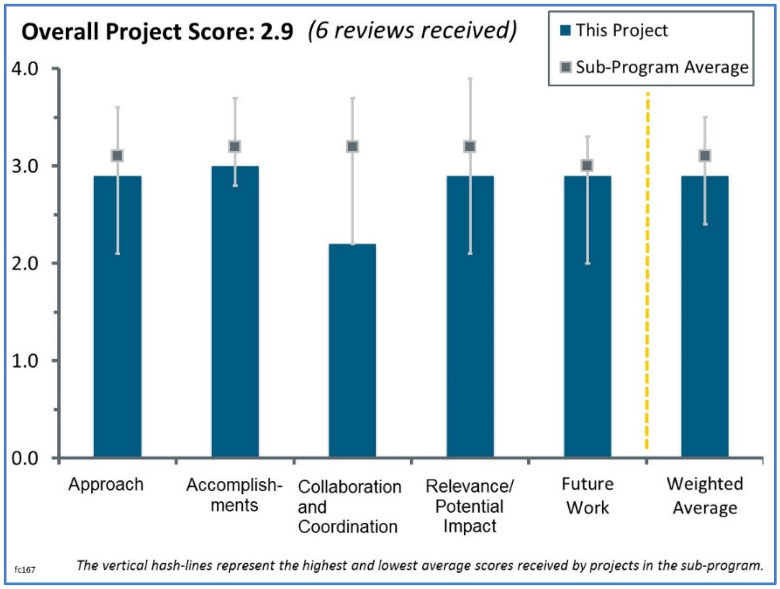
- From a stability standpoint, 3 nm particles may be a bit small, as previous work has shown slightly larger particles to be more stable toward dissolution. A study looking at the effect of Pt–support interactions on particle-size stability might be beneficial.
- There are no recommendations. The team is on the correct path to develop and demonstrate these materials. If funding increases, the project will want to partner with an OEM for large-scale fabrication and testing, but that is at least two years away.
- The project should continue focus on MEA development and testing to high current density at low Pt loadings, the removal of iron from supports, and the demonstration of high surface area.

Project #FC-167: Multi-Functional Catalyst Support (Small Business Innovation Research Phase I)

Minette Ocampo; pH Matter LLC

Brief Summary of Project:

This project seeks to develop a multifunctional carbon support engineered to perform better than conventional pure carbon supports used in polymer electrolyte membrane fuel cells (PEMFCs). The support material being developed aims to meet U.S. Department of Energy targets for durability and oxidation resistance and increase hydrophobicity to enable higher current density. Project tasks include (1) material synthesis and characterization, (2) membrane electrode assembly (MEA) fabrication and characterization, and (3) MEA testing.



Question 1: Approach to performing the work

This project was rated **2.9** for its approach.

- The approach addresses the barriers of durability and cost. The project is well defined and reasonable, and the approach is feasible and integrated with other efforts addressing platinum-group-metal-free (PGM-free) catalysts. The approach to utilize active PGM-free catalysts as supports for low-Pt electrodes is logical, and the N sites should lead to increased Pt dispersion and stronger Pt–support interactions. The support developed by pH Matter demonstrated good durability, even at the high potentials seen in electrolysis as they have been tested in reversible fuel cell mode cycling from 0.6 to 1.7 V. Therefore, the supports should have improved durability for start–stop-type cycling (which goes only to 1.5 V). It is likely the Pt will bond at the active sites for the support, poisoning those sites so the activity of the new structure is not likely to be Pt activity plus the activity of the support without Pt. However, this should lead to stronger Pt–support interactions and more stable Pt.
- This project repurposes a non-PGM carbon-based catalyst as a support for Pt particles. The non-PGM catalyst has demonstrated good stability during oxygen reduction reaction/oxygen evolution reaction (ORR/OER) potential cycling in alkaline conditions. The proposed approach is simply designed, straightforward, and feasible.
- The project's approach is related primarily to using PGM-free ORR catalyst-related materials as a support for Pt to increase Pt mass activity. This approach addresses performance and cost targets. However, it likely does not address the durability-related targets. The approach is likely using materials as a support that are less durable than traditional carbons and especially graphitized carbons.
- Starting with a doped carbon support with intrinsic activity is a good approach if it is well established. It is good that it is not iron-based. However, more detail is necessary to evaluate the approach. Tuning for hydrophobicity is stated, but it is unclear what the target is or why a particular hydrophobicity target should be chosen. It is also unclear what the approach is to determine optimum hydrophobicity (e.g., what the tests and metrics for success are).
- This project applies Pt to pH Matter's iron-free, water-selective, PGM-free catalyst support for improved catalyst stability at low platinum loading. The idea is generally good, although the scientific rationale for the support stability is not clear.

- The objective of this project is to develop a multifunctional carbon support that is engineered to perform better than conventional PEMFC pure carbon supports. It is not clear what kind of multifunctional carbon support will be developed.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.0** for its accomplishments and progress.

- This is a Small Business Innovation Research (SBIR) project that just started and had approximately one month of work prior to having to submit slides for the DOE Hydrogen and Fuel Cells Program (the Program) Annual Merit Review (AMR). It is too early to grade on accomplishments. Pt dispersion has been achieved on the pH Matter support showing good dispersion (by transmission electron microscopy [TEM]). Rotating disk electrode (RDE) results show a similar on-set potential as Pt/C but with widely varying limiting currents. It is unclear why limiting currents vary so much. These RDE measurements should be made in acidic media, if they were not. Slide 8 says 0.1 M $HClO_4$, but the slide does not indicate media. In terms of results, pH Matter demonstrated some durability in alkaline media but not yet in acidic media, which is the much larger challenge.
- The project started only two months before the AMR slides were due. Therefore, not much has been accomplished. There is some preliminary evidence that the use of the project's carbon supports results in a higher ORR activity than commercial Pt, potentially related to the dispersion of the material on the support. No results related to the durability of the materials have been presented.
- The project has been active only a short time but in this time, pH Matter has shown data indicating the researchers can get good RDE performance with Pt deposited on their active supports. The RDE data showed better performance than a commercial Pt/C, and TEM showed good Pt dispersion.
- The team has shown good dispersion and some activity with ultra-low PGM loadings, so the project has a fair start, given the very limited project duration thus far.
- Through this project, pH Matter developed a catalyst with CNxPy support that demonstrated good ORR activity with low Pt loading.
- The project started only two months before the AMR presentation was due. It is too early to assess the full accomplishment. Initial data from the previous studies look promising.

Question 3: Collaboration and coordination with other institutions

This project was rated **2.2** for its collaboration and coordination.

- There does not appear to be any collaboration at this stage in the work, though this is an early-stage SBIR. Collaboration with an MEA developer is planned in Phase II and would be helpful. Potential collaborators are not identified.
- This is a Phase I SBIR with no partners; collaboration is not expected. The researchers have shown collaboration with Giner and National Renewable Energy Laboratory (NREL) on similar materials.
- There is collaboration with Giner and NREL on another SBIR project. The collaborators on this project are not identified.
- There are no collaborations. If that is not expected in a Phase I SBIR, it is up to DOE to increase the rating or ignore it.
- There are no collaborators in this phase of the project.
- The project at Phase I does not have any collaborators.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **2.9** for its relevance/potential impact.

- While carbon corrosion at operational temperature is less of a priority now, because of original equipment manufacturers, system mitigation, high activity, high performance at high current density, and catalyst durability at temperature remain priorities, and thus the project retains relevance.
- The project supports the goals and objectives of the Program and, if successful, would have an impact on reducing Pt loading and increasing durability, thus decreasing costs.
- Stable carbon supports can significantly improve the operational durability of PEMFCs. This project has a direct impact, as it addresses one of the core metrics for PEMFCs provided by the Fuel Cell Technologies Office.
- The project addresses fuel cell catalyst performance and support durability. The team's tests so far were mainly on catalyst performance tested by RDE. Fuel cell data should be forthcoming.
- This project primarily addresses cost and performance. It is unclear what its impact will be on durability.
- It is too early to judge. More progress has to be made.

Question 5: Proposed future work

This project was rated **2.9** for its proposed future work.

- The project team proposes to address not only the impact of support structure and composition but also the catalyst deposition procedure on the durability of the catalyst material. Additionally, the team proposes to study the degradation mechanism to gain further important insight and guide the further development of the material. This last part is often neglected by other projects, yet it is critical to the development of more durable materials.
- Almost the entire project at this point in time is future work, as the project just was initiated. Initial experiments rely on RDE testing for both performance and durability (support oxidation). After RDE, gas diffusion electrodes (GDEs) will be made for MEA testing and then durability testing. RDE performance can vary widely, and many developers have substantial difficulty in obtaining similar results in MEAs. RDE testing should include ionomer in the catalyst layer. Even initial materials should be moved to GDEs for MEA testing to understand how the RDE tests correlate to real systems. "Alternative" preparation methods are to be explored. These methods should follow on only if RDE and MEA tests show that the carbon support materials have good durability. PGM-free materials based on carbon have not shown good durability to date. Varying the Pt deposition method is not going to affect the support durability; thus, the support durability should be demonstrated before exploring a sequence of Pt deposition methods.
- The proposed future work is logical and addresses the relevant barriers. Partnering with the Fuel Cell Consortium for Performance and Durability (FC-PAD) may be beneficial for electrode characterization and the breakdown of potential losses. Work tailoring structure of the support (carbon porosity and pore structure, agglomerate size, and structure) may be needed and is not apparent in the future work description.
- The focus on quickly moving to MEA fabrication and testing is appreciated. However, the project should set a higher goal than "achieves >0.8 A/cm^2." State-of-the-art catalysts now perform at >1.0 W/cm^2 (>1.5 A/cm^2 with >0.66 V), a suitable metric for comparison. High-current-density performance should be the goal and will better identify proper property tuning.
- These bullet points are all too general, and the team needs to be more specific in saying who will do what:
    - Explore alternative preparation methods for low-PGM alloy catalysts, such as electrochemical, colloidal, or ion-exchange
    - Further MEA optimization to address mass transport and cathode flooding issues
    - Electrode characterization before and after cycling to better understand degradation mechanisms
    - Partner with MEA manufacturers
- A fuel cell test needs to be carried out soon to verify the RDE data.

Project strengths:

- Use of previously developed material should help shorten development time. The team has significant expertise in catalyst and support development. Support development already shows stability in reversible alkaline fuel cells.

- The use of pH Matter's stable C-NxPy PGM-free catalysts as a support is a strength, as these catalysts have shown excellent stability and good activity for ORR.
- The team has demonstrated the ability to make non-PGM catalysts with some activity and low-loaded-PGM electrodes with reasonable dispersion.
- The project approach has a good initial start.
- The project attempts are promising with functional carbon support.

Project weaknesses:

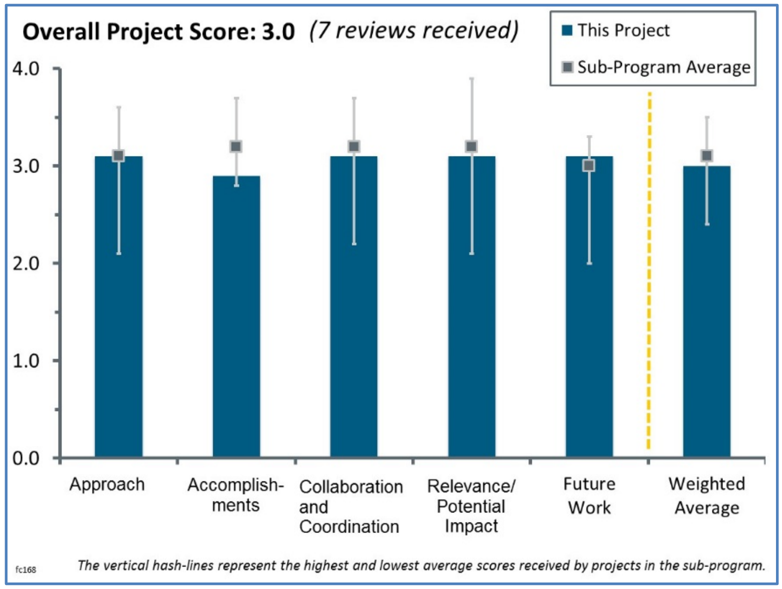
- There is a lack of evidence of proposed support stability in acid; it could be different from that observed in alkaline electrolyte. The potential for improvement in durability is obvious; however, the mechanism of improvement in activity is less obvious. It is unclear why a carbon support would make low-PGM catalysts viable. At low catalyst loadings, oxygen starvation is a big problem at high current densities, which does not appear to be addressed. It is unclear what makes metal adhesion better on the proposed support materials.
- It is unknown how ionomer in a catalyst layer will interact with these carbon-based support materials; increased hydrophobicity is not necessarily the correct optimization strategy. The authors state that the support will include better durability, but it is unclear what the basis for that is.
- It is unclear whether the team has expertise in fabricating state-of-the-art electrodes and MEAs. The project will benefit from collaboration with FC-PAD in this regard (as stated in the future work).
- The project does not appear to pay sufficient attention to the physical structure and porosity of the support, which will have a large impact on high-power performance.
- For presenting catalyst data, the principal investigator is advised to provide the numerical results such as onset and halfwave potentials for better assessment.
- MEA data needs to be presented as soon as possible.

Recommendations for additions/deletions to project scope:

- The project should focus more on high-current-density (>1.5 A/cm^2) operation under both wet and dry conditions to lead the team's catalyst down-selection.
- "Alternative" preparation methods should be explored only after demonstrating support material durability in acidic media.
- The project should assess the impact of support morphology on oxygen starvation for low-PGM materials in MEAs.
- The project should focus on generating more data.

Project #FC-168: Highly Robust Low-Platinum-Group-Metal Membrane Electrode Assemblies Based upon Composite Supports

Arrelaine Dameron; Forge Nano



Brief Summary of Project:

The objective of this project is to demonstrate a successful overcoat method on commercial low-platinum-group-metal platinum–carbon catalysts by targeting uniform coverage of the carbon support with gas phase access to the platinum catalysts. Project activities include evaluation of the activity, ohmic resistance, and cycling stability of overcoated catalyst materials by rotating disk electrode (RDE) and membrane electrode assembly (MEA) testing; demonstration through MEA testing of improved cycling durability of optimized encapsulated catalysts without significant loss in activity; and down-selection of viable encapsulated platinum–carbon catalyst material based on performance, process scalability, and technoeconomic considerations.

Question 1: Approach to performing the work

This project was rated **3.1** for its approach.

- The approach directly addresses the barrier for durability. The project appears feasible, but the feasibility is tied to the overcoat materials being investigated, and they are proprietary; so it is not clear whether they will have the appropriate cost, conductivity, or other properties. The overcoat technique has been used to limit noble metal migration and agglomeration on other catalysts and is likely to improve Pt stability and reduce corrosion. The synthetic approach is novel and cost-effective for a deposition technique. The investigators can produce catalysts in large quantities. It would be helpful to have a conductivity target for the overcoat. It may also be helpful to do some deposition on a substrate where the conductivity of the overcoat could easily be measured on a planar surface. It is not clear how deposition of the overcoat on the Pt or deposition blocking access to Pt sites inside the micropores will be prevented or minimized. A target or milestone to demonstrate selective deposition or deposition without blocking access to Pt sites should be included early in the project. Testing should also include cycling over the operating range of interest (at least 0.6–1.0 V vs. standard hydrogen electrode) as well as the start–stop cycle. Phase II studies should go to MEA-level testing as early as possible. Optimum coating thickness and pore size for performance in the RDE liquid environment could be quite different from the optimum for the environment in an MEA.
- This project applies atomic layer deposition (ALD) to overcoat Pt and carbon support as a means to protect catalyst degradation. The idea is generally good, backed up by previous publications. To demonstrate its feasibility, the project must move aggressively in the actual catalyst testing, at least at the RDE level.
- The ALD overcoat approach to addressing electrode durability is relatively novel. It will be interesting to see whether this can be achieved without sacrificing performance, specifically, potential mass transport limitations at higher current densities.
- The project has a good focus on key barriers with mitigation strategies in place. Multiple material approaches and barrier strategies are planned.
- The project approach is to demonstrate an overcoat for the catalyst support to improve durability. It seems that this approach addresses the durability target. However, the approach does not address cost and/or

performance targets and likely makes for a more expensive catalyst. The project has plans to prevent over-coating.
- This project offers a good approach. It is clear how they plan to coat the carbon but not the Pt. The document provided by the project team includes a relevant figure on slide 7 (top right).

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **2.9** for its accomplishments and progress.

- The project has just begun. The investigators have prepared 11 different batches of catalysts, which seems reasonable and on schedule for the synthetic portion of the work. However, it is not clear how physical properties of the coating or samples (e.g., thickness, conductivity, hydrophobicity) have been varied. According to the schedule, there should have been some RDE results by this time, but none were available.
- This is a Small Business Innovation Research (SBIR) Phase I project that had approximately only one month after project initiation before slides were due for the Annual Merit Review (AMR). As such, limited progress to date is expected. The ALD process has been demonstrated forming nano-islands.
- Given the early stage of the SBIR, limited progress is to be expected. The project presented some initial ALD results (slide 11), but it was not clear what the target or metric of success was. It was unclear if the team replicated the durability results as shown in the literature in slide 6.
- The project is only a few months old. The project has made good progress for this time. They have made several samples.
- Initial materials have been produced, and electrochemical tests have begun.
- The project began only two months before the AMR presentation was due. Therefore, limited accomplishment is to be expected.
- The project just started.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.1** for its collaboration and coordination.

- The project offers excellent collaboration. There will be complementary capabilities between the University of Connecticut (UConn) and Forge Nano.
- The project has well-qualified collaborators for electrochemical fabrication and testing.
- Forge Nano is collaborating with UConn for the electrochemical measurements while Forge Nano concentrates on catalyst synthesis.
- The project collaborates with two research groups at UConn with fuel cell catalyst research experience and testing capability.
- It is difficult to determine how well the collaboration is working because the project has just begun. However, there were no testing results yet. It would be helpful if an MEA developer was involved in Phase II because there are integration issues and an optimization of electrode layer properties (e.g., hydrophobicity, ionomer content) will be needed.
- There is adequate collaboration for a Phase I SBIR (UConn for testing/characterization). The project mentions using commercial catalysts, but it is unclear who is fabricating MEAs. The project could consider working with the Fuel Cell Consortium for Performance and Durability and Los Alamos National Laboratory for fabrication purposes.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.1** for its relevance/potential impact.

- This is an excellent translation of demonstrated technology from gas-phase catalysis to electrocatalysis. There is a high probability of success and impact.
- Catalyst sintering with voltage cycling remains a key area of interest in developing high-performance, low-/ultra-low loaded catalysts. As such, anything that can arrest Pt dissolution is of interest. It is unclear whether this performance can be maintained.
- The project is relevant, supports the Fuel Cell Technologies Office goals and objectives, and directly addresses catalyst durability and performance issues.
- The project addresses fuel cell catalyst durability, which is a key challenge for the current catalyst.
- The relevance and impact will be higher if the team defines concrete targets for both Phase I and Phase II. It is unclear what the targets are for conductivity, activity, and durability.
- The project addresses the durability target. However, it does not address the cost and/or performance targets, which likely makes for a more expensive catalyst.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- The inclusion of MEA testing and an economic assessment is appreciated. It is not clear whether high current density and potential mass transport limitations are being tested or addressed. If the process meets the initial metrics, those results are make-or-break and should be included. It is unclear whether the expanded lifetime testing listed on slide 16 follows the high current density demonstration. Durability, conductivity, and potential contamination issues are all of interest. If the project is successful with commercial platinum–carbon catalysts, the demonstration of a state-of-the-art platinum–alloy catalyst would be valuable. It would be especially valuable to explore the impact on pore-size optimized state-of-the-art catalysts as the FC-144 project demonstrates.
- The project's future work and targets are well laid out. A material down-selection early in the project and additional focus on characterizing transport properties through layers would be beneficial.
- An ALD-based approach has not been used in a fuel cell catalyst; an exploratory study can verify its feasibility.
- The proposed future work is appropriate, but it may be too focused on RDE testing. The liquid environment of RDE minimizes some transport issues that can exist in an MEA and could be affected by coating thickness, coating composition, etc.
- This project just started; therefore, the majority of the project is future work.
- The project should define MEA performance and durability targets to define success criteria of Phase I.

Project strengths:

- The project's main strength is Forge Nano's continuous ALD system and the potential for an overcoat to stabilize platinum or platinum–alloy nanoparticles.
- This project offers an excellent concept to build on with a good starting material set. Forge Nano has a track record of scaling up ALD. The property measurements appear complete.
- An overlayer by ALD that is not line-of-sight limited is a novel approach to improving durability.
- This is a novel method addressing an important durability problem for catalysts/supports.
- The project approach is reasonable based on the publications in the field of catalysis.
- The team's expertise in ALD is an apparent strength.

Project weaknesses:

- The use of an overlayer coating by ALD likely makes for a more expensive catalyst. It is also likely the catalyst will have performance limitations. The type of carbon used is potentially crucial to this project. High-surface-area carbons have a large degree of Pt in the interior of the carbon. Other carbons (such as graphitized) have little interior Pt. It is unclear how the ALD process will be at coating the carbon in the interior and whether the pores in the higher-performing carbons will remain open or will be “plugged” by the coating. If they become plugged, that could greatly limit the catalyst performance and make interior Pt inactive. The coating thickness appears critical to this project’s success. If the layer is too thick, the Pt particles will probably be covered, resulting in additional mass transport limitations. To evaluate, UConn should measure electrochemical surface area, mass activity, and high current density performance and impedance.
- It is not clear whether selective deposition on carbon or optimal deposition thickness is targeted. Material down-selection should answer that question as soon as possible. Ballpark resistivity and permeabilities should be known for some ALD layers and may aid in down-selection.
- The project would benefit from an experienced MEA developer in testing at higher current densities that are necessary for investigating potential mass transport limitations.
- Durability improvement should be demonstrated soon, at least at RDE level, which should not be too time-demanding.
- The project weakness is the lack of details available about the overcoat composition.
- The project does not offer any quantitative milestones.

Recommendations for additions/deletions to project scope:

- After initial characterization, if successful, investigating mass transport and high current density performance is suggested, followed by testing with state-of-the-art, porous, high-surface-area platinum–alloy catalysts.
- The type of carbon should be carefully documented and controlled. In addition, various carbons should be evaluated. The project has plans to prevent over-coating when coating the Pt. This needs to be proven as true.
- The addition of microscopy as a morphology descriptor would aid the understanding of resulting performance. This may fit well into Phase II.
- Bringing an MEA developer into Phase II would be beneficial.

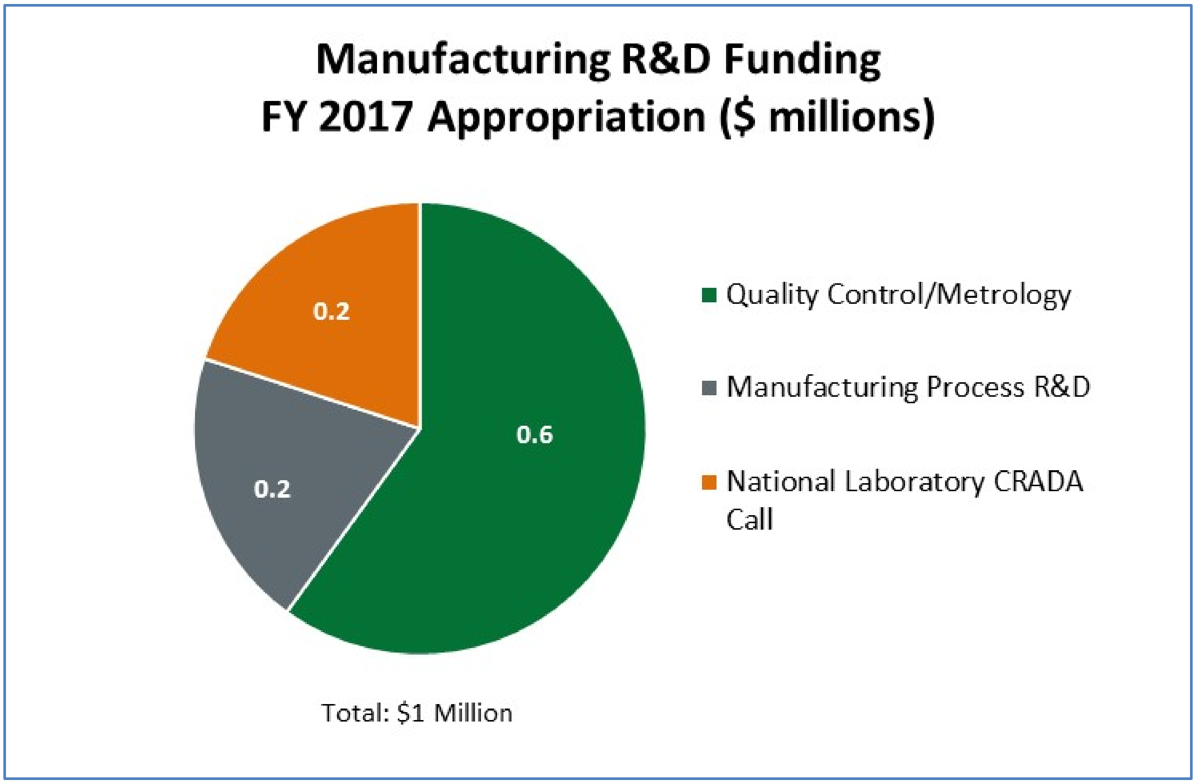
2017 – Manufacturing Research and Development (R&D)
Summary of Annual Merit Review of the Manufacturing R&D Sub-Program

Summary of Reviewer Comments on the Manufacturing R&D Sub-Program:

In general, the reviewers felt that there is great potential to break through the manufacturing R&D barriers and challenges that the U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program (the Program) faces. They commended the sub-program for supporting projects that are well structured, effective, and significant in reaching goals and milestones. In particular, reviewers recognized efforts to enhance imaging and defect detection techniques in real time that could greatly reduce the cost of high-volume manufacturing of fuel cell membrane electrode assemblies (MEAs). They also commended efforts to create a more comprehensive fuel cell component manufacturing supply chain to enhance industry collaboration.

Manufacturing R&D Funding:

Fiscal year 2017 funding for the Manufacturing R&D sub-program was $1 million. This funding was primarily provided to existing Manufacturing R&D projects for quality control (QC)/metrology, for national laboratory support for development of a new pipeline coupling, and for new cooperative research and development agreement (CRADA) projects associated with the Roll-to-Roll and H2@ Scale national laboratory CRADA calls.



Majority of Reviewer Comments and Recommendations:

This year, seven projects funded by the Manufacturing R&D sub-program were presented and reviewed at the Annual Merit Review and Peer Evaluation. The reviewers' scores ranged from 2.9 to 3.3.

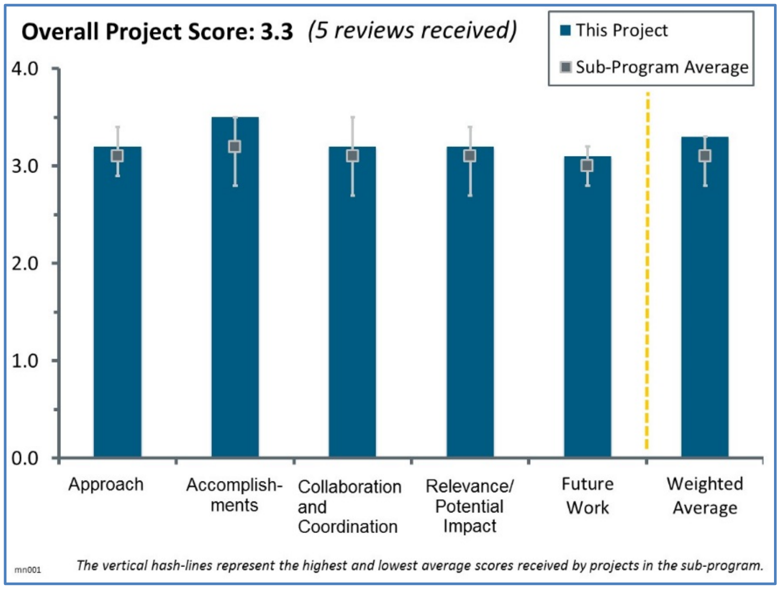
QC/Metrology: Two projects were reviewed in the area of QC/metrology, receiving scores of 3.3 and 3.2. Reviewers generally agreed that the MEA defect detection project had made important progress in defect detection and imaging techniques, which will be helpful in manufacturing membranes and in cost-reduction efforts within the Program. They suggested that the project focus on developing a few techniques to detect critical defects and variances (as identified by membrane manufacturers) instead of examining and imaging a large variety of membrane phenomena. Reviewers felt that the project could use additional industry collaboration for increased real-world results and real-time feedback in defect detection. Reviewers also noted the relevance and progress of an in-line QC technique, noting that the team is working with a Small Business Innovation Research program Phase II project to commercialize the technique. They suggested it could be highly beneficial to roll-to-roll (R2R) processing and DOE cost/performance targets, and that the future focus should be on increased detection in systems outside of a laboratory.

Analysis: Four projects were reviewed, with two projects receiving scores over 3.0 and two projects receiving scores of 2.9. The reviewers were impressed by the Hydrogen Fuel Cell (HFC) Nexus project for the significant progress toward establishing a website that provides product information on hydrogen and fuel cell components and systems to the fuel cell community. However, the reviewers expressed concern about maintaining and updating the website once federal funding for the project ends. The reviewers felt that the Ohio Fuel Cell Coalition clean energy supply chain project provides an interesting approach to creating and supporting future regional technical exchange centers for manufacturing. However, some reviewers questioned the impact the centers will have on the manufacturing and industrial supply chain needs for hydrogen and fuel cells. Reviewers also recognized the importance of the global and regional competitive analysis of the fuel cell industry, which will help DOE more accurately address barriers to competitiveness. They suggested that future work more precisely target specific fuel cell components. Lastly, reviewers urged more actionable results and clarity of analysis for the hydrogen refueling station analysis project, suggesting more data regarding standardization of stations and intra-country trade flows.

Manufacturing Processes: One project was reviewed in the area of manufacturing processes, receiving a score of 3.2. Reviewers praised the project for its approach in adjusting component materials for the coupler and said that the work will have a positive impact on pipeline safety and integrity. They noted the need to develop a full prototype as the next major objective for the project.

Project #MN-001: Fuel Cell Membrane Electrode Assembly Manufacturing Research and Development

Michael Ulsh; National Renewable Energy Laboratory



Brief Summary of Project:

The objectives of this project are to (1) understand quality control needs from industry partners and forums, (2) develop diagnostics by using modeling to guide development and in situ testing to understand the effects of defects, (3) validate diagnostics in-line, and (4) transfer technology to industry partners.

Question 1: Approach to performing the work

This project was rated **3.2** for its approach.

- The National Renewable Energy Laboratory (NREL) integrated its tasks with the subject funding opportunity announcement (FOA). The emphasis was on fuel cell manufacturing technology and on the strengthening technical abilities within the United States to enhance competences in that area. This involved close cooperation with large original equipment manufacturer (OEM) interests, pertinent support for the Fuel Cell Technical Team, and support and guidance for others funded under the FOA who seek to foster efforts to build a U.S.-based supply chain for fuel cell technologies. NREL reported very relevant, interactive support for the entire U.S. Department of Energy (DOE) effort. NREL began interactions with Gore, a U.S. company with extensive experience in membrane electrode assembly (MEA) technology, another solid part of the team's approach.
- The tools that are being developed are very important, including the segmented cell to determine local effects that might not be visible at the full cell level. The table breaking down total cell versus local effects and the longer-term impact on performance helps provide industry relevance. If possible, it would also be good to look at commercial electrodes as well as simulated defects. The General Motors (GM) half cells are a good example. It is also good to see alternate test cycles that may better inform degradation mechanisms.
- The approach of this project is good. However, the project should be a lot more focused. It seems like the partners are trying to do many things, which dilutes the project's impact. It would be better to see the principal investigator (PI) focus on a few techniques, clearly quantify their impact on fuel cell performance/durability, and transfer the technology to industry. For example, the researchers are developing techniques to look at membrane thickness variation, membrane pinholes, membrane irregularities, catalyst layer loading uniformity, bare spots, etc. It would have been better to identify key problems faced by roll-to-roll (R2R) MEA manufacturers and develop tools specifically to solve those problems.
  - NREL seems to be studying many interesting phenomena without regard to their importance. For example, it is not clear why the team wants to measure membrane thickness variations. It is not clear whether there is a need. It is not clear what the current variation in thickness of commercially available membranes is, what its effect on performance/durability is, or whether there is a need to monitor this. The impact of this good project would have been excellent/outstanding over the decade of this project if the PI had focused on a few important techniques and commercialized them to make an impact on U.S. manufacturing.
- Some effort should be placed toward using "real" defects in accelerated tests to see whether failure occurs similarly to manufactured defects.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.5** for its accomplishments and progress.

- The technical focus was on the development of new and improved techniques that serve to evaluate the physical properties of the MEA, which includes evaluation of individual components of that device, for example, the polymer electrolyte membrane. The developed procedures were suitable for R2R manufacturing. This is a tough task. The materials are subject to contamination or damage throughout the several manufacturing steps. Clearly, it is necessary to disqualify faulty materials as soon as possible. Therefore, the focus appropriately was on diagnostics for polymer sheet materials.
- There is excellent progress. Many results have been shown in this DOE Hydrogen and Fuel Cells Program (the Program) Annual Merit Review. Modeling from Lawrence Berkeley National Laboratory should be used more extensively to supplement the limited experimental data and to analyze the effects of various defects at different levels. Other projects within the Program could be leveraged for this purpose. For example, the Fuel Cell Consortium for Performance and Durability can be leveraged to get durability data that will enhance the value of this manufacturing project; the team can then focus on developing techniques to improve manufacturing reliability and decrease costs. Relationships with OEMs should also be leveraged to address real-world problems.
- Good progress has been made in setting up defect visualization equipment.
- The differentiation of membrane thickness and impact of defects makes sense but is useful to quantify. Leveraging these techniques to understand the sensitivity of advanced materials to defects is key to defining manufacturing specifications for electrode manufacture—thinner membranes will require tighter manufacturing control. The imaging capability is also a significant accomplishment to provide additional understanding into failure mechanisms. Full electrode imaging at a reasonable timescale would be a huge benefit versus point measurements of loading, which can be misleading.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.2** for its collaboration and coordination.

- There are good collaborators. The addition of Gore is much welcome. The results from duPont's N211 and N212 membranes might not be relevant to state-of-the-art membranes. The addition of Gore and development of techniques specifically for advanced membranes is a big step in the right direction.
- NREL played a key management role in the funded FOA on manufacturing. It worked cooperatively with a major U.S. OEM and cooperated with, and perhaps encouraged, other FOA participants, helping those participants to achieve better results. NREL has also begun cooperation with a fuel cell membrane supplier. This seems to be all just well done.
- The team has a diverse skillset that addresses a number of critical items. Efforts should be made to attract new collaborators with specific expertise in creating/identifying defects of interest.
- Interaction with Tufts University and GM are well described with examples. The Georgia Institute of Technology's role was not a focus. A project this important should also have additional industry involvement.
- It would be good to see how the team can leverage any previous work done in photovoltaics (PV) on R2R technologies and its experience with defect detection.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.2** for its relevance/potential impact.

- The results are in a one-for-one agreement with the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan. Impact is hard to assess, but the potential impact is significant. Even so, this same sort of diligent engineering will be necessary for every component in the fuel cell systems, so this activity is just the beginning of manufacturing engineering.

- The project is very relevant, especially the focus on technique development, which is the strength of this project. This project will be more impactful if the team focuses on this and leverages OEMs and other projects to figure out what the needs are in this area (rather than mapping the impact of various defects on performance and durability).
- This type of work and understanding is essential to driving understanding and manufacturing. The goals beyond automotive fuel cells are not really defined at the manufacturing level yet.
- This work helps support the cost-reduction goals by potentially reducing waste and understanding the process improvements necessary to increasing fuel cell efficiencies.
- This effort, if the results are adopted by industry, can significantly lower the cost of MEA manufacturing.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- There is plenty of future work possible with this project, but it is difficult to lay out a plan without an assured budget. The team is working to mitigate this through collaborative efforts and cooperative research and development agreements.
- Certainly, the work is ongoing and will continue throughout fiscal year 2017. The present plans to extend or modify this activity are not clear. There is much to manufacture in a fuel cell system. Emphasis on the MEA is appropriate and has considerable promise to enhance durability and performance targets.
- This project has been ongoing for a decade. It would be beneficial to see more of "seek opportunities to demonstrate and implement diagnostics in industry" and less of "study the effects of relevant defects on cell performance and failure onset." Before developing a new technique, the team should make sure there is actually a market for this and it is actually an industry need.
- It would be interesting to understand the feasibility of implementing a real-time feedback loop for adjusting process parameters or the use of real-time predictive modeling.

Project strengths:

- The NREL team is excellent, and DOE has provided resources to NREL to allow it to acquire, install, and operate quality instrumentation and hardware. The strength is people who are knowledgeable and facilities that permit those people to accomplish the tasks. It is also a great strength that NREL has a fully interactive fuel cell team, perhaps the best and most useful collaboration on this activity.
- There is lots of great work on a variety of things of relevance to manufacturing and the impact of manufacturing defects on fuel cell performance and durability. The team is working on the Small Business Innovation Research Phase II project to commercialize the technique developed under this project. The project has the potential to affect U.S. manufacturing in a positive manner.
- The analysis techniques that have been developed for catalyst layers and membranes is impressive. These have improved over the course of the project, becoming higher-resolution and more closely tied to performance. The addition of modeling and more fundamental analysis to understand the mechanism of failure adds to the value of the work.
- This work opens the doors for having a platform to build tools for in-line process optimization.
- The utilization of R2R equipment in real time to identify defects is a project strength.

Project weaknesses:

- It is not clear whether manufactured defects and real-world defects are similarly visualized.
- The largest focus has been on platinum catalyst layers; there was some preliminary work on other materials, but it would be good to keep up with the work on electrolysis catalysts and non-platinum-group-metal fuel cell catalysts as these two areas gain momentum to further leverage this capability.
- It would be good to see connectivity and collaboration with other projects funded by DOE.
    - The project should leverage thin-film PV work with R2R defects and link to other funded fuel cell and MEA projects.
- Fuel cell technology is being explored throughout the global community. Through the last two decades, a certain pathway has developed in the United States that may or may not be what actually dominates the

future marketplace. This project correctly focuses on what the community knows and accepts. The possibility that others have different approaches exists. The other weakness is that others are now manufacturing hundreds of thousands of fuel cell systems. Each manufacturer faces quality-control issues and selection of techniques to access quality control. Successful approaches will be held as intellectual property and not shared. The fact that the fuel cells now being marketed tend to work for a long time suggests that many quality control issues have been addressed successfully.

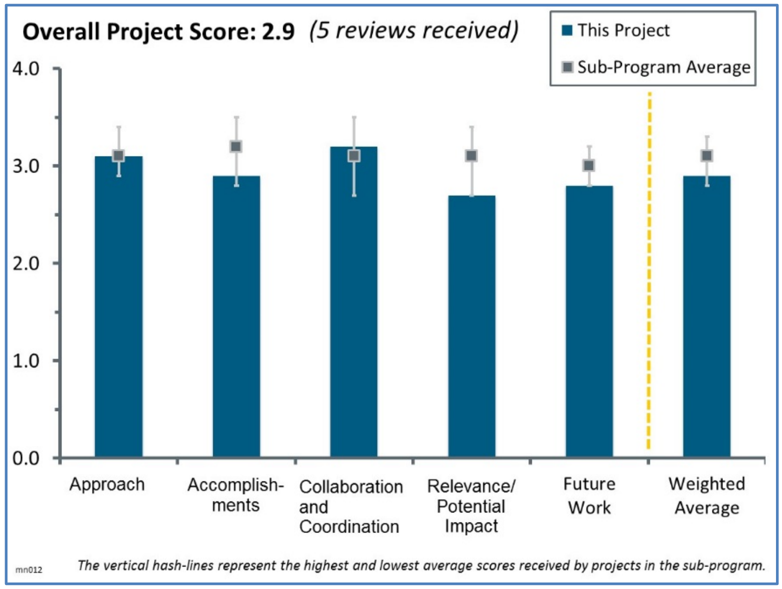
- It seems as if the PI is developing all the techniques that he can and looking at the impact of various defects on fuel cell performance and durability without regard to need or impact. Therefore, the science is good, but the impact is low. It would be good to see more focus to steer this great team to have a greater impact on a few problems of relevance to the MEA manufacturing industry.

Recommendations for additions/deletions to project scope:

- This project is valuable to continue, and it should be expanded to understand the range of technologies to which it can be applied.
- Identical quality control issues confront other fuel cell systems and electrolysis systems. It would make sense for the NREL team to bring its many skills into those areas as well. It is well understood in any technology, like in fuel cell technology, that the greatest majority of financial resources are spent not in fundamental or basic research but in bringing promising technology to the marketplace.
- A study of "real" defects, their identification, and the effect on life should be conducted. A more scientific approach to understanding defect effects on life would give manufacturers a better idea of how to address defect occurrence.

Project #MN-012: Clean Energy Supply Chain and Manufacturing Competitiveness Analysis for Hydrogen and Fuel Cell Technologies

Pat Valente; Ohio Fuel Cell Coalition



Brief Summary of Project:

The objectives of this project include the following: (1) establishing regional technical exchange centers to increase communication between original equipment manufacturers (OEMs) and hydrogen and fuel cell component and subsystem suppliers; (2) establishing a web-accessible database containing inputs from suppliers and OEMs along with a supplier contact list; (3) standardizing component and subsystem component specifications; and (4) developing strategies for lowering cost, increasing performance, and improving durability of components and subsystem components.

Question 1: Approach to performing the work

This project was rated **3.1** for its approach.

- This project was chosen competitively as a response to a U.S. Department of Energy (DOE) funding opportunity announcement. Clearly, this selection is the result of an application that addressed specific DOE goals. It is apparent that manufacturing competitiveness involves manufacturers that have both the competence and resources to design, develop, and manufacture components for hydrogen and fuel cell technologies, while they are being rapidly commercialized in the global community. Pat Valente took on the task of building from the ground up a group of U.S. companies that could be part of a "supply chain," making parts that are essential for final, successful products. It is obvious that there were no clear, well-identified pathways to have this happen. However, Valente proposed a pathway that was similar to what is done in the U.S. automotive industry. Certainly, this was the place to begin. This task involves the initiation of a supply chain for hydrogen fuel cell components, and the plan is to do exactly that.
- The approach includes focused workshops and intense "speed dating" events to facilitate in-person, face-to-face information exchange on OEM requirements and supplier capability. Consideration of possible component standardization could prove to be very beneficial to the industry and keep costly duplication to a minimum. Compilation of a list of possible suppliers and technologies will facilitate development and market penetration. It is not clear what fuel cell types are being considered.
- The approach of "speed dating" has considerable potential to facilitate fuel cell supplier interactions. The approach of implementing working groups on selected topics (e.g., part standardization) delivers a high probability of some (limited) shared benefit to the U.S. supplier community. The geographic distribution of the data exchanges is reasonable.
- This project now focuses on the technical exchange centers while leveraging MN-013 for the website. This is a very good approach. However, it seems as if the principal investigator (PI) is just putting up one exchange after the other without understanding the actual efficacy of these exchanges and improving them with time. It would be good to see more metrics developed for "success criteria" rather than counting OEM–supplier matchmakings or survey scores. Maybe the team could track actual sustained supplier–OEM relationships and actual purchases made from the suppliers by the OEMs.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **2.9** for its accomplishments and progress.

- The mere ability to get interested parties in same room for dialogue and discussion of common topics of interest is a significant accomplishment. Data exchanges were modestly well attended by a good/appropriate mix of suppliers and integrators. The selection of components on which to focus ongoing component standardization discussions is a significant achievement.
- The accomplishments are that a "supply chain" has been birthed. The activity is small, involving U.S. companies that currently manufacture stuff and are interested in selling into the hydrogen market. None of the reported activities are focusing on essential hardware, such as the fuel cell stack. Rather, the initial interest is in other components, such as filters, which although essential are a minor component. The details of the interested "supply chain" participants are not available. Most likely the filter company already manufacturers and markets filters. Hence, the accomplishments are small steps, perhaps, but visible steps. This is the beginning, and there has been progress and commitment.
- The project appears to be on track, but it is difficult to assess the overall impact on DOE goals for fuel cells. Exchange meetings have been held with good attendance and very positive feedback. The number of follow-up contacts was significant, but their effectiveness was not known. Substantive standardization discussions were held, revealing possible candidate balance-of-plant components for joint development. Cell/stack components were generally excluded because of the proprietary nature of the fuel cell technology. It would be informative to report what types of integrators participated (automotive, backup, etc.), what components/technologies were offered (sensors, humidifiers, compressors, plates, etc.), and what technologies were covered (fuel cells, hydrogen storage, etc.).
- In fiscal year 2016, the second quarter (Year 1) milestone was "[Ohio Fuel Cell Coalition] produces brochure to attract new suppliers." This task was supposed to be in progress even at the last DOE Hydrogen and Fuel Cells Program Annual Merit Review. However, this seems to be moved to September of 2017. It seems like this project has just evolved into putting up these regional exchanges every few months. While this is the strength of this project, the scope seems to be far less than originally intended. It is not clear why this is not reflected in the budget. The PI needs to provide concrete evidence that the supplier–OEM meetings from the first few exchanges are actually helping either the supplier or the OEM. It is understood that these are well attended and that may be an indication of value, but the difference between each of these exchanges (other than location) is not clear. It seems like a better idea would be to focus each of these on a specific theme, get a few people, and actually make a difference—instead of making it like a conference where everyone goes their own way after the meeting and very little technical collaboration is fostered. This field is not mature enough to benefit from such broad exchanges. More needs to be done to accelerate the development of a robust supply chain.
- International and regional connections should also be sought for integrators to obtain the best components for their applications. Lessons learned from similar foreign efforts of similar scope should be sought.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.2** for its collaboration and coordination.

- Collaborators are appropriate and correctly do not include industry or suppliers that might have specific parochial agendas. Communication among the named collaborators and with industry stakeholders is pervasive by the nature of the project, which has hundreds of contacts.
- The PI has made excellent attempts to coordinate with other projects, including MN-013, which is very valuable for DOE.
- The project team has significant fuel cell experience and seems to represent a well-integrated, well-rounded set of participants. Interaction with other DOE-funded efforts (James Madison University, GLWN) adds significantly to the project. The team is seemingly limited in other non-DOE/non-project collaborators. Interactions with industry groups/associations were not shown.
- The collaboration is somewhat disappointing. Partners are those in the fuel cell technology area, but the people have limited experience in building manufacturing companies. Joel Reinbold, a "collaborator," heads the Connecticut Center for Advanced Technology, an organization that is working in parallel on the

fuel cell/hydrogen component development task. It would seem more appropriate if partners were more involved with the development of fuel cell/hydrogen devices. Interestingly, Ohio houses two technology powerhouses, NASA Glenn and the Wright-Patterson U.S. Air Force (USAF) Base. Both institutions have decades-long experience developing specifications and empowering vendors for fuel cell parts. Partners might have included staff at the Japanese Ministry of International Trade and Industry or a German institution that has recently been tasked with the development of fuel cell components. (Siemens sells a fully useful polymer electrolyte membrane fuel cell submarine, a boat full of fuel cell parts, for example.)

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **2.7** for its relevance/potential impact.

- Certainly, as of now, the impact is minimal. However, because of Pat Valente's efforts, some number of U.S. engineers and other managing manufacturing firms have been alerted to these new market opportunities. The project is barely half finished, and it is too early to actually decide on "impact." It would take only one "big success" to demonstrate impact. That could happen with any of the interactions that are the result of bringing a potential supplier together with a potential manufacturer, if productive. U.S. industrial history is a story about such interactions and successes.
- The potential impact is positive but limited. It is suspected that many of the critical interactions would have occurred even without the intercession of this project. However, the project does facilitate those interactions and thus has a (modest) benefit.
- It seems like there is much reluctance from OEMs to share their needs. This is a critical handicap of this project. Unless that is fixed, the impact of this project will be low (it is understood that this is not in the hands of the PI, and this is how things are). An alternative would be to look at OEMs for non-transportation and early market applications, such as fork lifts (Nuvera, Plug Power, and Ballard). If these OEMs are more willing to share their needs, then OFCC can make more progress in these early market applications.
- It is not entirely clear how this project directly advances the Manufacturing R&D sub-program goals, which are cost-related. It is not clear whether this project is really necessary. The OEMs surely know how to find suppliers for their requirements.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- Substantial work is laid out; there is much to be done even after the data exchanges are completed to ensure that something useful and lasting comes out of the exercise. The most important future activity is the establishment (and exercise) of the standardization working group.
- The focus on standardization is good. Identification and exploitation of U.S. technical advantages is crucial for U.S. competitiveness. It is not clear what happens in August 2018 when this project ends.
- Future work is mostly the continuation of the existing policies and functions established now. This is appropriate. The "supply chain" conferences seem to be worthwhile and useful.
- New engagement with the Fuel Cell & Hydrogen Energy Association (FCHEA) will help.
- OFCC needs to better quantify the impact of these regional exchanges before just doing more of the same.

Project strengths:

- The project is run in a professional manner that entices significant industry participation at the multiple data exchanges. Prodding the industry in pursuit of standardized fuel cell components is a major effort and may ultimately be more significant than the database and/or data exchanges.
- The PI is well skilled in component development. He seems to know many people who could affect project success. The project seems to be merging into a national effort, which is a very good direction.
- The large and comprehensive database of suppliers and integrators is a project strength.
- There is good collaboration with other projects.
- Regional engagement of both suppliers and integrators is helpful.

Project weaknesses:

- The United States has, in general, limited ability in this sort of endeavor. Certainly, the U.S. Department of Defense knows such a drill. One creates intelligent engineering designs and specifications for all necessary components as well as for the subject hardware. Strict attention is given to material quality, assessing details such as exactly which mine produced ore that resulted in the necessary parts. Therefore, this activity is admirable and necessary. Even so, it is a long shot. DOE deserves credit for having the insight and courage to accept the challenge and address it. There is always risk. Reward is less certain.
- Engagement is somewhat limited and should be expanded to a wider network of fuel cell industry representatives.
- There is weak discussion of the efficacy of the workshops and exchanges meet-and-greets. It is not clear what percentage resulted in non-disclosure agreements or other formal arrangements.
- The project has not completed the OEM needs brochure yet, which was due the second quarter of this project. It seems like a very low-impact project, especially without critical OEM involvement. If the OEMs are not that keen to participate, maybe this supply chain is not a problem, and maybe DOE should not invest as many resources.
- The benefits of a supplier database are fleeting and run the risk of being obviated by commercial (public access) databases that have a multiyear lifetime (because they have an incentive to keep them fresh/ updated). The value of (or focus on) a “brochure” of project findings is questionable. It is unclear whether this is the same as a report. It is unclear whether the list of information gained is so short that it fits in a bi-fold brochure.

Recommendations for additions/deletions to project scope:

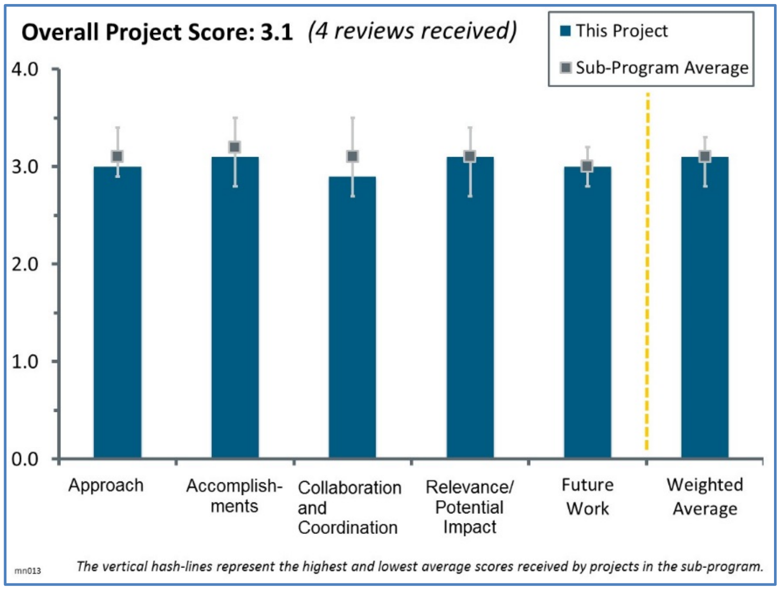
- It might make sense to explore the NASA and USAF staff who worked earlier to develop fuel cell hydrogen hardware. The staff may have insight into other contacts and opportunities. There is also expertise in the intelligence community, which might be useful.
- OFCC should place greater emphasis on creating and using the standardization working group. Most important, the project needs to establish a platform that lives on past the duration of this DOE-funded project. Having a few data exchanges and building a (limited) website are beneficial to project total goals, but they are ultimately inadequate if they fall apart upon project end. Consequently, the project should place great emphasis on establishing entities/events that live on (preferably without DOE funding) past the end of the project.

Project #MN-013: Fuel Cell and Hydrogen Opportunity Center

Alleyn Harned; Virginia Clean Cities at James Madison University

Brief Summary of Project:

The project aims to facilitate the widespread commercialization of hydrogen and fuel cell technologies by expanding the domestic supply chain of hydrogen components and systems. The Fuel Cell and Hydrogen Opportunity Center is building and populating a comprehensive communications database and using an aggressive outreach campaign to drive U.S. companies to the database website.



Question 1: Approach to performing the work

This project was rated **3.0** for its approach.

- As is apparent from the title of the project, the intent of the Hydrogen Fuel Cell Nexus (HFC Nexus) is to create a web-based computer platform that highlights individual companies or individuals that are active in the business of fuel cells and hydrogen technology. The principal investigator (PI) Alleyn Harned is associated with Virginia Clean Cities and is well skilled in promoting new clean technology. Alleyn Harned works to enlist companies to submit data that are posted at hfcnexus.com. The approach is apparent when one thinks about the goals. This is a project to create and manage a new website. HFC Nexus went down that pathway. Obviously, selecting a group of people who excel in web-based projects was an important part of the approach.
- Given the goal is to address the lack of updated, readily available supplier information, a website (and updating structure) to do that is a reasonable approach. The intent is to reach a critical mass of suppliers within the database, such that future/remaining suppliers will sign up on their own. This strategy addresses the critical need to have a self-sustaining method of database perpetuation.
- This is a very focused project with clear deliverables.
- The approach appears to have been executed exactly how it is proposed. It is difficult to assess the success of this effort in addressing barriers without metrics based on successful matches made.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.1** for its accomplishments and progress.

- The progress is excellent. The website is up and running and has plenty of information. Maybe the PI can advertise this at the Fuel Cell Seminar, the Electrochemical Society meeting, and other meetings where original equipment manufacturers, fuel cell researchers, and suppliers are expected.
- The website is professionally done and contains relevant information for a variety of suppliers. Window scalability and a U.S. map with clickable entries are nice features. The website and database are an overall well-executed project. The website has ~337 organizations out of an estimated several thousand of eligible companies: a small percentage.
- Evaluating progress and accomplishments of this project is not simple. Clearly, the number of companies that have submitted information is substantial. The task also involves weeding out inaccurate or inappropriate listings. Hence, there is a considerable amount of effort in this endeavor. There are a good number of other similar global hydrogen fuel cell companies, and no effort was made to compare the quality or quantity of such similar activities. There was no mention that Harned had attended global

technical meetings, perhaps the Fuel Cell Seminar, to display his wares. The DOE selected Harned as a Hydrogen and Fuel Cells Program (the Program) participant and judged his proposed activities to be in consort with the Program plans. On a positive note, opening his website shows an artful, well-done information set. The progress seem to be exactly what was promised.

- It is extremely difficult to assess progress toward the project and DOE goals when the only metrics are the number of vendors participating and the number of website hits.

Question 3: Collaboration and coordination with other institutions

This project was rated **2.9** for its collaboration and coordination.

- Partners are in the Virginia Clean Cities staff at James Madison University and Robert Rose's Breakthrough Technologies Institute (BTI). (Rose is a well-established spokesperson and advocate for hydrogen and fuel cell technology and brings with him considerable grassroots contacts.) Harned also has tasked the Birch Studio to build his website, which seems to be well done. There is no indication that interactions with other groups promoting fuel cell technology were established.
- Collaboration with BTI is a critical element because it has historical perspective and specific knowledge of the fuel cell marketplace. However, there does not appear to be much collaboration outside of the project team.
- There is good collaboration with other projects.
- It would be nice to see some collaboration between Virginia Clean Cities and the Ohio Fuel Cell Coalition, because these projects have essentially the same objectives.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.1** for its relevance/potential impact.

- It takes a large number of excellent companies to develop new excellent technology. Much depends on getting groups together that choose to work cooperatively to make necessary progress. Making those associations happen is essential. A project such as this facilitates progress, or it can do that.
- There is excellent relevance. It would be good to see more quantitative metrics. It is not clear whether there is any way to track actual exchanges facilitated by this website.
- Reducing barriers to hydrogen education is a worthy goal, but how this project accomplishes that is less clear. It is not clear that other websites are not accomplishing the same mission.
- The relevance is difficult to assess.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The proposed work is to continue the existing work. Importantly, the website needs to be maintained, kept current, and expanded, a continuing task for skilled people. Obviously, questions arise about the durability of the website, especially after DOE funds are depleted. It is not clear whether this task, a necessary task should the United States decide to compete in fuel cell technology, needs governmental support. One might argue that this is a more appropriate task for the U.S. Department of Commerce than DOE. However, it is very clear that it needs to be done only once, and it needs to be a U.S. project, not a task funded by a state or local government. It is an easy task to identify similar ongoing tasks in China, the European Union, and Japan, for example. For now, it is in the DOE portfolio. It is an asset.
- It seems like most of the work is already done and the focus is on maintenance. It is very critical to keep this website updated and relevant to the community and to continue to advertise it after the end of this specific project.
- Future work rightfully focusses on expanding the breadth of the website and securing sponsor(s).
- This project is entering its final year. It is not clear how the website created is to be sustained without continued DOE funding. A plan needs to be created and executed.

Project strengths:

- Alleyn Harned seems very competent and able, bringing necessary skills to the project. The Birch Studio does good work. The concept of having a thorough, available list of competent suppliers seems obvious, should one be concerned about the future.
- The project has set realistic goals and achieved them.
- The website is professional and functions clearly.
- The website appears to be online and very functional.

Project weaknesses:

- The obvious weakness is that the United States is trying to play "catch up," competing with some rather well-staffed global economies, and this very small project has keen competition. It is very clear that the fuel cell electric vehicle business is serious, real, and offers a broad range of compelling advantages, both technical and social. DOE gets good marks for doing the correct thing by sponsoring this activity. One hopes that the "too little, too late" thought is not appropriate.
- The project team needs to plan for the sustainability of the website. Metrics are needed to show true success (e.g., number of partnerships created).
- The project needs more quantitative metrics to assess the impact on industry.
- It is not clear that competing websites are not duplicating the function of this project, making this project redundant/obsolete. A website of companies is only marginally beneficial in assisting fuel cell business-to-business interactions. The website/database will be quickly out of date unless a sustainable method is developed for updating and recruiting the participation of new/emerging companies. A strategy to develop a self-perpetuating mechanism for database maintenance/rejuvenation has not been articulated.

Recommendations for additions/deletions to project scope:

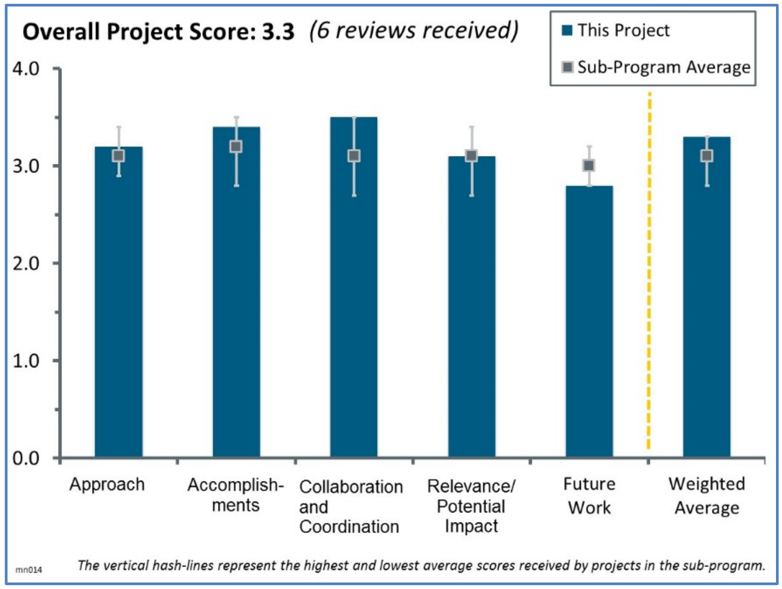
- The project team should focus efforts on identifying a strategy to make suppliers want to update their company listings.
- There needs to be a thorough study of global competition in fuel cell/hydrogen technologies. The trouble with focusing on U.S. companies is that the excellence is most likely not based in the United States. Hence, the appropriate next task would be to determine the nature and identity of companies that are now providing global fuel cell and hydrogen components. The business remains a global one, and a competitive global one.

Project #MN-014: U.S. Clean Energy Hydrogen and Fuel Cell Technologies: A Competiveness Analysis

Patrick Fullenkamp; GLWN – Westside Industrial Retention & Expansion Network

Brief Summary of Project:

This project falls under the Clean Energy Manufacturing Initiative mission to increase domestic manufacture of clean energy products and increase energy productivity. Competitiveness is driven largely by cost, so GLWN is examining current and projected costs, supply chain evolution, and global trade flows of clean energy hydrogen and fuel cell technologies. Project results will help identify strategic investments, identify technology areas for research and development (R&D) investment, and lay out a prospective future supply chain.



Question 1: Approach to performing the work

This project was rated **3.2** for its approach.

- The team actually traveled to multiple sites to assess suppliers and original equipment manufacturers (OEMs), which is the only way to really understand the manufacturing status. This is probably one of the few analyses that is this grounded.
- The approach is what would be expected from a quality engineering concern. A good team was built. Initial activities led to the selection of a few key issues. The project was done well enough. The team includes an excellent European engineering firm, adding considerable talent and scope to the study.
- The project clearly presents a summary of the current state of the industry and regional strengths and weaknesses.
- The cost analysis benefitted from Strategic Analysis, Inc.’s (SA’s) involvement, but it was unclear whether the project unnecessarily duplicated any of SA’s cost projections. The Approach slides do an adequate job of describing what is being done and the associated tasks, but they do not adequately describe how the tasks fit together to arrive at a competitive position. Some additional information on the interviews, such as the nature of the questions and their weighting, would be instructive.
- This is great work, but U.S. manufacturing competitiveness will be based on OEM demand.
- It is unclear how much, if any, effort was spent on generating cost estimates. The project should use the data generated by SA and focus on improving manufacturing competitiveness.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.4** for its accomplishments and progress.

- The competitive analysis part of the project is essentially complete. Conclusions are clear and instructive and intuitively reasonable. The remainder of the project is collection of market data.
- The project met the goals of the Program. As an analysis task, it does not directly advance the technology toward the DOE goals, but it helps in providing a roadmap of important indicators and priorities.
- Progress is great.
- It is not obvious that the “barriers” are totally valid. For example, “lack of high-volume [membrane electrode assembly] processes” involves some definition of “high-volume.” For example, when 1,000 fuel

cell vehicles are produced and assuming each fuel cell stack has 100 cells, the production volume is 100,000—perhaps not "high-volume," but high enough to get much attention paid to production technology.
    - The interviews and plant visits were a good idea. It was interesting to understand the percentage costs, such as for the "pressure vessel," vary with production level.
    - It was also interesting that the "catalyst ink and application" accounts for only 12% of the fuel cell system cost, even though DOE has spent considerable resources to lower that cost. (Of course, a customer buys not a fuel cell system but a car that has a fuel cell system. If the car costs $60,000 and the fuel cell system costs $15,000, the "catalyst ink and application" comes to about 3% of the cost.) Therefore, the data collection was good work.
    - Interesting results were obtained (Figure 9) that indicate the "Direct Labor Jobs" give nonsense results. That 30–40 people are required for the bipolar plate, for example, totally ignores the people needed to dig the iron ore and so forth. ("Indirect Labor" will be far higher.)
    - The competitive analysis sections seemed haphazard. Broad generalizations are seldom correct. For example, saying that a U.S. strength is a "high technology domestic automotive industry" is okay, depending on whom you talk to, but there is no doubt that this is also a strength of the European Union, Korea, China, Japan, India, etc. The United States does not have a "high corporate tax rate"—in fact, the actual tax rate (after subsidies) is one of the lowest in the world. Therefore, Chart 10 seems inaccurate and full of "I wish it were true" sort of stuff. A competiveness position means the United States has an advantage over competitors. No credible thoughts were presented as to what might influence the existing situation, changing it for the better.
- The presenter did not present a clear slide with milestones and deliverables, so it is difficult to judge the progress.
- The project does not go far enough as to what could be done to overcome regional barriers using local resources or from exploiting strengths or possible synergies between regions—i.e., how a global company might help overcome certain barriers.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.5** for its collaboration and coordination.

- With the resources available, collaboration was well done. Figure 11 (the existing markets) was informative. The fact that deployment of stationary fuel cells was a highly successful endeavor by Japan is apparent but not widely understood. It would have been better if the "by fuel cell technology" was displayed by kilowatts rather than by number. Some of the stationary units, say molten carbonate in Korea, are large-scale devices. No information was given about procedures required to gather the data and who did what. That said, the work resulted in excellence, a wonderful and interesting snapshot of "Fuel Cells Today." It would have been useful if the team had also interviewed other governmental agencies, such as the Japanese Ministry of International Trade and Industry, to better understand status and goals within the global community.
- The project team members are well known, well connected, and well respected domestically and internationally. Interactions (interviews with fuel stakeholders and suppliers) were apparently successful.
- This whole project hinges on engagement with industry, and detailed interviews and visits provide strong evidence for the conclusions.
- Having 8 OEMs and 21 suppliers participate in interviews is good. The SA partnership is excellent.
- This is good work with a diverse supplier base globally.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.1** for its relevance/potential impact.

- Leveraging this work to set strategy in manufacturing and investment is very important. The work clearly points out the lagging position of the United States in many component areas, which is disappointing given

the strength and depth in the United States in fuel cell and electrolyzer technology and scientific understanding.
- Results from this competitive analysis provide DOE and industrial stakeholders with insight into areas in which additional R&D resources could technically and economically benefit the U.S. fuel cell industry and suppliers.
- This project was funded by DOE, with funding provided to the team that submitted a winning proposal. It is apparent that this report directly addresses exactly what was called for by DOE, based on the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan. The results can serve as a guide for future technology studies and as a guide to instruct investors. The information is clear and informative. The "impact" depends on those who read and consider the results.
- The project identifies strengths and weaknesses and potential areas for future work.
- The impact is not very clear. The cost analysis by SA seems to be the basis for much of the input. The rest of the project seems very qualitative. It is not clear what guidance will come out of this project that will help DOE.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- The project is pretty much complete, and future work focuses on final reports and other DOE tasks. It makes sense to maintain this team and monitor future flows of cash and hardware in the global fuel cell endeavor. Those concerned about competitiveness would do that.
- Future work is straightforward and comprises completion and publication of the competitive analysis report and continued collection of market data by fuel cell application/technology and region.
- Future work should provide recommendations on how to overcome the challenges identified and what type of global collaborations would be required or improve the global situation.
- The project appears to be winding down and is mainly in a reporting mode.
- The publication of the global competitive analysis report will be a major deliverable for this project. It is not certain that having market survey data will be that useful, as there are many sources for this kind of data, and this information has been readily available historically.
- The most important work has been completed. Future work and its potential value are poorly defined.

Project strengths:

- The approach in gathering the information via site visits was a key strength. Another key strength was the global survey providing a comprehensive look at the field, including U.S. competitiveness. The division of the survey by volumes also provides an important perspective of the state of the technology (ability to produce a consistent and reliable product at low volumes) vs. the state of manufacturing (ability to produce high volumes).
- The quality of the team is apparent. Their approach was well-thought-out. The datasets are most informative and suggest both opportunity and danger to those attempting to create manufacturing activities in the United States.
- Project strengths include (1) a good summary of the current state of the industry and (2) clear and concise data.
- Strengths include assessment of global technologies and cost analysis of fueling station components.
- Worldwide analysis is a project strength.
- There is good collaboration with SA.

Project weaknesses:

- It would be good to extend this work to related components for related applications.
- Some of the conclusions seemed arbitrary. An example are the conclusions of what to manufacture and where to do that. It is apparent that there are many "auto jobs" in the United States that have absolutely nothing to do with manufacturing. One example is a banker who makes car loans. It is true that fuel cell vehicles will be different from internal combustion engine vehicles, but much remains exactly the same.

One issue is the creation of capital to finance such endeavors. Many industries in the United States are profitable only because of considerable federal investment. A good example is airplane manufacture, an endeavor that borrows heavily from U.S. Department of Defense technology assets. It would have been interesting for the team to consider synergies in the U.S. economy that, when utilized, would promote and subsidize fuel cell vehicle markets.

- The principal investigator (PI) uses only current vendor thoughts and does not consider what the future will hold, how the manufacturing technologies will change, or what technological and economic changes would alter this analysis.
- The PI needs to be clear on milestones and progress and how this project helps U.S. manufacturing.
- There is not much insight as to what needs to change to move each geographic region's ranking in the categories studied.

Recommendations for additions/deletions to project scope:

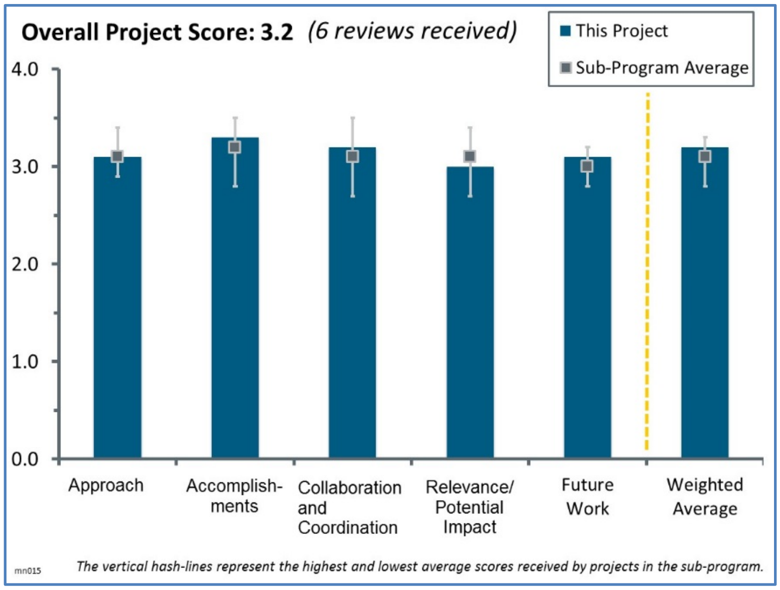
- This analysis would be hugely interesting and informative to do for polymer electrolyte membrane electrolysis. The supply chain is rapidly expanding, and the United States will likely be similarly left behind in this area, but understanding the extent and quantitative growth in this area would help prove this point.
- The rest of the world is into fuel cell buses, trains, boats, and planes. It would be most interesting to continue this effort with a far broader brush.
- A scenario analysis should be performed on possible future occurrences (wide use of additive manufacturing, wide acceptance of smart/connect car technologies, etc.).

Project #MN-015: Continuous Fiber Composite Electrofusion Coupler

Brett Kimball; Automated Dynamics

Brief Summary of Project:

The objective of this project is to advance the state of the art for hydrogen transmission and distribution by improving the joining method for piping that is used. A composite-based coupler will be designed and tested, with the goal of achieving transmission pressure of 100 bar with a flow leak rate of less than 0.5% and 50-year expected life of the part. To achieve project goals, work will focus on addressing three independent challenges in joining pipes: (1) tensile load through the coupler, (2) burst pressure, and (3) sealing of hydrogen in the pipe.



Question 1: Approach to performing the work

This project was rated **3.1** for its approach.

- This task proposes a new piece of hardware that will serve to join (connect) two lengths of polymeric tubing useful to the transport of pressured hydrogen. The concept involves a fitting that accepts the ends of two lengths of tubing, and when inserted into the device, it couples the tubing, making it suitable for underground installation. The approach was appropriate, with identification of the problem, a review of existing, competing hardware, a design of an improved piece of hardware with enhanced performance, and manufacture and testing. This is exactly what one would expect in any quality engineering house.
- Working with an established pipeline component supplier is a major advantage. Use of existing components/pipelines to the extent possible is a critical design approach. The project showed flexibility in switching from an all-composite design to a mixed metal composite design.
- The approach shows efficiency in following up on the previous problem with modified tactics, enabling full learnings from prior work, as well as incorporation of new solutions. The approach appears to minimize added costs or costs associated with "starting from zero." Incorporation of National Oilwell Varco (NOV) components and understanding appears to be very important. New addition of finite element analysis (FEA) modeling fatigue appears to be a good decision, regarding the large unknown associated with the key target of a 50-year lifetime. Parsing the approach to address each of the separate mechanical challenges seems prudent. The one thing that is not clear, with regard to the approach, is related to the problem statement on slide 3. The fundamental problem is stated to be replacement or maintenance of existing seals that are already underground. It is not clear how these couplers can be installed in already-in-the-ground pipes and (similarly) how the electrofusion for sealing will actually be performed. The researchers should clarify this in their presentation next year.
- The performers made a quick decision to move from the adhesive approach and rapidly gained confidence in their composite materials approach. The project is on track for success if they can prove that fatigue is not an issue during the next project year.
- The approach is one of application of mostly existing technologies to the design of hydrogen pipe couplers. Cost is barely addressed.
- The approach should start with more clarity about challenges with existing piping and coupling systems.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.3** for its accomplishments and progress.

- Progress seems to be strong, and it appears that key initial decisions have been made successfully with regard to design aspects (all-plastic versus composite design). In particular, the key 2016 go/no-go testing targets were all met. All partners appear to be contributing well. It will be good to see the FEA modeling results next year.
- The current design has achieved pressure and leakage goals and is on track to meet other goals. The design concept maximized use of existing design coupler technology. The use of electricity to melt/cure thermoplastic/thermoset material for sealing is an elegant solution. While cost analysis has not yet been conducted, the design is expected to be low-cost and implemented quickly in the field (<30 minutes).
- An appropriate coupler has been identified as critical for the success of any hydrogen pipeline based on reinforced thermoplastic pipe. The performers have made significant progress toward development of this coupler using an innovative approach.
- The project is funded at about $1.8 million, cost-shared, with a federal cost of $1.5 million. This seems generous, but obviously such hardware will necessarily demand strict manufacturing standards. Such specifications were not discussed. Progress seems apparent, and technical targets were achieved. Of course, the big question is durability, with the target set to 50 years, and it will take decades before convincing durability has been demonstrated. There are no assurances with that important target. The design involves "electrofusion" of a thermoplastic-coated plastic, polyethylene, and fiberglass-enforced polyethylene. Apparently the polymer-coated wire is wound around the tubing end, and the electricity flows through the wire, resistance heating, to "fuse" the connector to the tube. Automated Dynamics staff seem to know what they are doing and documented passing all go/no-go criteria. As of this presentation, required progress was demonstrated.
- The first go/no-go was passed, according to slide 8's first bullet, but slide 7 shows the go/no-go as "on track" for December 2017. The prototype has been fabricated and passed initial testing.
- The work addresses the new coupler but does not attempt to quantify the potential cost benefits. It is unclear whether there are benchmarks on traditional pipelines that could be used for comparison.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.2** for its collaboration and coordination.

- The collaborations with Savannah River National Laboratory (SRNL) for testing, NOV for pipes and components, and recently, Materials Research & Design (MR&D) for modeling appear to create a strong team with excellent capabilities for the development of the coupler. A higher score would have been given if there were an established pipeline "owner" or "end user" on the team who could provide actual in-application demonstration for the new design.
- It is clear that Automated Dynamics has established excellent working relationships with SRNL (development partner) and NOV (pipe manufacturer). When the researchers identified that fatigue was the primary issue that needed to be addressed, they brought on another partner (MR&D) to support fatigue testing.
- Although it is understood that this project applies to hydrogen pipelines, involvement of a hydrogen fueling station "expert" would be beneficial. Current collaboration outside the project team is not evident, but development of additional partners is underway.
- NOV is an experienced partner and a good addition to the team. Not much other collaboration is indicated (other than among project team members).
- There seems to be good collaboration using each of the partners' expertise to fabricate the new coupler.
- Collaboration was not well described. One of the partners was DOE, the sponsor, so that does not count. SRNL was involved, but their role was not described. The assumption is that they had minimal technical roles, but that is not necessarily the case. NOV is an oilfield supplier, certainly people who know how to join pipes. Role and participation were not discussed.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.0** for its relevance/potential impact.

- Many people in the global community are scheming about a hydrogen economy. The DOE's H_2@ Scale is one example. Bringing hydrogen into the urban environment is probably far safer than bringing in gasoline. Even so, a significant hydrogen "event" is not something desired. The impact of this project, if successful, will never be mentioned but is still essential. No one will report that "no hydrogen pipelines burst today." So this could turn out to be money well spent. There is no way to compare this design with competing designs. Even so, the engineering appeared credible and well done. One suspects the highest risk to hydrogen pipelines will be a backhoe, and safety will be much the result of careful documentation and regulation, with competent management. Certainly, the pipes must not leak, but they also must be protected from malpractice.
- The project is relevant to achieving hydrogen delivery goals. Existing coupler technology will require maintenance for underground service. The project projects a 50-year life for the subject coupling (to be validated in 2018).
- Focus is on the coupler: exactly where it should be, as the coupler is the slow point of the installation process and a failure point source. Achievement of a 50-year, no-check lifetime would be a significant pipeline advance.
- The reinforced thermoplastic pipe is one potential material approach that is being considered for hydrogen pipelines. Thus, even if successful, the coupler being developed will be viable only if the reinforced pipe approach is successfully developed and the cost of the reinforced pipe is reduced to required levels.
- To those with little expertise in pipelines, it is not at all clear how the developed coupler will be installed, and the electrofusion process initiated, on an already-underground pipe coupling. Thus, it is hard to understand how the pursued approach fully addresses the stated need (maintaining existing underground seal components). In the larger picture, the effort seems to clearly address future needs relative to build-out of a pipeline infrastructure with characteristics necessary for hydrogen service.
- The potential impact to total installed costs needs to be quantified more clearly.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- Future work appears to be straightforward, with the need to finalize design elements and complete required mechanical testing. One element that the presenter mentioned, but that is not shown on the "Future Work" slide, is a cost analysis. In the application, it seems critical, and DOE must be able to ultimately judge whether the new solution will be cost-effective, relative to overall infrastructure cost targets. The results of the FEA modeling, as related to the stated need for a 50-year life, are anticipated with interest.
- The primary focus of work planned for the next year is, and should be, focused on addressing the question of fatigue life. It will also be important for the manufacturing process and manufacturing cost of the coupler to be considered. A stated goal of the project is to take the coupler technology from technology readiness level (TRL) 3 to TRL 5. It would be worthwhile for the performer to define the transition plan for taking the technology all the way to TRL 9.
- Future work is predictable: complete the design and make prototypes. Fatigue testing brings risk to the enterprise and will be addressed. In the end, the task is to bring the coupler from a TRL 3 to a TRL 5, a good progression forward.
- The safety aspects should be the first issues to be addressed, and this seems to be the case.
- The milestone chart details next steps very concisely.
- Future work involves validation testing of the design for repeatability in terms of fabrication and performance/durability. Fatigue testing to failure will be performed to establish 50-year service life. It is not at all clear how the tests will be performed, under what conditions, and what criteria will be applied. It is unclear whether there is an established American Society for Testing and Materials or ASME protocol. Slide 12 looks like the basis for testing. Future work also includes development of relationships for commercialization.

Project strengths:

- This is a good team, with testing, components, modeling, and industry knowledge all well covered. Leveraging the prior project to the fullest extent is a strength. Capabilities and knowledge at SRNL are strengths—it is good to see leveraging of laboratory capabilities.
- This is a simple design concept with fast field installation and flexible project execution to allow changes of design without imperiling the schedule.
- Collaboration among the team, a pragmatic approach to development, and an understanding of the technology are all strengths.
- The project offers the potential to join pipes more quickly, saving time.
- There is a good understanding of design requirements and approaches.
- The staff at Automated Dynamics seem excellent.

Project weaknesses:

- It is not clear how the pursued solution will be relevant for back-fitting an already-underground pipe. This detail should have been made clear. The lack of a specific end user for actual in-field testing as a current weakness should be addressed over the next year.
- The budget seems a bit high for design/fabrication/testing of a component with limited size, limited cost, and non-exotic materials. The presenter (partially) addressed a question about the 0.5% leakage target. Actual leakage should be presented in same units as a goal, and the basis for the numerical target should be discussed (even though this target comes from DOE). There is concern that the target is not low enough.
- There is no baseline cost data for comparison. The team should offer a comparison of current to future costs and the project's impact on total cost. It is unclear whether there are well-published data on current costs. New pipe material could outweigh the benefits of a coupler. It is not clear how the new pipe cost compares with steel pipe.
- Utilization of the coupler technology depends on other successful transitions of reinforced thermoplastic pipe for hydrogen pipelines.
- A minor weakness is the apparent lack of refueling station perspective.

Recommendations for additions/deletions to project scope:

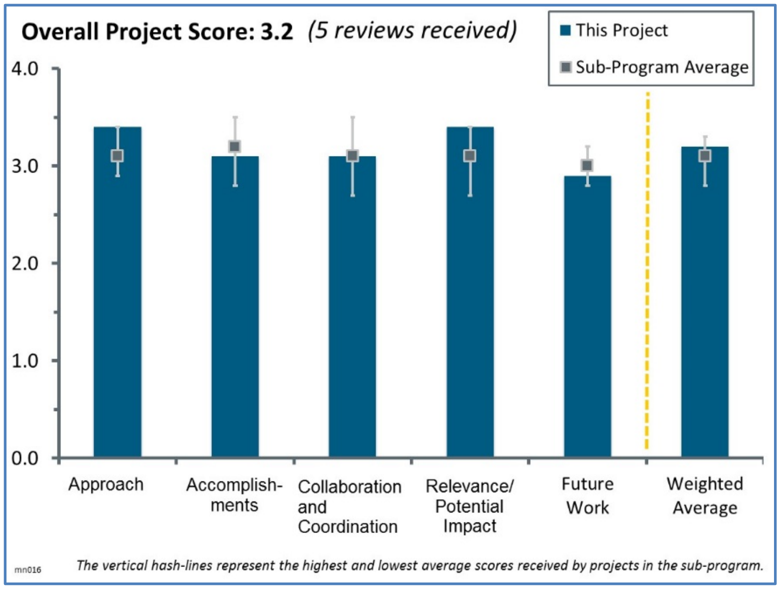
- It seems like Automated Dynamics researchers have defined a set of tasks that lead to technical feasibility assessment. They do not seem to be unsure of their design. Therefore, their concluding tasks are appropriate and do not need to be changed. This project is focused on a specific engineering hardware solution and evaluating the proposed hardware.
- Total cost stack should be developed for traditional piping materials and joining systems for benchmarking. Expected cost versus benefit for a new system should be developed, if the project moves through all gates.
- It is recommended that DOE ensure that a cost model is presented and that in-field testing is performed with an end user. These may be planned, but it was not clear from the presentation.
- Testing should be accelerated as much as possible to allow introduction of (minor) design changes (and re-testing) within the three-year project timeframe, should they be needed.
- Cost analysis and transition planning should be added.

Project #MN-016: In-Line Quality Control of Polymer Electrolyte Membrane Materials

Paul Yelvington; Mainstream Engineering

Brief Summary of Project:

With the goal of improving the reliability and reducing the cost of automotive fuel cell stacks, this project seeks to improve in-line quality control technologies that are used in the manufacture of polymer electrolyte membrane (PEM) materials. To achieve this goal, the project team will build a prototype system capable of simultaneously measuring defects in a moving membrane web and membrane thickness over the full web width. The developed system will scan the manufactured membrane with 100% coverage, marking and logging defective regions.



Question 1: Approach to performing the work

This project was rated **3.4** for its approach.

- The investigated approach is appropriate to address the main barriers and to reach the technical targets.
- The approach and testing plan are basic and elegantly simple.
- The approach is exploratory and seems usual and expected. The concentration on camera speed was unexpected. Again, the approach to address optical issues (camera speed) seems well thought out and correct.
- Automated optical membrane inspection is an obvious method that needs to be developed for high-speed quality assurance/quality control.
- Mainstream Engineering should provide a better understanding of material defects and impact on downstream processes, allowing for improved process control.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.1** for its accomplishments and progress.

- The progress seems satisfactory. The technique (cross-polarization) is complicated and perhaps difficult to use effectively because of localized strain in the polymer material. Even so, there is much potential in this specific spectrometric technique, and it may take time to explore the full possibility and scope. Certainly this addresses DOE goals of getting manufacturing costs lowered. It is very foolish to use inferior membrane samples to formulate membrane, and the membrane electrode assemblies (MEAs) would be doomed to fail. It is far more intelligent to screen membrane samples and eliminate bad material.
- This Small Business Innovation Research project has made significant progress towards developing high-speed, polarized light inspection methods.
- There was good progress at the midpoint of the project, although the web speed is only half of the target, and the defect size is much larger than the target. Nonetheless, the approach is very promising.
- Progress is good regarding the defect detection in particular for supported membranes, but no clear evidence of progress has been presented on membrane thickness determination or on other membrane applications (same slides as last year). For the membrane thickness determination, it would be

interesting to study the sensitivity of this measurement for lower membrane thicknesses (<15 µm), as the current trend is. The National Renewable Energy Laboratory (NREL) has indicated that defect sizes lower than 10 µm have no effect on performance. If so, then it is not clear why the remaining target of defect detection is at <4 µm at 100 feet/min.
- The project is on track.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.1** for its collaboration and coordination.

- The project is a good example of technology transfer from a national laboratory to a small business.
- This project collaborates with NREL and with those NREL staff working on manufacturing. Indeed, there are somewhat parallel NREL activities that support these efforts. The project also utilizes Dr. Harris, who prepares test samples. However, there are many endeavors that produce large areas of polymer film, and there did not seem to be any interaction with the technologists who are capable in that area.
- Incorporation of three different groups ensures consideration of a variety of perspectives/ideas. The project would have benefited from incorporation of an industrial partner.
- Collaboration with NREL and Georgia Institute of Technology appears well coordinated. Collaborations with MEA manufacturers would be appreciated.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.4** for its relevance/potential impact.

- The project is highly relevant to the DOE Fuel Cell Technologies Office goals. In-line defect detection is critical to roll-to-roll (R2R) processing, and R2R processing is critical to low system cost.
- The relevance and potential impact of this in-line defect determination is of most importance to reach MEA cost targets as performance and lifetime targets.
- The project will help membrane manufacturers identify flaws that limit fuel cell durability.
- Useful fuel cell systems require useful components, and the soundness of materials needs to be assessed throughout the manufacturing process. Defective membranes need to be discovered and discarded early on in the process, well before the expensive catalyst ink is deposited. This technique for screening membranes has potential for impact in lowering device costs. The emphasis here is the use of cross-polarization spectroscopy to evaluate fuel cell components in an R2R process. Clearly this is just one of many options for such quality control technology. There was no discussion about alternative approaches.
- It is unclear whether the expected outcomes can be better quantified as to how much cost impact could result from better process control. The current cost of quality for various defects is not clear.

Question 5: Proposed future work

This project was rated **2.9** for its proposed future work.

- The future proposed work seems appropriate and worthwhile. Improvements, both in hardware and software, continue to open up new possibilities for detection of a variety of parameters. One interesting measurement is the thickness of the material. This is important because “thinning” of membrane materials can precede the beginning of crossover leakage. Additional analysis of the cross-polarization optics seems useful and doable. Some of the tasks involve “scale-up” to large sizes and higher speeds. That may be politically necessary, but the questions should remain focused on what you can measure and not how fast you can measure. Speed is easily addressed with multiple cameras. The issues with “defects” at this time are whether one can see them and how serious they are. It is also important to discern whether the “defects” are the result of manufacturing technology or result from improper handling, shipping, and storage of subject materials.
- Real web testing and feedback cost data seem critical to understanding the cost benefits and practical implementation of learnings.

- The Gantt chart lays out the next steps in the project, but the timeline is confusing. This is a three-year project, but the Gantt chart shows only two years. Current status is not clear. The “Remaining Challenges” list is very clear, concise, and identifies the essence of each barrier.
- The future work is generally good; however, it should address methods to assess smaller defects than what is presently proposed for next year’s work.
- The proposed future work is just a copy/paste of last year’s review. Specific work for the coming year has not been presented.

Project strengths:

- The Mainstream Engineering team seems fully competent. Dr. Tequila Harris has learned how to create “defects” in subject membranes in very small sizes and in ways that are precise and reproducible. It appears that Mainstream Engineering is able to find the micro defects that Dr. Harris creates. This is a good team.
- The technology of defect detection and its maturity evolution are strengths. Collaboration with NREL is of high value to speed up the development and the validation of this technology. This technology may be applied on membranes other than for fuel cells.
- This is a practical approach to methods used to identify defects. The project has stayed on track and maintained focus on key priorities.
- This is a seemingly effective solution to an important in-line diagnostic problem. The project team is well balanced.
- The science and engineering approach is very sound.

Project weaknesses:

- This sort of thoughtful quality control technology needs to extend to all of the fuel cell materials, and techniques need to be developed that result in useful tools for complete membrane and electrode materials, including components such as the diffusion layer. Much as it makes no sense to continue manufacture with bad membranes, it makes no sense to assemble a stack with a bad MEA. Bad actors need to be eliminated as early as possible. There is much for Mainstream Engineering to accomplish, and much left undone.
- Current performance levels are significantly lower than targets, although the targets may exceed what is operationally needed.
- Closer collaboration with MEA manufacturers would be appreciated in order to validate the technology on real industrial web lines.
- More collaboration with MN-001 seems to be an opportunity for additional learnings.
- Collaboration with a membrane manufacturer would strengthen the project.

Recommendations for additions/deletions to project scope:

- Mainstream Engineering should revisit the level of detection truly needed. Mainstream Engineering should address the following:
    - The scanning speed reported in area per minute should be defined more fully/completely.
    - There should be fuller discussion of whether computer processing speed will be a limited factor.
    - The effect of membrane thickness on performance (especially thickness measurement and in light of the current generation of membranes being substantially thinner than those used within the project) should be defined more fully.
    - The effect of supported (versus unsupported) membranes on performance (since the support is expected to reduce detection performance) should be defined more fully.
    - The statement that 40 µm pinholes do not have a performance impact should be revisited/ explained.
    - The project should test using supported 10–20 µm membranes.
    - The total in-line diagnostic system capital cost should be estimated (for a specified web width and web speed).
- It would be interesting to provide information on the cost of this technology once implemented on an industrial web line and the impact of this quality control on the cost of an MEA. How to follow the evolution of cameras, filters, and computers—which is very fast—is unclear, as is how that evolution will affect, or not, the current developments.

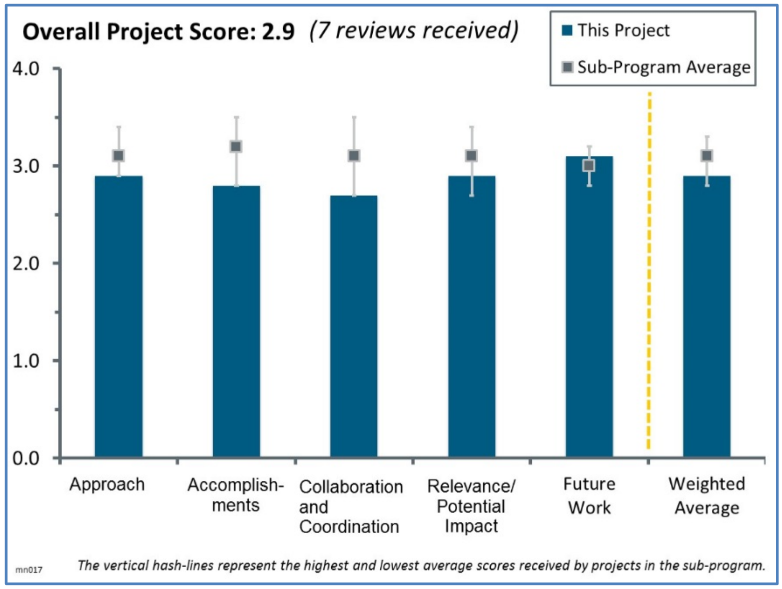
- It is appropriate and necessary to complete the work. There is nothing obvious to delete. Additions are perhaps another project.
- The project should ensure real web data are developed and gather actual quality versus the impact of costs in downstream processing.
- The project should identify a membrane manufacturer and test the technology on production-sized equipment.

Project #MN-017: Manufacturing Competitiveness Analysis for Hydrogen Refueling Stations

Margaret Mann; National Renewable Energy Laboratory

Brief Summary of Project:

This project contributes to manufacturing cost analysis for major hydrogen refueling station (HRS) systems. The project will work with the Fuel Cell Technologies Office to establish HRS manufacturing cost models and a manufacturing cost framework to study costs of HRS systems, including the compressor, storage tanks, chiller and heat exchanger, and dispenser. Investigators will assist in highlighting potential cost reductions in the manufacturing phase for future research and development (R&D) projects in this field.



Question 1: Approach to performing the work

This project was rated **2.9** for its approach.

- The project addresses the key components that drive the HRS costs and provides good detail on cost breakdown, which is consistent with industry experience and data.
- The approach is comprehensive and well constructed. Benchmarking against existing products is a very important step.
- The approach is rather ordinary. There is nothing particularly incorrect, but the theme tends to ignore that HRSs are now deployed in significant numbers globally. There are credible global concerns that are designing, collecting parts, assembling, and installing these stations. One would expect that the opening play would be to evaluate current hardware. It is also apparent that market opportunities are influenced by codes and standards, and those are hardly standardized in the global community. Also, the idea of subsidies and incentives was not described. Certainly several of the concerns now selling fuel cell vehicles are also encouraging HRSs. This project tended to conclude that an HRS has a fixed design, with a certain number of identified components. The approach is acceptable, but if successful, the results may not be exactly what is being experienced in the marketplace. There seems to be a lack of concern for durability, as well as any reaction to the concern that HRSs have some difficulties in reliability.
- It is not certain that there is any value in doing a study of HRSs between four national laboratories without the involvement of any industry (any one from slide 36) or Strategic Analysis, Inc. It seems like the California Energy Commission (CEC) is well ahead of the U.S. Department of Energy in this regard (slide 42). Perhaps DOE should use the CEC data from all the deployments and not have a separate project on this.
- Slide 5 should be more detailed to expand on the approach. It is not clear what (quantitative) metrics will be used to assess competitiveness. It is not clear what cost estimation methodologies are being used (e.g., Design for Manufacture and Assembly). Key milestones and go/no-go's must be presented with dates. It is unclear how international inputs are obtained and what industry (original equipment manufacturers and suppliers) input is used.
- The proposed approach seems to be working in particular for the manufacturing cost model but not for the HRS rollouts and trade flows, where data appear not at all complete.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **2.8** for its accomplishments and progress.

- There was considerable discussion about global trade in components that are useful in HRSs. These data were interesting, even though it was apparent that those regions that are installing HRSs dominate the picture: the European Union, the United States, Japan, etc.
  - The team decided to focus on cost reduction of components, specifically a hydrogen heat exchanger and a compressor. It was interesting that "labor" costs are always a small component, even though trivial differences in labor costs are discussed as if they were significant. Far more significant was "profit margin" and the fact that high profit margins in some companies must result in lack of competiveness in those places.
  - There was no discussion about the cost of a "gasoline refueling station," which, although clearly less, is far from zero. It is interesting that gasoline is almost always dispensed from buried tanks, which are conveniently out of sight and have no footprint.
  - Hydrogen tanks tend to be inconveniently large and troublesome. The polymer electrolyte membrane (PEM) electrolyzer costs were interesting, especially the cost variation with volume. It would have been interesting to include costs of contemporary commercial electrolyzers at times that high-current devices have some predictive insight into the scaling issue.
- Trade flow maps are a very useful illustration of global trends. From the question-and-answer session, the "Rest of the World" category also includes trade flow of unknown nationality. Given the size of this flow, it seems reasonable for more work to be done to figure out where those products come from and whether they are from truly from the "Rest of the World" or primarily from Europe/Asia/North America.
  - The detailed component and cost list for the refueling station is a good addition.
  - It is not clear how margin is applied/varies with manufacturing rate. The basis of manufacturing rate cost reduction ("20% discount per 10x increase in purchased quantity") is not explained.
  - From the country-to-country comparisons, the part costs appear identical. It is unclear whether this is a reasonable assumption. Also, it is noted that Mexico has an advantage in building costs, yet the building category is not even visible in the stacked column chart.
- When comparing with the 2016 presentation, only a few changes and new information are noticed. This is consistent with no change in the same 75% complete project as in 2016.
  - New information is about PEM electrolyzer stack cost. The added value of this information for achieving the project objectives is not demonstrated. This cost analysis may already have been done in the Hydrogen Production sub-program.
  - The trade flow mapping is difficult to understand, with clear missing information. For instance, Japanese bars are very small, whereas more than 90 HRSs are in operation with a majority of domestic production. France is only exporting, whereas 15 HRSs are in operation with a majority of domestic production. Norway is mentioned but with no bar at all. Germany has high bars, but only 23 HRSs were in operation at the end of 2016, plus 10 in commissioning.
  - Dispenser cost analysis has focused on H35 and dual H35/H70. It is not clear why the team did not focus on single-hose dispenser H70.
  - It is not clear how this project addresses the current barriers.
- The estimated minimum sustainable price (MSP) of several key components was presented geographically to show where the United States stands with respect to international competition. References for the international data would be helpful. HRS capital cost is reported by geographical region and capacity. Slide 7 energy flows should be revisited and verified, especially Japan and the "Rest of the World" (it probably is not important for the project).
- Data seemed unreliable since a number of well-established international stations were not accounted for. Intra-country trade appears very large but not analyzed. The "Rest of the World" is too large to be lumped together and needs to be analyzed.
- It does not appear that the effects of standardization and scale were clearly addressed. These should be key drivers for reducing costs.
- Much work has been done on this project, but there was no clear slide with milestones to quantify progress.

Question 3: Collaboration and coordination with other institutions

This project was rated **2.7** for its collaboration and coordination.

- The National Renewable Energy Laboratory (NREL), as usual, contacted a wide range of experts, and the collaboration is obviously well done. It was mentioned that NREL needs to "involve more organizations" in the hydrogen refueling study. It would make sense to get into Chinese technology and data, as there is some evidence that the technologists there have done recent work to reduce cost and enhance durability. It would also be interesting to understand technology deployed by the U.S. Navy, such as their "oxygen generating plants," used for naval submarines to supply oxygen for the crew, with byproduct hydrogen production.
- In addition to the three national laboratories on the project, NREL has collaborated with a suitable mix of component suppliers and developers.
- Collaborations include three national laboratories and "other industry advisors and experts." "Industry experts" include foreign and domestic suppliers of compressors and HRS installations. Additional experts in other areas would add credibility to the analysis. Recognition of other cost studies might provide insight (e.g., Battelle, Strategic Analysis).
- There was good collaboration on the diffusion-bonded compact heat exchanger (DCHE). However, there should be more work with industry to understand how scale could motivate more competition and bring others into the space. Perhaps interviewing companies that have the capabilities, but little incentive without scale, could provide insight as to how much competition could result (e.g., nozzles, hoses, dispenser systems).
- No clear new, complementary collaboration since last year has been presented, whereas there is a need to involve at least some HRS electrolyzer manufacturers. International collaboration is focused on Japan, and none is mentioned with Europe. This would allow more precise data on trade flows.
- This needs to be significantly strengthened. The team needs to add at least one industry that actually deploys HRSs. The project should come up with a clear plan to leverage the information with CEC.
- International contacts need to be strengthened with the aim of obtaining a better understanding of their current position.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **2.9** for its relevance/potential impact.

- Cost information, broken down into the components, gives a clear understanding of the cost of an HRS and will be valuable for focusing future R&D on the critical components.
- It is well recognized that it is hard to sell fuel cell vehicles in places where gaseous hydrogen is unavailable, so there is considerable possible impact resulting from this project. NREL is well positioned to evaluate a wide range of hydrogen production techniques. Therefore, this study can produce better understanding of costs and routes to reduce costs. It would be interesting to bring in some of the results of monetary considerations resulting from improved human health as a result of fuel cell vehicles cleaning up the urban atmosphere (work done by Lawrence Berkeley National Laboratory). NREL should consider the "full cost" of technology, now and then, to supplement detailed cost for one specific technology.
- The project cost and competitiveness analysis will provide insight into HRS cost structures, high-cost or high-uncertainty components, and the U.S. technoeconomic position, thus revealing high-impact R&D opportunities for DOE.
- Understanding of HRS cost drivers, issues, and projected future costs is critical to the fulfillment of the DOE Fuel Cell Technologies Office mission.
- Lowering costs of HRSs and accelerating deployment is a worthy goal. However, it is unclear how this project achieves that goal.
- The project should create compelling arguments for standardization and scale. Actionable results are not clear.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- Future work is the logical continuation of manufacturing cost analysis for the remaining key HRS components and continuation of development of industrial relationships. Future work also includes investigation of the effect of qualitative factors.
- Proposed future work is right on. There is a current return to methanol and considerable improvements in small-scale methanol production hardware, so a look at methanol reformers, with an eye to the future, might be valuable. It would be interesting to fully understand the costs of production and distribution of other fuels in the United States. Obviously the methane distribution system is universal. Someone pays for installation of the distribution system. Gasoline is also broadly distributed. The costs are covered somehow. There might be some learning possible and perhaps better routes to finance HRSs regardless of what they cost.
- Future work should include electrolyzer manufacturers or people having participated in previous projects on electrolysis cost analysis to avoid duplications. Regarding the study on hydrogen prices, operating expenses (OPEX) should be taken into account. It would be interesting to analyze the impact of future technologies on the associated OPEX of these new HRSs. International trade flow activity should be decreased or even stopped, as it is difficult to see how it contributes to leverage the current barriers.
- Examination (and comparison) of PEMs and alkaline electrolyzers is of value.
- Standardization and scale should be a key priority this year.
- The project has clearly identified the remaining challenges and barriers.
- The electrolysis system needs to incorporate compression to achieve 350 or 700 bar.

Project strengths:

- NREL has grown strong capabilities in technology evaluation. The fact that NREL also has capable, stable technologists working on new stuff is very much part of that excellence. It would be hard to suggest a better place to dive deeply into the costs of hydrogen technology. The keynote presentation at the 2017 DOE Hydrogen and Fuel Cells Program Annual Merit Review suggested that the excellence in the national laboratories in the United States is recognized. The project team is fortunate to have the NREL team on board.
- This project shows a good understanding of component trade flows and good accurate details on dispenser costs. Heat exchanger cost and production process analysis provides good insight into producing this key component that drives a large portion of the HRS OPEX.
- This is a comprehensive and methodically executed project with a clear display of results and (most) key assumptions. The comprehensive integration of manufacturing cost with trade flows to assess potential cost differences between countries is a project strength.
- Comparison and analysis of component costs in other countries with those in the United States are revealing and instructive.
- The cost analysis of the different components of an HRS is a real strength of this project.
- The cost analysis is extensive.

Project weaknesses:

- At times, NREL is too U.S.-centric and perhaps not fully aware of others in the global community. The results showing global trade are a good start, as was clear in this presentation. It makes sense to explore how others are financing their hydrogen refueling facilities and seek to get some "real" numbers about actual costs. How these funding techniques affect the cost of fuel for the consumer is the only thing that really matters. This study was all about capital expenditures (CAPEX). There needs to be some thought about OPEX and the real costs required to service and maintain hardware so that required reliability (filling up a customer's tank when the customer wants to do that) is achieved.
- There is not enough industry participation. This would be helpful in understanding what market conditions would bring more players into these new markets. OPEX is not taken into account with CAPEX. For example, the DCHE may be more expensive, but refrigeration power costs could be greatly reduced. It is

unclear how the project team would address this. The project seems to be wandering in many directions and should be focused on HRS costs.
- Use of weighted average cost of capital (WACC) is not well explained, and WACC may not be an appropriate value to use within the analysis. While some new technologies were contemplated (i.e., compact heat exchangers), overall, the impact of new technology on future cost of systems is not explored.
- International trade flows appear not to give the real picture of the current situation. The project addresses the supply chain, but no information is given, either on the name of component suppliers or on the number of manufacturers for each component.
- The right partnership with industry is needed, as is more collaboration with CEC to provide DOE more value.
- A wider variety of industry partners would bolster the analysis and resulting conclusions.
- Understanding of international capabilities is lacking.

Recommendations for additions/deletions to project scope:

- The following additions are recommended:
  - Additional new technologies (at least as part of the sensitivity analysis) should be explored as a way of illustrating cost drivers and the potential for future cost reduction.
  - Additional cost benchmarking is needed for all system components. Inclusion of graphs (in backup material) was a good start, but the data does not differentiate between competing technologies and thereby potentially masks cost trends.
  - The "Rest of World" trade flow data should be further identified.
  - It is clear from the country-to-country comparison that WACC is the driving factor in the MSP differences. More attention needs to be paid to the use of WACC and also to whether the resulting cost differences are substantial enough to have significant impact on trade flow.
  - The process flow diagram would be improved with the addition of key processing parameters for each step.
  - Microchannel heat exchangers should be cost-benchmarked against a conventional 16 kW heat exchanger.
- NREL should stay focused on HRS costs. Onsite production seems to stray from the original scope. The analysts should concentrate on standardization and scale effect. They should allow OPEX to be part of the analysis and use the DCHE work as an example. More industrial players should be brought into the discussion and results development.
- NREL should dive deeper into the global technology base, with concerns for financing routes, actual costs, and other issues that are critical in refueling systems.
- How the results of this study will be disseminated and transferred to the industry should be described.

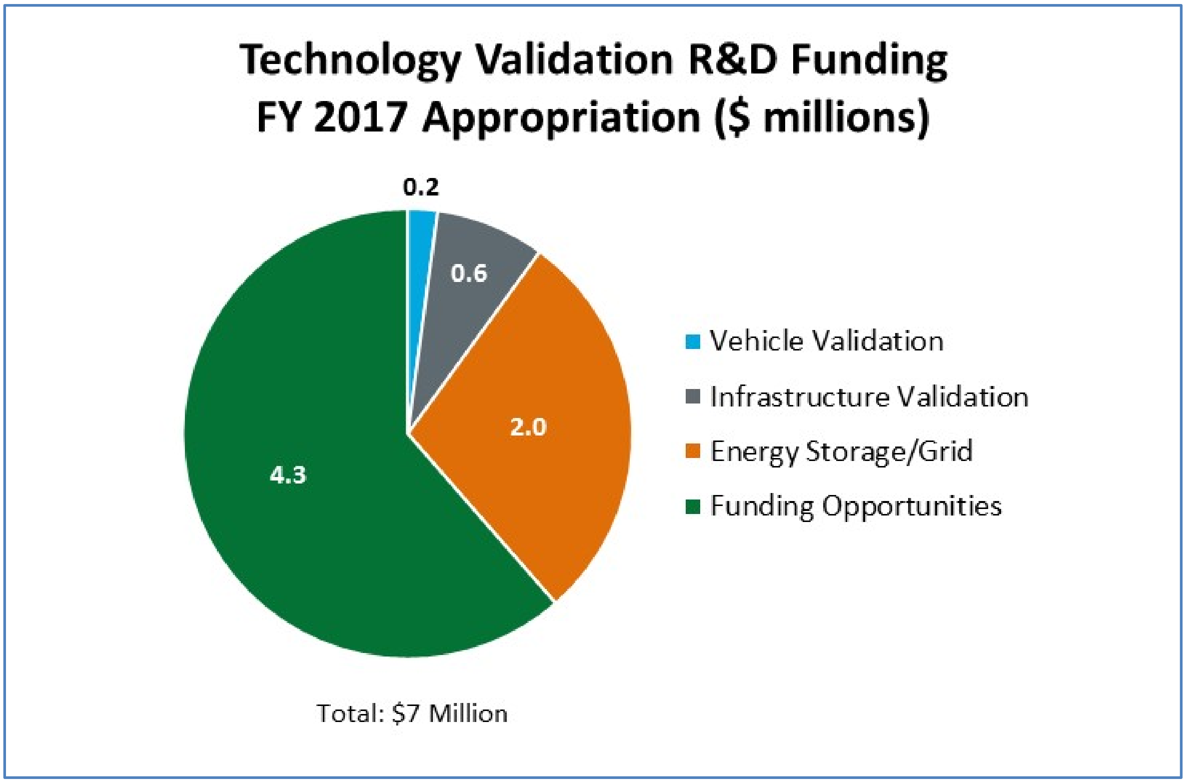
2017 – Technology Validation
Summary of Annual Merit Review of the Technology Validation Sub-Program

Summary of Reviewer Comments on the Technology Validation Sub-Program:

In general, reviewers commented that the Technology Validation sub-program is well managed, with a balanced set of projects that is both appropriately broad and flexible enough to consider market changes. It was noted that this sub-program is well informed of real-world challenges and addresses both fundamental and practical issues. While the reviewers valued the accomplishments presented, it was noted that progress in projects was not clearly benchmarked against the past year. Reviewers further recommended that failures (and related lessons learned) should also be reported, projects that have diminished in relevance because of changes in the landscape should be pared down, and interactions with utilities should be strengthened.

Technology Validation Funding:

The fiscal year (FY) 2017 Technology Validation sub-program funding totaled $7 million. This funding enabled the continuation of data collection and analysis from fuel cells operating in transportation applications (e.g., light-duty vehicles, medium- and heavy-duty trucks, and buses), while validating and evaluating hydrogen infrastructure (e.g., fueling stations, components, and delivery/dispensing). In coordination with the Office of Electricity and other offices in the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy, major focus areas in FY 2017 were hydrogen-based energy storage and grid integration activities, including Hydrogen at Scale ("H2@ Scale"), an approach to enable the widespread use of hydrogen across multiple sectors, and the national laboratory cooperative research and development agreement (CRADA) call.



Majority of Reviewer Comments and Recommendations:

The 14 Technology Validation sub-program projects had a maximum score of 3.7, a minimum score of 3.0, and an average score of 3.4. Key strengths identified by reviewers across the Technology Validation projects were the collaborations with key partners and the potential for the projects to contribute valuable data, enabling stakeholders to gain enhanced insights and successfully deploy hydrogen and fuel cell technologies.

Transportation Applications: Three projects relating to transportation applications were reviewed, with an average score of 3.5. The highest-ranked project in this grouping received a score of 3.7, while the lowest-ranked project scored 3.2.

Reviewers noted that the ***fuel cell electric vehicle data collection*** project is a well-designed project that continues to provide high-quality data. The move toward developing a predictive fueling model was praised as a progressive approach to providing the kind of information that could be most useful today. Reviewers observed that interaction with the participating original equipment manufacturers went above and beyond collecting and submitting data, but expressed concern over the age of the project and whether industry needs it as much now as it has in the past ten years.

The learnings from the ***fuel cell electric bus data collection*** project were deemed also to hold value in serving as a context for assessing the technology potential in the trucking industry. Reviewers commented that the project provides quality data to decision makers and that team members maintain good collaborations with transit agencies. The newly developed technology maintenance readiness level (TMRL) guidelines were highly praised. Reviewers recommended conducting more comparisons with battery-based buses and providing data on fueling infrastructure availability for fuel cell buses.

A well-designed truck platform and detailed simulations of actual routes and fuel requirements were considered strengths of the ***fuel cell hybrid electric delivery van*** project. However, reviewers expressed concern over the project's delayed start and uncertainty regarding remaining cost share. It was suggested that a fueling test should be scheduled and that more hydrogen tank suppliers should be involved in supplying a new "off-the-shelf" tank.

Infrastructure and H2FIRST: Six projects focusing on hydrogen infrastructure were reviewed, with an average score of 3.4. The highest-ranked project in this category received a score of 3.6, while the lowest-ranked project scored 3.0.

The project team involved in the ***hydrogen station data collection*** project was praised for achieving improved data quality, working well with the many collaborators, and having the ability to change and remain relevant as the industry matures. Suggestions included categorizing data based on station technology, collecting certain information more often (e.g., monthly), and working with entities deploying hydrogen stations in the northeastern United States. Reviewers also commented that they would like to see additional analysis on how station capacity utilization affects costs per kilogram for each station type, as well as hydrogen losses in the system for each station type.

While acknowledging that the ***performance evaluation of delivered hydrogen fueling stations*** project has made progress in installing and collecting data of value on two stations, reviewers expressed concern over permitting challenges and whether there was adequate time for data collection on the remaining three stations. They further suggested that the project team outline a specific plan to communicate lessons learned on subjects such as system development, network communications, and commissioning.

Reviewers saw the ***advanced hydrogen mobile fueler*** as an enabler in filling infrastructure gaps, with design features considered to be well-thought-out. Suggestions included performing Hydrogen Station Equipment Performance (HyStEP) testing to prove fueling performance per SAE J2601 requirements, engaging Northeastern U.S. Weights and Measures Association officials with their counterparts in California, and improving the user interface for the dispenser to support unattended fueling.

The test rig developed and the use of statistical methods for characterization were regarded as unique value-added capabilities of the ***hydrogen meter benchmark testing*** project. Reviewers strongly advised performing some complete J2601 fills, and they stressed that the meter manufacturers should be involved as actual project partners.

Reviewers commented that the results of the ***hydrogen component validation*** project can assist with addressing issues that deter the progress of hydrogen stations. It was suggested that a more representative cross-section of the industry (e.g., various types of station designs and automakers) could be included to provide feedback, and that collaboration with the station developers could be increased. Reviewers also suggested providing clarity around the mechanisms of component failures, investigating high-throughput stations and dispenser failures, developing best practices for evaluating power use, and expanding data collection beyond compressors to include other failed station parts (e.g., chillers).

The ***performance and durability testing of cryogenic vessels and liquid hydrogen pump*** project was praised for collaborating with experienced project partners, but concern was raised over whether the approach will offer a competitive solution. Reviewers recommended further discussion on what could be achieved to limit hydrogen losses, and also suggested conducting a more detailed well-to-wheels analysis of boil-off and energy use.

Grid Integration and Energy Storage: Four projects focusing on grid integration and energy storage were reviewed, with an average score of 3.3. The highest-ranked project in this category received a score of 3.6, while the lowest-ranked project scored 3.0.

The ***energy dispatch controller*** project was praised for having well-designed modeling to demonstrate savings and to have shown good progress in its initial year. It was stressed that the project should include input from relevant stakeholders and end users, and that these users should be consulted during the model development phase.

The ***stationary hydrogen-vehicle-grid integrated systems modeling*** project was perceived as the core of the H2@ Scale concept, and reviewers noted that the approach provides flexibility and synergies. Reviewers strongly suggested an outreach strategy and additional discussions with grid operators, station owners, and related stakeholders, especially with regard to gaining their input on underlying model assumptions.

The ***dynamic modeling and validation of electrolyzers in real-time grid simulation*** project was commended for its unique approach to integrating modeling and hardware and for its productive collaborations with a wide range of stakeholders. Cooperation with utilities in obtaining real-time electric grid data was seen as having great value, but reviewers suggested that interactions with electrolyzer manufacturers should also take place.

The ***modular solid oxide electrolysis cell system*** project was regarded as having a progressive approach and the potential to advance the understanding of high-temperature electrolysis. Reviewers highlighted that progress has been steady and suggested that there should be a third-party validation of the system performance.

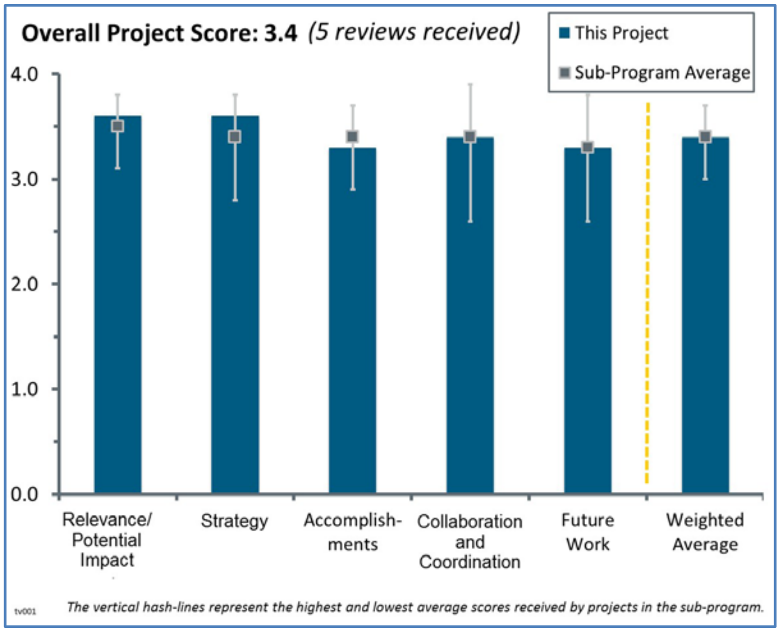
Hydrogen at Scale (H2@ Scale): The ***H2@ Scale analysis*** project was regarded as a comprehensive evaluation that uses well-established models. It received an overall score of 3.6. Reviewers expressed concern that this analysis might be too internally focused and thus encouraged the project team to seek additional collaborations with industry, consider a range of policy decisions that may add uncertainty about hydrogen market growth, and analyze nearer-term projects.

Project #TV-001: Fuel Cell Electric Vehicle Evaluation

Jennifer Kurtz; National Renewable Energy Laboratory

Brief Summary of Project:

The objectives of this project are to validate hydrogen-powered fuel cell electric vehicles (FCEVs) in real-world settings and to identify the current status and evolution of the technology. The analysis objectively assesses progress toward targets and market needs defined by the U.S. Department of Energy (DOE) and stakeholders, provides feedback to hydrogen research and development, and publishes results for key stakeholder use and investment decisions. Fiscal year 2017 objectives focus on analysis and reporting of FCEV durability, range, fuel economy, fueling behavior, and reliability.



Question 1: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.6** for its relevance/potential impact.

- The project is relevant and has many positive impacts (existing and potential) and uses within the fuel cell transportation industries. The project is a data aggregator, reporter, and information and knowledge provider about FCEVs to the industry and research and development community. This project follows and fulfills the mission and the goals of DOE: publish results about the adoption and sustained use of FCEVs and provide information for investor decision-making. This project provides an evolutionary perspective about FCEVs. The real-world use of FCEVs is reported. Industrial players need these data to articulate and evaluate FCEV usage and other aspects about the vehicles. The provision of these data assists in hydrogen refueling station planning and rollout. This project entails working with seven partners—in many cases over a long period of time—and thus represents a fairly significant population. The data collection and internal analysis is consistent with that used in 2016. The National Renewable Energy Laboratory (NREL) team provides an independent assessment of data from multiple FCEV original equipment manufacturers (OEMs). This project addresses fuel economy, range, and consumer fueling behavior, in addition to predictability and performance according to DOE requirements and metrics. OEMs send proprietary data, including voltage data, which are evaluated quarterly. Reports are published more often.
- This project is continuing to address a critical need of the DOE Hydrogen and Fuel Cells Program (the Program) in understanding the state of development of FCEVs. The project still appears to be filling a role that could not be filled adequately in the private sector, and NREL continues to be a trusted partner for automakers. However, not having Toyota contribute at this stage is a clear weakness, given Toyota’s leading role in early commercial deployments.
- The reviewer wanted to award a grade higher than 3.5, given the necessity to measure performance—something the NREL team seems to have greatly improved upon—but by definition, the 4.0 grade requires the project to have the potential to significantly advance DOE research, development, and deployment goals rather than the goal to “advance progress.” The lower grade is regrettable, but the need to stay within grading guidelines is recognized; a higher grade would have been assigned if the parameters were wider.
- The project fully supports the Program goals and objectives.

- While this project has been around for some time, it is good to see that there are changes made in the primary objectives to better align with the kind of information that could be most useful today (i.e., vehicle–station interface, because customer experience is a primary topic for vehicle OEMs at the moment).

Question 2: Strategy for technology validation and/or deployment

This project was rated **3.6** for its project design, approach to addressing barriers, feasibility, and integration with other efforts.

- The strategy for technology validation in this project hinges on the technical capability of the NREL team, the need for the information when aggregated, and a reliable source of the information. The FCEV OEMs trust the computer security used at NREL to the extent that they provide car-use data. NREL aggregates the use data with the fuel economy and fueling behavior data. The project design supports regular participation, and the participation is straightforward and continued by those involved. Data are returned to the data providers. Honda, Hyundai, and Mercedes (2008–2016) all send FCEV data to NREL. At least three OEMs have to provide enough data, or the team will not publish. Now fewer vehicles are being analyzed.
- Clearly, the NREL team has applied a critical eye toward the data provided, but more importantly, NREL appears to have improved its approach to collecting data. There are no issues on this subject.
- The project continues to focus on critical barriers in an effective manner and seems well thought out. The proposal to shift toward developing a predictive fueling model is intriguing and demonstrates the project's continuing relevance.
- The project data collection and analyses are well designed.
- The once-a-year publication (down from twice a year) seems reasonable, given that fewer vehicles are analyzed (fewer partners).

Question 3: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.3** for its accomplishments and progress.

- There are 7.1 million miles worth of data. DOE targets are not fully met, but great progress has been made. It is definitely nice to have these data compiled somewhere and to be able to access them and tell the story.
- The team has made good progress toward the project objectives; however, it is not clear how the analysis and data are used to improve technology progresses/advancements.
- Per slide 11 (the spider chart), several DOE targets are addressed: efficiency and so forth. The FCEVs have made progress toward DOE targets, but future work remains in some areas. The fueling data are used to develop a model to predict fueling demand (this is useful for hydrogen refueling station rollout).
- Against DOE goals and performance indicators, NREL progress appears to be fairly complete, i.e., NREL has done what DOE asked it to do, and its presentation of the data this year is clearer than it was in the past. However, there are a few issues:
    - NREL claims the slide 10 chart analyzes FCEVs and miles traveled since 2006, but neither the chart nor the work behind it seems to analyze anything, and in fact the NREL chart and work do nothing more than provide a year-by-year count of vehicles and miles. The chart seems to do little more than raise the presentation's slide count. Conversely, the slide 11 spider chart provides a much better view of various specifics. Slide 11 analyzes, not slide 10.
    - A number of slides discuss fuel station activities, and while it is understood why FCEV OEM data are hidden, especially when fewer than three providers are available given the nature of the competition between FCEV providers, it is much less clear why station identification data are not provided, given the absence of competition and the completely different funding model for the stations.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.4** for its collaboration and coordination.

- There seems to be very good interaction with the participating OEMs (over and above just sending them data).
- Collaboration with OEMs has been excellent.
- While the grade for relevance/potential impact was lowered based on the definition of the grades, the recognized inability for NREL to do much about coordinating with partners did much to ensure that the NREL grade for this category was not lower. From the presentation and a review of the documentation, it appears that manufacturing an FCEV qualified an organization as a partner, but the reality indicates that for this project, NREL performed almost all the work (while the partners did get to review the reports).
- The project is an excellent partner for OEMs, but not having Toyota as a partner is a real drawback.
- The collaboration does not include the one OEM that sells FCEVs, and one of the OEMs included has reported plans for new models (but does not sell or lease the new models).

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- The direction of the future work is thinking outside the box (operating a station to reduce costs). It should keep going in that direction.
- The idea to use the data collected to develop a predictive fueling model is a real step forward and shows good creative thinking by the project team on how to provide maximum value from the data collection.
- Future work includes a plan for publishing results of the number of on-road FCEVs in May 2018. Additionally, the future work includes developing and validating predictive FCEV fueling demand based on fill and drive data to decrease operations and maintenance costs, which currently exceed an average of $10,000 per month. It is not clear whether the station use can be optimized so the cost to operate a station goes down. Other future work is to include durability of the fuel cell stack (voltage degradation/drop).
- It is not clear that this project has a decision point.
- The future work is for routine results.

Project strengths:

- The dissemination of FCEV metrics is important to vehicle acceptance. A major project strength is the fact that the data and information originate from a neutral party (NREL) with no ownership of stock in the station component providers or the vehicle providers, and that data and information are disseminated. Information about how to better operate the stations based on their use is very important to the financial solvency of the hydrogen refueling industry. The value and strength of this project are clear. The output from this project is strong, and the experts who work on this project are strong; therefore, the work is used by both public and private sectors. The approach is one in which the data are shared with those who provide the data in the first place, and aggregated data are used by public and industrial groups and organizations.
- Project strengths are the high-quality data collection and the project team’s ability to track progress over a long period. The project’s value as an independent validation of FCEV progress and continued weaknesses is high.
- The project helps with business intelligence in that it can validate the information and/or provide new or different data. There is a robust procedure for securing data. The team has a long history of data collection and analysis. Jennifer Kurtz is really working to redefine the project and come up with new and innovative outcomes. It has improved over the previous year.
- The data collection and analysis are well designed.

Project weaknesses:

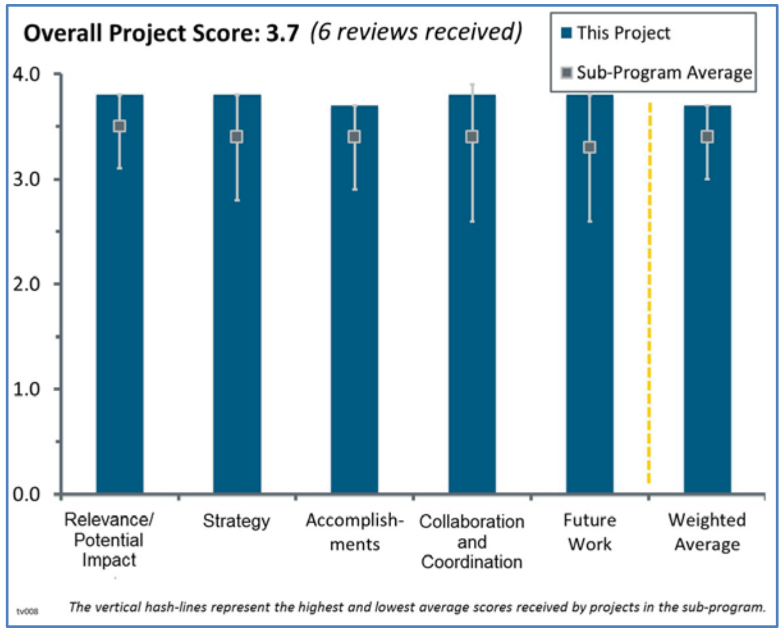
- A project weakness is the limited number of OEMs, which is largely a function of limited vehicle availability and thus not a "fault" of the project, but practically speaking, it means that there is less public access to the data results where the data cannot be sufficiently anonymized.
- The only weakness is that Toyota is not presently involved (apparently).
- A potential downside is the age of this project and whether the industry needs it as much now as in the past 10 years (even though not all DOE targets are met). The fact that there are fewer participants may be a testament to this fact.
- The project activities seem to be going on without decision points or endpoints.
- The project amounts to little more than a report; the report may be necessary, but it is still a report. This may not be NREL's fault.

Recommendations for additions/deletions to project scope:

- It is recommended that the project add a customer experience element. This would have to be voluntary, but because this is still in the early market, it might be doable. It could tie in with customer/user social media. Maybe Sandia National Laboratories could make a Facebook, Instagram, or Pinterest page for FCEV users and collect data such as vehicle use frequency, fueling frequency, and where people are going in their vehicles (for input for station locations).
- The project could have been a much better project if there had been more analysis. The slide 11 spider chart demonstrated that the NREL team can analyze, and its "Remaining Challenges & Barriers" and "Proposed Future Work" sections advise that NREL wants to analyze. It would have been nice to see more analysis in this presentation.
- The project should add metrics that the NREL experts want to add to the "Summary of Key FCEV Metrics" (slide 23). The team should also add a built-in learning capability to the approach so the NREL experts can change this evaluation from year to year (if not already included and used).

Project #TV-008: Fuel Cell Bus Evaluations

Leslie Eudy; National Renewable Energy Laboratory



Brief Summary of Project:

The objectives of this project are to validate fuel cell electric bus (FCEB) performance and cost compared to U.S. Department of Energy (DOE)/U.S. Department of Transportation (DOT) targets and conventional technologies and to document progress and lessons learned on implementing fuel cell systems in transit operations. Annual FCEB status reports compare results reported from transit partners and assess progress and needs for successful implementation of FCEBs, addressing barriers to market acceptance.

Question 1: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.8** for its relevance/potential impact.

- This project is highly relevant to the data analysis about the deployment of FCEBs, and it supports and advances the progress toward the DOE Hydrogen and Fuel Cells Program (the Program) goals and objectives for zero-emission vehicles. Analysis based on actual operating FCEBs is needed to provide a perspective for suppliers, transit agencies, and policymakers as they consider long-term commitments to deploying/using FCEBs, which are capital-intensive. The relevance and potential impact of this third-party review (neutral) is important because the upfront costs of capital equipment and the operating costs of buses are high, and from a planning perspective, people need this information so they spend their funds correctly to obtain the greatest amount of greenhouse gas emission reductions possible. In some cases, transit investments are "one-time shots," and neutral, mathematically grounded reviews and "walk-throughs" prior to investment are integral to sound directions. This project advances Program objectives; it is based on DOE and DOT metrics (i.e., the life of the power plant). This project discusses sharing components with conventional buses and is based on comparisons with the existing diesel and compressed natural gas (CNG) bus infrastructure.
- With the advent of fuel cell electric trucks under consideration as a potential alternative for limited-range battery electric trucks, the operational data collection and lessons learned documented about FCEBs in revenue service is even more essential than before. Not only will transit agencies rely on a neutral party to collect and analyze this data, the trucking world will now also need this as context to assess technology potential. On the fueling infrastructure side, because of lack of published (anticipated and/or modeled) cost information from hydrogen suppliers on medium- and heavy-duty vehicle fueling (including FCEBs), this effort is needed even more to support progress.
- Buses have been, and will continue to be, an important platform for fuel cell system commercialization. Tracking progress toward achievement of targets and comparisons with performance of conventional technology buses are valuable for fuel cell and related technology developers, bus manufacturers, and transit fleet managers. On slide 3, relevance is stated succinctly and is easily understood. The table nicely summarizes the targets/metrics for FCEBs.
- The project fully supports the Program goals and objectives, especially regarding deployment of FCEBs.

- The presentation did an outstanding job explaining why the study is important. The slide 3 chart, "Relevance," clearly presents relevant facts on one slide.
- This continues to be a valuable project for providing insight into development of FCEBs, a key goal. It does seem as though the current crop of buses has reached the limits of insights to be gained from its analysis at this stage, so it is good that analysis on them will be closing out in 2017.

Question 2: Strategy for technology validation and/or deployment

This project was rated **3.8** for its project design, approach to addressing barriers, feasibility, and integration with other efforts.

- The approach to identifying data elements, collecting information, analyzing data, and reporting has been well refined over a number of years. The strategy is straightforward; success in implementing the strategy is dependent on establishing and maintaining solid working relationships between the National Renewable Energy Laboratory (NREL) and the various providers of data. The ongoing and potential future involvement of transit agencies and other data providers indicates that NREL's team has continued to build credibility. The approach, which results in efficiently translating raw data into reports that have value for decision makers, contributes significantly to effective communications and trust among project partners and contributors.
- The strategy for technology validation is to compare buses with the industrial guidelines, i.e., features and functions. For example, FCEBs have accumulated an average of over 14,000 hours of use per FCEB power plant. The output is a real-world review of the features and functions. The project is well designed and can be integrated with alternative fuel deployment efforts.
- The approaches regarding information and data collection are well designed for this project.
- The processes in this project have been fine-tuned based on feedback from transit agencies, but they would benefit from the inclusion of additional bus projects, both FCEBs and battery buses (for comparison of zero-emission options).
- The project is well designed and continues to provide quality data as well as maintain good collaborations with transit agencies. It would be improved by doing a comparison against battery buses as well as the baseline diesel or CNG, because batteries are the main competitor to fuel cells in the zero-emission bus space. Agencies will want to see what the comparative benefits are.
- The approach is crystal clear, both in the verbiage and also in the charts.

Question 3: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.7** for its accomplishments and progress.

- This project results in a very clear picture of the progress being made by FCEBs relative to DOE and other stakeholder targets and how the performance of FCEBs compares to that of conventional, mainstream bus technology. Nine "Accomplishment and Progress" slides are outstanding. Ms. Eudy's superb presentation highlighted and summarized both project accomplishments and FCEB progress. Information was provided that demonstrates achievement of project objectives (as stated in the "Relevance" slide); documents FCEB performance; and details maintenance costs by bus type, system, and sub-system. Comparative information on maintenance costs is included in response to a prior review comment; the detail serves to indicate that the number of data elements associated with the project is extensive. Taking the initiative to develop a draft technology maintenance readiness levels (TMRL) guideline is commendable (slide 14).
- The targets/performance indicators are clear, so by measuring the correct data points, it appears that progress has been made for the technology. The TMRL guideline stands out as a gem that has been undervalued by government, but it is highly appreciated by industry (both transit agencies and heavy-duty vehicle manufacturers) as a tool to assess the status of vehicle technology and what to focus on next.
- This project includes comparisons of performance at the existing sites of FCEBs. Additionally, this project addresses the expected growth in FCEBs. Results include the following:
    - The top fuel cell power plant exceeded expectations for the 2016 targets.
    - The bus availability improved over 2015 and 2016.

  - The miles between a road call increased over the last four years.
  - The aging buses and their need for increased maintenance is addressed.
  - The TMRL is discussed (developed with fleet and original equipment manufacturer [OEM] partner input).
- The project has done an excellent job providing facts as well as an analysis. There is quite a bit of data and solid analysis.
- Progress has been good. The TMRL guideline is appreciated. It is important to make sure that it is clear to anyone reviewing this analysis that the increased labor time for these buses is because of the shift from maintenance being performed by the technology company to transit agency. This is an important and necessary step, but the team just needs to be careful that it is explained as such.
- Excellent progress has been obtained regarding data on cost and reliability/maintenance.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.8** for its collaboration and coordination.

- It seems NREL has maintained an excellent working relationship with data providers. The transit agencies that operate the majority of FCEBs in the United States are project partners. Continuous communication is required for efficient inputs of agreed-on data elements to NREL and review of NREL's products by its project partners. Information is shared with other U.S. and international organizations that have a stake in the evolution of bus technology (slide 16). While not specifically mentioned under "Collaborations," the project-funding support by the Federal Transit Administration and California Air Resources Board (slide 23) is another factor in the reviewer's score of "Outstanding."
- This project includes collaboration with both national and international organizations to validate bus performance and cost. Additionally, the TMRL guideline was developed in collaboration with fleet and OEM partner input.
- This project continues to be a model for collaboration with private-sector partners and public agencies.
- Many different projects and entities come together in this project, including hydrogen infrastructure and other vehicle applications.
- Given the conditions, there is perfect collaboration.
- Collaboration is excellent with transit agencies and bus/fuel cell manufacturers.

Question 5: Proposed future work

This project was rated **3.8** for its proposed future work.

- Collecting data for FCEB projects that are coming online will provide the comparison data needed to get a better overview of what a significant difference in climate may have on the performance of FCEBs.
- Expectations about tracking FCEBs coming into service underscore the value of the project. NREL continues to work on bringing in additional transit agencies in order to collect data on new FCEB designs and systems. As long as new FCEBs are being acquired and they are not yet comparable with other bus types regarding performance and cost, it seems appropriate that the project be continued. Proposed future work (slides 18 and 19) is clearly and succinctly articulated.
- The most important aspect of NREL's planned future work is that the work is consistent with past actions.
- The addition of buses in colder climates and with battery-dominant systems is pleasing to see. It is not clear how the battery-dominant FCEBs will be evaluated and how the evaluation be different from the benchmarking assessment for a fuel-cell-dominant system.
- The proposed work is well planned to address identified barriers/issues.
- The plan is to present the TMRL guideline to a broader group of transit agencies (via a public conference).

Project strengths:

- The NREL project team, led by Ms. Eudy, is providing superior returns for a relatively small investment by DOE. Having managed the project for an extended period, the NREL staff has great experience and superior knowledge of bus technologies. The project approach is well tested and refined. NREL staff is aware of what needs to be done in order to achieve continual improvement in project value (slide 23). Documentation of bus performance, comparative analyses, etc. is excellent. Timely reports on results are published by NREL for use by those with an interest in FCEBs, advanced bus technology, and transit/ energy policy. Presentations are also made at bus workshops and conferences.
- The project strengths include the following:
    - Unbiased data collection and analysis
    - Data variables that align with industry practices on what to collect data on
    - Long-running data collection process with international recognition by industry
- There are good collaborations with transit agencies and technology companies. The comparison to baseline buses provides valuable insights.
- The project approaches are well designed, and collaboration with transit agencies and bus/fuel cell manufacturers is excellent.
- The completeness of the work, obvious professionalism, and thoroughness of the team are project strengths.
- Public transit is often misunderstood, and this presentation does a decent job at showing the business nature of public transit. The project addressed maintenance (cost per mile) and hinges on collaboration with transit agencies, OEMs, and policymakers.

Project weaknesses:

- No project weaknesses are noted.
- None are noted.
- Limited funding is a project weakness.
- Some slides could be redone into more slides with fewer concepts, but this is a minor issue.
- A key weakness is just the age of the buses being analyzed, but that should be resolved with the conclusion of the current bus fleet assessment. Another weakness is that the FCEBs are compared only to existing diesel and CNG technology and not to their most likely competitor for agencies looking to move to zero emissions: battery buses.
- As part of the Program Annual Merit Review process, the presentations were handed in early this year, so the data collection reporting ended in December 2016; it would be good to see more current information. The differences between 2016 and the "ultimate target" could be explained for those not experienced in this area. Also, a slide on the definition of a commercial bus could be added, e.g., Commercial bus: sold in large quantities, and major OEMs sell them. Perhaps refueling cycles for the sites could be added as well, e.g., average volume of hydrogen used in refuel. The summary slide would be a great "explainer slide." Perhaps the summary slide could be broken down, item by item. This would be very valuable. It is not clear how to continue to collect data as the quantity of buses increases.
- International collaboration is weak.

Recommendations for additions/deletions to project scope:

- Full funding is recommended.
- The team should publish the TMRL guideline separate from a large report so that the transit industry can use the guideline in a manner similar to the 2012 Fuel Cell Bus Technical Targets, i.e., as a benchmark and assessment tool for the status of the context that supports optimal performance of FCEBs. The TMRL guideline concept also applies to new vehicle technologies in the trucking sector. The TMRL guideline should be considered and reworked to apply to fuel cell electric trucks as well (as a separate project). The project should include numbers for overall bus availability of conventional buses in the host agency's fleet—to make the benchmark even stronger. The team should add numbers for infrastructure availability for FCEBs fueling at each of the project locations.

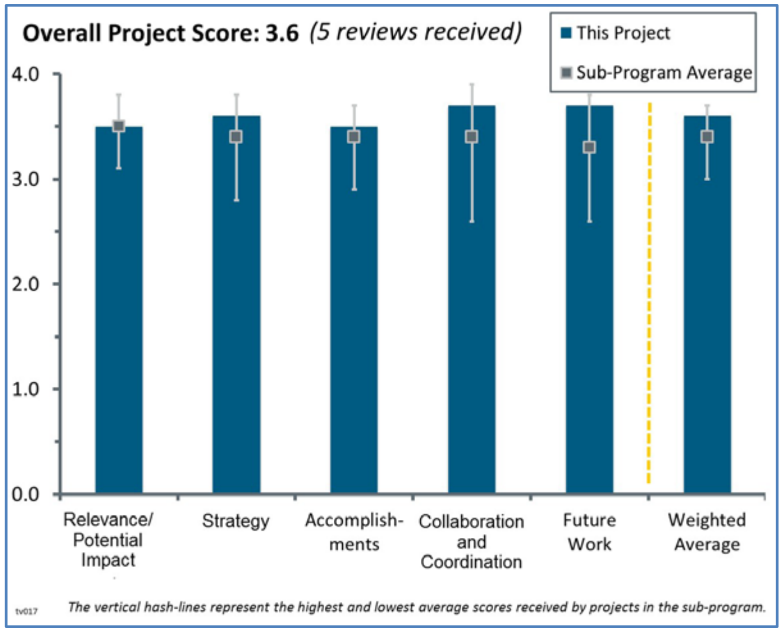
- The project would be improved by coming up with a way to compare the FCEBs to battery electric buses, to inform transit agencies considering both options.
- If success is achieved in bringing additional transit agencies and buses into the project, and funding is not increased, the focus on data collection should be on the new buses and most current designs—for both FCEBs and other bus types. (This does not suggest a change in project scope.) Funding is recommended that is sufficient to support data collection, analysis, and reporting for as many currently operational FCEBs as possible.
- There is an issue of air conditioners that are a new design; these are expensive. It is not clear why. Perhaps future work can be done here. Another issue is that the buses are out of warranty and parts are in need of replacement. Perhaps information can be added here as to how this is resolved. Of course, the obvious questions concern how NREL can collect more data on more buses and work on parts pooling as a partial answer to the parts supply issue.

Project #TV-017: Hydrogen Station Data Collection and Analysis

Sam Sprik; National Renewable Energy Laboratory

Brief Summary of Project:

This project evaluates hydrogen infrastructure performance, cost, utilization, maintenance, and safety. Data analysis supports validation of hydrogen infrastructure, identifies status and technological improvements, provides feedback to hydrogen research, and provides results of analyses for stakeholder use.



Question 1: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.5** for its relevance/potential impact.

- This project is to collect, sanitize, and produce analyzed results suitable for public consumption. This is extremely valuable to understanding how stations are improving, identifying areas in need of improvement, etc. The approach taken by the National Renewable Energy Laboratory (Sam Sprik) is very good. Clearly, as this technology matures, the data collection, analysis, and analysis deployment will need to be modified. This project has a history of being receptive to these needs and providing the data and analysis that is most valued. This is excellent.
- Data collection and validation are of high importance for the further development of the U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program (the Program). Therefore, the approach is excellent for improving the knowledge regarding hydrogen stations.
- Independent data collection on hydrogen stations is absolutely critical to understanding progress, costs, issues, and challenges associated with deploying the fueling networks that will support fuel cell electric vehicles.
- This project is clearly making progress toward removing the barrier outlined by DOE: "Lack of Hydrogen Refueling Infrastructure Performance and Availability Data." However, no goals/objectives in the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan were called out in the slides or the presentation.
- It is a well-organized approach.

Question 2: Strategy for technology validation and/or deployment

This project was rated **3.6** for its project design, approach to addressing barriers, feasibility, and integration with other efforts.

- The output from this project is excellent. It remains resilient to the current data and analysis needs of this community in its infancy stage of development.
- This project is addressing barriers by providing accessible information and analysis of station data to the community and the public. The work plan is feasible. Future areas for integration include installation of data collection devices, such as the ones outlined in the Program Annual Merit Review 2017 TV-025 presentation, if they are not already installed.

- The project has an excellent approach to collect data from stations and integrate further stations that are not part of the funding.
- The strategy includes good parameters for hydrogen station performance.

Question 3: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.5** for its accomplishments and progress.

- The summary of stations and their performance is very good.
- Further expansion of collected data and inclusion of non-funded stations give additional benefit.
- The goals outlined in the slides include using the existing stations as a guide for future innovations and issues for research. The slides and data provided are of great quality and interest, but the presentation would be improved by providing a summary and emphasizing the specific issues or research areas identified from the data collection. However, it is clear that these results will influence research directions (e.g., identifying causes of dispenser failures).
- The data acquisition, analysis, and distribution are critically important to help guide the maturity of this embryonic technology.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.7** for its collaboration and coordination.

- Coordination with station operators as well as station deployment in California shows a comprehensive approach in cooperation with relevant stakeholders.
- Collaboration appears to be great for getting necessary data.
- The group appears to be working well with the many collaborators to obtain the data.
- The project has a strong team and good interactions.
- The reviewer scored it a “3” principally because there was no real discussion about who collaborators might be; instead, a very broad statement with no specificity was provided. The principal investigator (PI) simply noted that the project works closely with industry and government, but it is not clear whom. Presumably, the principal government collaborator is DOE (which is a funding entity, not really a collaborator); the California Energy Commission, which is the entity funding stations in California, is a non-DOE government agency, which is very appropriate. Also, some industry collaborators can be the stations providing data. These collaborators will help the project understand the data needs of these stations as both retailers and station operators, which means that these operators should be keenly interested in component behavior. Hence, there likely are a large number of potential entities that are contributing to this work. This requirement was not really addressed by the PI.

Question 5: Proposed future work

This project was rated **3.7** for its proposed future work.

- This project has already demonstrated the flexibility to be responsive to the data needs of this nascent industry as hydrogen fueling stations (HFSs) are deployed. This is excellent.
- The plans for the future are to continue to achieve the proposed goals, with more of an emphasis on the analysis and publication. It is important that the team clearly communicate its recommendations for future research or development needs from this data collection activity. It may be beneficial to separate data based on technology as more stations in each category come online.
- Enhancements of data collection show a learning curve and improve data quality and availability of relevant information.
- The work plan built on current results is very good.
- There are only 35 stations with data. Obviously, the project needs to continue to collect data as the fueling network grows.

Project strengths:

- The project is providing relevant data as HFS deployment continues. The PI has demonstrated the ability to change and remain relevant as the deployment and the industry mature.
- The project clearly addressed a DOE barrier, and it covers a large number of stations. Future plans are appropriate with a focus on continued data gathering, analysis, and reporting of the data gathered.
- The comprehensive information availability for the evaluation of hydrogen stations and further project development are strengths.
- The project is very relevant to current industry needs.
- The project team is a strength.

Project weaknesses:

- No major weaknesses are detected.
- To collect (some) information more often (e.g., monthly) might be interesting.
- It would be good to see additional analyses, including (1) how station capacity utilization affects actual costs per kilogram for each station type and (2) assessment of hydrogen losses in the system for each station type.
- There was no concrete plan to work with the entities deploying HFSs in the Northeast. The funding (ownership) model in the Northeast is very different from the one in California. This fact makes the ability to get data from those stations very different. It would be beneficial to see an aggressive plan to get those agreements in place. The PI did comment that “they are working” to get the data, but that demonstrates a desire rather than a plan. Developing relationships with the station provider (Air Liquide, Shell, etc.), potential operators, and the governments in the Northeast would be beneficial.

Recommendations for additions/deletions to project scope:

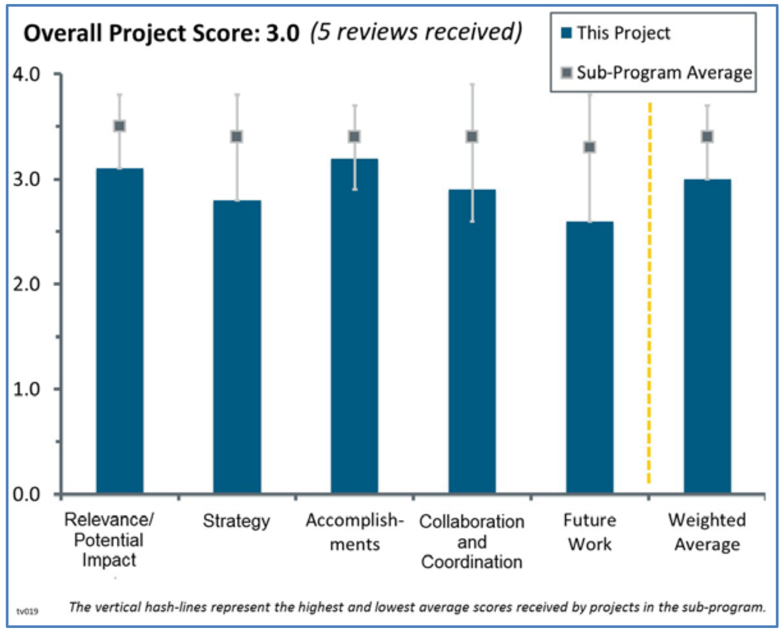
- The project should keep up the excellent work. This project is working hard on solving the data acquisition issue from stations going into the Northeast. Also, it is recommended that the PI work with the Pacific Northwest National Laboratory (PNNL) to investigate putting the database into the PNNL portal so that the industry and public can easily gain access to these data.
- The project scope is appropriate; no changes are recommended.
- The project should continue the California focus and identify a strategy on increasing station usage/ capacity factors.
- A supply of relevant information for hydrogen station users/customers might be of additional value. This might also lead to live information for station availability/price/etc.
- The project needs to continue to add stations as they come online.

Project #TV-019: Hydrogen Component Validation

Daniel Terlip; National Renewable Energy Laboratory

Brief Summary of Project:

The objectives of this project are to (1) reduce fuel contamination introduced by forecourt station components, (2) improve station reliability and uptime, and (3) increase the publicly available energy and performance data of major station components. The project is focusing its efforts on understanding common component failures and sources of particulate contamination at hydrogen stations, while quantifying the related costs incurred when operating a hydrogen station.



Question 1: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.1** for its relevance/potential impact.

- The project has high relevance and a high potential impact on the hydrogen refueling industry. The project supports the goal of advancing the use and efficiency of the use of hydrogen as a transportation fuel by using the facility/equipment at the Hydrogen Infrastructure Testing and Research Facility (HITRF) at the National Renewable Energy Laboratory (NREL). The facility is configured for 700 bar refueling, which is up to par with most of today's refueling stations. By addressing contaminants in hydrogen, this project looks at a key point of today's hydrogen refueling infrastructure. The research entails collecting samples from station operators. The concern with today's stations is how much testing is needed to "be as good as" in situ testing. The issue is that in situ testing costs too much (as much as $300,000), and this additional cost is not feasible for today's station operators. The project can provide assistance with the question of how many tests are necessary (for contaminants). By addressing power use, this project looks at another key point: how much power is needed for the compressor and the polymer electrolyte membrane electrolyzer and how this can be decreased. Overall, the cost of stations continues to be affected by energy consumption and reliability (contaminants). The industry needs answers as to how to better design stations to address both. It should be noted that from January 2016 to today, the overall reliability of stations (nationwide) has stabilized, but the compressor reliability and energy consumption continue to be problems with some station developers without resources to counteract. This research assists in both areas, which are likely to change over time.
- This project directly addresses the barrier outlined by the U.S. Department of Energy (DOE): "Lack of Hydrogen Refueling Infrastructure Performance and Availability Data." It is likely that the results will be of interest to the community and will affect decisions made as hydrogen fueling infrastructure is designed. It is somewhat unclear from the slides which goals/objectives in the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan are being addressed, although it seems that the project does address some key goals.
- The project fully supports the DOE Hydrogen and Fuel Cells Program (the Program) goals and objectives.
- This project is relevant to the extent that results can assist with documenting and addressing issues that deter progress in achieving hydrogen station objectives. The "Relevance" portion of the presentation (slides 3 and 4) was not particularly helpful in clarifying the focus of and rationale for the project. During

discussion at the poster session, however, the project manager stated the focus is on sources of hydrogen station costs and how to reduce them.

- Using $758,000 to identify the power consumption of obsolete production, compression, and cooling technologies along with high-school-level assessment of cleaning procedures is not a wise use of funds. The impact is limited because there are no clear innovations, no transfer to industry, and no industry-led efforts. It is not clear why DOE is allowing this project to proceed with 0% industry cost share. Industry cost share of 50% or greater would ensure that DOE dollars are spent appropriately. The facility at NREL appears very capable of providing high-value work; the potential impact is the only redeeming feature of this project.

Question 2: Strategy for technology validation and/or deployment

This project was rated **2.8** for its project design, approach to addressing barriers, feasibility, and integration with other efforts.

- The strategy for technology validation of the hydrogen compressors (outreach to three compressor manufacturers and seven station operators) to review maintenance events, develop best practices, and review existing materials that degrade fuel cells is both appropriate and sustainable. The use of the NREL test station (HITRF) is reasonable. Although this is a test station and not a commercial station, and it does not serve customers (non-commercial), the station encounters similar or the same "major maintenance burdens." The research team reviewed both the research station and the HITRF station and showed data expressing similarities. The NREL team tested the valve failures and the valve seals (with wide temperature ranges), and the same (or similar) failures were exhibited.
- Analysis of collected data and information is excellent.
- The project is addressing barriers, is feasible, and is well integrated with other efforts. Failure analysis may be improved by providing a comparison to non-failed parts and perhaps by doing more to understand/ describe how these particles contribute to the ultimate failure.
- Having clarified that the overall focus is on hydrogen station costs and cost reduction, each of the three topics in the "Approach" portion of the presentation (slides 5 through 7) seems appropriate for inclusion in the project. However, no information is provided about a general strategy or approach to determining the priorities for using project resources. It appears that the varied topics being addressed within the project may be determined by the interests of one or a few stakeholders.
- Technology validation should ensure relevance to industry and technology transfer, or in this case, acceptance of suggestions for industry best practice should have been the objective. It is not clear how the article and presentation at a conference in Europe affects DOE objectives and relevant U.S.-based best practices.

Question 3: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.2** for its accomplishments and progress.

- This project outlined three goals, which were to (1) understand common failures at hydrogen stations, (2) understand the source of particulate contamination in hydrogen stations, and (3) quantify the costs incurred when operating a hydrogen station. The progress made addresses all three goals. The work done to investigate cleaning of pipes is particularly practical and useful, although more could be done to test whether properly cleaned equipment or intentionally dirty equipment does lead to fewer failures or more failures, respectively. Also, it might be helpful to consider other sources of particulates besides cleaning.
- Good progress has been made toward addressing the barrier (lack of hydrogen refueling infrastructure performance and availability data).
- The "Accomplishments" portion of the presentation indicates the following:
    - The HITRF at NREL is providing relevant information, e.g., on station energy measurements and cost.
    - Particulates, which have an impact on component failure, can be affected differently by selection of tube cleaning methods.

It is assumed that the accomplishments documented in the presentation were achieved since the previous Program Annual Merit Review (AMR). Because DOE funding was $47,000 carry-over in fiscal year (FY) 2016 and zero in FY 2017, it would be helpful to have information on the timeframes associated with the accomplishments, confirmation that work is ongoing, and the sources of funding for the continuing activity.

- This test process responded to the 2016 reviewer's comments about broadening the types of compressors and the routine data collection for each. The number of hours for this testing were increased, and the failures are documented. The most hours were spent testing the valves/filters in the dispenser and the hydrogen pre-cooling process. The testing includes the number of car fills and the power and energy demand for the components. For the maintenance and reliability of the station components, the NREL team plans to continue collecting data.
- The accomplishments and progress by the researchers are good, given the project objectives. However, it is not clear why the researchers and DOE Program management did not scope a more aggressive technical challenge. There is very limited value in this assessment; no one learns anything from a detailed description of power consumption and particulates. Anyone operating a hydrogen station is well aware of these issues and could have provided this insight.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.9** for its collaboration and coordination.

- The "Collaborations" slide (slide 14) suggests that a number of organizations that have a stake in hydrogen station design and operation are working with NREL on quantifying performance metrics and resolving issues related to station cost. The institutions listed indicate NREL's credibility and outreach.
- Collaboration is excellent with various appropriate organizations.
- It appears the partners are participating in the project and there are no issues with gathering data.
- The number of gas companies involved with this work could be purposefully increased. Likewise, the collaboration with the station developers could be increased. Also, at least one additional transit agency could be contacted and collaborated with.
- Collaboration and industry cost share would resolve the issue of relevance. This project is off track and needs significant realignment with the capabilities and value of national laboratory involvement in industry activities.

Question 5: Proposed future work

This project was rated **2.6** for its proposed future work.

- The plans for tube cleaning communication and outreach are great. It is also good to investigate high-throughput stations, as scaling up throughput will likely bring the costs down. It is unclear what impact investigating the variable suction pressure might have. It is also unclear what the outreach for more failed parts entails, and a clearer plan would be helpful. Finally, the project might also consider investigating dispenser failures, as this becomes the most common maintenance issue with time (see the TV-017 presentation in the 2017 AMR).
- Although this project started in 2012, the team proposes continuation in the future. The areas proposed are needed: conducting research into linking station failures to contaminants (increases are planned in the number of participating members of the contaminant library) and pursuing new ways to predict failures. Root cause analysis for failures will also be studied to decrease the quantity of replacement with like parts "because one did not know the cause and that seems to be the logical solution." For the energy and power demand of stations, the team plans to increase the data-sharing with modeling projects.
- The proposed future work is well planned.
- Presumably, NREL and selected stakeholders have reasons for the entries on slide 16 of the presentation, addressing proposed future work. There is some concern that the topics selected are not the result of an overarching approach to determining project priorities. In response to a question posed to the project manager during the poster session about how he would spend $100,000 per year, he stated that he would focus the resources on particulate studies. The second bullet on slide 16 ("Outreach program for station

fabricators on tube cleaning techniques") is questionable as an activity for support by the Technology Validation sub-program. If future DOE funding is provided, it seems appropriate to focus on compressor operation and reliability, as proposed by a previous reviewer.
- The future work will not lead to any new information within the industry and, therefore, will add no value to addressing barriers and challenges.

Project strengths:

- The strengths of this project include how the project is grounded in the test facility already at NREL and the technical NREL staff. This test system is not disturbed by a commercial use for the station, and test setups can be, therefore, more efficient. Further, the understanding of contaminants, reliability, and power use at NREL is excellent, and this understanding makes for a strong project.
- The project strengths are the very practical, relevant findings—particularly the tube cleaning—and the good future plans for communication.
- The project uses excellent approaches for data collection and analysis.
- NREL collaborates with multiple stakeholders having an interest in the project; information, advice, and failed parts are received from them. To the extent that there is a clear focus on reduction of hydrogen station costs, that is also good.
- The researchers have good technical strength.

Project weaknesses:

- None of the weaknesses are significant.
- The project weaknesses include the need for more participants in the contaminant- and component-testing category. Additionally, a more representative section of the industry should be sought—various types of station designs, for example—and potentially the automakers could be included to provide feedback on the impact of contaminants on vehicles.
- The failure analysis lacks some clarity as to how the particles are causing the failure. The tube cleaning data in the presentation seem to have high error, and the interpretation is difficult because of this.
- There seems to be no overarching approach or strategy for the project. There should be a framework or process for determining how best to apply available resources. Based on the lack of DOE FY 2016 and 2017 funds, there is an implication that this project will be low-priority, particularly in a reduced overall budget environment.
- The project is very poorly aligned with DOE objectives.

Recommendations for additions/deletions to project scope:

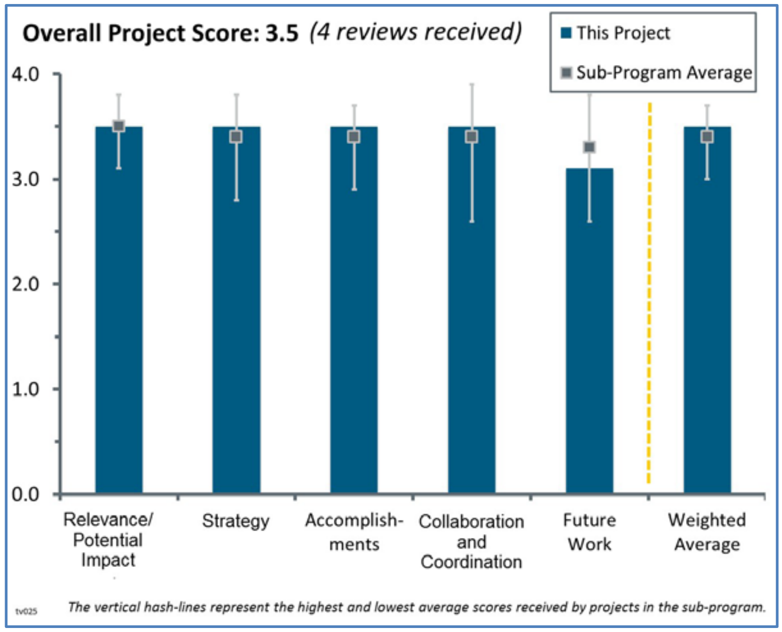
- While the project has some great activities and scope change is not necessary for success, more detailed and systematic failure analysis and understanding may be considered, because it may lead to other preventative measures in addition to careful tube cleaning.
- The project should increase the focus on the installation of power meters and their use in evaluating energy demand and use by the various station components. Also, the project should provide the following: practical best practices for evaluating power use; overall case study impacts of the relationships of contaminants with station component reliability; and a collection of information and data about the failed station parts, i.e., chillers (other than compressors). This is asking a lot.
- Absent a positive reassessment of this project's approach, focus, and priorities, a renewal of DOE funding is not recommended. Such an assessment should be done in conjunction with a study on how best to utilize the HITRF. The concern about funding for this project should not be construed as applying to support for the HITRF.

Project #TV-025: Performance Evaluation of Delivered Hydrogen Fueling Stations

Ted Barnes; Gas Technology Institute (GTI)

Brief Summary of Project:

The objectives of this project are to (1) install data collection systems at five 100 kg/day delivered hydrogen fueling stations located in California for a 24-month period, (2) submit station data specified in the National Renewable Energy Laboratory (NREL) Hydrogen Station Data templates, and (3) provide useful data to accurately characterize stations' performance.



Question 1: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.5** for its relevance/potential impact.

- This project directly addresses the barriers outlined by the U.S. Department of Energy (DOE) and outlines specific DOE technical objectives. The data gathered will be useful in estimating hydrogen fuel demand and the need for more stations.
- Data collection is an important part of measuring station maturity and advances toward the Fuel Cell Technologies Office's (FCTO's) goals. Lower-cost stations that meet efficiency and reliability targets can be enabled by this project.
- The technical objectives in the "Relevance" portion of the presentation (slide 3) reflect the objectives and directly address the barriers associated with hydrogen refueling infrastructure, as discussed in the FCTO Multi-Year Research, Development, and Demonstration Plan (MYRDDP). The table in slide 3 defines project objectives and goals succinctly and well.
- This project fully supports the DOE Hydrogen and Fuel Cells Program goals and objectives.

Question 2: Strategy for technology validation and/or deployment

This project was rated **3.5** for its project design, approach to addressing barriers, feasibility, and integration with other efforts.

- The strategy for validation and deployment appears sound. While the data are aggregated, DOE will still have some idea where additional research and development might be needed and what gaps remain. The data can also be used to encourage other stakeholders and private industry to continue or start investment in certain types of stations.
- The project is well designed to address the barriers regarding hydrogen refueling infrastructure performance and availability data.
- While the data collection design and related systems are relatively sophisticated, the project approach is straightforward. The approach is articulated well in presentation slides 4 through 7 and is readily understood. An important and positive aspect of the project is the collection and transmission of component, performance, and cost data to NREL's National Fuel Cell Technology Evaluation Center (NFCTEC).

- The project is directly addressing the barrier of providing performance data. It is integrated with efforts to post information publicly in the same format. It is somewhat unclear how the work relates to the barrier of "Codes and Standards" directly.

Question 3: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.5** for its accomplishments and progress.

- Excellent progress toward data collection has been made to date.
- The initial phase of the project went well, with two stations completed. The team did have to adapt its strategy regarding the data collection board; however, the biggest challenges remain around permitting, which this project cannot change.
- The status of each of the five stations in the project, and data collection for the two operational stations, are nicely summarized in presentation slides 8 through 12. Consistent with project plans and goals, data are being collected and provided to NREL for the sites located at West Sacramento and San Juan Capistrano. The project transitioned to Budget Period 2 nearly two years ago. Based on the material presented in the slides and on the poster display, it is clear that two years of data collection from each station will not be accomplished prior to the stated end point for the project (January 2018). This was discussed with Tony Lindsay of the Gas Technology Institute (GTI) during the poster session. He stated that because of delays in permitting of three stations, the current intent is to provide 10 "station-years" of data. In that circumstance, it seems data provided would be primarily from the two currently operational stations. It is recommended that FCTO and the project managers collect at least four quarters of data for each of the five stations; such a requirement would necessitate a no-cost extension, which is evidently in the works. At the poster session, the reviewer suggested including a spreadsheet with more specific information on the data being collected and sent to NREL. Slide 5 has some information, but Mr. Lindsay agreed with the suggestion.
- Progress has been made, as equipment has been installed at another site and complete data sets have been gathered. One of the goals is to collect "high-quality data"; however, it is unclear what is considered high-quality. A list of pros/cons of this particular data-gathering system would also be helpful. Permitting continues to be an issue, but it is great to have data on stations that have gone through the process.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.5** for its collaboration and coordination.

- The combination of GTI and the Linde Group produces a strong, experienced project team. Their respective project responsibilities are reasonable and appropriate. Good coordination between them is required. Collaboration with NREL's NFCTEC is an important aspect of the project, and it has evidently been successful.
- The project team appears to be well coordinated, and team members are working well together.
- There is good collaboration between Linde and GTI. Data collection had to be split between the two entities based on individual capabilities and then compiled for the data collection process.
- There is collaboration with Linde.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- Future work appears on track with the continued two years of data collection. The biggest challenge is around the last of the five stations, which still needs permitting approval and construction before the data collection equipment can be installed and used. The Foster City station should have more support from project stakeholders outside of GTI and Linde, where possible.
- The plans for the future are a logical extension of the work already conducted, and those plans and work will likely result in a successful project. One suggestion for improvement is to outline a specific plan to

communicate lessons learned to, or even develop case studies for, the community on the topics outlined in the slides such as system development, network communications, and commissioning. Strategies for this enabling of communication while remaining sensitive to intellectual property can be developed or at least discussed internally.
- The presentation materials and poster do not mention plans for a no-cost extension and do not address the issue of providing data from stations for differing periods of time. It would have been helpful if the project had cited alternative approaches to dealing with the delays in permitting new stations and included a selected alternative for proposed future work.
- It is not clear how the data will be analyzed.

Project strengths:

- Project strengths include the following:
    - Experience and capabilities of the project team
    - Collaboration with, and submission of data to, NREL's NFCTEC
    - Strong linkage between project goals and the objectives/barriers included in the Technology Validation sub-program portion of the MYRDDP
- The data acquisition systems appear to be successful, and more sites are being installed. The team has good experience and connections.
- Effective communication and data manipulation by the partner companies are project strengths.
- The project has well-defined plans and well-designed approaches.

Project weaknesses:

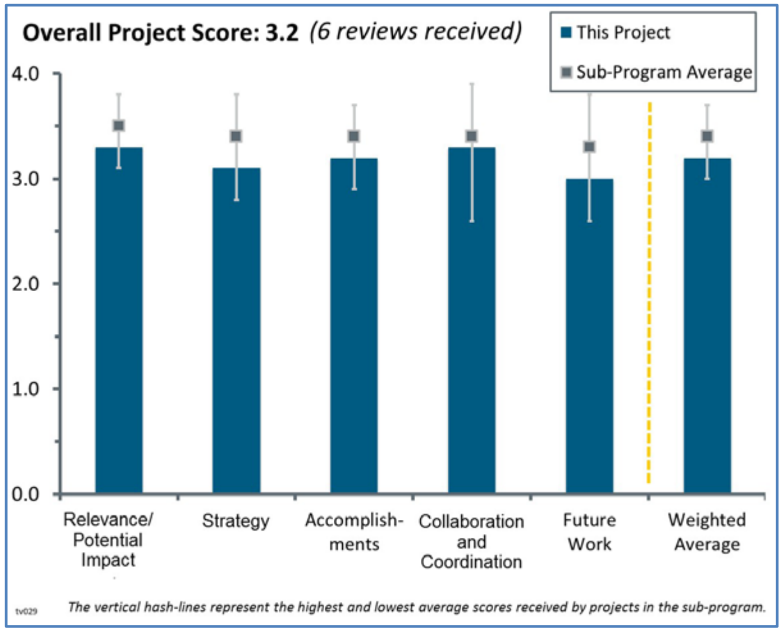
- The lessons learned should be communicated more specifically and more broadly.
- A potential weakness is the limited period during which data are collected and submitted to NREL for up to three of the five stations in the project.
- Weaknesses include the challenge of developing a project dependent on permitting and other aspects that are outside of the team's control.
- Planned analysis of collected data is lacking.

Recommendations for additions/deletions to project scope:

- The project scope is appropriate as long as the permitting issues are solved. The plan for a no-cost extension may be appropriate in this case.
- The project should add an additional station if the Foster City station cannot be completed in a timely manner. It is also recommended that the project add no-cost extensions where required, and it should ensure that follow-up continues and data are shared.
- The reviewer has no recommendations for additions or deletions but has concerns about severely curtailing data for some of the five stations under a "10 station-year" plan. It is recommended that at least four quarters of data be provided for each station.

Project #TV-029: Performance and Durability Testing of Volumetrically Efficient Cryogenic Vessels and High-Pressure Liquid Hydrogen Pump

Salvador Aceves; Lawrence Livermore National Laboratory



Brief Summary of Project:

This project explores the potential for reaching high volumetric (50 g H_2/L target) and gravimetric (9% H_2 weight fraction target) storage performance within a small (63.5 L internal volume), high-aspect-ratio (34 cm outer diameter and 100 cm length) cryogenic pressure vessel with long durability (1,500 thermomechanical cycles) refueled by a liquid hydrogen (LH_2) pump to be tested for degradation after delivery of 24 tons of liquid hydrogen. Cryogenic pressurized hydrogen storage and delivery provides safety, cost, and weight advantages over alternative approaches to long-range (500+ km) zero-emissions transportation.

Question 1: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.3** for its relevance/potential impact.

- This project fully supports the U.S. Department of Energy (DOE) Hydrogen and Fuel Cell Program (the Program) goals and objectives.
- The project has high relevance because it looks at one possible solution to a key set of challenges for hydrogen-fueled vehicles—fuel storage density and storage system cost. If these problems can be solved in a meaningful way, the impact is high. Whether the approach being studied will offer a commercial solution is an open question.
- The presentation is outstanding.
- The project is aligned with Program goals and has made progress. However, without a more detailed full well-to-wheels analysis, there are concerns about overall efficiency. Boil-off is being investigated at the pumping station, but there is still a significant loss. Moreover, trucking from the hydrogen generation facility is not addressed.
- Research, development, and analysis prior to this project have indicated advantages for cryogenic pressurized hydrogen storage, transportation, and dispensing. Based on the presentation (slide 4, "Relevance"), this project has focused on the issue of LH_2 pump performance and durability. While this issue is important, it is one of multiple challenges that must be successfully addressed before LH_2 can be considered commercially viable and competitive as an automotive fuel.
- At the moment, the relevance of the project regarding market uptake might be low because most of the carmakers are pushing compressed hydrogen. With a view on future large-scale deployment of hydrogen, LH_2 might get a further push.

Question 2: Strategy for technology validation and/or deployment

This project was rated **3.1** for its project design, approach to addressing barriers, feasibility, and integration with other efforts.

- The approach looking at vessel durability and hydrogen pump performance and durability is excellent.
- The project has an excellent approach for the evaluation of LH_2 vessels.
- The approach allows two components of the project to be tested at once. (The vessel has been cycled in temperature and pressure using the cryo-pump, so both are being tested.) This also allows system interactions between the two parts to be considered.
- The project approach—cycle testing of a prototype pressure vessel using the LH_2 pump—seems reasonable as a means to determine storage vessel and pump performance. However, if one is not familiar with the rationale and alternatives for the project approach, it is unclear whether any alternatives could have resulted in more performance and durability data. For a $4.7 million project with a duration of 3 years and 9 months, the 456 cycles, 19 days of data collection, and 1,650 kg of hydrogen dispensed seems limited. It would be good to know more about what accounted for the time and funds.
- The project focused on improving storage cylinder and pumping station losses in a very applied manner. Progress was made on the storage cylinder, but much more is necessary on improving pumping station efficiency. Also, to be effective, it would need to integrate with the entire LH_2 transportation infrastructure system, which was not shown.
- While boil-off and venting losses, as well as how to manage these losses, were discussed, the cost of liquefying hydrogen and a comparison with the compression of hydrogen were not as well addressed.
- Boil-off for fuel cell electric vehicles not in use was discussed and appeared to have been deemed acceptable, but it is not clear whether consumers will accept the loss of their fuel dollars. Venting losses associated with delivery truck depressurization was discussed, and while the audience was advised that the problem would be addressed, there was no indication of how.

Question 3: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.2** for its accomplishments and progress.

- Excellent progress has been made, especially regarding collecting data from LH_2 pumps.
- The "Accomplishments" portion of the presentation (slides 6 through 13) provides excellent information resulting from 19 days of storage vessel and pump cycle testing performed during May 2016. Some results (e.g., pumping rate) were positive. Other results indicate a need for further technology development and testing. The project demonstrated that significant work remains to be done on topics such as LH_2 storage vessel design and excessive venting of hydrogen to the environment. However, there are concerns about minimal documented accomplishments, given a relatively large project budget and nearly four-year duration.
- LH_2 might have a growing relevance in future hydrogen deployment. Therefore, the results contribute to future technology development, although basic research is needed.
- The testing cycles were completed as noted. Perhaps the most eye-opening finding from this is the amount of hydrogen lost to boil-off and venting.
- The project is effective, the Lawrence Livermore National Laboratory team must be working on barriers, and the presentation did advise that boil-off losses were being addressed; however, there was inadequate discussion on what could be achieved to limit system and consumer losses.
- The project has made progress on advancing storage cylinder cycling on simulated operational cycles and high refill rate capability. However, there are concerns about efficiency at 1.1 kWh/kg hydrogen and 1.5 kVAh/kg hydrogen electric consumption. While claimed to be low consumption, it appears to be a high energy penalty. What it is being compared with is unclear. More concerning is boil-off by the pumping station demonstrated at 26% of pumped hydrogen. This is unacceptably high. Projections claim this can be reduced to 3.6%, but this is still significant and ignores boil-off in the trucking transport of LH_2 to the pumping station and other overall losses.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.3** for its collaboration and coordination.

- No collaboration weaknesses were noted; collaboration is significantly better than for most other presenters.
- The project has excellent collaboration with industries.
- Collaboration is good in the pump and tank parts of the overall fuel value chain. It would be useful to include more technical detail and cost analysis of the interface parts of the system. For example, it is likely that this technology still requires a cryogenic fueling hose, but the principal investigator (PI) did not seem able to answer that question during the review. There are also concerns that the energy of liquefaction and the amount of boil-off and venting throughout the entire hydrogen production, transport, storage, dispensing, and use chain are too high to be viable (the 3.6% loss number cited is likely only for a very small part of the chain).
- Collaboration with BMW is appreciated, especially with the next phase of testing of the BMW prototype vessel. Other collaborations should be considered with market players that look into LH_2.
- The project is partnering with BMW, the Linde Group, and Spencer Composites.
- Slide 15, addressing collaboration with industry leaders, provides information only on the three project partners. Nothing in the slide set or the oral presentation indicated collaboration or communications outside the project team. The reviewer agrees with a previous reviewer comment about conducting a stakeholder workshop (slide 14). The project team could benefit from recommendations and input provided by those who are skeptical about the use of LH_2 as a vehicle fuel.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The proposed future work is consistent with work completed and challenges recognized.
- Testing of the BMW prototype and the extension of testing parameters are highly appreciated.
- The future work is on increased cylinder cycling durability and improving filling station infrastructure, but greater focus is needed on improving pumping efficiency and decreasing boil-off.
- The current project is scheduled for completion in September 2017. Future work, as outlined in slides 17 and 18, seems to be more of the same, i.e., demonstrating performance/durability of a cryogenic vessel prototype and a pump. The Program Annual Merit Review presentation and project results have not made a convincing case for the future work described. The issue of LH_2 feasibility should be addressed by DOE before any further investment in similar testing and validation. LH_2 may have potential advantages, as suggested by the project team. However, an objective, hard-nosed, and comprehensive assessment of the current state of the technology, and technology prospects, should be done prior to making another significant investment in validation of selected components. In response to a question, the presenter noted that some fundamental research is still needed, e.g., on storage vessel design.
- The project needs a more thorough understanding of vehicle fueling process and equipment. Also, the project needs a metric for comparing technologies—maybe energy per kilogram delivered to the car—and it needs to include the energy of liquefaction (even if called an investment). Also, the project needs to understand vehicle fuel tank latency—it is likely that an order-of-magnitude improvement (something like a 10% loss in 30 days) in vehicle loss/boil-off is needed. The PI wants to use a "typical driver only loses x% of [hydrogen] in normal use" metric for latency. It is not clear whether this would work from an automotive industry perspective where typically things have to be designed to accommodate 98th or 99th percentile uses and situations.
- It is not clear how the "slow and complex" manufacture of vacuum vessels will be addressed.

Project strengths:

- Cycle testing using an LH_2 pump seems reasonable as a means to determine storage vessel and pump performance. The involvement of Linde and BMW as project partners is a plus. They have relevant expertise and a commitment to LH_2 technology.

- The project has well-planned and well-designed approaches, especially regarding LH_2 pumps.
- The project has a good plan to test the specific elements included in the scope and good collaboration to achieve that testing/data.
- This is interesting work on a technology with some opportunities that were not previously evaluated in comprehensive research projects. The project might show important advantages if it can get vessel manufacturing and losses in the whole chain under control.
- The aggressiveness of the effort is a project strength.
- The project has demonstrated high cycling capability and fill rate for LH_2 storage cylinders.

Project weaknesses:

- The shortcomings were not always explained.
- Significant boil-off needs to be addressed as well as improving cycle efficiency.
- The future work needs more details and definition.
- The project does not really address whether the whole LH_2 system from production to power generation can be economically viable (e.g., cradle-to-grave boil-off, energy per mile driven, cryogenic fueling hose, etc.).
- Market relevance of LH_2 is not a given at the moment. It is unclear whether LH_2 will increase in relevance in the future. Results of the project show opportunities but also point out some challenges in LH_2 storage.
- The project has limited results for a significant expenditure of resources. A basic premise linked to the project seems to be that LH_2 is the most viable approach to hydrogen distribution and vehicle fuel storage (see slide 14). However, the results of the project fail to provide evidence that supports the premise, even though the presenter stated that performance (presumably of the pump) was consistent with Argonne National Laboratory analysis. Including a spreadsheet that compares selected metrics for LH_2 and other hydrogen vehicle-fueling options, and provides context for this project, could have been helpful in evaluating project focus, relevance, and approach.

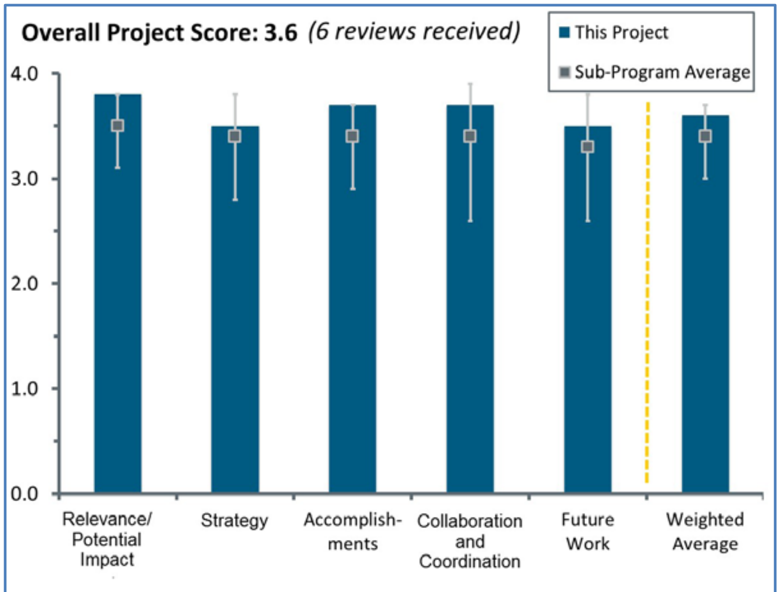
Recommendations for additions/deletions to project scope:

- It would really be good to see the whole system energy use and boil-off losses needed to implement this type of storage, as well as more consideration given to defining acceptable tank latency.
- The project should address well-to-wheels efficiency: boil-off and electric consumption.
- Further stakeholders should be included.

Project #TV-031: Dynamic Modeling and Validation of Electrolyzers in Real-Time Grid Simulation

Rob Hovsapian; Idaho National Laboratory

Brief Summary of Project:



The vertical hash-lines represent the highest and lowest average scores received by projects in the sub-program.

This project is demonstrating the fast-reacting performance of electrolyzers and characterizing the potential and highest economic value of their installation to enable participation in energy markets and demand response programs. A novel approach of distributed real-time simulation is used, with electrolyzer hardware at the National Renewable Energy Laboratory (NREL), used in conjunction with power system simulations at the Idaho National Laboratory (INL).

Question 1: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.8** for its relevance/potential impact.

- Grid integration is very important for increased renewable energy and more rapid deployments of fuel cell electric vehicles by providing lower-cost hydrogen. This foundational work will meet Fuel Cell Technologies Office goals and accelerate the deployment of electrolyzers while increasing grid reliability.
- This project is directly aligned with the goal of demonstrating grid energy storage and hydrogen production from potentially renewable resources. The interactions with the electrical grid are quickly becoming recognized as one of the largest unknowns with the most urgent need for insight and clear understanding within this space. This project is essentially the only work looking to demonstrate real-time capabilities of hardware systems that will need to be placed in the field in the near future and validated for the intended two-pronged purpose of hydrogen production and grid services to enable increasing implementation of renewable electricity on the grid.
- This project clearly addressed U.S. Department of Energy Milestone 3.9, related to Systems Analysis and Technology Validation. The impact of this project is far-reaching, and it identifies areas for future development that make good economic sense, as well as the possibilities for what can be done today to implement hydrogen technology.
- The project basically explores the possibility of cross-linking hydrogen production (cheap and renewable) with the power sector. It addresses the capacity of electrolyzers to balance the electricity grid, namely owing to the fluctuating electricity production from renewable sources and variations in demand. This entails the need for fast response for real-time adaptation to production and grid conditions. Production of hydrogen through electrolysis when electricity is in over-supply (hence "cheap" according to supply–demand trends) should allow the production of low-cost hydrogen, thus allowing for feeding low-cost hydrogen to the user, namely, users in the transport sector. Furthermore, increasingly "low-carbon" hydrogen can be produced if the grid renewables content is increased.
- Grid balancing and grid services can be some of the advantages of electrolyzers as part of the energy system. These can also contribute to a business case for the operation of electrolyzers (and therefore the deployment of the technology) and support the integration of the growing share of renewables in the electricity system.

- The project provided a clear description of its relevance and objective, including statements of how the objective will be met. However, it is not clear how this will reduce hydrogen costs. It is not clear that there is a reduction in the cost of the electric power used for the electrolyzer because it benefits the grid.

Question 2: Strategy for technology validation and/or deployment

This project was rated **3.5** for its project design, approach to addressing barriers, feasibility, and integration with other efforts.

- The excellent approach from the high level of grid signals and hardware response from the electrolyzer clearly shows the capability and goes into intricate details that are often missed with other studies. The 500-hour test with the electrolyzer and the Real-Time Digital Simulator (RTDS) are uniquely set up to show stakeholders the value, capability, and reliability resulting from close integration.
- This project to date has addressed the barriers of a lack of data in real-world operation and also hydrogen–electricity co-production and the milestones/goals are well-thought-out. The integrated approach between modeling and the use of real hardware is very good, and it makes the economic results relevant and convincing. Future work will address the barrier of hydrogen from renewable sources, and it should be interesting to see how this affects the cost of delivered hydrogen.
- The project combines tests with real-life data from grid operators. Therefore, the relevance regarding the transferability of the results for the operation of electrolyzers is high. The early interaction with grid operators is crucial for the further awareness of the technological advantages.
- The project does an exemplary job of addressing the noted barriers to renewable hydrogen and electricity co-production. However, other barriers that were listed include the implementation of stationary fuel cells in real-world operation. There does not appear to be any inclusion of a fuel cell in the test system. None were mentioned in the methods or in the remaining challenges and scope for future work. While an electrolyzer is similar to a fuel cell, and the merits of the electrolyzer work on its own are significant enough validation of the need for this project, it appears to be that the project does not address one of the claimed barriers at all.
- This is essentially a modeling project based on the simulation of an existing electricity grid (in California) interconnected with hydrogen refueling stations (although the stations themselves are not integrated in the model). A real (experimental) electrolyzer is connected to the model grid, and its response to impulses and effect on the grid is monitored. The point of view is essentially from the grid standpoint. It looks at what improvement on grid stability can be provided by the electrolyzer while also monitoring the derived effect on hydrogen production costs. No detailed information is given on the electrolyzer itself (250 kW—presumably a polymer electrolyte membrane electrolyzer, but nothing else is disclosed), and hence, the electrolyzer-improvement lessons cannot be drawn from this project. The project appears well designed and feasible.
- The project provided detailed identification of the components used in the experimental setup under the approach and an explanation of the testbed configuration. There was a good explanation of the components and functions of the front-end controller. It is not clear how the front-end controller yields fast response because of dependence on balance-of-plant (BOP) response time. Identification of metrics is at a top level; e.g., it is not clear what “safe operation” entails. The explanation of optimization of BOP does not provide a comparison describing the improvements or what was changed.

Question 3: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.7** for its accomplishments and progress.

- The unique capability that this project demonstrates is how to use physical HIL in response to real-time electric grid data, which is on its own a unique and major achievement. Additionally, the demonstration of grid support capabilities, while not unique or a first, makes significant contributions to the growing body of knowledge regarding real-world expectations of electrolyzer performance. The business case analysis is also among the highlights of accomplishments for this project. The ability to translate highly technical capabilities of the electrolyzer into the opportunities and limits of real-world application is one of the greatest information needs in the area. The particular approach this project takes toward that end adds confidence to these results and is highly valuable.

- The grid modeling results from Pacific Gas and Electric Company (PG&E), with the map of regions and locations of electrolyzers with actual load profiles, gives an excellent view and provides education to those who might not understand the use and capability of electrolyzers and grid integration. The clear example of a fault situation and how electrolyzers can respond rapidly shows the clear value of the project. This is especially important when traditional generation with "grid inertia" support (reactive power) is gradually declining with increased solar and wind generation. The efficiency results were clearly demonstrated as well as grid simulation capabilities. All of these results can be fed back to research and development efforts on electrolyzers, fed to the grid integration and modernization efforts, and—most critically now—passed forward to grid stakeholders so appropriate policy frameworks can be implemented.
- The project's great success in showing the positive effects of the front-end controller and pointing out the advantages of electrolysis for grid operations contributes highly to a positive perspective for future electrolyzer deployment. The excellent approach and the high quality of work regarding verification and validation of the results are highly appreciated.
- Good progress has been made on all goals outlined, except Milestone 2, but it is expected that the milestone will be complete by the new deadline. While potentially outside of scope, it would be interesting to investigate the effect of electrolyzer and system scale on the economics with the model. Generally, scaling the systems up has resulted in lower cost per kilogram of hydrogen.
- The milestone table gives the status of recent and past accomplishments. Chart 14, "Summary of Accomplishments," is more of a shopping list and does not fully explain what the barriers or accomplishments are. Subsequent charts yield additional information explaining benefits. Electrolyzer data provides a basis for improving the controller and optimizing electrolyzer performance. It is not clear what the benefit of demonstrating HIL capability is and how it moved the project forward. It is not clear whether charts 16 through 19 include an electrolyzer with BOP or just a stack. It is not clear how the electrolyzer response is determined. The business case analysis reduces the cost of hydrogen by 50%, which is extremely good. This should be cross-checked by an independent third party. It is not clear whether the analysis includes the delivery of hydrogen to the user. The economic benefit for a U.S. state assumes a demand for hydrogen. It is not clear whether utilities go into competition with the gas industry. It is also not clear who the owner/operators of the electrolysis systems are and whether the cost includes delivery to the user.
- The presentation was very difficult to follow owing to the wide use of acronyms and the technicalities related to unfamiliar grid operations. The results presented demonstrate the relevance of electrolyzers for stabilizing the grid against frequency and voltage peaks, while at the same time producing hydrogen in a more or less efficient manner, depending on the power feed and according to grid needs. In parallel, the perspective of electrolyzer cost and revenue optimization are also modeled in the optics of producing hydrogen using cheap electricity at times of favorable supply–demand conditions (high supply, low demand) while attempting to maximize electrolyzer operations. A comparison across the U.S. states is made according to utilities' rates. The project is progressing steadily toward its goals, albeit with some delay. It is expected to reach the 500-hour operation milestone by end of 2017, somewhat late compared to the project plans. Initial results are encouraging, showing the swift response and beneficial effect of electrolyzer "intervention" in case of simulated faults in specific locations (nodes) of the grid, be it in terms of voltage or frequency peaks/troughs.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.7** for its collaboration and coordination.

- Because of the nature of the work, there was extremely tight collaboration with INL, with the RTDS and grid signals, and also NREL's support and management of the electrolyzers, monitoring of individual components, and capability to respond to variable operation. The highlight and most important collaboration is the early input from end-user stakeholders: PG&E, California Independent System Operator (CAISO), Xcel Energy, and EnerNOC. The input from Humboldt State University and Florida State University is very important for workforce development and encouraging the knowledge and capability expansion outside of California. The California Air Resources Board is an important stakeholder, and the business case evaluation will further push this project forward with electrolyzers and lower-cost hydrogen coming into the market.

- The direct collaboration for this project, with utilities in particular, and the ability to use real-time data based on their system performance and knowledge are accomplishments that several other projects have not previously been able to achieve. These partners and their contributions are a key part of this project's usefulness and success. All other project partners present a wide range of knowledge bases and end uses for the information produced by this project. Engagement with the state of California is likely to be a boon to faster implementation of this project's goals, given the state's current efforts in renewable energy and hydrogen.
- The efforts would seem well distributed among the project partners where roles and tasks are effectively respected. A wide range of stakeholders from various fields (utilities, environmental boards, DOE laboratories, and academic research) is taking part in the project, and the collaboration appears constructive.
- The team is well organized and well qualified, and all parties appear to work well together.
- Including real grid data and the grid operators already in the early stage of the project emphasizes the relevance of the topic for operations.
- Collaborations include key energy producers but do not include electrolyzer manufacturers. It is not clear how chart 22 got the electrolyzer cost reduction without having an electrolyzer manufacturer collaborating with the project. The power production industry is heavily regulated and does not have a reputation for innovation. It is not clear where the rest of industry is for this project. Subsystem characterization for stack is reported, but the feedback comment does not address BOP response time. Direct electrolyzer response time should be fast, but BOP hardware will be slower. The question addressed BOP. The project managers are attempting not to answer reviewer questions. This type of response reduced the rating in question 7.

Question 5: Proposed future work

This project was rated **3.5** for its proposed future work.

- The proposed future work hits all the key points. The ability of the grid-controlled electrolyzer to reduce the cost of produced hydrogen is the key underlying question. The front-end controller and cost analysis are very important to enabling the electrolyzer integration. The real challenge and success will be when grid rules and requirements can be adjusted for full electrolyzer integration into electricity markets in California and then in other states.
- The plans for the future are to continue to achieve the proposed milestones. The focus on renewable energy is appropriate. The plans to communicate the findings through a webinar and papers are excellent.
- Further work items, including validation and verification, show the excellent approach to facilitating the integration of electrolyzers in real-life grid environments.
- The only concern is the time left for the future work to be completed. The work is logical, and risk mitigation is planned, but it seems like it will take longer than the remaining project time, especially considering any documentation time that may be required.
- This is not really addressed in the presentation, and in fact, the project is virtually finished (ending in September).
- It is not clear where and when the response time of the BOP (not the stacks) will be reported.

Project strengths:

- The direct applicability of the project and the imminent and significant knowledge gap that it addresses are core strengths. Additionally, the unique approach, collaborations, and tie to real-world business case analysis will prove extremely powerful in the project's outcome.
- The project addresses multiple barriers and specifically addresses a DOE milestone. Progress has been mostly on schedule, and the results and tools delivered so far are useful for understanding the role of electrolysis with the technology available today. Plans will also likely deliver data that has high impact, and the plans to share results are notable.
- The project has an excellent approach, with comprehensive grid modeling based on real-life data. Collaboration with grid operators is also a project strength.

- Projects strengths are the collaboration and well-thought-out design of experiments and equipment integration.
- The project has a well-organized approach and an acceptable team, except that an electrolyzer manufacturer is needed.
- The project has powerful modeling work capable of illustrating the mutual benefits of water electrolysis for grid services and hydrogen production for an effective cross-linking of the two sectors.

Project weaknesses:

- No major weaknesses are detected.
- The project would benefit from a better roadmap and explanation of how the project information can be directly input into an electricity market formulation so that electrolyzers can be treated as being as capable as batteries.
- The only weakness is that the project approach allows only for evaluation of the possibilities provided by present-day electrolyzer technology. Electrolyzer hardware is rapidly evolving, and there are expectations for significantly greater operational capabilities in the not-too-distant future. Although projections of future capabilities are beyond the core scope of this project, it would have been favorable to see some of this added to the project.
- The project has not fully demonstrated that the BOP response time will be acceptable.
- The main weakness does not address the science but rather its dissemination; the project could benefit from a clearer presentation and illustration of the benefits from both the grid and the hydrogen production standpoint, using terms that both sectors are able to understand. It was difficult to follow the grid standpoint because of a lack of familiarity, and this was not helped by the wide use of acronyms. For the electrolyzer part, there appeared to be no statement on the technology addressed and other specificities, while presumably this must play a significant role in some of the results.

Recommendations for additions/deletions to project scope:

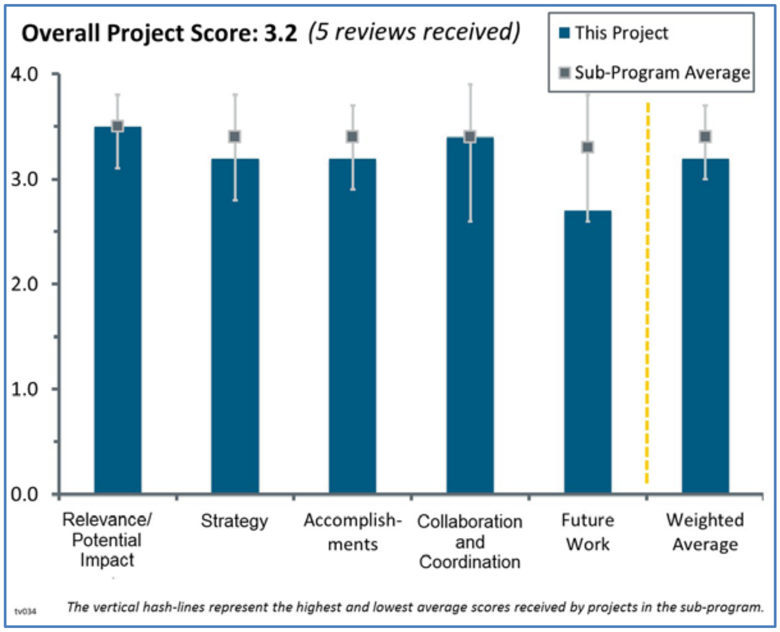
- The project scope is appropriate as long as the delay in the 250 kW testing does not delay other milestones. It did seem it would not pose any issues.
- Where scope and budget are available, the project should look for further meetings with CAISO, the California Energy Commission, and the California Public Utilities Commission to discuss how these results can inform electricity market updates and to start discussions with the Federal Energy Regulatory Commission.
- A good addition would be some way to project differences in the grid-integration-level possibilities for future electrolyzer technology. This is simply in acknowledgment of the rapid pace of development in that field currently and the potential for this project’s results based on current electrolyzers to under-predict the benefits of such a system by the time it could be implemented in the real world.
- It is recommended that the project bring in an electrolyzer manufacturer that will guarantee the response time of a commercial electrolyzer. The project should explain why the BOP response time was not specifically given, because previous years’ work assumed an electrolyzer stack response. An independent third party should analyze the business case.
- Future work may also include the integration of different electrolysis technologies to see whether any of them can show further advantages for grid services.
- The project is about to finish, so no recommendations appear to be relevant at this stage.

Project #TV-034: Fuel Cell Hybrid Electric Delivery Van Project

Jason Hanlin; Center for Transportation and the Environment

Brief Summary of Project:

This project aims to increase substantially the zero-emission driving range and commercial viability of electric drive medium-duty trucks by integrating a hydrogen fuel cell into the powertrain. Investigators will develop and validate a demonstration vehicle to prove its viability and then build and deploy up to 16 vehicles, which will perform at least 5,000 hours of in-service operation. The project will also develop an economic and market opportunity assessment of medium-duty fuel cell hybrid electric trucks.



Question 1: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.5** for its relevance/potential impact.

- The project scope is relevant in that it aims to validate, in real-life conditions, the combined use of battery electric drive with hydrogen fuel cell electricity generation for extended-range versus battery-only electric motors, combining the best of both worlds in the quest for effective zero-emission solutions in United Parcel Service (UPS) parcel delivery vans. The project has the potential to bring evidence that the technology is ready, competitive, and effective in practice, with the elimination of battery-only limitations such as range.
- The fuel cell hybrid delivery van has the potential to reduce operating costs, reduce fossil fuel use, and commercialize the application of fuel cells for medium-duty transportation. Fleets of zero-emission delivery vehicles provide enormous market potential, and this project will showcase the capability and is a potential key to convincing industry and other players to invest. Fossil fuel reduction and zero emissions at the community level will be a visible end result to prove the value of the technology.
- This project has enormous potential to address a critical need in terms of viable medium-/heavy-duty commercial vehicles using fuel cells and in long-range applications. Unfortunately, funding gaps suggest it may end up being of less value than it could have been.
- The project fully supports the U.S Department of Energy Hydrogen and Fuel Cells Program goals and objectives, especially for fuel cell vehicles.
- There is a high potential impact owing to the limited range that comparably sized battery-powered electric medium-duty delivery trucks have been shown to deliver.

Question 2: Strategy for technology validation and/or deployment

This project was rated **3.2** for its project design, approach to addressing barriers, feasibility, and integration with other efforts.

- The project and system validation are well planned and will provide the critical element of performance and durability data. By using the system in real-world applications, the market acceptance barrier can be overcome and help educate decision makers regarding the economic value gained from using low-carbon transportation. User experience from driving these vehicles and managing infrastructure will be key to providing know-how and the opportunity for improving and optimizing the system with future improvements. Funding should not be a barrier and speaks to the design of the state and federal demonstration programs and the need for better coordination, which is outside of the control of the industry project partners.

- The project has some excellent components, such as developing an option for longer-range delivery services (which lack good zero-emission vehicle options) and an opportunity to work closely with a shipping concern such as UPS to ensure fuel cell system integration meets UPS's needs. It is understood that dual-port fueling will be performed for practical reasons, but it is noted that it makes the viability of this technology less clear.
- Regarding project design:
  - The project foresees the initial development of one prototype vehicle and test-driving that vehicle for six months before making a go/no-go decision for the development and further testing of up to 15 additional vans. The project design appears sound, although the criteria for the decision to move to Phase II are not clear.
  - With respect to implementation, it seems to have slipped more than one year without explanation. The presentation suggested that delays are due to a modification of the consortium, although this remains vague. Further problems appear to be due to funding, which is not yet secured, so that the number of additional vehicles to deploy in Phase II may be reduced considerably in comparison to the 15 originally planned.
  - Surprisingly, a fueling problem is described in which the fueling stations to be used for the project are not configured for fueling 10 kgs of hydrogen in a single operation; two tanks will be refueled separately through different ports (one at each side of the van). This will inevitably increase the refueling time but is a viable solution at this stage. Ultimately, UPS would, if the technology is widely adopted, install its own refueling station.
- The project activities are well planned and well designed.
- The go/no-go decision point is February 2017, an apparent typo as the Phase 1 demonstration had an estimated completion date of January 2018. The approach is good, but there is a very tight timeline considering the vehicle build status in June 2017 and the goal of collecting six months of operational data. It is not clear whether the arrangement (fueling contract and payment card) is in place to fuel vehicles at a hydrogen station (West Sacramento or elsewhere). Fueling may also require a number of fueling tests, as it appears the assumption is that this vehicle can be fueled without any challenges.

Question 3: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.2** for its accomplishments and progress.

- The project has an outstanding platform design and went into significant detail to model and simulate actual routes, fuel requirements, and the difficult challenge of sizing batteries and the fuel cell. With 50% of the project complete, the real test will be how much data is collected and to identify a clear path around the challenges of refueling infrastructure. The delayed start due to funding issues may result in fewer metrics or less progress.
- The project demonstrates improved progress in this past fiscal year, although it still has a long time horizon and seems to be struggling to keep pace with that. There is a concern that while this project is working to get off the ground, other technology developments will be occurring that will make the results of this analysis less relevant.
- Satisfactory progress has been made to manufacture the first vehicle, showcasing the chassis and components at the Advanced Clean Transportation Expo in Long Beach in May 2017. It would be good to hear that a fueling contract is in place and that fueling tests are scheduled.
- The project seems to make steady, albeit slow, progress, and it would seem that the first vehicle will finally be deployed in the coming months. Currently, and at least until the first vehicle is demonstrated, it is difficult to decide whether the design will work or drawbacks will emerge. In any case, learning could be drawn even from problematic setbacks, so steps toward DOE goals will still be made, albeit more in terms of what not to do.

- There have been delays in the demonstration vehicle build.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.4** for its collaboration and coordination.

- The collaboration required for route simulation and vehicle component sizing between UPS and the integrator is a difficult challenge that was satisfied. The design and tank development require close collaboration, and perhaps more suppliers could be brought in to compete for supplying a new “off-the-shelf tank” choice, or looking at a new design shared among multiple customers.
- There is excellent collaboration among several organizations, especially UPS.
- There is little information about this in the presentation, but there is no reason to doubt good collaboration now that the consortium is confirmed.
- It appears that the right partners are on board and actively contributing now. Insufficient cost-sharing commitments have put the project’s go/no-go decision point at risk.

Question 5: Proposed future work

This project was rated **2.7 f**or its proposed future work.

- This project should include fueling tests, as a single-tank system (times two with independent receptacles to get to the 10 kg total vehicle capacity) falls within the 35 MPa SAE J2601 fueling standard; dispensers at California retail hydrogen stations may respond differently for multiple-tank systems from the single-tank systems on passenger fuel cell electric vehicles. It should not be a problem, but with the current schedule, additional delays cannot be afforded.
- The main decision point is the go/no-go decision to be taken after deployment of the first vehicle.
    - This makes perfect sense, although the criteria to be used to determine whether the project should be continued are unclear. The bottleneck of vehicle construction should nevertheless be addressed since it took more than three years from the project’s start to completion for the first van; it seems important to ensure that the following vehicles are produced significantly more rapidly so as to be deployed in time to produce relevant performance data by project end. There are doubts that a 5,000-hour operation time per vehicle (apart from the first prototype van) will be possible by the end of 2020.
    - The go/no-go decision (scaling from 1 to 16 vehicles) was initially intended for February 2017, yet even the first vehicle is not yet deployed, and the decision seems to be now scheduled for “early 2018.” At the submission deadline for the AMR presentation, the first vehicle was still only 50% constructed, so it is hard to believe that in the first quarter (Q1) of 2018 the vehicle will have been on the road for the intended six months to allow for an informed decision to scale up the demonstration fleet. Furthermore, the principal investigator mentioned that the prototype van would not be deployed over the Christmas period, so the utilization period will be further reduced. Currently, the project could be ready for a go/no-go decision no earlier than April–May 2018, assuming that the first vehicle is deployed this fall (it is unclear if it will really be ready by September). It is difficult to be confident of the scheduling indicated for Q1 2018.
    - Should a “go” decision be taken, it is uncertain that the project can secure the funding for all 16 vehicles originally foreseen. Phase II vehicles would then need to be built, placed into service (with possibly one year required for production), and operated for two years to comply with the project plans. This may not be feasible within the current project end date in November 2020.
- While future work appears logical, the shifting target on remaining cost share did not appear promising. The most critical elements will be to finish the vehicle build and vehicle operation in order to collect data. There does not appear to be a risk mitigation option if the funding is not available. Training and education are also important and should be straightforward after the vehicles are complete.
- Unfortunately, this project is suffering from elements outside its control, namely funding availability. It appears that the Phase II development of pre-commercial volume may not happen; this is a real limitation on the project’s real value to move fuel cell technology forward in this application. It appears that it may be up to the private sector partner to carry this forward.

- Details for the proposed future work are lacking.

Project strengths:

- The project has strong collaboration between partners, including a thorough review of component requirements needed to advance the DOE Fuel Cell Technologies Office (FCTO) roadmap goals. The project team provided detailed modeling and simulation results required for system sizing. This will ensure the results are accepted by industry and that regulatory agencies see the technology potential needed to ensure a higher chance of commercialization, which is the ultimate goal of FCTO in bringing new technologies to market. An important strength was the clear collaboration between multiple project partners and sponsors to share the data and knowledge from the publicly funded project. Detail-oriented safety hazard and operability analysis, including operator training, will be vital to ensuring the smooth introduction of the new technology and gaining acceptance from the public, the industry operator, and communities where the trucks will be used.
- The project has the potential to bring high visibility to fuel cell technologies owing to the relevant vehicle fleet operator (UPS). The presence in the media since spring 2017 will hopefully allow the technologies to reach a wider public and feed into the goals of the "Education and Outreach" technical plan, namely on technology awareness and acceptance. This could result in increased market uptake, at least in markets with favorable infrastructure density, such as California.
- This addresses a real gap among current technology solutions for low-/zero-emission delivery vans. Collaboration with UPS is a plus. The vehicle appears to have been designed largely to meet real-world delivery needs.
- There is potential of a fuel cell drivetrain in the project's truck vocation. Partners and component suppliers are a strength.
- The activities of the project are well designed and well planned.

Project weaknesses:

- There seems to be a high uncertainty as to what the project will eventually develop into, namely the total number of vehicles deployed (in the case of a "go" decision). In addition, the schedule presented appears unrealistic and will lead to a non-completed project unless the timeframe is extended beyond 2020.
- The need to use public fueling is unfortunate in the impacts it had on vehicle configuration. Clearly the biggest weakness is the potential for this not to move to Phase II. That is a risk with this type of project configuration, but it does seem as though the project may end in "stranded" vehicles that do not move to a commercial phase.
- Funding, or lack of funding, coordination between local, state, and federal agencies is a project weakness.
- Project delays and lack of details (including risks and risk mitigation) for proposed activities are weaknesses.
- A funding shortfall, the cost of 70 MPa tanks, and (external) fueling protocol limitations are weaknesses.

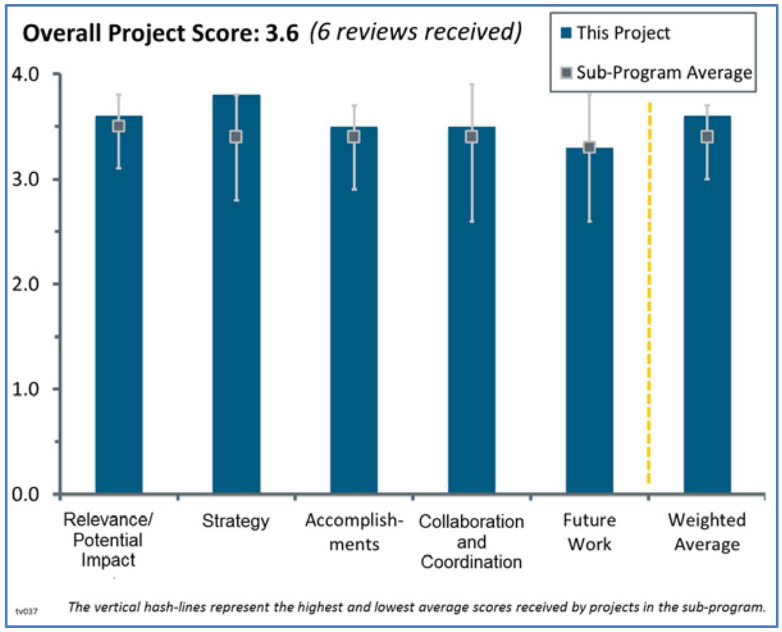
Recommendations for additions/deletions to project scope:

- The project should consider using 70 MPa tanks similar to those used for Toyota Portal truck or passenger car tanks and purchase through car manufacturers to take advantage of scale contracts with tank suppliers. The project should explore larger batteries or battery systems (from existing passenger vehicles such as BMW or Nissan; BMW battery systems are showing up in other applications as a reliable supplier-supported system) to deal with challenges of fueling protocol limitations at 70 MPa. Relying on passenger vehicle battery systems may also aid in reducing overall costs, including cost reductions that can be achieved by using/acquiring smaller fuel cell systems—possibly 16 or 20 kW. For future marketing of developed systems and focus on "kit approach," the project should consider approaching an entity such as Freightliner Custom Chassis.
- In the light of all information available in the presentation, there should be a more realistic plan and strict implementation management to avoid further delays. This should also include specific, measurable, achievable, relevant, and time-bound criteria that will be used in the critical go/no-go decision step so as to be able to apply them promptly and objectively to take the appropriate decision. In case of a "go" decision,

given the uncertainty on the total number of vans that can be funded, partners should make relevant scenarios according to ultimate deployment numbers. The plan should also include preparation for the building of the additional vans in view of minimizing the time needed for further deployments.
- Funding should be increased for storage development for 10 kg modules that could be used across multiple fleet applications, not just for UPS. The project should develop an explicit off-ramp for the project and criteria needed for actual adoption by industry for zero-emission, medium-duty delivery trucks.

Project #TV-037: Hydrogen Meter Benchmark Testing

Michael Peters; National Renewable Energy Laboratory



Brief Summary of Project:

This project designs and builds a laboratory-grade gravimetric hydrogen standard for measurement of hydrogen flow; conducts performance testing of commercially available flow meters, replicating conditions specified in the SAE International J2601 fueling protocol; and reports on flow meter performance against National Institute of Standards and Technology (NIST) Handbook 44 (HB44) requirements and California Code of Regulations accuracy classes.

Question 1: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.6** for its relevance/potential impact.

- This project is highly relevant to the support and advancement of the progress toward reaching the U.S. Department of Energy Hydrogen and Fuel Cells Program goals and objectives. The metering in a hydrogen refueling station is integral to designing, building, commissioning, and operating a hydrogen refueling station, which is often required by regulation to undergo testing and certification to sell the fuel. The development of a robust supply of accurate flow meters is essential to the proliferation of stations. The development and production of accurate flow meters that the public can rely on to output reliable, repeatable, systematic, and trustworthy data so both the hydrogen refueling station operator and the consumers that drive the fuel cell electric vehicles (FCEVs) are charged equitably is a cornerstone of the retail sale of hydrogen, and this is part of the project relevance.
- This project is highly relevant because it addresses real-time gaps in knowledge and potentially even equipment design that are affecting the real-world deployment of hydrogen fueling stations and hydrogen-fueled vehicles today. Meter accuracy is considered a key enabling technology in jurisdictions where hydrogen fueling stations are currently being installed because the ability to accurately meter dispensed hydrogen qualifies a station for retail sale of fuel. Without retail fuel sales, hydrogen FCEVs and stations will not be able to proliferate, and essentially the goal of demonstrating station capabilities is lost in real-world applications.
- The coordination with the California Division of Measurement Standards is excellent and absolutely necessary. The fact that one of the meters is a Coriolis that is in development is very good; perhaps it should be a prerequisite for this project that meters to be tested are not be commercially available or used.
- This project is important to benchmarking state-of-the-art metrology technologies and to doing so under actual filling protocols currently established (SAE J2601). The measurements performed are important and clearly quantify the accuracy shortfalls of the meters tested. The measurement test method is good, and the accuracy of the test facility is good enough for this application (+/-2.5 gm out of 4.0 kg). There is some concern, however, that some critical elements specified in J2601 were not tested. The test protocol included a start-and-stop sequence, but it did not include the sequence specified for leak testing (National Fire Protection Agency), which is a sudden stop, followed by a short time of zero flow, followed by a return to the pressure ramp specified in J2601. It is anticipated that this leak test sequence will result in significant

error, particularly because all the meters have a delay in measurement as identified by this project, and no known meter will measure accurately if the frequency of the data is infinity (sudden stop and start have frequency responses of infinity). Also, it would be beneficial to see the testing done across an entire J2601 fill process. This project was dinged on approach principally because only parts of the fill protocol were tested. The project should either test across the entire J2601 protocol or provide convincing reasons why that is not necessary.

- The project contributes to the understanding of metering devices and the relevant parameters that need to be addressed in regulations, codes, and standards.
- Three units were benchmarked: two Coriolis meters and one turbine meter. One of them is commercially available. A number of variables were changing during the fill: flow rate, temperature, pressure, readout response, etc. No attempt was made to remove a variable to determine individual effects. For example, if the fuel density range during the fueling process was reduced by 50% by controlling the meter inlet pressure and temperature, it is not known how this would affect the measurement accuracy. Expecting a meter to be accurate over a 15,000 psi pressure range and a 100°C temperature range may be unrealistic.

Question 2: Strategy for technology validation and/or deployment

This project was rated **3.8** for its project design, approach to addressing barriers, feasibility, and integration with other efforts.

- The first major highlight of the approach is the test rig that was developed for this work. This appears to be a unique capability and is providing data that no other entity currently seems to be investigating. In addition, the use of statistical methods for characterization in this work was an intelligent choice and adds power and meaning to the results. Presentation of probabilities of meters to meet tolerances is a clear advance in the ongoing conversations in this area and is a necessary addition. It is encouraging that this project presents its results in this manner.
- The strategy for technology validation and the deployment of flow meters developed and presented in this project is reasonable and logical. The project is well designed; it started with data collection. The project analyzed station data, including efficiency, downtime, maintenance cost/time, capital cost, integration, and controls of stations in the field. The strategy also included engaging industry stakeholders to find solutions to meter benchmarks.
- The project has an excellent approach to contributing to awareness for improvements in metering accuracy as well as the understanding of critical parameters for metering.
- It is pleasing to see that the project is working to meet the +2%, because it is necessary for station deployment.
- The progress made to date is excellent, but it needs to go further.
- The test results support the concern on the measure range (pressure and temperature). During the process, it is not clear whether the researchers thermally choked the flow in the meter. The issue with vibration is interesting, but it is not clear whether it was from an external source or was flow-induced. If the vibration was from an external source, it is not clear whether there were ideas on how to isolate the meter from the source. If it was flow-induced, it may be an artifact of the meter or the installation. It is not clear whether the meter is experiencing vortex shedding or periodic thermal choking. It is not clear whether the meter is installed correctly. For example, the flow is usually disturbed for 5 to 10 pipe diameters after a component that might disturb the flow. Perhaps the meter was too close to a fitting or a device was located immediately upstream.

Question 3: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.5** for its accomplishments and progress.

- The project has numerous accomplishments:
    - The station layout is complete.
    - The station components are purchased and installed (including a chiller and dispenser). Quality testing is complete.

  - The station flow diagram is complete.
  - Vehicles are on site.
  - An on-site electrolyzer is installed.
  - Power supplies are installed.
  - The Hydro Pac compressor is installed.
  - Low, medium, high pressure are installed.
  - In this two-year project (ended in 2016), there is a flow meter that works for compliance with HB44 (5% accuracy) and 2% meter accuracy. This project tested three flow meters, including one flow meter that is commercial.
  - The project simulated SAE J2601 fills and typical fueling conditions for FCEVs (0.5 kg to 1.2 kg fills). To simulate fills in the field, the project used +/-2%. This project tested the probability that the fill falls within a 2% accuracy. High flow rates (the meter did worse), pressure ramp rates, and the position of the meter were tested. The project observed false readouts under conditions of vibration. The time between when the flow stopped and when the meter stopped incrementing changed with the various meters.
  - The overall goal is to charge the customer the "right amount" and also charge the station the "right amount." This project made substantive progress to achieve this goal.
- This, in particular, is an area where the project has improved over the past year. The project's intent is now absolutely clear and is in the correct direction for meeting the needs of demonstrating the viability of a hydrogen fueling station. To that end, this project is providing much-needed insight that will enable deployment, use, and long-term viability of the types of hydrogen fueling stations that are part of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan goals.
- Metering is one of the crucial issues in the future deployment of hydrogen in the market. This project contributes to improving the accuracy of metering and, therefore, the market readiness of hydrogen as a transport fuel.
- The project has a lot of good information/learnings, but it would be nice to know which of the two Coriolis meters had the 73 g add with the 8-second delay and vibration (the one currently in use or the pre-commercial one). Either way, the project provides excellent information for station developers, meter manufacturers, and weights and measures officials.
- The work done to date may transfer to the dispenser product safety testing protocol.
- Meter accuracy is critical to the selling of hydrogen to the public. Current meters are not sufficiently accurate to satisfy the eventual accuracy of the needs of metrology (the relaxed accuracy classes currently used in California will sunset soon). This work should help meter manufacturers improve their devices.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.5** for its collaboration and coordination.

- The collaborators and coordination with other institutions are appropriate for this activity. This team consists of appropriate players in the field. Indeed, the Joint Research Centre Institute for Energy and Transport, which is well established as doing excellent work on understanding the fill physics, and NIST are both key partners. It is an excellent team.
- Collaboration included many stakeholders and end users. It is excellent across the board.
- There is great collaboration with producers of metering devices.
- The collaborative partners seem appropriate and complete. However, of concern are the noted difficulty with data confidentiality and, more important, the lack of clarity for a proposed solution to this issue. The ability to share the project's data and insights as closely as possible with equipment manufacturers will likely be the key to this project's ultimate impact. Additionally, there is noted collaboration with equipment manufacturers, but it could be preferable to have them as actual partners.
- Equipment suppliers, manufacturers, and regulatory agencies in California were included.
- The collaborators make sense. The issue is that none of the collaborators make flow meters.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- The development of a control scheme to improve accuracy is an excellent path forward; it would be nice to do some complete J2601 fills.
- The proposed future work is necessary and seems reasonable, although it might be a bit ambitious for the remaining time of the project (especially development of a controls scheme). One addition that could prove useful is to develop design suggestions of best practices based on the insights gained from this work.
- The proposed future work needs to also include filling over the entire J2601 fill protocol. The notion of developing a "calibration" algorithm to develop a correction for these meters is good. It will be good to see whether one can be developed using the "station" certification process to improve the accuracy of these devices.
- Inclusion of further metering devices and further parameters for testing is highly appreciated.
- Although this two-year project ended, the author proposes the following future work: power to gas, vortex tube, MC method fueling, tube trailer consolidation, and tests with new chiller technologies.
- The proposed future work might not be cost-effective. However, the following paths might be:
    - Working with a meter supplier
    - Generating testing protocols for measuring accuracy of dispensers and supplying them to the CSA Group and the International Organization for Standardization (ISO)
    - Looking at other technologies such as mass flow meters
    - Considering system design changes for dispensers to enable the meters to be more accurate

Project strengths:

- Significant strengths include the immediate applicability of this work, as well as its critical role in developing an enabling technology for hydrogen fueling station deployment. Additionally, the statistical characterization of meter performance is one of the strongest portions of this project because it moves the national conversation around meter accuracy forward with a needed degree of insight and nuance that has been lacking.
- The project is technically superior. From a presentation point of view, it used graphics well. The project tested numerous conditions and sets the stage for best practices to help station developers/operators to use the right meter, which is not necessarily the cheapest meter or the meter that is the easiest to get.
- Project strengths include the excellent test capability, very qualified principal investigator, and excellent collaborations and team.
- The project covers an extremely relevant field of research that affects acceptance of hydrogen for users as well as stations.
- The project ruled out some technology (or at least confirmed that it is not good for retail hydrogen stations). It also got useful information about vibration and its effects on the meter and accuracy. The project can potentially be a great service to the industry.
- The partners are a project strength.

Project weaknesses:

- The project may need control schemes for FCEVs containing different amounts of fuel (half full and completely full). It may need to develop a control scheme for each dispenser on the market.
- The project might formulate recommendations for future metering technologies as an outcome of the test results.
- This is not so much a weakness, but it is unfortunate that the project is not able to do a full J2601 filling event. Maybe the partial fill is fine, but it would be nice to confirm this by comparing the partial to the complete fill.
- An expansion of the number of different meter designs may be necessary in the future for this or a follow-on project. Inclusion of equipment manufacturers as full project partners may be a strategy to enable this expansion. Additionally, the project did not make it clear what types of information, insights, etc. would be passed along to manufacturers once the confidentiality issues were resolved.

- The project should fill out the test methods to include a more complete J2601 fill.
- There are no meter manufacturers.

Recommendations for additions/deletions to project scope:

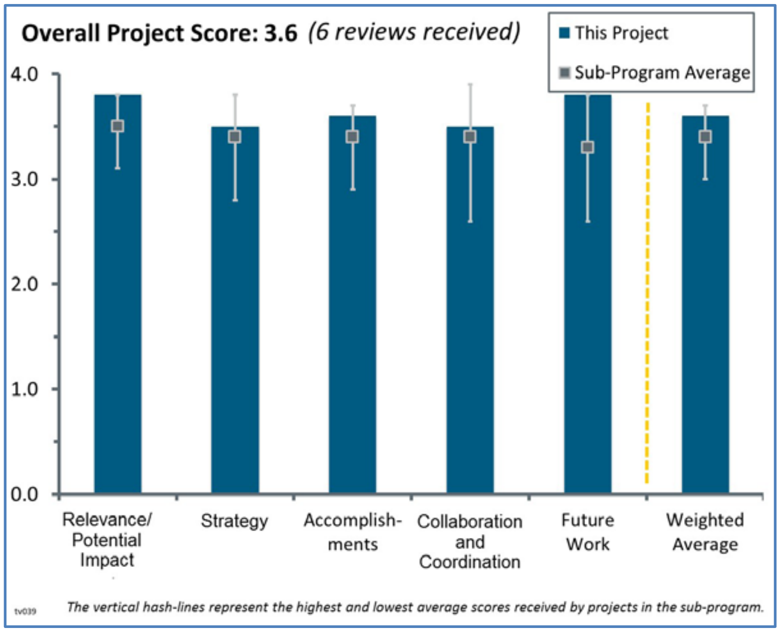
- If the project continues to test commercial meters as well as pre-commercial/prototypes, perhaps there should be two separate "arms" of the project. If a meter is already in use at hydrogen stations, the extent of testing may not be the same as ones that are prototypes. The pre-commercial ones, it would seem, have more opportunity for tweaks to improve them over the ones already out on the market.
- It is recommended that the project determine the probable causes for the inaccuracies and develop tests to verify that the deficiencies are addressed. The project team should work with CSA, ISO, and NIST to generate test methods to address these issues. The project needs an end game (goal).
- The project should add, as a project outcome, a technical brief that provides insight into potential solutions for the problems that have been identified by this project.
- This project term is over; the team is working on a National Renewable Energy Laboratory publication to disseminate. In the next phase, the team should implement a control scheme in the Northeast hydrogen refueling stations and get more manufacturers involved.
- Including further meters as well as test parameters can contribute to a growing understanding of metering issues.
- The project should fill out the test methods to include a more complete J2601 fill.

Project #TV-039: Innovative Advanced Hydrogen Mobile Fueler

Sara Odom; Electricore

Brief Summary of Project:

The objective of this project is to design and build an advanced hydrogen mobile fueler (AHMF). The developed mobile fueler will be deployed to support a network of hydrogen stations and vehicles, and fueling data will be gathered for analysis by the National Renewable Energy Laboratory Technology Validation Team. To reduce risk, the mobile fueler is based on an existing conventional station design, and project efforts are coordinated with station providers and automotive manufacturers.



Question 1: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.8** for its relevance/potential impact.

- The project is very relevant to the goals of petroleum reduction and collecting data to show market potential and enabling zero-emissions transportation. Objectives were clearly outlined with milestones for the design and build of the mobile fueler. The project will also increase the network of refueling stations to allow a network effect and accelerate customer acceptance. The data collection is important to prove technical capability and show safe operation.
- A 70 MPa, SAE J2601-compliant mobile/temporary fueler has not been built and operated in the United States before. This helps with understanding the gaps in the codes and standards framework. Population in the Northeast has limited awareness about hydrogen fuel cell vehicles, even less so about hydrogen fueling infrastructure. This mobile fueler will help educate and lay the foundation to understand the technology.
- The project has high relevance in that it allows gaps in the hydrogen refueling station (HRS) network to be filled and can contribute to the education, outreach, and acclimatization of authorities having jurisdiction and the public in areas (e.g., the U.S. Northeast) where there are few or no HRSs. In addition, resolving the U.S. Department of Transportation (DOT) issue with transporting charged storage systems can have significant impact. However, it seems like others have potentially already received this approval (OneH_2, Hydrogen Frontier).
- This project supports and advances progress toward the Hydrogen and Fuel Cells Program goals and objectives: reduced petroleum use, improved air quality, and the commercialization of fuel cell technologies. This project hinges on the perceived need of mobile refueling and, should that need come to pass, is highly relevant. An issue is that the industry cannot afford to wait, and if it waits too long, the opportunity window may shut.
- The mobile fueler option is a key to help bridge the infrastructure issue in case a station is down or a car is stranded. As an enabler, it could likely have a higher cost and still be attractive as an interim solution.
- The approach for this project is excellent, giving this project an excellent chance of successful completion. Reliance on existing design reduces the risk of failure.

Question 2: Strategy for technology validation and/or deployment

This project was rated **3.5** for its project design, approach to addressing barriers, feasibility, and integration with other efforts.

- Challenges and barriers are well laid out, with mitigation plans/solutions proposed. Discussion included safety considerations and the needs of users. Permitting considerations are also pointed out as a common opportunity that other suppliers can leverage. The project also leverages existing technology where possible to be consistent with existing stations.
- The mobile fueler is an option to start infrastructure to get over the hurdle of mass market required for profitability. Barriers related to transporting hydrogen, unattended refueling, retail sales experience, and component lead times are all barriers being partially addressed. Hydrogen transport and DOT permits with unattended retail sales will be key to working toward commercial viability.
- This is a new project (a little less than one year old), and progress to date is very good. The design is complete, with many of the long-lead-time items purchased. The project is poised to start assembly.
- The approach is straightforward. The design is a modification of an existing station design. It seems like the major hurdle is the total cost (approaching that of a permanent station) and the lead time. Using an existing design allows good specs and allows the focus of the project to be on solving the two significant hurdles.
    - Phase 1: Design and build.
        - Specs: 15 kg/hr., 100–120 kg/day, 70 MPa, pre-cooling temperatures of -30°C (T30) or -40°C (T40), dispenser human–machine interface at point of sale (HMI/POS) same as retail stations.
    - Phase 2: Test and deploy.
        - Fuel delivered to the mobile fueler using power cubes. It can be bump-filled or swapped out and taken back to a hub and filled. Also, one can hook into an off-board hydrogen (compressed hydrogen gas) supply.
        - The team is using a low-emission diesel generator that can plug into 480 V power.
        - SAE J2719 hydrogen fueling standards will be achieved.
- This is an effort to resolve known barriers, but at the same time, the project is most likely to identify new, unknown barriers.
    - Regarding vehicle grounding, there is a need for a grounded concrete fueling pad (blacktop/asphalt is not allowed for fueling operations). No alternative solutions are proposed, and considering the mobile nature of the device, this should be considered. Possibly there could be electrically conductive interlocking tiles or a mat onto which rear wheels have to be driven (to create a similar solution as grounded concrete fueling pad). Adding a grounding cable would change the steps a vehicle driver must take to fuel a vehicle, so that is not a good alternative.
    - For critical assumptions and issues, Option 1, without a DOT special permit, involves a high-pressure bank storage vessel. It is unclear why it would need to be purged, while "medium-pressure" DOT-rated tanks can be transported at ~50 MPa. It is not clear if this is an alternative solution to be discussed with DOT if the project is not receiving a special permit for 100 MPa.
- Permitting and the large footprint of a Class 8 truck need to be addressed. Many of the existing HRSs that this fueler would augment are too small for a Class 8 truck. The approach does not address permitting and fire codes. The approach does not address the footprint issue. The project team has completed an initial hazard analysis and will repeat the analysis in a future project. The AHMF is based on the Air Liquide C100 hydrogen station and will fill a vehicle in three to five minutes on a 25°C day.

Question 3: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.6** for its accomplishments and progress.

- The design was completed, and the design report has been submitted, which is good. It is unclear whether one can transport with both lower- and higher-pressure banks charged to lower levels and whether that will allow for faster set-up and avoid the need to purge high-pressure storage banks.

- The final design is completed, and the design report was submitted. Long-lead items were ordered. Initial hazard analysis was completed, together with a review by the Hydrogen Safety Panel. It is not clear how many long-lead items, such as a compressor and high-pressure storage vessels, were ordered.
- The collaborators and the coordination with other institutions are appropriate for this activity. There is a well-established gas supplier, consultants working with a major original equipment manufacturer and performing economic analysis, and entities well qualified for system design. This is a good team.
- Accomplishments include the completion of the fueler design (meeting current fueling protocol standards) that includes two Hydrogen Technology and Energy Corporation (HTEC) "power cubes" and provides an HRS on wheels. The next step is to build. The project milestone chart is complete. The project managers plan to send station data (from those vehicles to be fueled) to the National Renewable Energy Laboratory Technology Validation Team, and this data collection is very important to the overall refueling network. The plan is to be capable of refueling three fuel cell electric vehicles (FCEVs) in the first hour (~15 kg) and 20–24 FCEVs (~100–120 kg) per day.
- The project is just finishing the design phase, but design features were well-thought-out and included a review by the Hydrogen Safety Panel. There are still some uncertainties on permitting and what capabilities will be allowed on the fueler (such as transportation of high-pressure hydrogen or a need to purge the tanks before moving the fueler).
- The project is relatively new and will go through the most difficult phase with actual system builds. The cross-region applicability and critical path technology transfer activities are all in close alignment with DOE goals and show preliminary progress toward DOE goals of fossil fuel reduction and technology transfer to commercial applications.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.5** for its collaboration and coordination.

- When successful, this project will provide a critical capability to accelerate the deployment of hydrogen fueling station (HFS) infrastructure. A critical need exists for coverage, and soon capacity, to support the growing HFS infrastructure. Equally important is the critical need to improve station reliability. It is well recognized that HFS redundancy is needed to improve reliability and coverage. The AHMF will help solve this critical need.
- The project has five different partners that are all working in close collaboration. The complicated design and mix of technology and regulatory barriers speaks to the strength and need for tight collaboration. Involvement with local universities or other additional workforce development opportunities would be a possible addition.
- There is a good line-up of collaborators, with the hydrogen gas company as the main partner. The capacities/experience of HTEC with 100 MPa storage vessels (in pods), an area in which few entities have experience, are not completely clear. The project should consider engaging the California Department of Food and Agriculture – Division of Measurement Standards for introduction to the Northeastern Weights and Measures Association through gas company partners and/or a California network of contacts.
- The project partners are logical for gathering the components needed for the project. There are unconventional/unique partners that could be engaged to support/resolve the two key barriers (transport of charged storage and hydrogen metering).
- The project includes collaboration with vehicle companies and other stakeholders. The team is also pursuing permitting with DOT that would enable better station utility.
- The team began collaborating with others, developing fueling systems after the design was complete (it may or may not have been better to collaborate at the beginning of the design).

Question 5: Proposed future work

This project was rated **3.8** for its proposed future work.

- The next stages are basically to procure components and build and test the mobile fueler. The team has addressed most of the barriers, but the potential impact of any issues that would change the design should be resolved before the components are purchased.

- It is time to execute. It seems like the project will be highly successful if it can build the AHMF and resolve the two key barriers.
- It is not clear whether this AHMF could serve as an early fueling solution before officially opening at Northeast stations selected and funded for implementation (Air Liquide stations). This could develop early demand in the region and prove operational capabilities of the fueler until more vehicles are available in the Northeast. Sales of FCEVs have not started in this region and may still not be available by the second fiscal quarter of 2018.
- The presenter did not discuss future work, but the presentation includes future work: building the fueler and starting the tests in the Northeast (for commissioning new stations). Other future work includes certifying the mobile fueler to sell hydrogen, subsystem testing, and safety testing.
- The future work described is simply build it, test it, and deploy it in suitable regions (California) to test and sell hydrogen to the public.
- The next steps will be the most difficult for the project. Hardware and safety testing often carry the greatest risk. The project partners will need to work very closely to ensure successful completion.

Project strengths:

- The strength of this project is that it addresses the issues of unattended fueling. The project managers have already purchased a compressor, which shows commitment to the project. Another strength is that the project is based on already existing hardware design and equipment (i.e., the Air Liquide C100 hydrogen station and the Kobelco heat exchanger). The fueler will have an HMI/POS.
- The project has strong integration and collaboration components. The technical challenge of fitting 700 bar fast-fill equipment on a truck is very demanding. The project has a good team, and the design appears functional.
- The design is self-contained but still provides the ability to use stationary storage and off-site power. The proposed design is patterned after a well-established and used design; this reduces the risk of execution.
- The project had good assessments of the potential risks and mitigation plans for dealing with them. A review of the design was completed by the Hydrogen Safety Panel.
- Strengths include the project partners, the use of existing stationary fueling station components, and a mobile fueler capable of meeting J2601 fueling protocol requirements.
- There are clear goals, and the barriers/hurdles are well defined.

Project weaknesses:

- On-board power with a diesel generator is a weakness. The project should consider replacing this with an alternative fuel. The size is a drawback (the fueler will not fit in many HRSs), but the fueler can fit into larger areas. The fueler “weighs a lot” (the speaker did not give the weight).
- The physical size/dimensions of the mobile fueler are a weakness. It is not clear what the countermeasures are with regard to the adaptation of stationary station components or a trailer to withstand vibration from transport over the road.
- No clear economics of mobile fuelers were shared. It is unclear how much public funding is required to make a sustainable business case, even at $15/kg.
- There are still some uncertainties on siting and transportation considerations with the fueler that should be resolved.
- The team does not seem to have fully researched innovative solutions to the barriers that others may have found.

Recommendations for additions/deletions to project scope:

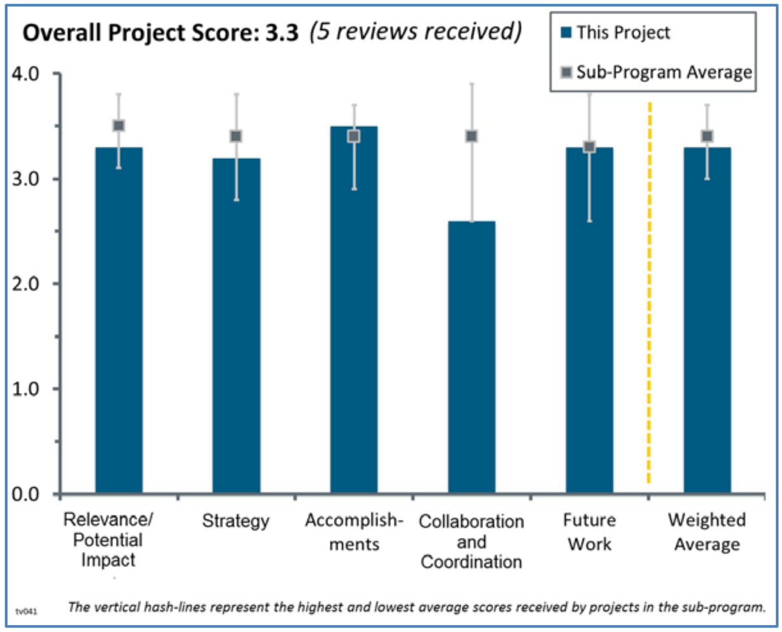
- It will be a significant accomplishment to reach the goals of the project as currently planned.
- The project should clarify the nature of “unattended fueling requirements” or develop the requirements comparison table between unattended fueling and attended fueling. It is unclear what the network of secure card lock fueling stations is. The team should investigate whether 24/7 fueling is possible in all locales with the generator in operational mode (the fueler not connected to on-site 480 V). Hydrogen Station Equipment Performance testing should be used to prove fueling performance per J2601 requirements.

- Alternative fuel (instead of diesel) should be used for on-board power. The team needs to work on regulations for the retail sale (metering) of hydrogen for this fueler. As an option, the team could adopt the California regulations for this. The team should work on the user interface for the dispenser to support unattended fueling. The team is doing excellent work.
- The economics of mobile fuelers, including lessons learned and the current pace of technology development, should be evaluated.

Project #TV-041: Modular Solid Oxide Electrolyzer Cell System for Efficient Hydrogen Production at High Current Density

Hossein Ghezel-Ayagh; FuelCell Energy

Brief Summary of Project:



This project seeks to demonstrate the potential of solid oxide electrolysis cell (SOEC) systems to produce hydrogen at a cost less than $2 per kilogram, exclusive of delivery, compression, storage, and dispensing. Project activities aim to (1) improve SOEC performance to achieve greater than 95% stack electrical efficiency based on lower heating value (LHV) of hydrogen, resulting in significant reduction in cost of electricity use for electrolysis; (2) enhance SOEC stack endurance by reducing its degradation rate; (3) develop an SOEC system configuration to achieve greater than 75% overall (thermal and electric) efficiency; and (4) improve subsystem robustness for system operation compatible with intermittent renewable energy sources and their load profiles.

Question 1: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.3** for its relevance/potential impact.

- SOEC systems at 90% electric efficiency with an ability for intermittent operation is very relevant to U.S. Department of Energy (DOE) goals and long-term cost targets. High-temperature electrolysis is more efficient and needs more development to get a better understanding of future cost reduction potential. A total of 1500 kg H_2/day is the right size for a hydrogen refueling station. The big challenge will be onsite storage, use profiles, and actual installed capital costs/durability.
- This technology could represent a significant step change in our ability to meet the hydrogen needs for the medium and long terms. If the project can meet the $2/kg targets, it would essentially replace the existing steam-methane-reformer-based infrastructure in the industrial hydrogen sector as well as scale to meet the needs of hydrogen energy for mobility.
- The project is indirectly relevant to the hydrogen production goal "research and develop technologies for low-cost, highly efficient hydrogen production from diverse renewable sources," although the project basically focuses on the solid oxide electrolysis technology widely, irrespective of electricity origin. The DOE Fuel Cell Technologies Office objective directly targeted is the costs from electrolysis (<$2.30/gge, exclusive of delivery, compression, storage, and dispensing) mentioned in terms of $2/kg H_2 in the project. Related objectives concern electrical efficiency of the stack (95%) and electrolyzer (90%). The degradation rate (<1%/1000 hours at cell level, <2% at stack level) and robustness in operations are linked to intermittent power sources (i.e., renewables).
- The project has the potential to advance our understanding of high-temperature electrolysis technology, especially with respect to stack energy efficiency of SOECs.
- This project seems to be a technology development project and not a technology validation project. The researchers are testing new materials and fabrication methods. Maybe the project should be moved to the Hydrogen Production sub-program area.

Question 2: Strategy for technology validation and/or deployment

This project was rated **3.2** for its project design, approach to addressing barriers, feasibility, and integration with other efforts.

- The milestones were met, and hardware has been built. This shows initial progress and builds confidence. Upcoming milestones toward 1000 hours and 95% efficiency by LHV look challenging and should meet or exceed DOE targets. Cost and operational targets are most difficult to meet, and looking at start–stop and long-term operation will show technology capability. Cell degradation is a difficult barrier, and the project has shown very positive initial results with less than 3.5% degradation in 1000 hours for 2400 hours. The full demonstration will prove how well the barriers were actually addressed.
- The approach is a progressive one. Research is first to be conducted at the cell level to optimize working conditions versus performance (including degradation). Then, scaling up is performed gradually up to 4 kg H_2/day at the stack level, with further design of components for the additional scale-up to 38 kg H_2/day for the system, and, further still, technoeconomic considerations to reach 1500 kg/day. This rather academic approach appears very relevant here since cell-level testing and characterization are intended to allow for optimal material design. The project includes two go/no-go decisions that are well defined: first for stack performance after 1000 hours, and then during the system configuration leading to the design of the 4 kg H_2/day system (45 cells).
- The approach of developing a full-size stack baseline module for a scale-up concept and then validating stack components at subscale is sound. Using a breadboard system demonstration approach to test the milestone metrics is also a good idea.
- There are many questions around the technology related to the robustness of the solution (degradation issue) and in the economics of the solution. In the project, addressing these two topics needs to be moved to the forefront. To date, significant testing has been completed on the existing technology, but it is not clear what will be done to address degradation. Testing shows that degradation remains an issue, but it is unclear how it will be addressed in this project. Regarding the technoeconomic analysis (TEA) of the overall system, it is not clear what is meant by operating efficiency, what the boundaries are for this, and what the impacts on the cost of hydrogen are if this efficiency is not met. It is unclear if it includes the energy for the steam production and how it would be integrated into an existing power generation structure.
- The strategy for validation and/or deployment comes at the end of the project and is very poorly defined.
  - The technology transfer activities are poorly defined.
  - The demonstration needs to be defined.
  - The parametric studies are well-thought-out.

Question 3: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.5** for its accomplishments and progress.

- It is not clear how many of the accomplishments were carried out after project kick-off or funding availability, but given that the project is only few months in, much has been accomplished. The progress on systematic isolation of multiple parameters (temperature, pressure, inlet concentration, steam usage) and their effect on stack performance was impressive.
- Hardware has been tested, and hydrogen is being produced with limited degradation. There is a good description of remaining challenges and exploration of operation range with multiple parameters: pressure, temperature, steam utilization, etc.
- Results to date are very impressive with respect to the amount of testing completed. It is not clear how many of the results shown were for this project exclusively and how many are leveraging previous results and related programs. Project leads should be careful to clearly delineate when work is directly a result of this funded project and when results are from previous work or from related programs.
- To date, the eight-month-old project has essentially focused on cell- and stack-level observations including the variation of working conditions such as current density, steam use and concentration, pressure, temperature, and oxygen concentration. Correlations are made between variations in operating conditions and efficiency, lifetime, and downstream requirements in the purification step. The actual reporting of a

cost indicator, which is the ultimate project objective, is still missing and will be tackled at a later stage. Similarly missing is a scientific description of the systems, materials, and set-ups tested or the changes implemented for improving their behavior. Residual base work is still needed concerning degradation before upscaling.

- The accomplishments are all on developing the technology and not on technology validation. The parametric studies are important to understanding how the technology should be operated.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.6** for its collaboration and coordination.

- Little is explained concerning the distribution of tasks in the partnership between the National Energy Technology Laboratory (NETL) and Versa Power Systems (VPS)/FuelCell Energy (FCE) within the project other than in slide 17. Overall, there is no doubt about the good collaboration and coordination between the two partners, although it is somewhat confusing that VPS is mentioned throughout the presentation while the heading mentions parent company FCE.
- The role of the partners (VPS and NETL) is not clear. It appears that all project work to date has been with FCE exclusively. Given the broad questions around the system performance, it would be particularly valuable to have a third party complete the TEA and validate the performance, efficiency, and economics of this solution.
- The VPS collaboration is confusing since FCE owns VPS; it is unclear if this is really an external collaboration. The NETL collaboration is to "support development of solid oxide fuel cell (SOFC) technology for power generation." It is unclear how this helps with an electrolyzer that consumes power. The project needs to define the roles better.
- Although there is value in understanding the performance and cost of SOFCs, the role of the collaborators appears to be solely on the fuel cell development aspect, not the electrolyzer.
- There is limited outreach with industry and end users, who would be most likely to purchase these systems, or low-cost electricity providers.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- Overall, the stated future work sounds reasonable. Early cell and stack fabrication and durability testing of high-temperature components is critical. The performance model development followed by system demonstration is the logical approach.
- Future work consists of a clear path through continued degradation characterization and high-efficiency system demonstration. This should include more details on total energy in and hydrogen produced with cost of electricity or a spread to show some parametric analysis toward meeting the target of $2/kg of hydrogen produced. All assumptions should be transparent. More explanations should be given toward intermittent operation verification and test cycles.
- Good stage gate milestones are defined for the project in 2018. It will be interesting to see progress against these in the near future. It is not clear what tasks will be undertaken to improve the degradation. A plan or potential areas of focus for this would be valuable.
- It seems that the project is well managed and followed with clear milestones, targets, and reviews of progress towards each of them, and a plan for future work.
- The demonstration takes place late in the project and does not seem to be the focus of the work.

Project strengths:

- The technology leverages work done previously in NETL and other programs. There is significant potential to change the industry if the targets are met.
- This is good initial work and data collection of actual hydrogen production.
- The previous experience and background of FCE with SOFC development is a strength.
- The project is well managed and is making steady progress.

- The researchers have a good technology. They are well funded.

Project weaknesses:

- The project would be strengthened by independent evaluation of the TEA results. Many questions from reviewers on the technical validity of the results in the areas of energy integration and overall process efficiency could be addressed by the addition of a partner to complete/validate this independently. It is not obvious what roles the partners are playing in the project.
- There is little mention of state-of-the-art or competing technologies that would ascertain the relevance and comparative advantage of the current work.
- Optimistic assumptions are a weakness. The team needs to address the source and availability of "waste heat" for vaporization of water.
- More details are needed on cost analysis and how the technology will be brought to the market.
- The technology validation and technology transfer plans are poorly defined. The partner roles are poorly defined.

Recommendations for additions/deletions to project scope:

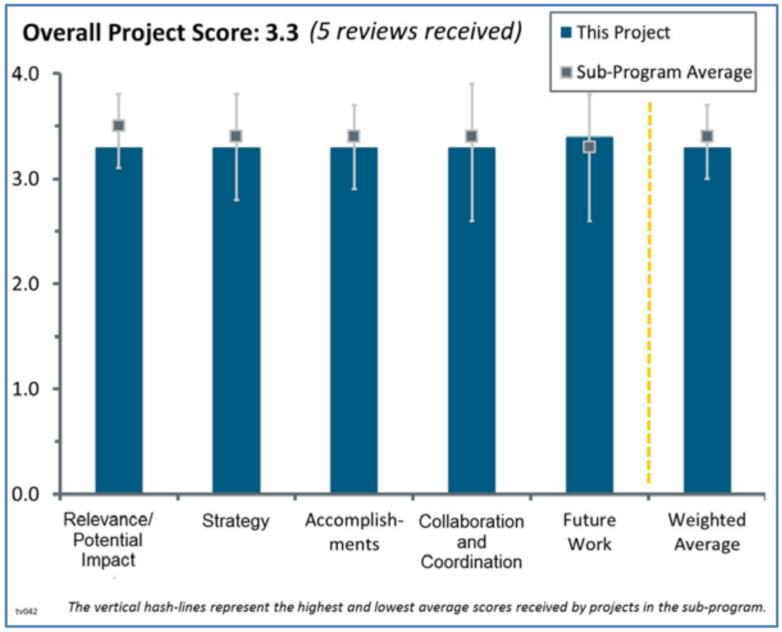
- The project should account for the impact of integration with renewable and intermittent power (one of three stated barriers to address) on the system performance and cost. It is suggested that the project add this factor to the operating window exploration (slide 11). The same is recommended for the impact of operating in reverse SOFC mode.
- A review of the state of the art to position this research versus competing technologies or research groups worldwide is recommended.
- It is not clear that this project really is a technology validation. It seems to be more of a technology development project.

Project #TV-042: Optimal Stationary Fuel Cell Integration and Control (Energy Dispatch Controller)

Genevieve Saur; National Renewable Energy Laboratory

Brief Summary of Project:

Current control strategies for building systems tend to be simplistic. The objective of this project is to create an open-source, novel energy dispatch controller to optimize the dispatch of different building components such as combined heat and power, storage, and renewable generation systems. Such a controller, which will incorporate improved forecasting capabilities and model predictive control strategies, would enable these building systems to participate in grid ancillary services markets. A planning tool for sizing building components utilizing simulated dispatch will also be developed.



Question 1: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.3** for its relevance/potential impact.

- Grid modernization is a recent element of the U.S. Department of Energy (DOE) Fuel Cell Technologies Office (FCTO) but is key to showing the full value cycle of using hydrogen for both transportation and supporting the grid with additional variable generation sources (wind and solar). The three main impacts include new energy management, grid modernization, and the fuel cell vehicle market. Stationary fuel cell integration enables all three topics and will have a significant impact on reaching the FCTO's Hydrogen and Fuel Cells Program (the Program) goals. The model development and predictive controls are required when anticipating variable electricity generation, which may have a mismatch with supply and demand timeframes. Both the graphical user interface (GUI) and building design framework are needed to ensure the output can be adopted by end users outside of the national laboratory environment where these tools are needed most.
- This project has excellent potential to help fuel cells capture some of the interest in combined heat and power and dispatchable energy.
- Regarding relevance, the impact statements support the goal of optimizing fuel cell systems for energy management and control of buildings. The reviewer is not fully appreciative of issues with energy management and control of buildings and has difficulty fully understanding the benefits of this project.
- The project supports the Program goals and objectives. It appears this project supports energy management and the control of buildings, not vehicles.
- It handles part of grid control only.

Question 2: Strategy for technology validation and/or deployment

This project was rated **3.3** for its project design, approach to addressing barriers, feasibility, and integration with other efforts.

- The project utilizes the expertise of the team to address a very complicated issue and builds on existing technology to develop solutions. The project is broken down into components for addressing technical issues.
- The approaches are feasible and well designed.
- The project appears to be well designed, but it is not clear how difficult it will be to get the knowledge and solutions out of the laboratory and into real-world adoption. Some of the control strategies will be completely dependent on the local market and its ability to provide ancillary services. The heating and cooling examples show how these can be energy buffers and support decisions toward deployment. However, cost and relative magnitude of advantages versus savings were not initially obvious beyond moving in the right direction for saving energy and money.
- The grid needs both round-trip excess and shortage in energy, power, and other services.

Question 3: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.3** for its accomplishments and progress.

- The load forecasting for buildings looked to be complete and to match actual data collected from real-world applications. The work to ensure the forecast uses the right mix of models was encouraging and shows a high level of technical competence. The barrier to using this modeling in different regions or markets may be high. The visual feedback and GUI design may help with education, showing how the system is running and what might be saved, but there may be significant cost to adopting the approach to a new system or building. By using Energy+, the project team may have better adoption, but Energy+ appears to be used mostly by national laboratories and DOE rather than commercial building owners or other end users. Technology providers are well represented, but end users and other stakeholders were not obvious.
- Very good progress has been made in the first year.
- Progress has been made on the development of the electrically driven compressor (EDC).
- Chiller issues were identified and solutions proposed. Fuel cell set-points are set depending on the price of natural gas. The high cost of fuel cells typically suggests that the economic value of fuel cells can be achieved by running the fuel cell continuously. For FuelCell Energy molten-carbonate fuel cells (MCFCs) and Doosan phosphoric acid fuel cells (PAFCs), the fuel cell cannot be shut down because of heat-up (startup times) and must be run continuously at partial power. It is not clear that the project has addressed this characteristic of these fuel cells.
    - Pre-cooling consumes energy while cooling is not fully needed. It is not clear how big the battery must be to offset electricity from the grid when the price of grid electricity is increased.
    - For heating, the fuel cell does not go from zero output since MCFCs and PAFCs must be in stand-by condition to maintain electrolyte temperature. No analyses of stand-by power consumption were reported.
    - Chart 13 was not understood. The fuel cell as a heater (i.e., output determined by the heating load) is not considered an efficient device. If excess power is generated at partial load, it is unclear whether it can be returned to the grid or could have another use.
    - The whole-building forecast appears to anticipate load requirements. The reviewer is not familiar with Naive, so a better explanation is needed to comment on this approach.
    - Forecast methods appear to distinguish an autoregressive integrated moving average (ARIMA) approach as the best fit, but with less error in ARIMA. The reviewer requires a better explanation.
- The economic parameters relationship is not realistic. There should be input from a real-life group that makes money doing this. Fuel cells do not load-follow as well as assumed.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.3** for its collaboration and coordination.

- There is excellent collaboration with appropriate organizations.
- Once the model is released, it will be important to find additional end users. The pursuit of open-source solvers may allow for broader distribution, depending on the complexity and effort needed to populate the model with inputs.
- The project does not have a company that builds and markets energy management controls for buildings, and this is a weakness. Other collaborations are very good.
- The collaboration team should include real-life stakeholder input to make a good study.

Question 5: Proposed future work

This project was rated **3.4** for its proposed future work.

- The proposal to use the algorithms in an actual commercial building is the best step forward to ensure other users can adopt the information and resource through a clear example. The additional development of the co-simulation environment will be needed to ensure broader use, and the dual operating system capability as part of the optimization will help. Completing the GUI will be needed before the model can be adopted, in addition to including sample use cases and the Open Studio design interface. The most important gap is finding key stakeholders, which can ensure completion of the significant effort required so the software can be adopted and used outside of the national laboratories or DOE working space.
- Future work for the project has been well planned to address identified barriers/issues.
- The project's remaining challenges and barriers are listed. There should be a detailed list of proposed future work. Because of the reviewer's lack of experience in this area, it is not clear that all barriers are addressed.
- The project should consider a utility or the Electric Power Research Institute (EPRI) to help guide what is needed. This work so far is of only academic importance.

Project strengths:

- The strongest project aspect is the detailed modeling and efforts to make the information accessible to building owners by showing what savings are available.
- This is a good team that builds on previously developed expertise. The project appears well organized with understanding of pathways to resolve barriers.
- There are well-designed approaches for the development of an EDC.
- Some considerations of expected parameters and use of models are good.

Project weaknesses:

- There are no significant weaknesses.
- The project's biggest challenge may be to ensure that the project can move from the laboratory to actual end users, if those stakeholders are not consulted during development, to ensure it can mesh with existing tool sets. The positive aspect is that once initial results are available and the effort matures, this input can be provided before decisions are finalized that limit options or changes that would facilitate use outside of the laboratory.
- The project should include the industry partner with expertise in energy management and control of buildings.
- There is a lack of real-life stakeholder input.

Recommendations for additions/deletions to project scope:

- The project should find stakeholders early in the project to ensure GUI usability, metrics, and outputs are compatible with what a majority of building owners need to make a decision for incorporating and using the model.

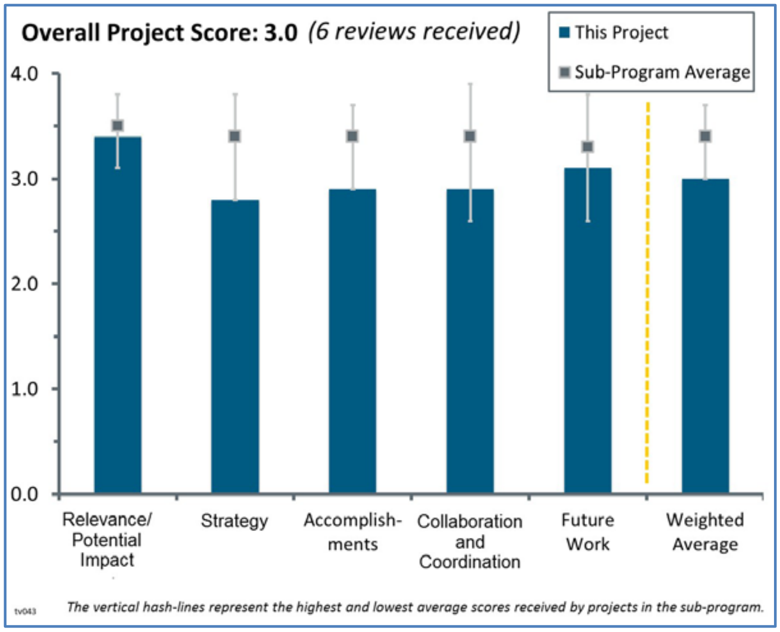
- The solution must be what the customer needs. Input from a real-life consumer of the solution should be included. An aggregator, utility, or EPRI may be better to have on the team to make good progress.
- The project should involve industry for energy management and control of buildings. Reviewers with expertise in energy management and control of buildings should be identified.

Project #TV-043: Integrated Systems Modeling of the Interactions between Stationary Hydrogen, Vehicle, and Grid Resources

Samveg Saxena; Lawrence Berkeley National Laboratory

Brief Summary of Project:

Hydrogen technologies offer the unique ability to simultaneously support the electricity and transportation sectors, but the value proposition for such systems remains unclear. This project is developing an integrated modeling capability to establish the available capacity, value, and impacts of interconnecting hydrogen infrastructure and fuel cell electric vehicles (FCEVs) to the electric grid. The potential to support the grid and to balance resources from flexible hydrogen systems, such as dispatchable production of hydrogen by electrolysis, are quantified. Methods to optimize the system configuration and operating strategy for grid-integrated hydrogen systems are also developed.



Question 1: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.4** for its relevance/potential impact.

- This project is very relevant, given the uncertainty around grid changes and economics of grid services that may be provided by electrolyzers. The grid is rapidly evolving, with increased renewable energy coming into the grid. If this shows an economic case and sustainable business due to the integration of multiple resources and demand centers, policies can be developed to accelerate the integration and optimization with existing electricity markets.
- The relevance is potentially huge; this is the crux of the H2@ Scale concept for leveraging renewables into grid support and transportation. Modeling is an excellent start. Next, the project should examine how this can lead to demonstration of the concepts that can attract commercialization and private investment.
- The Lawrence Berkeley National Laboratory (LBNL) team seems to have a clear understanding of the task before it, the importance being that its project advances fuel cell deployment and the maximization of renewable resources.
- This project is very relevant to the benefits of hydrogen economy. It will be important to make objective decisions with regard to the Hydrogen Vehicle-to-Grid Integration Model (H2VGI Model). Slide 5 does a good job capturing relevance to multiple stakeholders groups.
- Although the project does not specifically address Fuel Cell Technologies Office (FCTO) Multi-Year Research, Development, and Demonstration Plan (MYRDDP) stated objectives, its scope and goals are certainly valuable in advancing the implementation of U.S. Department of Energy Hydrogen and Fuel Cells Program objectives. The potential flexibility and synergy that can be realized from integration of stationary hydrogen sources, FCEVs, and the grid are worth exploring.
- The “Relevance” portion of the presentation (slides 3, 4, and 5) indicates that the focus of this project is on development, validation, and implementation of the H2VGI Model. This initiative may have merit for the overall FCTO. However, it does not support and advance progress toward achieving the goals and objectives associated with the Technology Validation sub-program. The barriers listed in slide 2 of the presentation are not among the barriers included in the Technology Validation sub-program portion of the

MYRDDP. The barriers cited for the project are also not specifically cited among those in the Systems Analysis sub-program portion of the MYRDDP. Were this project's relevance evaluated solely with respect to the Technology Validation sub-program, it would receive an "unsatisfactory" grade. Because the project may have benefits in the context of the Systems Analysis sub-program goals and objectives, a rating of "fair" was assigned.

Question 2: Strategy for technology validation and/or deployment

This project was rated **2.8** for its project design, approach to addressing barriers, feasibility, and integration with other efforts.

- The project addresses key questions needed to launch/commercialize key elements of large-scale, economical green hydrogen production. This approach provides an important first step and guidance as to what needs to be demonstrated in this space. Any additional clarification/modeling of the economics of the approaches modeled would be helpful. The approach cuts across many stakeholders—providing data to drive collaborative best decisions for policy, original equipment manufacturers, station owners, etc. The approach is to integrate many existing modeling components. For example, it expands the vehicle-to-grid (V2G)-Sim tool from the battery electric vehicle (BEV) model to include FCEVs. This feeds into the dynamic station model, etc. The project will then look at key case studies (e.g., the California duck curve issue and central vs. distributed hydrogen production). It is not clear whether this will offer needed resources such as grid transmission capability. There is a go/no-go plan at the end of 2017, but it is not clear whether there will be a plan for clear economic impact output by then (the project is pushing this with the Revenue Operation and Device Optimization [RODeO] model and fuel model, and also pushing on duck curve work). The project needs reports and good communication for this to be recognized quickly as the key data that can underpin policy and investment decisions. "Pathway to use" of data/reports is critical (there was a question from another reviewer about influencing grid operation rules/standards/policies). This emphasizes the need for hydrogen advocates to reach out to the California Independent System Operator (CAISO).
- The approach looks comprehensive, but it could use additional feedback from a broader industry perspective beyond transportation. However, this could be done in a Phase II because transportation may have the highest value and the greatest demand. Heavy-duty hydrogen vehicles may be more easily integrated than light-duty hydrogen vehicles.
- The approach appears to be good. It would be good to see more about the validation plan, as well as more information about how each of the variables are accounted for (for instance, station hydrogen storage did not appear to be addressed).
- The "Approach," slides 6 through 8 of the presentation, describes a plan for integration of multiple existing models and national laboratory initiatives to create a sophisticated H2VGI Model. The results would be applied for analysis of hydrogen-related issues, questions, and case studies. The project phases outlined in slide 8 seem reasonable—for a Systems Analysis sub-program project. Objectively, rating this project on "Strategy for Technology Validation and/or Deployment" would result in an "unsatisfactory" score. However, because of its potential benefit as a contributor to Systems Analysis sub-program goals, a rating of "fair" is assigned.
- A concern is the information presented on the slide 6 chart "Approach – H2VGI Model Structure" because if the chart is indicative of the end product, the end result may look complicated but not be a usable tool. The slide 7 chart "Key planned case studies" and slide 8 "Approach: Project Phases and Selected Milestones" indicate LBNL plans to perform a great deal of modeling and data review, but they do not mention that LBNL will examine existing renewable-grid electric-hydrogen systems such as Hawaii Natural Energy Institute's megawatt-sized battery systems supporting the grid in Kona (Hawaii County) and Honolulu, Hawaii, or the Navy's hydrogen station at Joint Base Pearl Harbor–Hickam. It is recommended that LBNL use the existing systems coupled with the use of models rather than perform a model-only review.
- The project's technical validation approach appears to rely heavily on the existing Vehicle Grid Integration (VGI) model, which is based on BEVs. However, the project needs to specify how this model would be different from VGI; for instance, it is not clear whether there is any interface between FCEVs and the grid similar to VGI's two-way integration to enable BEVs to provide grid services. Moreover, unlike utility-

scale solar or wind, it is not clear how multiple and much smaller stationary hydrogen stations (with expensive reverse electrolyzer configuration or added stationary fuel cell units) or FCEVs are supposed to be coordinated and satisfy smoothing the demand and supply curves. Ultimately, because of the added energy conversion step in the case of hydrogen, the peak-shaving or valley-filling prospect or justification for this project to resolve California's net-load or duck curve issue may not be as strong as presented.

Question 3: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **2.9** for its accomplishments and progress.

- The case studies were well developed and important to show the capabilities and impact of the chosen approach. The modeling of FCEVs' hydrogen demand as an aggregated demand may need finer fidelity, unless additional hydrogen storage is used as a buffer.
- The preliminary results and baseline scenarios for hydrogen demand, dynamic power consumption, and prices are a good start. The early result on electricity consumption and the grid support model presented should be helpful in fully understanding the station's energy management and revenue assumptions.
- It would be helpful to see specific pointers to things that can be implemented and demonstrated so that stakeholders can see hardware and get energized around investing. This can help set priorities on what the work suggests as the first/highest-impact part to implement/demonstrate. Some notes and accomplishments from the presentation follow:
    - So far, the project has some sub-models for vehicle activity and resulting hydrogen demand.
    - The Scenario Evaluation, Regionalization, and Analysis (SERA) model has generated scenarios for the geographic location of vehicles and hydrogen demand.
    - The project is quantifying the value of hydrogen production facilities to help mitigate the California duck curve. The project is reducing peaks, filling valleys, and reducing ramp rate.
    - Hydrogen station electricity consumption and grid support models (time-of-day analysis) represent opportunities to reduce the cost of operation/demand charges.
    - The National Renewable Energy Laboratory (NREL) RODeO model application and integration with the U.S. Utility Rate Database represents progress.
- The "Accomplishments and Progress" portion of the presentation (slides 9 through 15) provides evidence of significant activity and results in the development and validation of sub-models, implementation of models and sub-models, scenario development and analysis, and analysis of the potential for hydrogen production facilities. For the project's contribution to overall project and FCTO goals, the reviewer's rating is "satisfactory." However, if the standard is accomplishments and progress relative to Technology Validation sub-program goals and objectives, the rating would be "unsatisfactory."
- There are many problems with information presented in the "Accomplishments" section:
    - On slide 9, "Accomplishments and Progress: Sub-models for vehicle activity initializer and individual vehicle models," LBNL uses the term "initializer" but does not explain what values are being set, why, or who is doing the setting. LBNL lists a category as "Development of preliminary mobility hydrogen demand sub-models," but it did not advise on the difference between models and sub-models, why the data is preliminary, or why the emphasis is on preliminary. LBNL uses the term "Calibrated fuel cell vehicle models" but does not explain what calibrated FCEV models are, what the models are calibrated against, or why. It is completely unclear what the initialization data for travel itineraries for large collections of vehicles using national household travel survey data is or why it is necessary as a first step. LBNL provides a chart showing hydrogen consumption over 40 days for 2,094 vehicles, but the chart is a waste of time and space because the data could be communicated more effectively by simply stating that 2,094 vehicles consumed about 16,000 kgs of hydrogen over a 40-day period and that consumption was at a steady rate. The right half of the slide 9 chart is no better, but further criticism seems redundant if not also overkill.
    - From the slide 10 chart, LBNL advises that the SERA model has been used to generate self-consistent FCEV adoption and hydrogen demand scenarios, and while the follow-on points are understandable, it is not clear why the term "self-consistent" applies.
    - Slide 11 "Quantifying the value of hydrogen production facilities..." proudly claims that centralized electrolysis to provide grid peak shaving valley support for California has been

modeled for the first time, but something seems missing if LBNL does not acknowledge that actual peak shaving and valley filing has been performed elsewhere outside the state of California.
  - The RODeO model discussion on slides 14–15 is unclear to the point that the chart and graphs appear to be little more than filler to add to page count.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.9** for its collaboration and coordination.

- The project represented good collaborations with NREL and the Idaho National Laboratory (INL); however, additional discussions with grid operators, station owners, and related stakeholders (CAISO, California Public Utilities Commission [CPUC], and California Energy Commission [CEC]) would lead to more relevant results. This should happen later in the project to ensure a better chance of the knowledge being incorporated into new electricity market rules for electrolyzers.
- Slide 17 "Collaborations" provides information on the roles of LBNL's project partners, NREL and INL. Presumably, there is good collaboration and coordination among the three laboratories. While stakeholder categories are mentioned on slide 5, no information is provided on plans for collaboration and communication with the many parties having an interest in the project's activities and results. However, the need for an outreach and engagement strategy is recognized on slide 18 on remaining challenges and barriers.
- Having NREL and INL on station and grid topics shows good collaborative effort. At some point, the project team should consider getting input from station owners and grid operators, especially on underlying model assumptions.
- Any collaboration with partners that could provide validation of any of the elements of the model would be a very helpful addition to the project. NREL is leading model integration. INL is leading the electrolyzer operation/application load dispatch model.
- While NREL and INL seem to be working well together, there appears to be no collaboration with any other organization.
- Outreach strategy and involvement of key stakeholder groups still need to be developed.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- The proposed future work is very sound, especially the scope involving model testing/validation, building case studies, and plans to seek stakeholder input.
- With the future work, it is important to get early input from other stakeholders, especially those who set the rules for electricity markets. The technical capability and the demand are there; however, the actual mechanisms for market integration are missing and skewed toward batteries for now.
- The future modeling work is well founded. It is not clear whether there are any opportunities for validation of the model results. Any integration/validation of economic models would be very helpful.
- It appears that NREL and INL have a lot more to do than what is listed in their future work chart. They need to tighten up their effort.
- Proposed future work, as described on slide 19, seems reasonable and appropriate for the project. My recommendation is that FCTO's Systems Analysis sub-program team should ensure that the work of this project does not duplicate or overlap other modeling and analysis efforts being funded by FCTO and other organizations. If actions to provide such assurance are already underway, that is good. To reiterate prior comments, Technology Validation sub-program resources should not be used to fund this modeling and analysis project. The project is not relevant in the context of the Technology Validation sub-program portion of the MYRDDP.

Project strengths:

- Project strengths include detailed and comprehensive modeling as well as the use of existing resources and capacities, e.g., models from other laboratories.
- The project's strengths include the collaborative effort among the three laboratories with complementary skill sets. The approach of leveraging the existing VGI model could also be a plus.
- The project relevance is important. The approach is good and has stayed current despite grid demand changes.
- Project strengths include the modeling and analytical expertise resident in the three national laboratory project partners. The project approach and phasing seem logical and should lead to achieving objectives—as a Systems Analysis sub-program project.
- The project offers a first look at key elements of H2@ Scale concepts.
- No strengths were noted.

Project weaknesses:

- It would be beneficial to understand more about how the project is accounting for variables and validation steps.
- The project seems to take a "top-down" approach to developing the model, such as quantification of economic benefits based on California-based average net load profile. Perhaps a model based on a "bottom-up" approach, building up from typical hydrogen station capacity and operations, may be more realistic and valuable.
- The project could use some elements to validate model results and to include economic modeling.
- The project needs early and frequent input from the main organizations responsible for market barriers to integrating electrolyzers with the grid: CAISO, CPUC, and CEC.
- There is need for a stakeholder engagement plan and follow-through in implementing the plan. In response to a question, Dr. Wei indicated that the project team is aiming to publish initial project reports by the end of this year. There is a need to establish the relevance of the project for stakeholders in government (public policymakers) and industry, e.g., electric utility and automotive.
- The NREL–INL team needs to couple its modeling efforts with real-world activities, even if those activities do not perfectly match exactly what the team is challenged with accomplishing. After that, the team needs to work on messaging so that whatever they are really trying to say is clear as crystal rather than clear as mud.

Recommendations for additions/deletions to project scope:

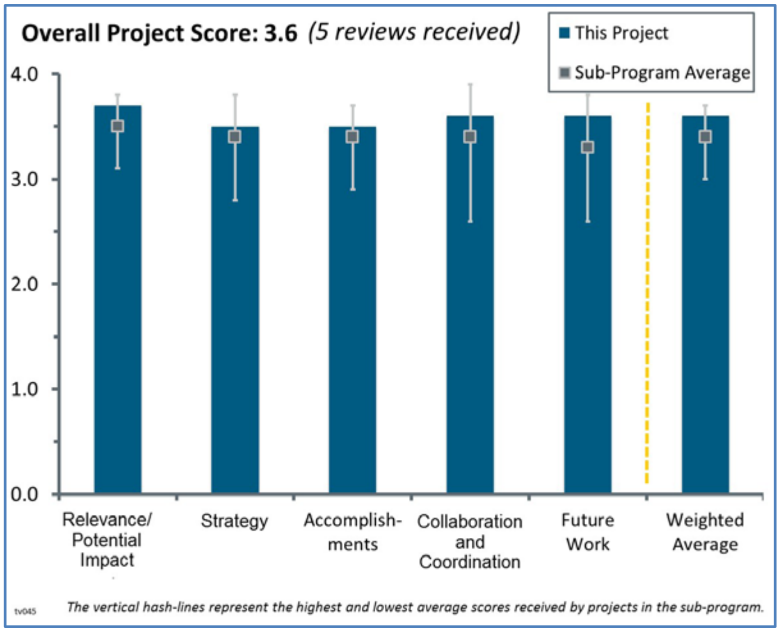
- The economics example for device optimization is a good start. However, going forward, more specific station configuration and realistic assumptions of capital cost (e.g., reverse electrolyzer or a separate stationary fuel cell) and grid support scenarios should be considered.
- The project should expand the scope for reporting feedback and requests from grid management and planning stakeholders for how electrolyzers can be more rapidly integrated.
- No scope changes are recommended, except accounting for hydrogen storage.
- The project may be scoped adequately, but the means of accomplishment and presentation need improvement.

Project #TV-045: H2@ Scale Analysis

Mark Ruth; National Renewable Energy Laboratory

Brief Summary of Project:

H2@ Scale is a concept that explores the potential for wide-scale hydrogen production and utilization in multiple energy sectors in the United States. The objective of this project is to improve the fidelity of the H2@ Scale value proposition. The analysis seeks to quantify the potential economic, resource, and emissions impacts from wide-scale hydrogen production and utilization. In addition to nationwide analysis, regional opportunities and challenges will also be identified. H2@ Scale analysis integrates many transportation, industrial, and electrical sector analyses and tools.



Question 1: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.7** for its relevance/potential impact.

- This project is extremely relevant in supporting DOE's goals in the Hydrogen and Fuel Cells Program. The recent increase in interest in hydrogen, not only as a transportation fuel but as a prospect for an energy source of the future, makes the H2@ Scale analysis fundamental to understanding the challenges and potential impact on the economics, resources, and emissions, as stated by the presenter.
- H2@ Scale is a real backbone initiative for the U.S. Department of Energy (DOE). The project potentially has impacts on industry across all spectrums of energy but specifically relative to hydrogen and its enormous potential.
- This analysis is highly relevant to the integration of multiple sources and users of hydrogen within an integrated network. The staged analysis includes theoretical, technical, and economic potential, and therefore, the project scope is broad. Economic externalities are among the remaining analysis.
- Arguably, the analysis portion of the H2@ Scale project is the most important component, as it has deliverables enabling actions and deliverables to the hydrogen energy community.
- It is appropriate to follow the steps outlined in the approach to assess the technical and economic potential. However, the market potential is being overestimated by double-counting hydrogen needs in some of the categories and assuming a high growth in hydrogen demand, particularly light-duty vehicles (LDVs). Further, although the concept is good and relevant, industry would prefer to see near-term projects.

Question 2: Strategy for technology validation and/or deployment

This project was rated **3.5** for its project design, approach to addressing barriers, feasibility, and integration with other efforts.

- The strategy taken by the project leader and team is very sound and well-thought-out. The presenter clearly identified the main gaps in the analysis and the approach to be taken to address these (slide 8). In addition, this project will integrate well-established models and tools for performing the analysis proposed.

- The strategy of producing and using hydrogen as an energy carrier with a quantitative, in-depth analysis is followed. The strategy includes quantitative analyses for economics, resources, and emissions. The strategy includes frameworks and integrates the transportation, industrial, and electrical sectors. The Regional Energy Deployment System (ReEDS) tool is an example of the models and tools included in the strategy (grid buildout). This project uses the strategy of evaluating the volume of existing hydrogen and applying existing tools to estimate the impact on infrastructure and emissions. Notably, this is a "first-pass" effort.
- The staged analysis is very organized and helps to reduce "noise" and potential confusion.
- The goal of the project with respect to green hydrogen production needs to be clarified. Originally, the project did not include (or at least did not show on the concept schematic) natural gas production and, to date, does not show coal production or whether the project team thinks coal will be a player in the future energy grid. If we are focused on only green energy, then why is natural gas included? Does it require carbon capture and sequestration?
- It would be more useful to validate this concept with a near-term project instead of doing analysis for long-term hypothetical hydrogen demand. Granted, it is necessary to understand whether this concept will be feasible in the future, but it is unclear what to do in the meantime. It is also unclear how to start building up the H2@ Scale idea now. It is recommended that the strategy also incorporate more tangible projects in collaboration with industry.

Question 3: Accomplishments and progress toward overall project and DOE goals

This project was rated **3.5** for its accomplishments and progress.

- The analysis is very comprehensive and really shows the enormous potential of hydrogen in the "big picture." Renewable hydrogen and its role in grid stability really needs to be highlighted and reported. People in the industry should get the word out to get utilities to start investing.
- Significant progress was presented, especially given that the project just recently started early in 2017. Progress was mainly on the impact on emissions and fossil use through the use of renewable electrolytic hydrogen.
- This project is at the beginning, and it is probably too early to comment on progress, other than to say that, to date, the project has had high visibility and has the potential to have a significant impact.
- The accomplishments include setting strategies and boundaries. The visualization of the stakeholders and ecosystems is drafted. The plan for the future (pending funding) has started. The attraction of participants has started. The evaluation of the demand for hydrogen is articulated; 60 MMT/year (total market/technical potential) begs the question of how many resources this took. This presenter quantified the technical potential. Total demand, including hydrogen, is satisfied by approximately 6% of wind, <1% of solar, and approximately 100% of hydrogen (required to get up to 60 MMT of hydrogen).
- The technical potentials for hydrogen demand are inflated. The inflation is partly because of double-counting, overestimation of LDVs in the market, and the hydrogen blended in natural gas pipelines. Regarding the latter, it is unlikely that blending hydrogen with natural gas will be feasible in the near term, given the price differential in the United States, the lower British thermal unit content of hydrogen, and the potential embrittlement damage of pipelines not designed to handle hydrogen.
    - In measuring whether resources will be sufficient, it is important also to consider transmission build-out and what is expected. High-voltage, direct-current (HVDC) transmission is being built, but it is expensive. It is not clear what is realistic to expect in the future.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.6** for its collaboration and coordination.

- The extensive collaboration with other national laboratories is very strong and is key for the significant progress of this work. The engagement with industry via external workshops is of extreme value as well.
- This project team collaborates and coordinates with other institutions. They held workshops to provide input and information from numerous sources: national laboratories, academia, and the private sector.
- The early incorporation of stakeholders and outside experts is excellent, and of course, so is the involvement of the national laboratories across the board.

- For the current work, collaboration is appropriate. However, the team should seek additional collaborations with industry, looking for synergies between supply and demand to start building the concept. It would be good to see where there is cheap, excess hydrogen capacity and whether it is close to demand areas. This project could really make strides by kick-starting this kind of action.
- The biggest concern with this project is that it is very internally focused to deliver insights and direction to the technical community within the national laboratories. While it is clearly important to provide guidance and direction to the technical stakeholders, it is not clear how this project will influence industry or policy decision makers. It is unclear what an industrial hydrogen supplier expect might out of this project or whether a hydrogen supplier should be using it to make technical investment decisions or marketing decisions. If so, the deliverables do not really help very much in these decisions. To address this, a stronger tie into industry and decision makers is needed.

Question 5: Proposed future work

This project was rated **3.6** for its proposed future work.

- The proposed future work (pending funding) includes drafting the strategy, the cost reductions in electrolyzers (for electrolytic reduction in hydrogen from wind or solar resources), and cost reductions realized from grid mix changes to determine price points, increased need for research and development (R&D) advances, and future work in the economic potential (bottom-up cost estimate used to estimate the potential). This project's future work will also include identifying price requirements and supply options (market-dependent price-point changes). Other future work includes looking at production costs such as steam methane reforming, nuclear, and curtailed electrical power with a focus on "what are people/ companies willing to pay." The plan is to present the roadmap and propose future R&D in September 2017.
    - Future work will help guide how the technical potential can meet the demand. Perhaps more policy makers need to be integrated. As new applications are included, the bottom-up summation will "move" and become summarized.
- The workshop with outside experts to prioritize the economics is excellent. It is good that the project is reaching across all areas of expertise, from the laboratories to industry, and incorporating all input.
- The proposed work on scenario generation and the planned review by the external experts' panel are key for the successful continuation of this analysis work.
- As far as analysis goes, the project has a good plan, but it would be even better to add uncertainty/ variability to the hydrogen market potential numbers and analyze additional near-term projects.
- It is concerning that the future work does not take policy scenarios into consideration. It appears that the analyses are based upon assumptions about future states of power, demand, and supply as inputs to determine what effect this will have on hydrogen supply. There is no mention of how policies will enable us to get to that state. The project should include a range of policy decisions as input to determine the effects on supply and demand in order to drive the technology needs to be included. Without this, it will be left to speculation to determine what decisions need to be made to enable the vision.

Project strengths:

- The strengths of this project include a focus on making the grid more efficient, reductions in greenhouse gas emissions, and the efficiency of using electricity required to produce an increased amount of hydrogen. This project also evaluates the amount of transmission needed to store and distribute power and conducts county-by-county analyses. Another strength of this project includes determining how placing resources near areas of heavy potential hydrogen use and demand affects the use, cost, and resource.
- The project is very well organized and looking at a variety of aspects such as demand, economics, and technical possibility. The project pulls in experts outside of (but in addition to) the laboratories, which is key to truly understanding all the elements of each topic.
- Strengths of this project are the analysis expertise provided by the project leader and the interactions with the other national laboratories.
- The team has strong analytic capabilities and good access to data, resources, and models.
- This is a highly visible project with broad input from across DOE.

Project weaknesses:

- There are no apparent project weaknesses.
- The team should be cautious that considerations such as those raised by reviewers (subsidies and incentives, for example) are not left out, which could have a significant effect on the outcomes. This is a complex thing to manage, and the team will surely be successful.
- The project is internally focused on DOE laboratories regarding the priority and direction of technology programs. Industry is on the outside looking in at this project, not sure how to engage or what to expect. Analysis does not have a policy impact component to drive timelines and roadmaps.
- The project has inflated long-term demand numbers, and there is a lack of realistic projects.

Recommendations for additions/deletions to project scope:

- In measuring whether resources will be sufficient, it is important to also consider transmission build-out and what is expected. HVDC transmission is being built, but it is expensive. It is unclear what is realistic to expect in the future. The team should add variability to the market's potential numbers. The current numbers for refineries, natural gas, and LDVs are inflated, given their low likelihood. For instance, refineries are not likely to uptake so much hydrogen from excess capacity generated elsewhere unless mandated by law or heavily subsidized. Natural gas pipelines are not likely to blend in 10% hydrogen, given the price differential, potential embrittlement, and decrease in energy contents. The near-term assessment is to approach utilities and companies that produce excess hydrogen, match them with the demand side, and help them with the technoeconomic analysis to start building a business case.

2017 – Safety, Codes and Standards
Summary of Annual Merit Review of the Safety, Codes and Standards Sub-Program

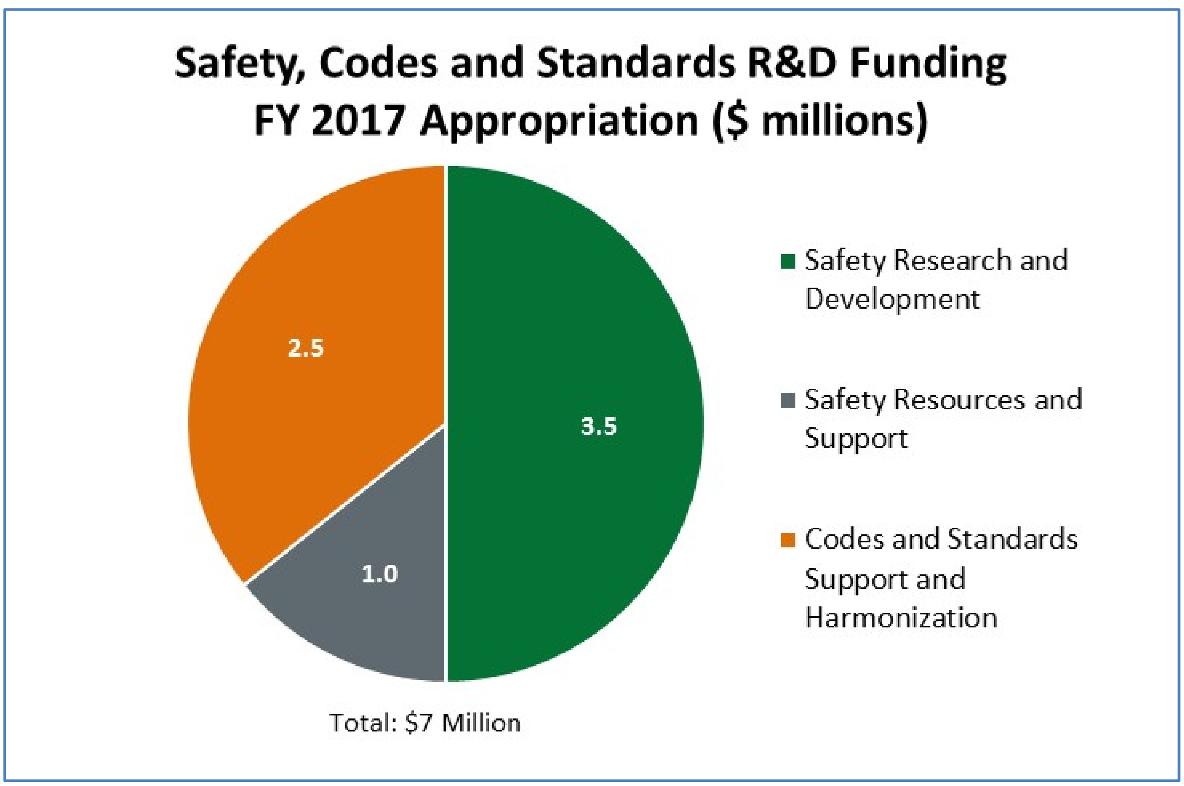
Summary of Reviewer Comments on the Safety, Codes and Standards Sub-Program:

The Safety, Codes and Standards (SCS) sub-program supports research and development (R&D) that provides critical information needed to define requirements and close gaps in safety, codes and standards to enable the safe use and handling of hydrogen and fuel cell technologies. The sub-program also conducts safety activities focused on promoting safety practices among U.S. Department of Energy (DOE) projects and the development of information resources and best practices.

Reviewers were highly supportive of the SCS projects and noted that the work of the SCS sub-program enables the accomplishment of the broader goals of DOE and the Fuel Cell Technologies Office. The collaborations in many of the projects were deemed noteworthy, as was the progress made since the previous year for projects related to hydrogen behavior, separation distances, materials compatibility, and fuel quality. Reviewers continued to praise the science-based approach and the provision of feedback to code development organizations (CDOs) and standards development organizations (SDOs). However, reviewers encouraged clearer descriptions of accomplishments achieved in this area. In regard to outreach projects, reviewers indicated support for this work, including H2Tools.org, and encouraged additional collaborations with state governments rather than with individual emergency response organizations. Key recommendations for R&D focus included development of fueling protocols for medium- and heavy-duty fuel cell electric vehicles and continued emphasis on hydrogen contaminant detection.

Summary of Safety, Codes and Standards Funding:

The sub-program's fiscal year (FY) 2017 appropriation was $7 million. FY 2017 funding has allowed for continued support of codes-and-standards-related R&D and efforts on domestic and international collaboration and harmonization of codes and standards, which are needed to support the commercialization of hydrogen and fuel cell technologies.



Majority of Reviewer Comments and Recommendations:

In FY 2017, 13 SCS sub-program projects were reviewed, with all of the projects receiving positive feedback and strong scores. Average reviewer scores ranged from 3.4 to 3.9, with an overall sub-program average score of 3.5, an increase from the previous year.

Safety Research and Development: Nine R&D projects were reviewed, earning an average score of 3.5. The highest-scoring project in this category received a score of 3.7. The R&D category is divided into three sub-categories: Sensors and Component R&D; Hydrogen Behavior, Risk Assessment, and Materials Compatibility; and Hydrogen Quality. The summaries of reviewer comments for R&D are provided below for each sub-category.

Sensors and Component R&D: Reviewers commended this project for its importance to infrastructure deployment. They particularly appreciated the project's collaborations and the value of the sensors to industry, and they encouraged additional collaborations as the project progresses. Reviewers suggested defining the focus and proposed future work in more detail.

Hydrogen Behavior, Risk Assessment, and Materials Compatibility: The science-based approach to codes and standards through hydrogen behavior and risk assessment R&D was applauded by reviewers, who noted the connections between these projects and increased value obtained through the team's strategy and collaborations. Similar to last year, the software and publication outputs of the risk assessment efforts were praised as being highly beneficial to stakeholders. Materials compatibility projects were praised for their relevance and for their efforts to enable stakeholders to utilize the data acquired during the course of the work. Reviewer recommendations included additional collaborations, particularly those that would ensure increased documentation through CDOs and SDOs.

Hydrogen Quality: Reviewers had positive feedback overall on the progress made to date and on the importance of these projects to infrastructure, particularly the development of an in-line fuel quality analyzer. For the in-line analyzer project, reviewers recognized that the membrane hydration challenge is a significant barrier and suggested adding deliverables to ensure that the product is moving toward being commercially available to station developers. For the other two projects, reviewers praised the approach and progress made on component R&D, but they requested more detail on proposed future work. Overall, reviewers would like to see additional collaborations to expand impact.

Safety Resources and Support: One safety management and resources project was reviewed, receiving an average score of 3.9. Reviewers praised the approach and future work for all three areas of this project, as well as the collaborations. Reviewers suggested that the project modify its approach to work more closely with state governments rather than individual emergency response organizations. Reviewers also indicated that it is critical to update and maintain H2Tools.org as a user-friendly portal.

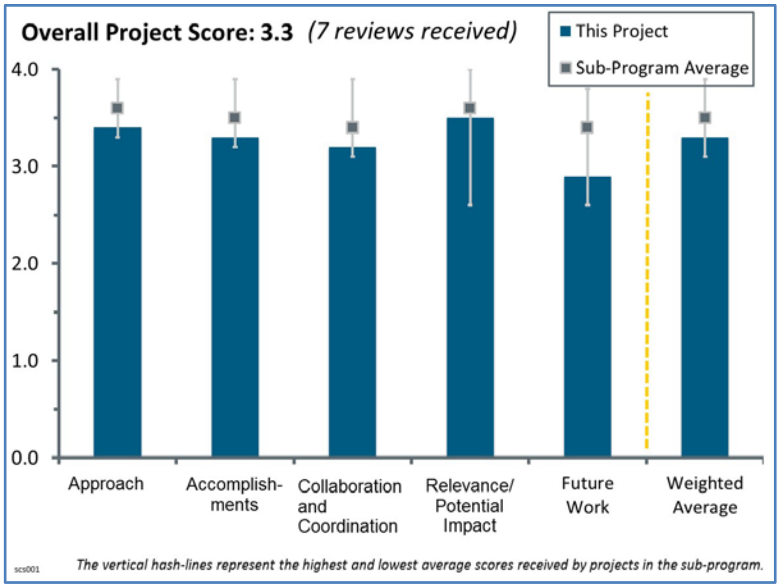
Codes and Standards Support and Harmonization: Three outreach projects were reviewed and received an average score of 3.5. Reviewers praised the outreach activities for engaging a diverse set of relevant stakeholders and for their importance to deployment of hydrogen and fuel cell technologies. All three projects were commended for their efforts to serve codes and standards activity coordination, which is a critical area of need. Reviewers encouraged further development of outreach on a regional level, focused on key stakeholder groups.

Project #SCS-001: National Codes and Standards Deployment and Outreach

Carl Rivkin; National Renewable Energy Laboratory

Brief Summary of Project:

The objective of this project is to further the deployment of hydrogen fuel cell technologies with particular focus on the infrastructure required to support fuel cell electric vehicles (FCEVs). This outreach and training project supports technology deployment by providing codes and standards (C&S) information to project developers and code officials, making project permitting smoother and faster.



Question 1: Approach to performing the work

This project was rated **3.4** for its approach.

- The project is very well integrated through a long history of involvement with regulations, codes, and standards (RCS) technical committees; through collaborations with all national and international players and partnerships; and through the iterative Continuous Codes and Standards Improvement process of improvement through analyzing field data, identifying research needs, and feeding new information back for modification of C&S. The outreach project is established and effective as well. The approach is excellent and has been very effective for a long time. The relationships with every sector of the hydrogen economy have been long established, so there is no need for improvement in the area of "approach."
- The approach for this work is exactly what is needed for getting U.S. Department of Energy (DOE)-funded fundamental applied research (technology readiness levels [TRLs] 2 and 3) into the hands of the technical committees who actually write the RCS.
- Clearly there has been significant effort expended to work with various interested parties, and the project team works to coalesce needed data to help answer safety questions and identify code gap priorities. Reaching out to developers and authorities that have already installed stations may show where a code has worked and where it has not.
- There is good work in organizing existing tools and monitoring the industry to identify new needs.
- The approach is quite broad and not well defined. This may be by design to allow flexibility to address the most pressing industry needs. The presentation states that outreach is conducted with stakeholders to identify needs, but it was not clear whether there was a formal methodology to capture stakeholder input to drive the needs of the project. If there was such a mechanism, a broad, flexible approach may prove even more beneficial. There might also be value in feeding other DOE work to the Safety, Codes and Standards (SCS) sub-program. There is a lot of work done that likely is not directly delivered to the appropriate committees.
- It would be helpful to understand the budget breakdown for the various efforts. Progress on some of the key items is not clear in terms of actual impact on code proposals and language. The papers are less effective than actual code language improvements.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.3** for its accomplishments and progress.

- The accomplishments for the past year have been varied and significant in promoting safety codes, standards, and outreach. There are several listed in the slide presentation for the DOE Hydrogen and Fuel Cells Program (the Program) Annual Merit Review (AMR). They include C&S gap analysis, Inter-Laboratory Research Integration Group (IRIG) activities, the National Fire Protection Association (NFPA) 2 and task groups, multi-fuel station analysis, large-scale grid projects, station aging, and international coordination between the International Organization for Standardization (ISO) and North American C&S organizations. All of these activities are integrated and coordinated under the National Renewable Energy Laboratory's (NREL's) guidance to address gaps, leverage resources, and provide a positive impact on safety, costs, permitting, and deployment of the required infrastructure to support FCEVs.
- The outreach and training component has some clear, significant achievements. There is less clear movement on the continuous C&S improvement component. While there are many activities in progress, there are not many clear achievements. It is not clear what the published papers (multi-fuel and station aging) will achieve. It is not clear how NREL has coordinated the international and North American activity. If there were achievements, they should be clearly stated. It is too broad to just say the activity has been coordinated.
- The reviewer applauds the station aging project and hopes data is forthcoming, but wishes there were more contributors. Even more support for the Bureau de normalisation du Québec (BNQ) and ISO standard coordination and a faster means to bring forth the necessary harmonized standards would be beneficial. It is good to see contributions to H2 Tools happening. H2 Tools content is becoming very extensive, so it would be good for this portal to remain supported.
- The accomplishments and progress for this project are strongly linked to the code cycles of the code development organizations (CDOs), which are outside the control of the project and the principal investigator (PI). However, the progress and accomplishments for this project are clearly noted by anticipated NFPA 2 changes expected in the 2020 edition. A direct response to knowledge transfer to the technical committee from DOE-funded TRL 2 and 3 work is changes to the lean hazards limit, liquid hydrogen behavior, and leak cross-section area. This is anticipated to lower setback distances significantly in the 2020 edition. Reducing the setback distances will enable siting of hydrogen fueling stations in urban settings that would not be possible with current setback distances.
- This project has mixed accomplishments. With regard to outreach, the project is "outstanding." The project played a critical role in facilitating hydrogen infrastructure in new areas of the United States and developed an excellent outreach video. With regard to gap analysis and C&S development, the project showed no progress or substantive impact. It is not clear why this project is not better connected to other Program activities. Lack of collaboration with other SCS sub-program projects is a major barrier to accomplishment.
- It is nice to see the video series complete and online.
- The permitting guideline seems like good progress. However, there do not appear to be specific improvements proposed to code language that have been completed or presented.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.2** for its collaboration and coordination.

- Although not called out so much in the slide presentations, the very nature of this project is collaborative. Under the approach and accomplishments sections, it is clear that there is a lot of cross-collaboration with national standard development organizations and authorities having jurisdiction (AHJs). In addition, this project and other related projects at NREL are coordinated with national and international regulators, such as the U.S. Department of Transportation (DOT) National Highway Traffic Safety Administration, the DOT Pipeline and Hazardous Materials Safety Administration, Transport Canada, the United Nations Economic Commission for Europe, national laboratories, and NASA.

- IRIG is a good initiative. It should be especially helpful in addressing issues such as vehicle use in tunnels, in which multi-dimensional analysis may be required.
- The reviewer is looking forward to the project's growth and support of regional hydrogen advocacy groups, such as Colorado and Massachusetts. There is good work with regional fire service outreach, but more will be needed help ensure safe deployment.
- The PI has been criticized in the past for not collaborating appropriately with others working in synergetic areas. This current work is much better in embracing the collaboration of other national laboratories (Pacific Northwest National Laboratory, Sandia National Laboratories, etc.).
- There were many collaborators listed but not much discussion or examples about how NREL coordinates the participation. It is critical to have stakeholder input and coordination. It may be occurring, but it was not clear from the presentation or materials.
- This project exceeds in one area (outreach) and fails in the other (C&S development).
- It is not clear whether there is any feedback on the permitting video as to its effectiveness and use by AHJs. There does not seem to be progress on the main technical issues being addressed, at least as shown by code language improvements. It is not clear that Zhejiang University brings any experience for station aging issues. It is not clear what expertise or experience it has and whether there is comparable experience locally in the United States.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.5** for its relevance/potential impact.

- The relevance of this work and potential impact (which is already evident) is exactly what is needed for the timely and targeted dissemination of the fundamental applied (TRL 2 and 3) science results from other parts of the overall SCS sub-program projects.
- This project is doing critical work in supporting the rollout of hydrogen infrastructure.
- The project's relevance is that it promotes a comprehensive and acceptable level of safety on national and international levels for deployment of hydrogen vehicles and infrastructure. Continued gap analysis is critical at current low levels of deployment as well, because any safety incident that occurs in the absence of hazard mitigation could kill the industry.
- This project aligns very well with deployment. It should continue to be supported (with scope clarified or tweaked) by DOE.
- The relevance and importance of this project are substantial. However, it is frustrating to review this project each year with the same comments. This project fails to meet its full potential in C&S development. The project lead fails to identify and articulate the key gaps in critical C&S. Meanwhile, the project lead provides excellent outreach.
- This effort is helpful, but it does not seem to be critical to the effort of expediting the rollout of hydrogen infrastructure or improving code language.

Question 5: Proposed future work

This project was rated **2.9** for its proposed future work.

- The proposed future work continues to address general and specific areas of safety that require attention. It is addressing the specifics of hydrogen use in tunnels, system maintenance, station aging, and venting, and it continues to close gaps in C&S. Updating permitting tools and training of code officials are also necessary to promote deployment, safety, and cost savings. It is not clear whether this project is ending in 2017, but continuing with the efforts identified here would complete much of what is left in C&S to support wide-scale deployment.
- The project may require less effort over time, but it should continue to check for gaps and work toward continuous improvement.
- The IRIG team has promised to further agency collaboration. It is hoped that support for the NFPA 2 next edition with task groups can continue, as well as international collaboration.

- It is understandable why the PI is suggesting the reduction of the "outreach" part of this project and increasing the more fundamental aspects; however, this should not be done. Instead, the project should continue the very important results dissemination to the CDOs in a fashion that the technical code committees can most readily use.
- There should be feedback from stakeholders about prioritizing research around C&S gaps. The project team should consider rebranding "station aging"—it is not clear how new deployments can be aging. It sends the wrong message to the public. The project should focus on "station maintenance." It is not clear how IRIG activities will be prioritized. Once again, stakeholder input is critical.
- The proposed work is very general and broad. As a result, it is not very focused and has no specific deliverables. For example, on station longevity, it is not clear what components are being evaluated. It is also unclear what the expected deliverable is and how that would affect the code. It would be better to narrow the focus and have specific goals. For example, it is not clear what proposals have been made to date, what proposals will be made to code language in the future, or what the timetable is. A number of areas are mentioned, but there is no clear breakdown of how much budget is spent on each.
- This project should focus future work in areas where it is successful. The project proposes four future work items: (1) development in tunnels and bridges, (2) gap analysis, (3) update to permitting tools, and (4) station aging analysis. Only the update to permitting tools has any value to the industry. The project team has demonstrated no value to this effort. The team should do more to demonstrate the value of the gap analysis. A station aging analysis may not be of the greatest use to industry, as the stations deployed today will be technologically obsolete long before they are old. Furthermore, station aging should be an industry concern.

Project strengths:

- This work is structured to most effectively disseminate findings to the technical committees of the relevant CDOs in order to expedite the transfer of scientific knowledge to those who need it. Without this activity and other similar outreach ("knowledge dissemination"), the only outlet for the science is the more traditional publishing and presenting of that scientific information in technical meetings and refereed journals. This in essence buries the information, "hiding" it from the CDO technical committees. This dramatically slows down and in some cases stops RCS development pinned to the most current scientific knowledge. This project and others like it are critically important for the targeted timely dissemination of state-of-the-art scientific information. Traditional dissemination vehicles are not appropriate for this community.
- This project has promoted cohesive and comprehensive data-driven C&S development from the beginning. The 2017 gap analysis should provide a snapshot of where the industry stands with regard to commercialization.
- The project is wonderful as a resource in outreach and should be focused on this effort. A national plan for outreach should be developed that includes close coordination with industry to identify SCS outreach needs in established areas as well as development of plans for new regions (the Western "Cluster" of Arizona, Nevada, Oregon, and Washington; Texas; and the Eastern "Cluster" of Pennsylvania, North Carolina, South Carolina, Georgia, and Florida).
- The project helps make complex information sets approachable for hydrogen stakeholders. It helps to bridge any gaps between code writers and code users.
- The outreach work with regional authorities is a project strength, although there needs to be more. The support of code development is very strong. The support and development of H2Tools resource permitting and training tools are also project strengths.
- C&S are important to hydrogen station rollout. Efforts to help this are important. Some of the separation distance work may have been supported with this effort. If so, there has been good progress on gaseous hydrogen but no progress on liquid hydrogen.
- Clear progress has been made on outreach and training. The flexibility that is allowed through the broad project scope may need to sharpened or better informed through stakeholder outreach.

Project weaknesses:

- The funding level is quite low for the project. It is unclear whether there are additional things that might be addressed with more funding or whether everything is being covered with the funds available. No weaknesses can be identified through reading of past AMR reports.
- This project has been criticized for its less-than-stellar collaboration with other relevant institutions—but this has largely been fixed. As such, the reviewer could not really find a weakness in this project.
- There is a lack of focus and deliverables on specific efforts. For the project as a whole, a better understanding of the main priorities and focus of the budget is needed. It is not clear on which activities the money is actually spent.
- Although flexibility of scope is helpful, clear stakeholder input to drive activity should be integrated. There are many ongoing initiatives. It is not clear whether all activities are truly priorities. Prioritization should be better refined, potentially through the integration of obtaining and synthesizing stakeholder input.
- The gap analysis and code development efforts should be an industry-led effort, with NREL used on an "as-needed" basis and with specific direction for research needs. The project should focus on outreach; the other efforts reduce the value of this vital role.

Recommendations for additions/deletions to project scope:

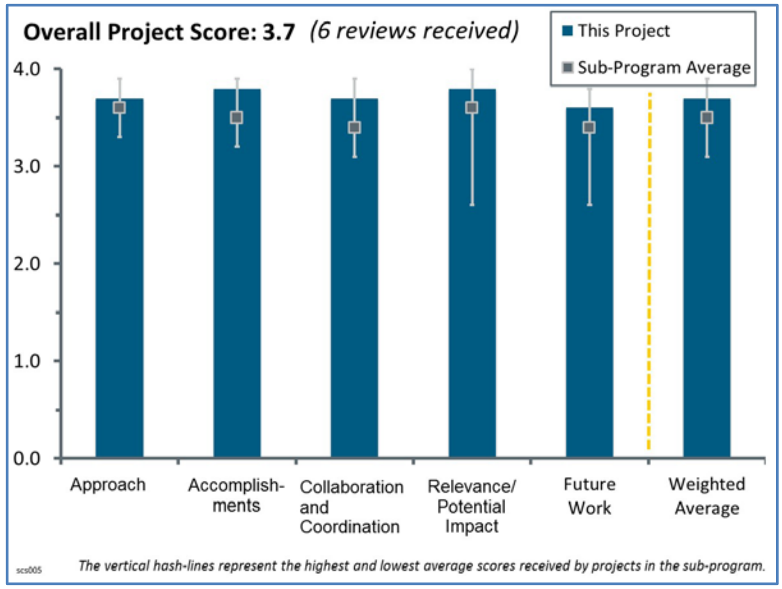
- The project should keep up the excellent work. The reviewer supports the increased attention to TRL 2 and 3 efforts, but not at the sacrifice of the scientific dissemination efforts with the CDOs and other relevant RCS bodies.
- It might be good to include some quantitative assessment of needs. It is not clear whether station approval/build/start-of-operation is improving over time, whether the safety record is improving, and whether operational reliability is improving.
- The project should clarify the broad scope. If it is meant to be broad to allow flexibility, a clear element of gathering and synthesizing stakeholder input should be integrated.
- For station siting, the project should consider alternative approaches to separation distances to obtain equivalent means of risk reduction. A major gap continues to be the perceived/real differences in approach between the United States, the European Union, and Asia. The project needs to reconcile these to facilitate siting and permitting. Research can focus on bringing new ideas to the table to supplant existing approaches. The project should narrow the focus to two to three key, specific actions per year for which progress can be demonstrated and be effective. For example, the longevity work does not appear to be clearly defined, and as presented, it may not be worth the effort at this time.
- There are no recommendations for additions or deletions. There is some overlap with other projects.

Project #SCS-005: Research and Development for Safety, Codes and Standards: Materials and Components Compatibility

Chris San Marchi; Sandia National Laboratories

Brief Summary of Project:

The main goal of this project is to enable technology deployment by providing science-based resources for standards and hydrogen component development and to participate directly in formulating standards. The project will (1) develop and maintain a materials property database and identify materials property data gaps, (2) develop more efficient and reliable materials test methods in standards, (3) develop design and safety qualification standards for components and materials testing standards, and (4) execute materials testing to address targeted data gaps in standards and critical technology development.



Question 1: Approach to performing the work

This project was rated **3.7** for its approach.

- The project's goal is the development of reliable and experimentally tested information on (1) the static and fatigue behavior of materials in hydrogen, including low-temperature effects, and (2) the fracture behavior of Ni-Cr-Mo steels. The project involves the establishment of performance and prescriptive criteria for safe and reliable operation of components in hydrogen. The developed performance metric on tensile fatigue is supported by experimental data obtained at Kyushu University in Japan. With regard to prescriptive metrics for stationary pressure vessel performance, the project developed a state-of-the-art fracture mechanics methodology. The project has also demonstrated that the key ingredient of this method, i.e., the crack growth rate versus the stress-intensity factor range, is almost independent of material type and not very sensitive to hydrogen pressure (slide 16). This is a truly remarkable result that enables the universality of the method. Lastly, the project's experimental results (see slide 15) demonstrated that the Ni-Cr-Mo steel can replace the typical Cr-Mo steel, which allows for a number of design modifications and advantages.
- The overall approach is appropriately focused on performance-based methods for on-board fuel cell electric vehicles (FCEVs). The project is effectively working with standards development organizations (SDOs)/ code development organizations (CDOs) to incorporate the outcomes of the project. The approach to provide design guidelines at one-third yield strength is useful for developing practical criteria based on the fatigue data.
- The approach of developing performance-based characterization of materials is appropriate. The method of using a tension–tension test with a notched specimen is practical (fewer number of cycles required) and relevant to the environment experienced by the liner of a hydrogen tank.
- The barriers of safety data and information access, enabling national and international markets, and insufficient technical data to revise standards were addressed. Prior-year efforts, including 2016, paid significant attention to access and availability through Sandia National Laboratories (SNL) software aimed at materials compatibility calculations. Current work is focused on developing test methodologies (fatigue testing) that can garner consensus from a broad range of stakeholders as well as construction of a low-temperature hydrogen testing rig that is new and unique on the international stage.
- The approaches of this project are effectively delivered. The way to present the approaches is simple and excellent, specifying a task focusing on and followed by detailed test methods, test results, and data.

- The reviewer had to read five slides before being told what the project is actually about. This should have been immediately after the cover page.[1] Data showing samples exposed to hydrogen versus samples not exposed to hydrogen from the same lot would be useful. The approach is sound and value-added. It is focusing on issues for higher-pressure hydrogen systems. More integration with ASME is warranted. Issues with specific slides are described below:
  - Slide 5 – It is not clear when Boiler and Pressure Vessel Code (BPVC) Section VIII Division 3 (D3) Article KD-10 became prescriptive. It is not clear when BPVC Section VIII D3 Article KD-3 (leak before burst) became prescriptive.
  - Slide 6 – It is not clear what test method (American Society for Testing and Materials [ASTM]) this work is following. It is not clear how closely the results match the data from the National Institute of Standards and Technology (NIST).
  - Slide 7 – This appears to be the standard fatigue curve for steel. It is not clear what alloy is represented.
  - Slide 9 – This shows the stress versus cycles-to-failure curve (S-N curve) for several austenitic materials. It is not clear whether this data is during hydrogen exposure. It is not clear how it compares to the same materials that were exposed only to air.
  - Slide 12 – The data supplied is on a tool steel (unified numbering system 41300). It is not clear whether this is only one sample. It is not clear how this matches up to the NIST work.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.8** for its accomplishments and progress.

- The project is very successful. The proposed fatigue performance metric of 100,000 cycles at one-third of the tensile strength, the generation of the crack growth rate versus stress-intensity-factor range curves for a large number of steels, the fracture mechanics methodology to ascertain potential fatigue crack growth in pressurized vessels, and the investigation of the promising Ni-Cr-Mo steels are all very significant accomplishments toward the DOE goals.
- Significant progress has been made toward the project goals. The project partners proposed a performance-based methodology based on materials properties (ratio of maximum stress to tensile strength) that is simple and proven to work for a range of materials and conditions relevant to hydrogen storage. Construction and preparation for low-temperature hydrogen testing are close to complete.
- The project has made very good progress in providing further fatigue data and practical design recommendations based on the one-third yield strength. It was also a good accomplishment to compare the conventional fatigue testing with the hydrogen “notched” fatigue testing within this project.
- One major issue that remained unresolved in Global Technical Regulation 13 was material compatibility. As a result, Japan allowed only one type of steel for use as a liner. The performance-based test developed under this project seems to correlate with other experimental data. In this test, a sample is cycled 100,000 times (tension–tension cycling with R=0.1), and the performance metric is that the maximum strength should be at least one-third of the ultimate strength of the sample. This performance test permits the use of a wide variety of materials for the liner of hydrogen tanks. The project also developed a database that characterizes low-temperature, high-pressure fatigue strength of different materials. This is a good tool for hydrogen tank manufacturers.
- The project has greatly achieved the goals to date, providing a solid foundation for the further improvement or development of a methodology that will be practically usable for global regulations or industry standards.
- Slide 14 shows a nice comparison of hydrogen exposure versus air exposure. There appears to be an expansion of the database. It is not clear whether SNL is doing single samples or multiple samples simultaneously. It is not clear how this matches up with the NIST data. The accomplishments to date are appropriate. Outreach through ASME, ASTM, and SAE International is appropriate because they generate the general design codes and are where engineers have been trained to look for materials information. CSA

[1] It should be noted that all presenters are required to follow a standard template for Annual Merit Review presentations, so this should be considered a fault of the template and not the principal investigator.

Group is a product safety standards organization. Outreach through CSA Group will have a limited effect as compared to ASME and SAE International.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.7** for its collaboration and coordination.

- The project involves considerable collaboration and coordination with various standards organizations (CSA Group, ASME, and SAE International), industries (FIBA Technologies, Tenaris-Daline, JSW Steel, BMW, Opel, and Swagelok), and research laboratories in Japan and Germany.
- This project leverages strengths of SNL's longstanding support of the National Nuclear Security Administration hydrogen (tritium) activities for commercial hydrogen applications. The degree of collaboration and interaction with Japan and Europe is impressive. Close contacts and collaborations will be essential components of establishing the "consensus" on standards.
- This project is an excellent example of collaboration by being directly involved with a significant span of entities, including SDO/CDO organizations, industry, and international entities.
- The collaborations with Kyushu University and MPA Stuttgart are very important for the comparison and validation of the experimental data. Collaborations with BMW, Opel, etc. are very important toward identifying gaps and needs for technology relevance.
- The coordination and collaboration seems valid, although a taxpayer might expect coordination and collaboration with NIST (Boulder, Colorado) and the U.S. Department of Transportation-funded research. The collaboration for documenting test methods is questionable. Test methods on this topic would most likely be published by ASTM. It is not clear why ASTM is not in the loop.
- This project presents collaborations with standards organizations, industry, and international organizations. It is unclear what the level of involvement of these collaborations and coordination is and how broad they are. While CSA Group is mentioned in the presentation, it is unclear whether there is any collaboration directly with the hydrogen storage industry. Further, this presentation gives little knowledge regarding coordination or collaborations with research institutions specialized in materials science or materials standard organizations, or why these collaborations are unnecessary.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.8** for its relevance/potential impact.

- All the features of this project are essential to successfully achieving the DOE Hydrogen and Fuel Cell Program (the Program) goals as laid out in the Program Multi-Year Research, Development, and Demonstration Plan. Most important is the development of materials testing methods and the coordination of activities with international partners to ensure consensus and ready adoption of standards to facilitate market penetration of FCEVs.
- There is limited information on the low-temperature, high-pressure fatigue strength characteristic of materials. This project reduces the gaps in knowledge. This project develops standardized test methods for evaluating materials for specific use in hydrogen storage containers. The project developed a performance-based test and a database of materials characteristics that is a useful tool for hydrogen container manufacturers.
- The project is impactful on the issues of safety and reliability of materials in hydrogen. The project results are essential for developing codes and standards in the most reliable and scientific way. Hence, the project is of tremendous value for the Program.
- The project is extremely relevant and will provide much-needed knowledge and have a great impact for hydrogen and fuel cell technology development.
- The project is highly relevant to providing the fundamental understanding to quantify austenitic stainless steels, rather than being limited by the historical prescriptive approach.
- The project is highly relevant. Accelerating the pace of the research would not be inappropriate.

Question 5: Proposed future work

This project was rated **3.6** for its proposed future work.

- The project's research advances sequentially over the years, from sophisticated testing of materials under various load and environment conditions to the compilation of materials selection tools for hydrogen compatibility. The plans for low-temperature testing in fiscal year 2017 and investigation of short crack behavior are right on target. The latter is of tremendous significance as far as crack initiation is concerned and, of course, as a scientific issue that is very poorly understood.
- Finalizing the standardized test methods and test apparatus, conducting round-robin tests internationally, and completing the database characterizing materials are important, so the proposed future activities are warranted.
- The project is well planned, and the future work appears appropriate to accomplish the stated objectives. Additional attention may be required on the "accelerated" test methodology. If international consensus is difficult to achieve with existing methods, the development of accelerated tests will be even more difficult to harmonize.
- The proposed future work is very good for the project at a high level. The project team should consider inserting more specific information in the future work.
- The proposed future work makes sense. If the reviewer were doing it, the reviewer would work to publish the test methods at ASTM, generate a non-mandatory appendix for ASME (either BPVC Section VIII D3 and/or ASME B31.12), and develop a technical information report through the SAE International Fuel Cell Standards Committee.
- The future work does not seem to address the complete list of challenges and barriers.

Project strengths:

- Project strengths include testing capabilities, international partnerships, and the recognized competence of the principal investigator (PI).
- The strength of this project is the high-level collaboration, technical performance-based approach, and practical consideration for providing design recommendations.
- One of the major project strengths is the background and experience of the team in applying fundamental materials science to applied problems of significance for national security and commercial hydrogen storage applications. All of the relevant codes, standards, testing methodologies, etc. rely on strong fundamentals of mechanical properties of materials.
- The project strengths are its science/data-based contribution to hydrogen technology development and its in-depth knowledge and excellent understanding of materials science.
- A project strength is the project's technical excellence; it is a value-added task in support of industry.
- Collaboration with international research laboratories, industry, and standards organizations is a project strength.

Project weaknesses:

- A challenge will be to predict performance of materials with an appropriate safety factor for finite life. Perhaps the project could propose a set of round-robin tests with the same materials and various testing methods at partner organizations in order to further the dialogue toward consensus. The behavior of "notched" versus smooth surfaces is not clear; one would expect the notched specimens to exhibit failure prior to the smooth ones. An overall plan for accelerated testing and the approximate timeline would be of interest—for instance, it is not clear what data the PIs believe is essential in order to achieve consensus.
- In the presentation, the test conditions associated with each set of test data shown in the figures should be specific.
- The materials used are only those provided by manufacturers. The database may not represent some materials.
- There is room to improve on the end-user side of the research.
- The project weakness is the complexity of the testing in order to qualify a new material for hydrogen compatibility.

Recommendations for additions/deletions to project scope:

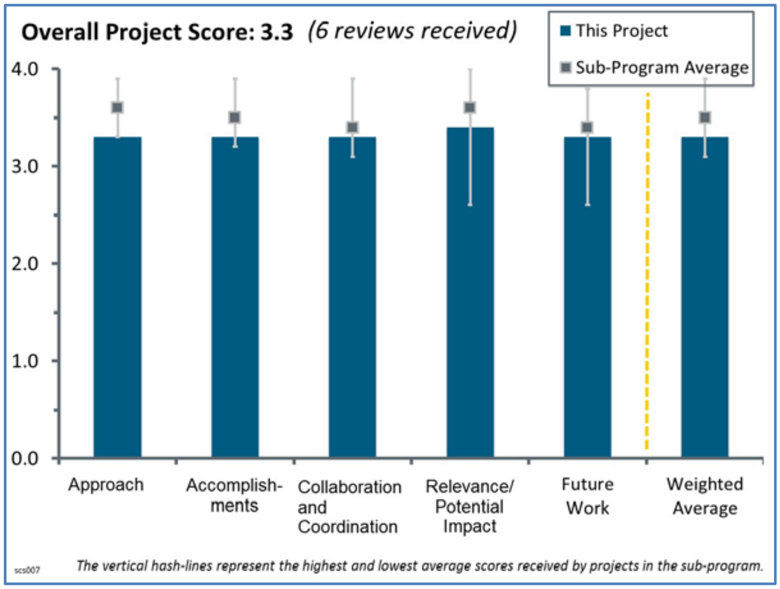
- At a later stage of the project, non-destructive testing would be of interest to validate models and measure crack propagation and growth in real systems. A “monitor” could be developed that alarms when the critical crack size is approached.
- The team should consider modeling that specifically addresses the subjects of the project, e.g., the effect of hydrogen on fatigue crack growth and the critical conditions for a proto-crack to become a “fracture mechanics” crack.
- More documentation through ASME, ASTM, and SAE International is recommended. Standardized, published test methods and direct comparisons of data on samples exposed to hydrogen and samples exposed to air are recommended.
- More collaborations with hydrogen tank industry/manufacturers, ASTM, and research institutions with excellence in related areas are recommended. Specific test conditions associated with the tests and a brief reason why should be included.
- The project team should review the barriers and incorporate a plan to resolve them in the future work, such as the simple metrics for material selection. In future project reviews, it would be helpful to provide information on the status and current gaps in the industry standards, along with the specific outcome or recommendation from this project to eliminate the gap.

Project #SCS-007: Fuel Quality Assurance Research and Development and Impurity Testing in Support of Codes and Standards

Tommy Rockward; Los Alamos National Laboratory

Brief Summary of Project:

The objectives of this project are to (1) focus on polymer electrolyte membrane fuel cell testing and collaborations and work with the American Society for Testing and Materials (ASTM) to develop standards and (2) develop an electrochemical analyzer to measure impurities in the fuel stream. The analyzer will be inexpensive, will be sensitive to the same impurities that would poison a fuel cell stack, and will support quick responses to contaminants.



Question 1: Approach to performing the work

This project was rated **3.3** for its approach.

- The concept of using a fuel cell membrane with scant platinum loading as a sensor for the damaging impurities that may be in a hydrogen supply stream is an excellent idea and well worth the effort to develop. The project team has made good progress in developing prototype devices and identifying further challenges to achieve a commercial product.
- This project takes an excellent approach in the way that it is combining two studies that are complementary to each other. The data and analysis generated from the impurity testing work will serve as an enabler for the development of the fuel quality analyzer.
- Development of a suitable sensor is important to helping avoid contamination of fuel cell electric vehicles (FCEVs) from fueling. Using components similar to fuel cell stacks is a reasonable approach. It appears that the need to determine a fuel flow rate that will not compromise sensitivity or response time indicates the analyzer will need to use siphoned fuel rather than analyze the fuel stream being pumped into a vehicle.
- The approach would be perfect if it were not for the membrane hydration challenge.
- Two tasks are covered in the presentation. The first is an in-line fuel analyzer. The second is more focused on testing to determine the effects of fuel impurity. The in-line fuel analyzer sounds rational; however, it is unclear how the membrane electrode assembly (MEA) is to remain hydrated. Perhaps the sensor is pumping into a moisture-rich and replenished receiver in which the hydrogen sample is removed from the process. The fuel impurity testing appears to be focusing on lower catalyst loadings. It is unclear whether the electrodes are from an experimental or product fabrication process. It is not clear how repeatability/reproducibility is addressed. A recycle loop has been set up in which a low dew point is used. It is not clear whether this in keeping with the current manufacturer's designs. Earlier designs had recycle dew points in the 135°F to 160°F range. It is not clear whether reducing the dew point affects the results of the tests. It is not clear how these data match previous data sets. The S testing may require rethinking.
- It is not obvious from the presentation what problem is being solved or what the targets for success for the analyzer should be. For example, it is not clear what the cost target is. It is not clear whether a reversible measurement is a requirement or whether a consumable indicator can be sufficient. It is not clear where in the station this will be located (before or after cooling, at the nozzle, etc.). The lifetime target for the device is also unclear. Quick response time is needed, but it is not clear what this means (whether a 1-second or 100-second response is required). The pressure and temperature ranges needed are also unclear.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.3** for its accomplishments and progress.

- This project has demonstrated excellent progress. On the fuel quality analyzer, it is great to see the significant improvement in CO sensitivity to <50 ppb, but the most significant achievement relates to the fuel quality testing work. The finding, which showed that low-loaded MEAs are not tolerant to SAE International J2719 levels of impurities, is a major one that should trigger additional analyses and studies as the automotive industry looks into lowering platinum loadings on the fuel cells. Currently, producing and maintaining hydrogen fuel to meet the SAE J2719 standard involves additional costs on the hydrogen fuel. The finding in this work shows that a balance between loading and fuel quality specifications must be addressed, because there needs to be an understanding on the additional fuel cost implications if tighter specifications are required.
- The development of a significantly improved test analyzer capable of working with SAE J2719 contaminant levels is excellent.
- This project has demonstrated the validity of the concept and has moved the state of the art forward. Response to SAE International threshold impurity levels has been seen in the laboratory work. A patent application has been made, and the team is collaborating with industry partners.
- Work on the analyzer is progressing well, although the analyzer has some limitations in the real-world hydrogen-dispensing environment. Also, the ASTM standards development work has not moved forward.
- It is encouraging to see the results of the prototype testing.
- The progress on the in-line fuel analyzer is not clear. The figure on slide 7 showing the N117 membrane looks just like the data reported last year (2016, slide 17). The change of scales between slides 9 and 10 makes it difficult to understand the points being made. The electrochemical impedance spectroscopy plots on slide 13 are interesting and may apply to the fuel quality. It is not clear why the CO does not come completely off as a number of laboratories have indicated in the past. If the 1 ppm exposure were repeated, it is not clear whether it would add to the results or if the system would return to the last cleanup point. The progress on the fuel impurity testing is unclear. Slide 18 does not reference data from other loadings. It shows single points at three concentrations, two supply pressures, and three dew points. There is nothing to indicate repeatability or reproducibility. Slide 19 shows a degree of instability during the test. It is not clear whether the instability is due to the electrodes, the dew point, or a test stand artifact. It is not clear what is causing the decay while operating on hydrogen (slide 21). It looks to be about 0.4 mV/hr for both plots. The cocktail testing in slide 22 is interesting. It reflects an acknowledgement that sulfur is not likely to be present in the fuel and more likely to be a result of a "housekeeping" incident. A tabulation of how sulfur was ingested into the cell for each incident and the calculated loss of active catalyst area may be useful. It seems likely that sulfur lays down in a front and not uniformly across the electrode. This would result in a current shift and a push toward limiting current (an accumulation model, which is the same effect seen in sulfur contamination of a packed bed).

Question 3: Collaboration and coordination with other institutions

This project was rated **3.3** for its collaboration and coordination.

- The collaboration with stakeholders at DOE, SAE International, and ASTM has been excellent. Working with the international partners Alternative Energies and Atomic Energy Commission (CEA) in France has been extremely important, as there is much work to be done in Europe to catch up with fuel quality testing, analytical work, and quality assurance work, which has historically received significantly more attention in the United States.
- It is good to see an international partnership approach to this problem. DOE projects too often do not result in a strong international solution to a problem, resulting in parallel work in different regions, leading to different standards and solutions. In this case, an international collaborative team is ideal.
- Collaboration with CEA (via the Hydrogen Contaminant Risk Assessment [HyCoRA]) is very good. As a suggestion, more expanded international collaboration could be beneficial (e.g., Shell Global Solutions is developing a similar analyzer).

- Certainly, the collaboration with SAE International and the International Organization for Standardization (ISO) is important. It would be good to see plans for future collaboration with hydrogen station developers to begin to identify suitable ways to use the analyzer in real-world hydrogen stations.
- There are some collaborators and partners mentioned throughout the slides, but it was not very clear what the roles and involvement of these on the project are. It is strongly recommended that the team present contaminant results on low-loading MEAs to SAE International.
- Collaboration with laboratories from three other countries (Japanese Automotive Research Institute, CEA, and VTT Technical Research Centre of Finland) and input from ISO and SAE International (automotive experts) do not appear to be appropriate. It is expected that the collaboration would include a body that could fabricate and commercialize, a body that actually designs and fabricates fueling stations, and a body that represents the fuel providers' viewpoint (e.g., the American Petroleum Institute or Compressed Gas Association). Otherwise, the project becomes myopic and may not meet the stated goals.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.4** for its relevance/potential impact.

- This project is critical to the DOE Hydrogen and Fuel Cells Program and has potential to significantly advance progress toward the DOE research, development, and demonstration goals and objectives of having a low-cost fuel-quality sensor that can detect fuel cell degrading impurities that are occasionally found in hydrogen fuel streams. The project team has also used the test device to evaluate the impact of proposed changes to the fuel quality threshold limits and project the impact of such proposed changes on the lower platinum loadings proposed for commercial (automotive) fuel cell systems.
- This project is extremely relevant, as more hydrogen fueling stations and FCEVs are being introduced in the market. Currently, there is no low-cost fuel-quality monitoring device for continuous monitoring. Such a device is critical for the reliable operation of hydrogen fueling stations.
- The relevance and potential impact are very high. The inexpensive and relatively quick response time to "canary" fuel contaminant species at the dispenser could significantly improve the confidence for original equipment manufacturers and users that their vehicles will not be contaminated at hydrogen refueling stations.
- Both topics are highly relevant. The impurities testing could use more experienced eyes. It is not clear why experts such as Molter, Scheffler, and St-Pierre are not being consulted. There is about 100 years of fuel cell and electrolyzer experience to draw on. Bonville at University of Connecticut and Wheeler would add another 40 years each.
- The problem being solved is very important to the industry, especially in the short term. There are two points to make:
  - The project is driving toward a scientific solution, but given the lack of commercial specifications, it does not appear to be driving toward a device that will be available on the market. There need to be deliverables around making this device into a robust, low-cost device that is available to the station providers.
  - It is not certain that, in the long run, this type of device will be needed on stations. As infrastructure is standardized and it is possible to ensure that high-quality hydrogen is supplied to the stations and that the stations do not reduce this quality, the need for continuous monitoring will reduce and perhaps even go away. In today's gasoline stations, for example, there is no continuous monitoring for water, sulfur, or other contaminants. Eventually hydrogen could get to this same position.
- There are concerns with the need to control sensor temperature, which may be impractical in the field. There are also concerns regarding a lack of full recovery with the sensor.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- The project team is sharply focused on critical barriers, including investigating the impurities in Grade 5 hydrogen, that still seem to be causing some degradation in the platinum on the test cell.
- Extending the current work to include both NH_3 and H_2S is essential for ultimately developing a multicomponent in-line analyzer as well as continuing the understanding of CO and H_2S tolerance levels of low-loaded MEAs.
- Future work is well articulated and planned.
- The proposed work is appropriate. Outreach to others versed in this type of research would help.
- It is recommended that the team clarify the future work line item regarding adding inline gas filters to clean hydrogen—specify that the filters are being added in the analyzer for the laboratory to calibrate the analyzer, not for the process stream of the dispensers. This could be very interesting work, as it could provide greater understanding of the impacts of specific impurities on MEAs.
- There did not appear to be a "recommended next steps" section in the presentation. It is not clear whether the project is ready for a commercial developer to start looking at it. It is not clear whether additional product development is needed. One conclusion from the fuel quality analysis was that low-loaded MEAs are not tolerant to SAE International impurities, but it is not clear what actions should be taken from this. It is not clear whether the standards need to be changed to address this. If so, it is not clear in what ways and how the project should look into this.

Project strengths:

- The project team has the technical knowledge and focus to develop this promising technology into a low-cost impurity detector and is also leading the efforts at ASTM to develop and improve test methods relevant to hydrogen vehicle fuel quality.
- There is excellent planning, dedication, and a strong technical background.
- Project results are aiding the understanding of typical contaminants on sensors and MEAs.
- International partnerships and the broad range of test data are project strengths.
- Strong technical capabilities for the development of the in-line analyzer to meet detecting levels below SAE J2719 specifications are a project strength.
- The expertise of the laboratory is a project strength.

Project weaknesses:

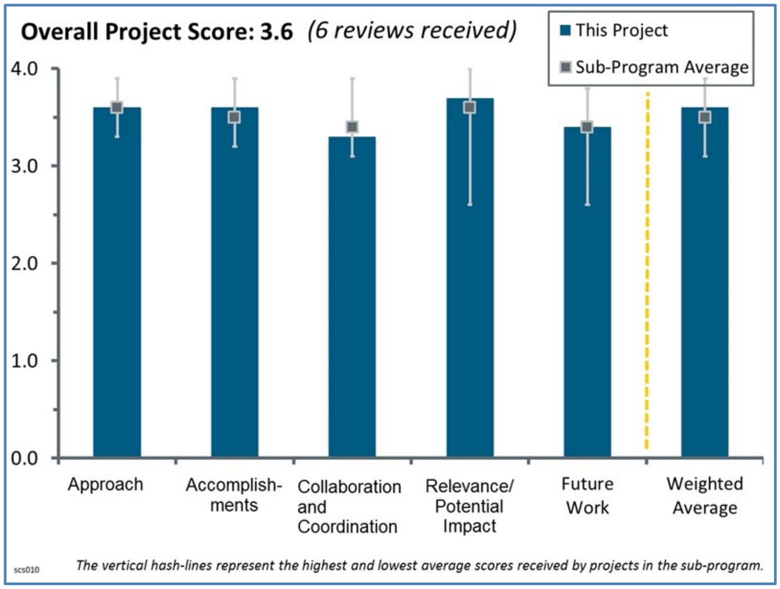
- The only weakness of this project is that there is not enough time and money to support the work at a faster pace.
- Input from others versed in this type of research would help.
- International collaborations with similar activities could be improved.
- The timescale for use of the analyzer in real stations is unclear, and it appears to be a long way off. Development of ASTM hydrogen contaminant testing standards is not moving forward.
- The lack of specifications for a commercially viable sensor is a project weakness. Next steps and future recommendations were not included in the presentation.
    - Program response: The Future Plans for this project were included on slide 25 of the presentation.

Recommendations for additions/deletions to project scope:

- Industry has filling time targets, and dispensers have flow rate requirements. It would be interesting to know what it might take to be able to monitor the dispensed fuel directly.
- The team should consider using commercial electrodes with lower loadings to address the repeatable/ reproducible concern.
- It is recommended that the project team expand international collaborations with similar projects.
- A high-level cost analysis of the device is strongly recommended.
- There are no specific recommendations for changes to project scope.

Project #SCS-010: Research and Development for Safety, Codes and Standards: Hydrogen Behavior

Ethan Hecht; Sandia National Laboratories



Brief Summary of Project:

The project's purpose is to perform research and development to provide the science and engineering basis for the release, ignition, and combustion behavior of hydrogen across its range of use (including high pressure and cryogenic). The research includes model and tool development to facilitate the assessment of the safety (i.e., risk) of hydrogen systems and enable use of that information for revising regulations, codes, standards, and permitting stations. The project began in 2003. Two main technical barriers were considered this fiscal year: "limited access and availability of safety data and information" and "insufficient technical data to revise standards." These barriers were addressed by developing a validated hydrogen behavior physics model to enable an industry-led codes and standards revision and quantitative risk assessment (QRA). Experiments are performed in this project to address targeted gaps in the understanding of hydrogen behavior physics (and modeling), such as cryogenic hydrogen dispersion and mixing phenomena.

Question 1: Approach to performing the work

This project was rated **3.6** for its approach.

- Sandia National Laboratories' (SNL's) approach of conducting the experiments indoors to improve accuracy of measurements seems to have worked. The approach to using the Raman imaging technique instead of filtered Rayleigh to Mie scattering provided good results for the measured concentration of cryogenic hydrogen releases.
- This is an excellent and very comprehensive approach to a family of experimental challenges and knowledge gaps in the field of liquid hydrogen (LH_2) safety.
- The "one-step-at-a-time" approach is conservative, but this may be all the work that the funding can permit. There also may be benefits in having a validated model for cryogenic gas releases before tackling liquid gas releases. However, spills, multiphase mixtures, and ignition behaviors involved with multiphase mixtures are sufficiently different that efforts to better understand the physics could be started in parallel. These behaviors are likely to be more complex. The presentation indicates studies of the spills, multiphase mixtures, etc. are planned for future work.
- The approach is excellent. As a suggestion for improvement, more consideration should be given to scaling future experiments. The selected combinations of release orifices and pressures do not fully represent exit conditions of anticipated real-life releases.
- The project is progressing in a logical fashion, building up test capabilities as necessary for model validation.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.6** for its accomplishments and progress.

- This project is very well linked to two other DOE projects: SCS-011 – Hydrogen Quantitative Risk Assessment and SCS-025 – Enabling Hydrogen Infrastructure through Science-Based Codes and Standards. The results from this study were used to validate and further refine the SNL Hydrogen Risk Assessment Model (HyRAM) developed in SCS-011. HyRAM was then used as a tool for evaluating infrastructure designs, including the Boston Harbor tunnel. This is indeed a very relevant and well-coordinated effort.
- The part of the project dealing with 2016–2017 goals shows excellent results, from the development and testing of a measurement technique for cryogenic gas characterization up to modeling validation at low temperature. The project has thus the potential to answer an important DOE goal related to LH_2 technologies, provided experiments with large volumes and liquid pools are executed, as planned, in 2018.
- Any claim that more might have been accomplished must be tempered by acknowledging that the practical aspects of this sort of experimentation (cryogenic behavior) are difficult to set up and that many "curve balls" are involved. The need to switch to Raman scattering from Rayleigh is an example. Techniques that are easy at ambient temperature may fail in cryogenic environments.
- Accomplishments and progress are excellent. A suggestion for additional work would be moving faster to integrate the ColdPlume model into HyRAM, as this would improve progress toward DOE goals.
- There have been significant accomplishments in test facility construction and analysis capability.
- The work is essential to understanding the ability to affect separation distances.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.3** for its collaboration and coordination.

- The project collaborates with BKi, which funds the experiments. Other entities such as Shell and Linde also offered support and commitment. The project coordinates with National Fire Prevention Association Hydrogen Technologies Code (NFPA 2) and HySafe for expert advice. The project also coordinates activity with other DOE laboratories (those that use HyRAM).
- Established collaborations are excellent. As a suggestion, more active/deeper collaborations could be established with the leading European research centers in LH_2 experimental work, such as the Health & Safety Laboratory (United Kingdom) and the Karlsruhe Institute of Technology (Germany). This may assist in better scaling the LH_2 experimental work at SNL.
- The project is well integrated with supporting organizations, codes and standards development organizations, and downstream tools (e.g., QRA tools).
- The partnership spectrum is broad and matches the challenges. Funding from infrastructure industries should be much higher, considering their interest and multiannual experience in this field. Unfortunately, there is nothing the project can do about this, but $175,000 for large pool experiments will not be enough.
- Collaboration with others in industry (Air Products, Air Liquide, members of the Hydrogen Safety Panel) might be sought. The project could inquire with station developers about proposed station geometries they are considering, including underground and elevated LH_2 storage.
- The identification of partners is provided, but the extent of collaboration is not clear. While research appears thorough, the complexity of trying to test in the cryo realm could benefit from outside expertise.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.7** for its relevance/potential impact.

- There is no question that this work is critical and must be advanced if there is to be any prospect for reducing the exclusion zones traditionally specified for liquid storage and handling.
- This project is relevant to advancing the Hydrogen and Fuel Cells Program goals because it enables validation of tools that would be used to design cost-effective infrastructure and evaluate the safety of existing infrastructure.
- Relevance and potential impact of the project results are very significant. However, the scope (which is constrained by the budget and resources) is limited to fully addressing the goals and objectives of the Multi-Year Research, Development, and Demonstration Plan. Collaborations with the leading European research centers may help compensate for the project scope limitations.
- LH_2 safety and behavior is an enabler for large-scale deployment of fuel cell and hydrogen technologies.
- It is not clear at this point how vital LH_2 is to 70 MPa hydrogen infrastructure, but it may be important for some high-volume stations or as an enabler for some future on-vehicle hydrogen storage approaches.

Question 5: Proposed future work

This project was rated **3.4** for its proposed future work.

- The large-scale hydrogen release experiments are needed to characterize hydrogen pooling, evaporation, and interaction with atmosphere and to develop and validate predictive risk models for unintended releases of hydrogen in containers.
- Proposed future work is excellent. As a suggestion, the emphasis should be put on integration of developed models into HyRAM. International collaborations within the International Energy Agency’s Hydrogen Implementing Agreement and HySafe should be exploited to assist this objective.
- Large-scale testing, which is critical for the development/improvement/validation of models and codes, is planned for 2018. Without this, the project will mainly have an impact only on the scientific community.
- It is important to look at NFPA high-priority scenarios, as well as ambient air temperature/consistency/movement effects.
- More could be presented on what this future work is to be and how it is to be conducted. Looking at the release behavior of cryogenic hydrogen vapor plumes is analogous to setting up base camp for an attempt at Mount Everest. Spills and so forth are more complex, pose many practical experimental challenges, and involve significant hazards in their execution.
- The project should include forecourt and equipment installations with four rectangular arranged walls with enclosure/accumulation experiments. Hazards associated with formation of liquid air about discharge should be considered.

Project strengths:

- The project has a strong scientific competence and approach, coupled with unique methods. Also, the strong collaboration and interaction between this project and the other two on HyRAM and QRA is an added value.
- Project strengths include focus on goals and objectives, attention to detail and thorough set-up of the experimental work, and a solid modeling approach.
- The methodical approach develops a basic understanding through controlled experiments for model validation. The project may also have a beneficial application to other cryogenic liquids or fuels.
- Strengths include the experimental methods applied and the direct feed into modeling activities (HyRAM).
- The approach is methodical and uses appropriate measurement and analysis techniques.
- Strengths include the project’s coordination with the two other projects, SCS-011 and SCS-025, and its clear objectives.

Project weaknesses:

- No weaknesses were found.
- The focus is directed toward understanding release behavior. There could be additional focus on how some of the observed effects—for example, condensation of air gases that interfere with desired hydrogen release and Rayleigh measurement—might be an issue in real-world hazards.
- The project will need to address a wide array of release scenarios in order to have an impact on setback distances. The investigators should work now to understand the scope of relevant scenarios and incorporate them into future plans (in addition to currently planned baseline work).
- The large-scale experiment will be critical. The project needs correct funding through increased contribution from industry.
- Project weaknesses include lack of practical knowledge in regard to the operating conditions of LH_2 facilities. This lack is reflected by potentially non-representative scaling of laboratory experiments.

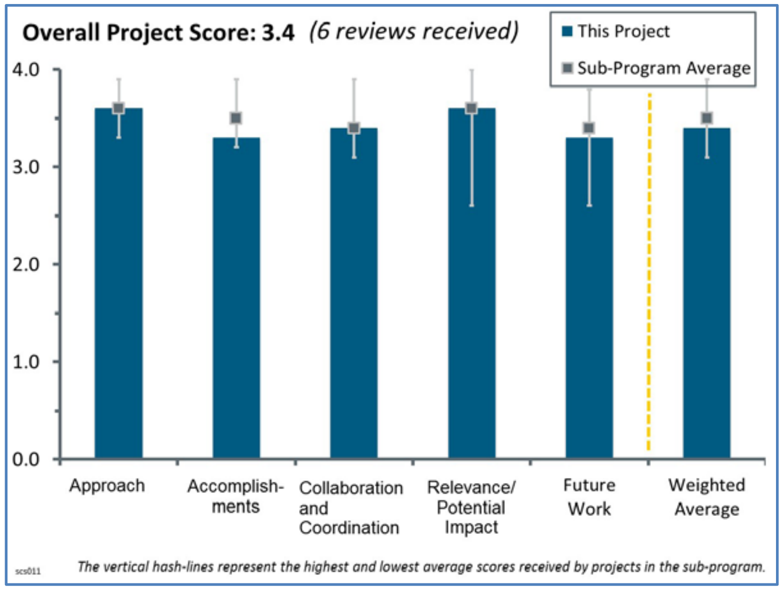
Recommendations for additions/deletions to project scope:

- Vent experiments with larger orifices (at least 10 mm) and lower pressures (less than 1 barg) should be benchmarked against the ColdPlume model predictions based on the current momentum-driven data. The investigators can determine whether the model can adequately predict buoyancy-driven plume behavior.
- The project should provide detail for future work, a roadmap, showing what comes next. The project should provide visibility to follow up on observed behaviors (condensation) that, while they may be secondary to current objectives and perhaps a nuisance, may be important in understanding the overall hazard environment presented by cryo storage.
- The project should work to understand whether there are worst-case conditions for a release, for example, windy, rainy, cold, snowy, humid, hot, or dry weather. If so, perhaps experimentation and model work could focus on these conditions as priority.
- One thing that could be perhaps be studied also at laboratory scale is the fluid dynamics of multiphase cryogenic liquid and other properties, such as the heat flow phenomena from liquid pooling.
- The effects of barrier walls should be considered when doing accumulation experiments.

Project #SCS-011: Hydrogen Quantitative Risk Assessment

Katrina Groth; Sandia National Laboratories

Brief Summary of Project:



The primary objective of this project is to provide a science and engineering basis for assessing the safety of hydrogen systems and facilitate the use of that information for revising regulations, codes, and standards (RCS) and permitting stations. Sandia National Laboratories (SNL) will develop and validate hydrogen behavior physics models to address targeted gaps in knowledge, build tools to enable industry-led codes and standards (C&S) revision and safety analyses, and develop hydrogen-specific quantitative risk assessment (QRA) tools and methods to support RCS decisions and to enable a performance-based design code compliance option.

Question 1: Approach to performing the work

This project was rated **3.6** for its approach.

- This project has been ongoing for several years. At this point, the approach is to maintain, enhance, and distribute the SNL Hydrogen Risk Assessment Model (HyRAM) to assess risk and mitigation of hazards. Industry users and safety experts can utilize this tool for QRA, running models of gas and flame behaviors much faster, which will bring down costs significantly. The quality assurance testing that has been conducted on the software improves user confidence and allows research data to be transferred to hydrogen industry users in a more meaningful, useful way.
- This is the first successful project aiming at an integrated tool for assisting safety design. Over many years, the project has been well coordinated with other projects planned to contribute to it. Its goals were very ambitious, almost risky, but nevertheless have been achieved.
- Partnership with stakeholders is critical for ensuring the model is relevant and used by industry. This project includes this critical engagement. Work is ongoing to ensure the engagement from stakeholders is sufficient to ensure relevance to industry and to provide confidence in the validity of the project assumptions so that industry stakeholders will use the tools in code development activities and engagement with authorities having jurisdiction (AHJs).
- This work bridges engineering model development with risk assessment and provision of applications applicable to real problems. The implementation of HyRAM addresses the practical aspects of maintenance needs and support for dissemination.
- The trinitrotoluene (TNT) equivalent model may be simplistic and problematic. There does not seem to be a solution to gain actual operating data from existing hydrogen installations that can be used to refine/ validate assumptions.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.3** for its accomplishments and progress.

- Several accomplishments are discussed in regard to the new features of HyRAM 1.1, which was released in February 2017. They consist of new modules/models, reduced run time, quality assurance, and bug removal. The technical reference manual for this version was also released this year. A user forum was established on H2Tools.org, and there has been extensive engagement with the user community over the past year through publications, webinars, conferences, HySafe, and the International Energy Agency's Hydrogen Implementing Agreement.
- Key issues are being addressed very well. Industry is anxious to address liquid hydrogen as soon as possible to facilitate science-informed code change proposals.
- The project has focused on refueling stations and, in this respect, has achieved considerable progress toward DOE goals.
- The project seems to methodically process research and development (R&D) results into applications made available to the user.
- It is not clear how effectively HyRAM has been used to actually further the effort of the C&S community. Perhaps the project could provide specific examples from Technical Standard 19880 in which results have had meaningful impacts on code language and results. The slide 6 "approach" does not seem to have specific impacts for this year that match up with some of the other slides. It would be good to have feedback from users as to the validity and usefulness, e.g., how often it is actually being used and the results are accepted by experts, or how it compares to commercially available packages in terms of confidence in its results.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.4** for its collaboration and coordination.

- Collaboration, coordination, and technology transfer with other institutions are comprehensive and include industry partners, other national laboratories, standards development organizations, and stakeholder groups such as the California Fuel Cell Partnership, HySafe, universities, and international users.
- The project has engaged with critical industrial stakeholders as far as possible and made use of international forums for the testing and improvement of the tool.
- Much has been done on this, with the relevant stakeholders engaged and extensive engagement with users.
- The partners are experienced, and combined with feedback from users, the collaborative process is augmented.
- This tool is essential in helping develop performance options for prescriptive requirements.
- While there is a large list of collaborators, it is not clear how effectively this project interacts with each. For example, it is not clear what specific items were accomplished that resulted in better installation or permitting of hydrogen stations.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.6** for its relevance/potential impact.

- Safety is the most important potential obstacle with any new technology, particularly when the exposure rate is high. Therefore, QRA tools are essential to providing data-driven safety C&S to protect the industry and the public. The project is highly relevant to the Hydrogen and Fuel Cells Program.
- Work being done in this project, as well as related work (SCS-010 and SCS-025), is critical to acceptance and safe deployment of hydrogen fuel infrastructure.
- Providing an application such as HyRAM directly aids the intended users. Often, without such aid, there is a lag in industry implementation of R&D findings.

- The availability of this tool will tangibly contribute to easing hydrogen technology deployment by enabling option comparisons by means of a science-based methodology.
- Tools like this are needed, as the existing code may not be fulfilling the needs of station implementers and permitters for tight installations.
- HyRAM can be used effectively as a valuable tool if it has widespread acceptance. However, the value of much of the proposed work and collaboration going forward is not clear. There are a number of papers and presentations, but it is not clear whether these are useful to the primary goal or directly relevant to furthering hydrogen infrastructure.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- Identification of gaps is very important. Engagement with stakeholders has been very good. The project team is encouraged to continue to cast a wide net when describing the upcoming opportunities for engagement—perhaps with press releases and articles describing the work and announcing opportunities to engage even further.
- Proposed future work aims to continue to provide fixes and distribution of HyRAM, conduct gap analysis and address those gaps, and extend methodologies to storage materials, which will improve the product and enhance utility to end users.
- The project's ambitions for the future years are not limited to incremental improvements but reach out to other infrastructure topics and to liquid hydrogen. To meet these ambitions, funds similar to those of the past years will have to be made available.
- It is assumed that incorporation of liquid release models into HyRAM will follow what has been done already.
- It is not clear how the proposed work has direct or positive impacts on hydrogen infrastructure deployment. It would be helpful if there were specific plans to broaden to liquid hydrogen and also to demonstrate how HyRAM can be used to support a performance-based approach accepted by an AHJ in the "real world" as an example. There are references to this support but no specific examples. That would show how it could be used for actual installations.

Project strengths:

- The project has produced a very useful, robust tool for AHJs to address enforcement and really promotes general safety, plus time and cost savings for designers and builders of fueling infrastructure.
- Strengths include validation of the models, use of the models in new areas (such as Hydrogen Fueling Infrastructure Research and Station Technology [H2FIRST] reference stations), and engagement with industry and various users of the model.
- Strengths include continuing improvement of HyRAM, expanding the user community, and outreach to external R&D and end users via a page on H2Tools.org.
- The project has an integrated approach, with different and strong scientific competencies and engagement with industry.
- The project directly tackles issues for industry implementation.

Project weaknesses:

- The proposed work for fiscal year 2018 does not show how the project will provide direct support for hydrogen infrastructure. Expanding HyRAM could be useful, but the project as presented seems to be losing focus on specific results other than maintaining the existing project. It is not clear what the expected long-term plan for HyRAM product support is or how it will be maintained.
- The collaboration appears to be successful for dissemination of HyRAM, but the slide titled "Remaining Challenges and Barriers" indicates that a good deal more could be added. It would be good to add those additional modules to the software, data permitting.
- Considering the limited deployment of the technology and its continuous development and improvement, it remains unclear how accurate failure frequencies used in the model are.

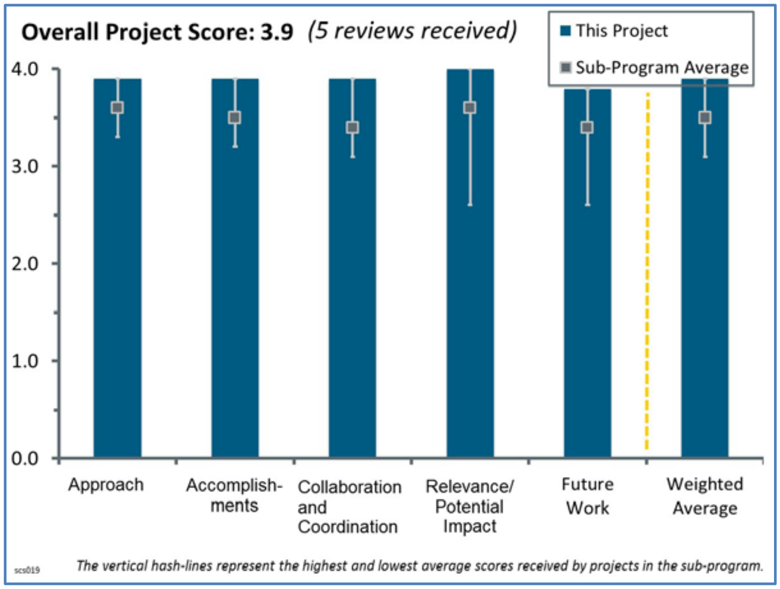
- A weakness is significant reliance on data that are difficult to obtain.

Recommendations for additions/deletions to project scope:

- This is excellent progress on a critical project. The only suggestion is even more outreach, such as articles published in a variety of trade journals, to increase awareness and use of the models. This may facilitate obtaining further data, support, and partners.
- Further broadening the focus on other public aspects of the technology would offer an important support to safety design in other areas. For example, a module dedicated to storage technologies would be important to answering many questions of local regulators.
- Liquid hydrogen should be added as quickly as possible. The project should demonstrate its use in a performance-based design for a real-world installation in which HyRAM was used to influence a code official.
- The project should look at four walls at 90 degrees, as seen in many installations (built despite code restrictions).
- The only recommendation is to keep expanding capability as models become available.

Project #SCS-019: Hydrogen Safety Panel, Safety Knowledge Tools, and First Responder Training Resources

Nick Barilo; Pacific Northwest National Laboratory



Brief Summary of Project:

This project provides expertise and recommendations though the Hydrogen Safety Panel (HSP) to identify safety-related technical data gaps, best practices, and lessons learned, as well as helps integrate safety planning into funded projects. Data from hydrogen incidents and near misses are captured and added to the growing knowledge base of hydrogen experience to share with the hydrogen community, with the goal of preventing safety events from occurring in the future. The project also aims to implement a national hydrogen emergency response training resource program with adaptable, downloadable materials for first responders and training organizations.

Question 1: Approach to performing the work

This project was rated **3.9** for its approach.

- The HSP project has been working a three-pronged approach: HSP, the H2Tools website, and first responder training resources (FRTR). This has been a major task with a large effort that is well done. The HSP has been very well utilized for current project support. The hydrogen tools web portal has consolidated best practices and lessons learned. The first responder training program is the best support resource in the world.
- This project is really three separate projects 1) HSP, 2) safety knowledge tools (SKT) and dissemination, and 3) FRTR. All three of these activities are carefully designed to meet the primary objective of enabling the safe and timely deployment of fuel cell technologies. The reviewer really likes this project.
- Three projects are in the report. The first is the activities of the HSP. The second is the SKT. The third is FRTR. The approach, as described in the presentation, is appropriate to the funding.
- This project is well organized, and the approaches of this project are excellent, with a clear structure toward the purpose of this project: hydrogen safety.
- The project has a comprehensive approach to facilitate the access to relevant information for stakeholders, which is especially relevant for permission, safety, and standardization.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.9** for its accomplishments and progress.

- The HSP continues to prove itself a valuable resource to DOE projects and now to activities outside DOE, in particular, the panel efforts with the state of California (e.g., the California Energy Commission [CEC]) and reviews and consultation as fueling stations deploy in California. This is in addition to the panel's already heavy workload for DOE project safety reviews. Just to note the total number of reviews performed were 30 is excellent. The Fuel Cells and Hydrogen Joint Undertaking will be starting an HSP similar to the one Pacific Northwest National Laboratory (PNNL) manages. Imitation is the highest form of flattery. The

SKT has clearly demonstrated its value to the international hydrogen community, with a total of 135,160 page views from around the globe. The principal investigator has been successful in making the SKT a one-stop shop for information on hydrogen safety—this includes papers from the International Conference on Hydrogen Safety (ICHS) series of conferences, a Hydrogen Risk Assessment Model (HyRam) discussion forum, and permitting videos. The work identified as "in progress" will strengthen the one-stop-shop notion. Indeed, the European Union is using this portal instead of building one of their own, noting the enormous value PNNL has provided in this work—outstanding. The FRTR effort by PNNL is a critical component of the PNNL work, enabling the deployment of hydrogen technologies. PNNL and the California Fuel Cell Partnership have performed numerous training sessions; as the fuel cell electric vehicle technology rollout is starting in the Northeast, this project is being proactive and providing outreach and training for those areas. The results speak for themselves: 1350 attending classroom training since 2009 and 330 national template downloads globally since 2014. This project is making an outstanding impact. This project is also partnering with HyResponse from France to improve training materials and is recognized globally for its quality and impact.

- The HSP has provided expertise and recommendations to numerous DOE- and CEC-funded projects. The SKT have evolved into world-class resources. The FRTR are very well focused on the needs of first responder training organizations.
- There are excellent accomplishments addressing the barriers that are identified in this project. While this project has "sharply focused" on identified "critical barriers," the project gives limited information about whether there are some barriers that are critical but difficult to approach.
- The Gantt chart in slide 6 addresses the accomplishments to date.
    - The HSP panel membership is a nice selection. Adding an official from Boston or New York (perhaps the New York Fire Department) would help with the roll-outs. If Boston or New York is not interested, then Atlanta, Baltimore, or Philadelphia might work.
    - The certification guide work should be handed off to either a standards development organization or a trade organization, the two venues where industry would normally look for this type of data.
    - The proposed changes to the HSP charter (slide 12) should be reconsidered. The awareness of the HSP and SKT should be by surrogates (National Association of State Fire Marshals, International Association of Certified Home Inspectors, and state equivalents). In Connecticut, the State of Connecticut Public Safety Department at 1111 Country Club Road, Middletown, Connecticut, is one-stop shopping for the fire marshals and the building inspectors. Other states have equivalent agencies. The recommendation is to start with the states from Massachusetts to Maryland first.
    - The project is advised not to deal with local incident response groups but instead to work with the states to address this need. The project should request that the states help populate the incident database.
    - The reviewer supports looking for alternate funding sources and the usefulness of additional site inspections. However, HSP is not, nor should it become, an authority having jurisdiction (AHJ) or nationally recognized testing laboratory (NRTL). The project should watch the fine line: voluntary project reviews for government projects is fine, but mandatory reviews of private projects is a gross overreach.
    - The SKT work is helpful. The tools portal information, like the certification guide work, should be handed off to one of the two venues where industry would normally look for this type of data: a state agency or a trade organization—preferably a state agency.
    - The generation and maintenance of tools can fall under the purview of the federal government. The approval of private sites and product listings is already addressed and entrenched. The U.S. Department of Labor's Occupational Safety and Health Administration deals in this area by approving NRTLs. PNNL is not an NRTL, nor should it attempt to become one.
    - SKT should stay away from claiming expertise in the National Fire Protection Association's Hydrogen Technologies Code (NFPA 2) and the International Fire Code. These are model codes and are not uniformly adopted from state to state (or even within a state). There is an industry of politically relevant local experts on local codes. They will retaliate if someone attempts to break their rice bowl.
    - FRTR is fully under the auspices of PNNL. Expansion in this area, especially in support of state and municipal training packages, should be readily welcome. The training should not be limited to hydrogen but rather should approach the topic as lighter-than-air transportation fuel. This would cover CH_2, compressed natural gas, and liquefied natural gas fuel vehicles and road and rail

transport of the fuel. The work should include the U.S. Department of Transportation's Pipeline and Hazardous Materials Safety Administration (PHMSA) and the U.S. Coast Guard for input and collaboration. Rather than backing a single horse, it is suggested the project support all the horses and let the market determine the winner.

- The project is demonstrating continuous development to further calibrate the information channels to higher fitting accuracy.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.9** for its collaboration and coordination.

- The collaborators for the HSP and SKT represent an impressive collection of international experts in regulations, codes, and standards; original equipment manufacturers (OEMs); energy companies; and laboratories. The development of training materials for the Federal Energy Management Program is excellent.
- There is excellent coordination with all relevant stakeholders and continuous collaboration to further increase the range of information provision.
- The HSP has become a major resource for the CEC by providing contracted safety reviews of all current hydrogen fueling station proposals, and the HSP has completed numerous technical white papers, publications, presentations, and webinars. The HSP has undertaken four accident investigations over the course of the project and one high-profile investigation this year.
- The collaboration and coordination are excellent, in particular among organizations, national laboratories, and some international partners. There is limited information about collaborations with OEMs heavily involved in the hydrogen vehicle technologies. In addition, this project gives little information about, or no consideration of, the collaboration/outreach with states/local areas away from these coastal states.
- The collaboration with different organizations should be evolving with time. PNNL should ultimately be supporting state public safety agencies, as does PHMSA and the Coast Guard. PNNL projects should be moving towards that goal with a focus on all alternative fuels. The project team should work toward being the testing and training support for PHMSA, the Coast Guard, and the various state agencies.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **4.0** for its relevance/potential impact.

- The relevance and impact of all three efforts for this work are excellent. This work has already demonstrated outstanding global impact aiding the safe deployment of hydrogen technologies.
- This project is critical and highly relevant to the DOE hydrogen technology development objectives, and the degree of potential impact to these objectives and to the future hydrogen technology applications is outstanding. The structures of HSP (in H2Tools.org), SKT, and FRTR (in H2Tools.org) built by this project will contribute greatly to hydrogen safety and thus to the hydrogen technology development.
- The H2Tools.org website has become a dependable resource used worldwide that continues to grow in usage. The support from the HSP for the current outreach to Bridge and Tunnel authorities in Boston, New York City, and Maryland has been very helpful in addressing concerns of local authorities.
- All three topics are highly relevant. The project should be careful to not overreach. PNNL should provide testing and training support for PHMSA, the Coast Guard, and the various state agencies. PNNL should not usurp the code authorities or the NRTLs.
- The project supports the further deployment of hydrogen and fuel cell technologies with relevant information in a high degree.

Question 5: Proposed future work

This project was rated **3.8** for its proposed future work.

- The proposed future work (pending funding) through 2021 is comprehensive and focused on the needs of an expanding use of hydrogen fuel cell vehicles and supporting technologies in a wide range of federal agencies.
- The proposed work for all the projects is poised to continue the excellent work already demonstrated.
- This is an excellent approach to target further information deployment.
- The proposed future work is well planned for continuously focusing on the ongoing barriers or activities. It does not score as "outstanding" since this plan seems still based within its comfortable zones. The plan focuses heavily on coastline areas and on infrastructure (fuel stations), and is not very specific about the personnel who should participate in the first responder training. If it is not a difficult barrier to overcome at this stage, the project should consider developing a future plan to conduct outreach to the states/areas away from coastline areas. Likewise, the project could work to convince OEMs to participate. The project should consider developing a plan to further define who should be the personnel that need to participate in the first responder training.
- The proposed work is appropriate. Outreach to other NRTLs versed in products in this field (Factory Mutual and Intertek/Electrical Testing Labs) may be of benefit to all. Outreach to supply research and training support to federal, state, and local officials who have authority in this area is a must. However, the offering should not be limited to hydrogen but rather should include all transportation and transported fuels.

Project strengths:

- The project is outstanding and highly critical and builds a foundation for future hydrogen technology development. Participants are very knowledgeable and have excellent expertise for this project.
- All three projects for this work contribute to the rapid dissemination of current knowledge developed in the DOE Safety, Codes and Standards fundamental sub-program. This outreach, education, and attention to safety by the HSP is critical focused and timely dissemination of the knowledge gained in the technology readiness levels (TRLs) of 1,2, and 3 research developed by this project. The traditional avenues of knowledge dissemination from TRL 1, 2 and 3 (publication in referred literature) will take years to filter to those who need it most (and it may never get to those who need and use it the most). These projects do that in an outstanding way and have been shown to be very effective.
- The HSP has become a significant resource that is effectively supporting DOE outreach projects such as tunnel AHJs and CEC projects. The H2Tools website has been adding tools to become an invaluable resource. The FRTR developed by this team have become the leading tools for hydrogen training of first responders.
- The expertise of the panel members is notable.
- The project exhibits comprehensive information availability and strong stakeholder collaboration.

Project weaknesses:

- There are no weaknesses other than potentially not enough funding to support this project in the future years through 2021.
- The ability of PNNL to keep the portal fresh and current is a concern. Maintaining websites is a big job and frequently results in the demise of the site. It might be better to allow the information providers (ICHS, for example) to maintain their own site and use the portal simply to provide a link. This is not an issue now but something to watch for.
- While this project has continued its outstanding work on identified critical barriers, the project maintains in the comfortable zones and gives little information about whether there are some other areas that are critical for spreading hydrogen technology applications, such as states/areas other than those collaborating closely with this project. The project also does not justify identified barriers that may prevent this project from approaching other areas. H2Tools could make users of this site confused or may need an update, a user validation, or routine maintenance.

- The presentation appears to show that the project may be drifting away from PNNL's (and DOE's) purview into other established AHJs. PNNL should support the AHJs, not compete with them.

Recommendations for additions/deletions to project scope:

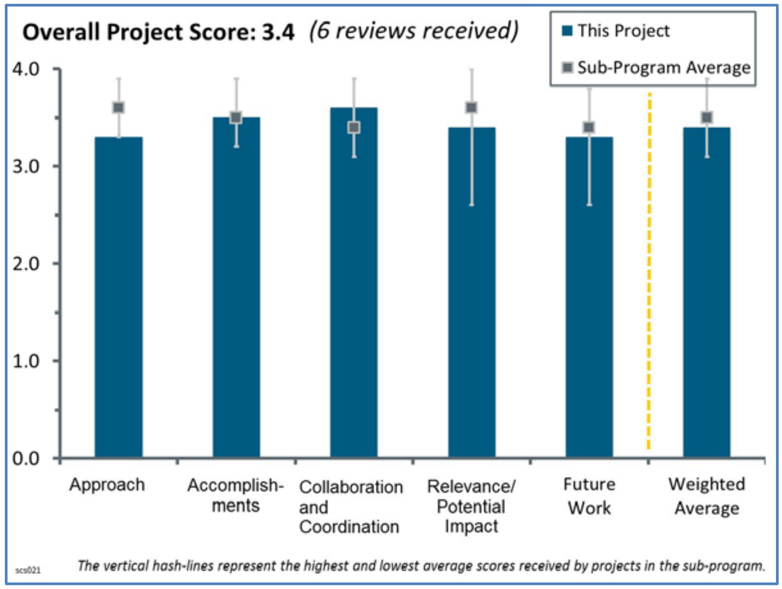
- Further alignment with available information from other international hydrogen markets might create additional value.
- As the deployment of hydrogen technologies accelerates, the need to train the trainer becomes even more acute. That area of this project could use increased attention.
- The project should consider focusing less on federal and state collaboration and on being seen as the model code experts. Working with the states by offering continuing education units for the AHJs might be a venue.
- The project should focus more and more on practical trainings of the first responders. H2Tools should be improved to make it more user-friendly. The project should expand the collaboration with and outreach to other states and local areas that have not been engaged yet.

Project #SCS-021: National Renewable Energy Laboratory Hydrogen Sensor Testing Laboratory

Bill Buttner; National Renewable Energy Laboratory

Brief Summary of Project:

Sensors are a critical hydrogen safety element and will facilitate the safe implementation of the hydrogen infrastructure. The National Renewable Energy Laboratory (NREL) Sensor Testing Laboratory tests and verifies sensor performance for manufacturers, developers, end users, and standards-developing organizations. The project also helps develop guidelines and protocols for the application of hydrogen safety sensors.



Question 1: Approach to performing the work

This project was rated **3.3** for its approach.

- The laboratory performance testing supporting codes and standards (C&S) development is evolving toward more real-world deployment/validation, providing good specific support to officials and industry. There is very good emphasis on data to input into the education/outreach process. This project involves multiple stakeholders in the Hydrogen Sensor Workshop (NREL and the Joint Research Centre [JRC]) to identify critical gaps: cost, stability, too many unique applications, complex/costly certification. Overall, the reviewer liked the way this project has evolved as it has progressed to remain focused on immediate challenges to hydrogen deployment and commercialization. The approach is well organized and well structured to keep the project focused.
- The approach was very well identified in the slides and presentation. There is an extraordinary amount of work, and the organization is superior.
- The approach is very well organized and collaborative. The principal investigator (PI) has excellent knowledge of the topic, and it is evident that he has worked extensively to inform the project.
- The approach of validating the accuracy of various sensors or sensor systems in a blind study is useful in itself to prove or disprove the myth that hydrogen sensors do not work. Results from the study can indicate which battery of tests is appropriate, which are inappropriate, and which can be misinterpreted. Slide 7 needs some clarification: DOE does not have jurisdiction on the Global Technical Regulation, and the International Organization for Standardization's Technical Committee (TC) 197 is not a regulation. Additional feedback on the test methods to upgrade the standards development organization documents would add value.
- Some activities under the project scope have well-established approaches with clear problem statements and methods to overcome barriers; others do not seem to define the problem well, and therefore the approach is lacking. For example, the fuel cell electric vehicle (FCEV) exhaust detector work seems to have a clearly defined problem and approach, while other activities such as the cold plume testing and indoor release model verification do not define the problem clearly enough, and therefore the test methods do not seem to address specific areas of research. These tests seem to have many variables, and therefore more clearly defined areas of focus may provide more useful data to code officials and system designers.
- The approach is comprehensive—but to the point of making one wonder if there is a focus. All the initiatives have value; however, this is a substantial undertaking when including verification of sensor claims, several C&S activities, and investigation into several application issues. Several teams could be managing the efforts (this comment is not intended as a criticism of the existing team).

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.5** for its accomplishments and progress.

- Accomplishments are very practical and relevant to what is happening in industry (repair facilities). They are also pertinent to current research that will directly affect the hydrogen economy (cold hydrogen plume analyzer). While some may think that there is nothing to be done with sensors, in actuality there is quite a lot of room for work (e.g., sensor placement). In reality, the industry depends on sensors, and it is good to see they are getting the attention they need. The project deserves kudos for the SAE International paper.
- This project has made solid accomplishments that directly address specific data and technology needs for immediate commercial applications and for developing, implementing, and testing C&S. These are great examples of the benefit of DOE projects executed by the national laboratories.
- Much has been accomplished during the project. A strength of the project team is the ability to adapt to the various needs of the industry and community. This flexibility has resulted in a wide variety of topics relating to sensors. However, goals and measurable targets were not clear during the presentation.
- The approach is well defined in the slides and shows the relationship of this project/laboratory in the national laboratory safety C&S program. While the accomplishments were many, the remaining barriers and future work remain similar to 2016.
- The "Toyota tent" shown in slide 10 seems to be overkill for most applications. Compressed natural gas (CNG) vehicles are routinely serviced and repaired indoors. The project might instead focus on additions or deletions to the CNG rules, especially the cold plume work. Rather than using computational fluid dynamic models because the boundary conditions are difficult to control and maintain, the site could be designed to use, not fight, the properties of hydrogen. Simple hoods or ridge line vents with Class I Division II suitable hardware in the plume volume should be sufficient. NREL and the California Fuel Cell Partnership sites do not provide ideal examples of effective means for hydrogen ventilation. However, progress and accomplishments to date are excellent.
- The accomplishments reported certainly demonstrate progress toward DOE goals. It was not clear from the presentation if substantial progress is occurring with all initiatives listed.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.6** for its collaboration and coordination.

- It was clear that there is impressive collaboration with both private and government partners. The collaboration slides identify the expertise and purpose of each partner. The laboratory offers excellent mentoring opportunities through the student internships. The NREL–JRC partnership will help share information internationally with the appropriate experts in a timely fashion. The exchange of personnel promoted the good work and may bring JRC personnel to the United States. It was disappointing to hear that there is a postponement (and potential cancellation) of the exchange/sensor workshop.
- The collaboration with industry to solve direct problems to enable commercialization is very valuable and important. Compliments to the PI on involving interns from Colorado School of Mines on the project—mentoring and developing these future researchers and engineers is critical to the growth of the hydrogen industry.
- Collaboration is excellent, including international and national C&S work, work with U.S. industry, and supportive experimental work.
- Collaboration is across all stakeholders and international. The fact that so many parties are working with the PI and NREL on this topic demonstrates the importance of the work.
- The collaboration list is extensive if not incestuous. It appears that the "car guys" (automakers) are for pushing the product and the hydrogen providers are for test sites. However, the developers seem to be small national laboratory spin-offs instead of major sensor developers (e.g., Element One Inc, KWJ Engineering Inc., KPA LLC, and AVT). Perhaps companies with resources for manufacture, distribution, marketing, etc. would be of greater utility. Companies such as Honeywell, Druck, and Rosemont have knowledge on high-pressure sensing and sealing. Companies such as Det-tronics, MSA Safety, or Kidde Fenwal are known for fire, smoke, and flammable gas detection. If the PI has not already attempted to contact these

companies, enlisting them and their strengths and knowledge should be a consideration. Classifying UNECE Global Technical Regulation (GTR) 13 as a collaboration does not seem fitting.
- The project team readily interacts with other institutions. The project team could hold closeout meetings with partnering institutions to understand whether the collaboration met expectations on both sides.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.4** for its relevance/potential impact.

- The work is highly relevant, with the potential to have a high impact in increasing the reliability of such sensors. It is to be hoped that increases in sensor reliability will also reduce the costs. Guidance on proper sensor locations is also a must.
- This project touches a large swath of critical territory for hydrogen commercialization and deployment and is well targeted to solve specific problems and advance knowledge and data to support specific standards development.
- The relevance is abundant. As stated in the presentation, sensors are required by code for most (if not all) hydrogen applications, given there are not many other methods of reliable detection of a hydrogen leak (e.g., pressure drop, detector tape).
- With the variety of sensor types and requirements, the Sensor Testing Laboratory provides a repository of expertise for the industry.
- All initiatives reviewed are important to DOE goals.
- The project team strongly focuses on sensor selection, location, and operation/maintenance as leading factors in sensor-related problems impeding FCEV deployment. In order to address these barriers, the impact of the project group's research must be measured by the ability to get the learnings and guidance out to the wider community and industry stakeholders. The project may set a target to provide guidance (in the form of a paper or other established method) to a wider audience (e.g., station developers, public officials, code officials, or industry groups).

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- The proposed future work is excellent.
- The stated goals continue the work of the sensor laboratory, but little detail was provided. The presenter ran out of time to fully elaborate what was planned. The comprehensive approach is still needed, but putting consideration into dividing the project into several efforts might be prove of value.
- This section was a bit vague, but that is understandable given the uncertainty of the budget. One hopes that industry will see the effort's value and step up to support it.
- The review/statement of future work was pretty generic. It is unclear whether there are specific projects that still need to be started and whether specific work and deliverables remain on the project as it winds down this year (September 2017 end date). It seems like there is still some work going on with the cold plume analyzer, though it is unclear what needs to be finished there.
- Future planning was lacking in the presentation (good ideas for supporting activities but little detail on future work scope). Planning may become difficult without clear problem definition and goals. Recognizing that this project has taken on various problems arising from need, this is without a doubt challenging; however, given that challenge, there remains room for improvement on planning, decision points, and project deliverables.
- This appears to be more of a "program" than a "project," and continuing to be available as hydrogen safety expertise and support for the industry is necessary. The proposed future work should continue to be supported by both DOE and the hydrogen industry.

Project strengths:

- This project covers a wide number of equally important applications for sensors, demonstrating the overall need for a project like this. The PI is extremely knowledgeable, as is his support team, and he has been proactive in expanding that knowledge (through his time at the JRC). The project strength comes from the PI's tenacity and hard work.
- The slides and presentation were very well organized. The domestic and international collaboration is impressive and should be continued. Presumably this project is not fully funded by DOE.
- There should be no question that the execution of work shows a team that is multifaceted and flexible.
- There is a focus on solutions to real-world problems that facilitate standards and commercialization.
- The competence of the team and the focused end goal to be value added to industry are strengths. This is not a science project.
- Strengths include the project's flexibility, adapting to many different problems relating to sensors, and demonstrating strong support of the C&S community.

Project weaknesses:

- No material weakness were noted, though additional specificity about future work needed would be useful, even if this particular project does not continue to be funded.
- The work undertaken seems to be more than the resources allocated. The work reported is excellent, but more could have been accomplished. Not much was said regarding review of sensors, which is assumed to be ongoing. Technical challenges to do with sensor capabilities and issues with application remain unchanged. While the project is addressing them, any one of the topics could be a project unto itself. Details on how future work is to be done are summarized in a slide but were not presented because of insufficient time for the presenter. Given the number initiatives in play, it is hard to see how all efforts could get covered.
- The remaining challenges and barriers, as well as the proposed future work and summary in the 2017 presentation, are nearly identical to the same in 2016. The comment that "…if the U.S. hydrogen sensor workshop happens, it will be in September rather than July 2017" was disappointing. It was not clear if this was related to current political climate factors or if there is another reason for failure to organize. One hopes it can come to fruition.
- Project weaknesses include deliverables and concise results:
    - Guidance to the broader community outside of C&S and DOE circles (how to have an impact on sensor users and system designers for better practices in industry)
    - Measuring impacts on achieving Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan (MYRDDP) goals and targets
    - Stakeholder follow-up, results delivery
- The apparent lack of collaboration with major sensor manufacturers is a weakness.

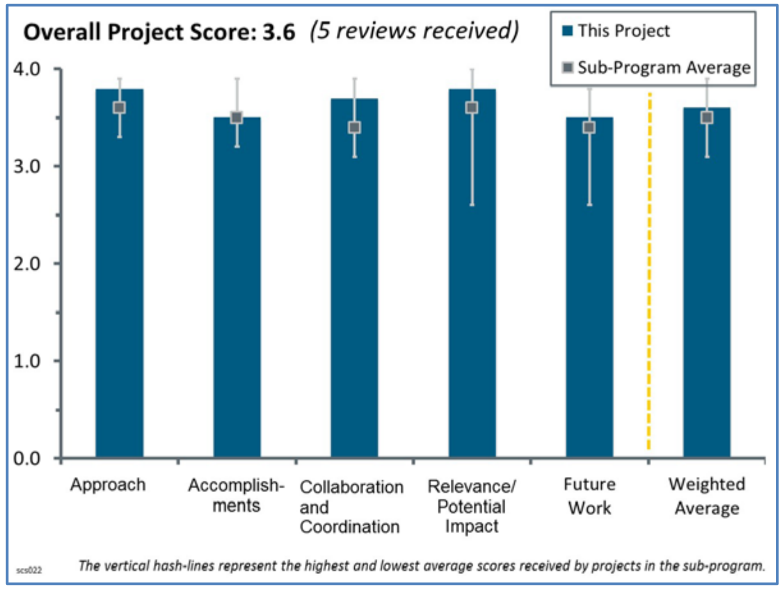
Recommendations for additions/deletions to project scope:

- No recommendations immediately come to mind. Overall, the project was well targeted and had a manageable scope and solid deliverables.
- The scope of the work performed seems more than what a single team can handle. Safety, Codes and Standards sub-program management could consider whether more or better would be accomplished if the efforts underway were handled by several teams. This is no criticism of the work reported, as the different activities range from worthwhile to absolutely necessary.
- The project should add a guidance document or other material that can be widely distributed for maximum impact, whereby proper sensor application and installation can support and accelerate FCEV deployment and MYRDDP targets.
- With the participation in various safety C&S development activities, the project should detail some of these accomplishments. It is to be hoped that the exchange with JRC will take place, and a report of the international exchange is pleasantly anticipated.
- The project should consider bringing major sensor manufacturers on board.

Project #SCS-022: Fuel Cell & Hydrogen Energy Association Codes and Standards Support

Karen Quackenbush; Fuel Cell & Hydrogen Energy Association

Brief Summary of Project:



This project supports and facilitates development and promulgation of essential codes and standards (C&S) to enable widespread deployment and market entry of hydrogen and fuel cell technologies. The goals of the project are to ensure that best safety practices underlie research, technology development, and market deployment activities supported through projects funded by the U.S. Department of Energy (DOE); conduct research and development (R&D) to provide critical data and information needed to define requirements in developing C&S; and develop and enable widespread sharing of safety-related information resources and lessons learned with first responders, authorities having jurisdiction, and other key stakeholders.

Question 1: Approach to performing the work

This project was rated **3.8** for its approach.

- The Fuel Cell & Hydrogen Energy Association (FCHEA) C&S support staff, vision, and actions are an essential force that facilitates the development of national and global technical standards for on-vehicle fuel systems, fueling station dispenser process operations including risk management, fuel quality sample procedures, and hydrogen test method analytics to quantify impurities.
- FCHEA is the industry association associated with supporting a hydrogen economy. Therefore, participation through their transportation, stationary power, and portable power working groups provides vital feedback to the DOE Hydrogen and Fuel Cells Program (the Program) that seeks to promote hydrogen as an alternative energy carrier. The project's approach to coordination, outreach, and reporting enables sharing between all stakeholders and gives a voice to industry partners in the development of the relevant C&S that affect them.
- The approach addresses needs for connectivity between U.S. national and international C&S, provides a forum for industry participation, coordinates interaction of participants, and helps to disseminate C&S information.
- FCHEA has done outstanding work leading the industry and standards organizations in the field of hydrogen and fuel cell technology.
- This is the way to do it.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.5** for its accomplishments and progress.

- The FCHEA C&S support staff and technical experts contributed to code development in the following ways:
    - National Fire Protection Agency (NFPA) 2 and SAE International fuel cell technical committees

  - Canadian Standards Association (CSA) component standards for hydrogen-powered industrial trucks (CSA HPIT 2) and for compressed hydrogen materials compatibility (CSA CHMC 1)
  - Global technical regulation (GTR) for on-vehicle fuel systems

  In addition:
  - The CSA hydrogen gas vehicle (HGV) 4.x series of component standards (dispenser, hose, station operation) has provided a basis for the International Organization for Standardization (ISO) Technical Committee (TC) 197 Hydrogen Technologies standard series 19880-x, including fueling station dispenser process operations such as risk management, fuel quality sample procedures, and hydrogen test method analytics to quantify impurities.
  - The principal investigator (PI) is the convener of ISO TC 197 Hydrogen Technologies standard 19880-x for hoses and has led the working group to great progress in fiscal year (FY) 2017.
  - The PI is the convener of ISO TC 197 hydrogen technologies standard 19880-x for compressors and has led the working group to great progress in FY 2017.
- This is an excellent effort in facilitating input to domestic and international safety C&S development activities from FCHEA's membership from all three pillars: transportation, stationary, and portable.
- Accomplishments through participation and reporting provide regular mechanisms to identify and address industry priorities. The significance of this for the Safety, Codes and Standards sub-program is that progress with C&S is shared directly with those in industry most affected by C&S.
- FCHEA has demonstrated accomplishments in multiple areas, including domestic and international regulations, codes, and standards (RCS) and maintained coordination with all experts in R&D and RCS activities.
- The project's activity addresses DOE goals.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.7** for its collaboration and coordination.

- The FCHEA C&S support staff and technical experts collaborate with various standards development organizations (SDOs) to co-develop technical standards:
  - Provision of code development language and "many suggested improvements" to NFPA-2, CSA-HVG/ISO TC 197 technical (product) standards
  - Work group management (as convener) for the global hose and compressor standards to support hydrogen vehicle fueling
- FCHEA represents members throughout the global supply chain of the fuel cell and hydrogen industry. Serving as a conduit between industry and the Safety, Codes and Standards sub-program fills a vital role.
- FCHEA working groups provide an avenue to engage industry in the development of RCS. Their work and communication expertise help keep everyone on track and focus.
- Project activity shows coordination with basic industry and code development institutions.
- Collaborations are well structured and well managed.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.8** for its relevance/potential impact.

- The relevance/potential impact of the FCHEA C&S support program is huge. The team is playing an essential role to help shape the development of GTR and ISO TC 197 hydrogen technical standards that will be then be re-adopted as national standards in the CSA HGV 4.x series of standards.
  - The global nature of these technological standards to support hydrogen vehicle fueling is the foundation of the global transformation to hydrogen as the number one fuel for mobility applications before the end of this century.
  - Local air quality benefits for some communities will drive the quest for zero-emissions vehicles, and the high-mileage vehicles will all trend toward the benefits of hydrogen fuel mobility; in some

cases, Japan, island nations, geothermal hotspots, local renewable power, or reduction in fuel imports will drive this trend toward hydrogen as a mobility fuel.
    - To the degree to which the FCHEA C&S support program advances progress toward the Program goals and objectives delineated in the Fuel Cell Technologies Office (FCTO) Multi-Year Research, Development, and Demonstration Plan (MYRDDP), the work focus on NFPA 2, CSA HPIT 2, and the global ISO TC 197 hydrogen technical standards is so mission-critical that this project should receive a score higher than 5.0.
- The monthly meetings, reporting, participation in technical committees, and working group activities are all relevant to the Program, with the most relevant aspect being the voice to DOE of the FCHEA members.
- FCHEA's multi-tiered approach helps support and advance progress toward DOE missions and goals. Their work also is on track and consistent with the MYRDDP.
- This effort must continue until fuel-cell-supported industries have entered the mainstream of U.S. and international business.
- Relevance and impact are outstanding; all identified barriers are addressed in the most effective way.

Question 5: Proposed future work

This project was rated **3.5** for its proposed future work.

- The continued efforts of the FCHEA C&S support team to update the national standards once the global standards are published is a critical task with an all-hands-on-deck approach of bringing U.S.-based technical experts to tailor the global standard to the American National Standards Institute process.
- The individual working groups look at specific barriers and work to resolve those issues on a task-by-task basis. At a higher level, the association holds meetings, workshops, and webinars to support their membership and others. The proposed continuation of this type of work is necessary and reasonable.
- The project should continue with the current work and, perhaps, increase public and government outreach. The PI should keep up the good work.
- The project's future work is well-defined and -articulated.
- While the future activities summarized are of merit, it seems there could be more. The project could at least provide more detail. As safety direction is developed from work at Sandia National Laboratories on liquid hydrogen, its introduction into code and dissemination will be important.

Project strengths:

- This project has enabled support for a wide range of hydrogen code development efforts, as well as some critical short-term support. The project brings the best minds of risk analysis from the national laboratories into local outreach efforts with authorities that have jurisdiction over Boston, New York, and Baltimore tunnels to testify about the negligible risks that fuel cell electric vehicles add to the mix of vehicles using the tunnels.
- The organization of activity is such that any topic/issue can be addressed and coordinated with industry participants.
- The project demonstrates collaboration between members, SDOs, and DOE and provides a link to global suppliers.
- The project team is highly motivated, experienced, and dedicated; organization and management are excellent.
- FCHEA has knowledgeable and strong personnel with excellent communication skills.

Project weaknesses:

- No weaknesses have been identified for this project other than the threat of loss of funding support in FY 2018.
- It is not clear if the activities listed are of top priority. However, if the participants identify critical needs, the way this work is performed will surely result in promotion of action to address them.
- A project weakness is the absence of FCHEA-led/-driven events. Participation in the 2017 Fuel Cell Seminar is a move in the right direction. However, a stand-alone FCHEA event in Washington, DC,

dedicated to one of the pillars (e.g., transportation) could have a significant impact on bringing U.S. politicians back to the hydrogen "support camp." This is critical in showing a helping hand to the FCTO.

Recommendations for additions/deletions to project scope:

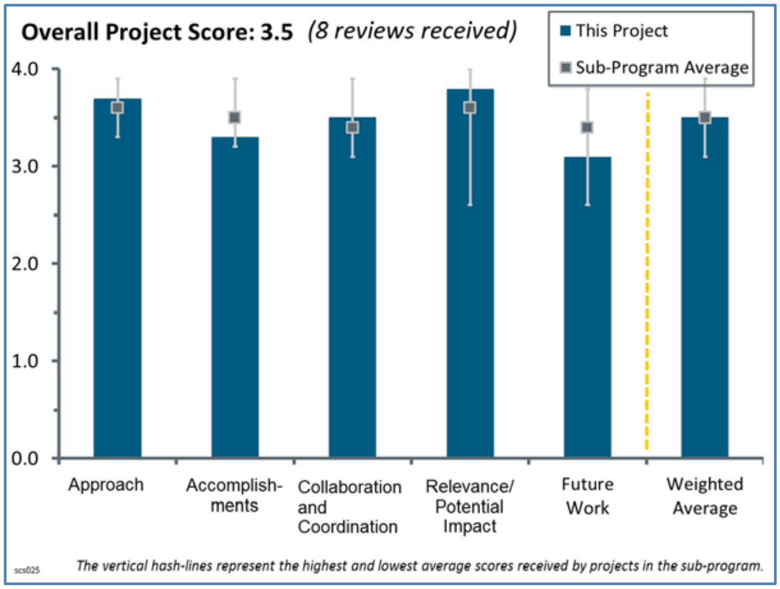
- This activity should continue. The funding is minimal but provides a link with DOE programs and a mechanism for SDOs, researchers, and regulators to engage with suppliers.
- FCHEA should consider (1) being more involved in the technical research and testing areas and (2) increasing public outreach.
- FCHEA should consider organizing/leading an event in Washington, DC, on one of the pillar topics to support the FCTO.

Project #SCS-025: Enabling Hydrogen Infrastructure through Science-Based Codes and Standards

Chris LaFleur; Sandia National Laboratories

Brief Summary of Project:

The goal of this project is to enable the growth of hydrogen infrastructure through science- and engineering-based codes and standards (C&S). Specific objectives include (1) streamlining cost and time for station permitting by demonstrating alternative approaches to code compliance and (2) revising and updating C&S that address critical limitations to station implementation.



Question 1: Approach to performing the work

This project was rated **3.7** for its approach.

- The approach to addressing barriers is excellent. First-hand/direct interactions with industry and fire code/permitting officials is critical to the project's success.
- The effort is critical to deployment of hydrogen infrastructure.
- The approach is good, in terms of scientifically based and risk-informed approach. However, in execution, the information needed (i.e., consequence analysis and safety data) has been both problematic and delayed. The project could consider (1) alternatives to how that work can be expedited; for example, other sources of liquid hydrogen (it is not clear that any data are being provided) and (2) that the separation distance is not the best means to obtaining the end goal of safety. It might be better to spend time on determining how to reduce the likelihood and severity of release with a goal of minimizing or eliminating separation distance. The reduced gas distances of four meters and five meters (increased above risk-informed with "safety factor") might indicate that the separation distance concept is a paradigm.
- The project's multipronged approach is appropriate to utilize models, data, and tools. However, it is not clear whether the C&S committees provide direct input into the approach.
- Each of the areas addressed in this project are thoughtful and consider end-to-end (from the science to the application) how the work will contribute to enabling improved infrastructure deployment. The principal investigator and team have engaged industry, government, and academia to understand key issues and identify science-based methods for helping address them.
- The approach is concise and on track in both technical tool development and standard synchronization and application.
- This work is necessary for widespread distribution of fuel cell electric vehicles (FCEVs).
- Barriers that the project has addressed are essential to risk-informed deployment of hydrogen fueling infrastructure.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.3** for its accomplishments and progress.

- The project demonstrated clear progress presenting findings to C&S committees, gaining acceptance/consensus (nationally and internationally), and working with code officials/regulators to address and eliminate regulatory barriers.

- This effort is directly tied to project numbers SCS010 and SCS011. As those projects progress, this project can move ahead more aggressively, with a likely feedback mechanism for improving the tools and models.
- The work and accomplishments are consistent and in line with DOE's goals and objectives.
- Solid progress has been made in most areas of work. For example, data collection for separation distances for gaseous hydrogen has enabled acceptance of draft revisions to the table, and an annex to the International Organization for Standardization (ISO) standard CD-19880-1 (Gaseous hydrogen – Fuelling stations – Part 1: General requirements) has been drafted, which will reduce potential infrastructure challenges for cross-border deployment. Additionally, since last year, a new area of work—tunnel safety evaluation—has been added that is critical for enabling deployment of infrastructure and FCEVs in the Northeast. Real-world testing has not progressed significantly, but the team appears to be actively engaged in identifying the right opportunity and is partnered with industry to help move this forward.
- The project's accomplishments are very impressive. To improve, some guidance should be given to the National Fire Protection Agency (NFPA) 2 Technical Committee to fix the logic/overall methodology behind construction of the separation distances table. The numbers for lower-pressure columns are still greater than for higher pressures, which does not make practical sense.
- Two of the major work items have had little progress: liquid hydrogen separation distance work and the use of planning, budget, and analysis (PB&A) for station siting. While influenced by external factors, it is still a reality for this project.
- The impact of the progress was not well presented.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.5** for its collaboration and coordination.

- Collaborations, both internal and external, are excellent. Contributions to safety C&S development to domestic (e.g., NFPA 2/55) and international (e.g., ISO Technical Committee [TC] 197) organizations are well coordinated and harmonized. Expanded collaboration should continue with HySafe on liquid hydrogen planned activities as well as tunnel modeling work.
- This project engages the appropriate partner stakeholders for each area of focus. It is critical that industry partners are engaged for real-world feedback and "ground-truthing" as well as creating buy-in for the work. The team is also working with partners to ensure linkages to code modifications and improvements and is involved in several organizations to share knowledge and remain up to speed on the industry.
- Collaboration with domestic and international partners is excellent.
- Supporting new C&S revisions is essential; this is well done.
- There is good work with regulators to eliminate barriers and good work collaborating with ISO and NFPA. The project team should consider working with certification bodies to gain traction with risk-based compliance. The team should consider when it is sufficient for a regulator to have data provided from national laboratories or whether that puts the government at risk.
- The project has the right industry partners.
- Further publication of papers and articles for stakeholder organizations, with the intent of increasing awareness and engagement moving forward, would improve the project. As industry rolls out vehicles and infrastructure, new stakeholders will have questions and a need for specific analysis. The availability of these tools and models, and how they are being used, must be easily discoverable.
- Additional collaboration may be needed to get alternative sources of data (for consequence and probability data) as well as to make progress on the performance-based approach. The project should consider whether alternate stations can be found if a station is not yet ready for demonstration.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.8** for its relevance/potential impact.

- This research is critical for addressing some barriers to infrastructure development. Scientifically demonstrating that smaller separation distances is safe will enable more compact infrastructure development, currently a limiting factor in station rollout. FCEVs on bridges and in tunnels is a big challenge for vehicle deployment in the Northeast states. This work will enable the authorities having jurisdiction (AHJs) to make more informed decisions and help reduce concerns about FCEV safety in these areas, or clearly outline the parameters under which risks outweigh the benefits. The project also supports and advances the goals and objectives outlined in the Safety, Codes and Standards sub-program section of the FCTO Multi-Year Research, Development, and Demonstration Plan. The project will provide critical data and information needed to update or modify C&S, which will help accelerate the hydrogen and fuel cell market. Through its partnerships, this project also provides data and information that is needed by AHJs, industry, and other stakeholders to help enable the market and overcome space and cost issues.

- Relevance and potential impact are very high. Reduction of NFPA 2 separation distances significantly improved the industry capabilities for placement of gaseous-hydrogen-based hydrogen refueling stations within an urban environment. The current work on liquid hydrogen is expected to achieve a similar effect. The work of tunnel modeling is instrumental for the deployment of FCEVs on the East Coast and other similar jurisdictions.
- Alternate means of code compliance are essential. Developing hydrogen infrastructure is challenged to meet existing code requirements, and creative solutions are being implemented without benefit of a complete knowledge basis.
- This project clearly advances the Fuel Cell Technologies Office (FCTO) goals; it is an excellent example of government-funded science supporting safe deployment of new technology, including direct engagement with regulators.
- This project provides support and helps advancing the DOE Hydrogen and Fuel Cells Program goals and objectives. The potential impact is in the areas of permit and approval processes of tunnels and fueling stations.
- Although much of this effort is applied research, it is essential to facilitate the tools and models used and accepted by industry and AHJs.
- The work is very pertinent to facilitating permitting of hydrogen installations.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- The proposed future work is well-defined, -articulated, and -balanced. Closer collaboration with industry and research partners—both domestically and internationally—will make the impact even higher.
- This project's continuation and budget are determined annually by DOE. Based on the outlined goals of the project, the proposed future work makes good sense.
- The project is urged to publish its findings in many technical outlets.
- The project should develop alternative pathways if it continues to be stymied by a lack of progress in the inputs needed for the work. This could be an alternative means to get the information needed, as well as a consideration if separation distances can be replaced by other means. The PB&A is not included on the proposed fiscal year (FY) 2018 work. If this omission is not intentional, the PB&A should be included.
- It seems that the most critical aspects of the work have been achieved (code acceptance, ISO acceptance, and education on the tunnel issue). Perhaps the next steps should include broader training efforts for the tools to allow code/standard committee members to use the tools to continue to inform refinements. Not to underscore the key achievements here, but the path forward may not be able to deliver as significant of results as what has been achieved.
- Proposed FY 2018 work should be more detailed. This sounds like the principal investigator would end the effort.

Project strengths:

- Strengths include excellent planning and management; an experienced, highly intelligent, and skilled work force; strong domestic and international collaborations; and first-hand/direct contacts with industry, C&S developers, and permitting officials.

- This project is filling critical data gaps in separation distances and tunnel safety. It is also effectively utilizing partnerships to ensure research is addressing real-world needs and to create conduits for the research to enable more informed science-based decision-making.
- Significant achievements are clear and seem to result from the level of direct engagement with C&S committees and regulators. Other projects should utilize a similar approach to increase impact.
- The approach is integrated with project numbers SCS010 and SCS011. The project is already proving its worth and versatility through use in addressing AHJ concerns for tunnels in the Northeast.
- Project strengths include its work with international groups and promotion of a science basis for exposures.
- Strong technical knowledge and standards participation are project strengths.
- The project addresses a critical need for FCEV implementation.
- This work is important to the code development process. The tunnel work is useful as well, but it might distract from the effort needed on separation distances.

Project weaknesses:

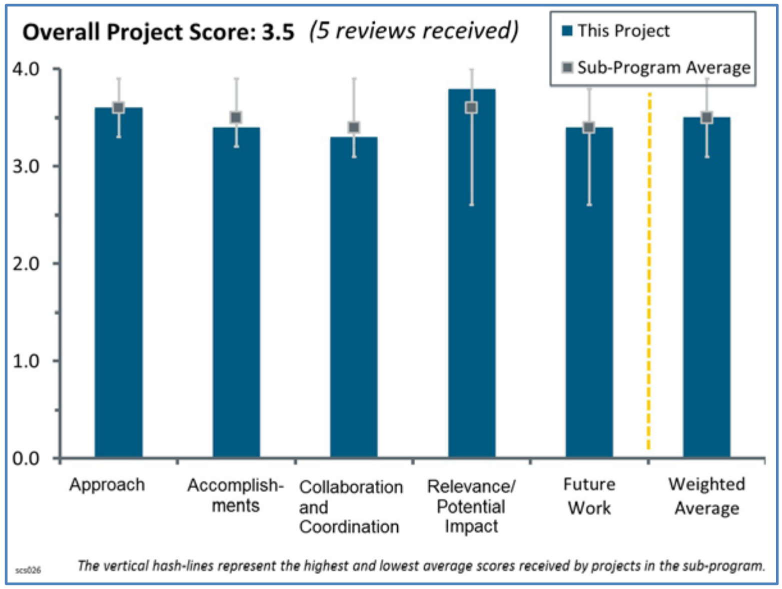
- Overall, this project does not appear to have weaknesses. One area that appears to be moving more slowly is the performance-based design for a real-world station. There are many factors that could be contributing to this that are understandable. Progress is being made, and it is an important aspect of the work, so it is not of real concern at this time.
- As hydrogen vehicles and infrastructure are deployed, the need for working with AHJs is likely to grow significantly. The project is not currently poised to handle a significant increase in working directly with AHJs.
- Interaction with, and contribution to, the Pacific Northwest National Laboratory's Hydrogen Safety Panel, if any, is not obvious or missing.
- Project weaknesses include (1) lack of control of the inputs needed to complete the work, resulting in large delays, (2) inability to come up with alternative approaches to speed progress, and (3) looking at separation distances as the objective rather than looking at alternative methods that could be more effective and used more broadly (e.g., in situations in which even reduced distances might be impossible).
- The project should conduct field data analysis and validation testing to support science-based computation.
- A more scientific approach to understanding what is needed in the future efforts should be projected.

Recommendations for additions/deletions to project scope:

- Regarding the tunnel modeling, it is recommended that the project team check the assumptions regarding the heat load of the non-premixed hydrogen–air flame. Available data from Powertech (horizontal) jet flames and Health and Safety Laboratory vertical venting flares analysis suggest that the higher temperatures (around 1900°C, as shown on slide 26 at 5.2 meters height) are contained within much shorter distances (less than 3 meters). It is also known from hydrogen tank bonfire tests that high-pressure hydrogen vented via a thermally activated pressure relief device may go through the flame closely positioned to the release orifice without being ignited. Hence, delayed ignition in a tunnel scenario with an overturned FCEV should be considered as a credible event.
- The project may broaden the scope beyond separation distance as the end goal and consider approaches where only nominal separation distances are needed. For proposed future work, the PB&A that has not yet been completed should be included.
- The main area of improvement is simply to accelerate the effort and engagement with stakeholders. This will become more feasible as the tools and models are completed and validated.
- The project should review and report stakeholder implementation plans resulting from this effort—and consider what the stakeholders think of this effort and how is it being used.
- The project could review gaseous release in four-sided, open-top equipment "corrals," as seen in several California installations.

Project #SCS-026: Compatibility of Polymeric Materials Used in the Hydrogen Infrastructure

Kevin Simmons; Pacific Northwest National Laboratory



Brief Summary of Project:

The project objective is to fill a critical knowledge gap in polymer performance in hydrogen environments. Investigators are gathering and assessing stakeholder input about the challenges, materials, and conditions of interest for hydrogen compatibility, to develop standard test protocols for evaluating polymer compatibility with high-pressure hydrogen, characterize polymers, and to develop and implement an approach for disseminating the information.

Question 1: Approach to performing the work

This project was rated **3.6** for its approach.

- The approach of this project is well focused and excellent. It does not score as outstanding since the engagements with stakeholders are not so clear, which, according to the presentation, seem to be mainly within the U.S. Department of Energy (DOE) and its national laboratories, except for Ford.
- The project consulted with all available stakeholders at the start. A failure mode and effects analysis (FMEA) approach has been used to identify priorities in terms of materials and operative conditions to be studied first; this is an overall strength of the project. There is also evidence of regular checks with stakeholders and regular striving toward broadening of the stakeholder group. However, the prioritization progress is, in some cases, not very evident. The new investigations reported this year on the combined effect of purge gases and hydrogen were not planned in 2016. This raised the question of whether this new line of research was requested by stakeholders.
- The approach is well-thought-out and realistic. The limitation to high pressure could be reconsidered. Storage will be at high pressure; usage will be at 150 psi or less. It does not matter if the incident is in the high-pressure or low-pressure loop; an incident is an incident.
- The work is building up capabilities to test under a full range of actual-use conditions.
- The project's approach is to develop test methods for the assessment of tribological properties and wear of polymer materials in the presence of hydrogen. Friction and wear is being investigated at Pacific Northwest National Laboratory (PNNL), and aging by pressure cycling is being investigated at Sandia National Laboratories (SNL). It is not clear what the purpose of collecting neutron scattering data at Oak Ridge National Laboratory (ORNL) is, given that no reference is made to the existing literature data of hydrogen-induced damage of polymeric materials. In other words, the research should identify what type of polymer degradation/damage in hydrogen, neutron scattering data are needed to help us understand or quantify the degradation better. Slide 25 does not clarify the issue. The project also aims at disseminating the relevant information and testing methodologies to be developed. No information was given in this regard.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.4** for its accomplishments and progress.

- The start is awesome. The information to date is value-added. Regarding the Viton A (vinylidene fluoride and hexafluoropropylene), the researchers should clarify whether there is literature of testing on other gasses and whether the results are similar. http://rainierrubber.com/wp-content/uploads/2014/01/Viton-Selection-Guide.pdf
- The project has made significant progress to date: it has developed new test procedures and equipment capabilities and produced new information critical to hydrogen fuel applications.
- Accomplishments on the selected tasks in this project are excellent, particularly the outstanding FMEA work to identify failure modes, the test method development, and the post-test data analysis/assessments. This category does not score as outstanding because this project gives limited explanation, either science-based or practical-based, to some parameters/selections that are used in FMEA, such as the pressure range defined in FMEA (i.e., why the maximum value is set to 875 bar, which is only 1.25 times higher than currently specified nominal working pressures in the global technical regulations for hydrogen tank on-board vehicles), or in tests, such as whether there is a particular reason argon (rather than helium) is selected for in situ high-pressure hydrogen testing of friction and wear.
- The project is on track and will eventually fill an important knowledge gap. Basic materials behavior differences have been demonstrated and quantified. At this moment of project development, however, it is not clear from the presentation which of the variations in behavior effects will really play a role in safety or lifetime performance of the up-scaled system.
- Slide 12 reports that PNNL is working on developing a methodology to test friction and wear of polymer–metal interfaces in hydrogen. In fact, measurements of the coefficient of friction and wear are reported on slide 13 for three different materials in 4,000 psi hydrogen. The results indicate an increase of the coefficient of friction in hydrogen in comparison to that in air. However, no comparison of the results with results in the open literature, either qualitative or quantitative, is given. Indeed, such comparisons with open literature results are very important for the NPRL methodology to be validated. Lastly, with regard to the pressure effects reported on slide 14, there is no information regarding the interaction of hydrogen with the fillers that could help us understand the nature of the results. The approach on high-pressure purge testing at SNL as described in slides 17 and 18 is physically sound, and the accomplishment reported on slide 20 on the reduced sensitivity of thermoplastic polymers in comparison to ethylene propylene diene monomer (EPDM) rubbers shows that the work at SNL holds promise for the future. Lastly, the testing system on pressure cycling to be built at SNL is also a sound approach toward the project's objectives.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.3** for its collaboration and coordination.

- The stakeholders are engaged and are collaborating well across multiple laboratories and organizations.
- There is a working collaboration within the project partners, and engagement with the infrastructure industry has started, upon requests from last year's comments. An interaction with other entities and projects is not evident (but the question is whether it is critical at this phase of the project). The international dimension is not very visible.
- The collaborations to date are appropriate. The project should consider how to supply this information to the stakeholders. Dr. Shin Nishimura of Kyushu University is doing similar research. Collaboration with Kyushu might be appropriate.
- The collaborations are excellent among DOE and its national laboratories. However, the engagements with other stakeholders (e.g., vehicle manufacturers [heavily involved in the hydrogen and fuel cell vehicles, hydrogen tank industry, fuel storage, or fueling industry) are unclear in this presentation, even though it says that this project has reached out to approximately 40 stakeholders.
- It is not clear how PNNL and SNL are collaborating on the project. It does not seem that the two laboratories are working on overlapping themes. Collaborative work between ORNL and SNL or PNNL and SNL was not explained during the presentation.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.8** for its relevance/potential impact.

- The project is extremely relevant to the DOE goals. Behavior of polymers and friction and wear in hydrogen are subjects that need to be understood, and relevant quantitative assessment methodologies need to be developed.
- This project achieves important progress toward new knowledge every year. Because of the time and resources available, the project will not be able to fill all the knowledge gaps in this sub-technology. A future strategy and further investigations should be considered as part of the final output of the project.
- This project is extremely relevant to the hydrogen and fuel cell technology deployment and applications. The tasks this project focuses on are critical, and these identified applications are among the key features for hydrogen safety.
- Understanding of the long-term impact of hydrogen (and purge gases) on polymers is crucial to safe use of hydrogen.
- On a scale of 1 to 10, this is a 12.

Question 5: Proposed future work

This project was rated **3.4** for its proposed future work.

- The proposed future work is well-thought-out.
- The proposed future work plan is excellent. However, the work to identify other critical areas of need for polymer/hydrogen testing that is planned in fiscal year 2018 gives some uncertainty about its purpose and goal. If the work will only explore the possibility (the areas that may be critical) and therefore provide findings as reference, the project should consider focusing on identifying more critical areas. The difference is that the latter task may require more time; one year or less may not be enough.
- Slide 30 describes a large number of future directions but nowhere lists any approach or task aiming at validating the results and the relevant testing capabilities.
- The project should consider expanding capabilities to fill gaps.

Project strengths:

- The participants have excellent expertise for this project and are extremely knowledgeable in both theory and experiment (material science and laboratory testing). The collaborations among national laboratories provide impressive and solid work results.
- This project will fill an important gap and tackles in parallel behavior of many different materials under various representative operative conditions.
- This work is able to provide high levels of technical expertise lacked by industry players.
- Project strengths include the topic, collaborations, and expertise of the laboratories.
- The project benefits from SNL's long experience with testing in hydrogen.

Project weaknesses:

- The project should increase outreach. For some reason, the national laboratories like to work with CSA Group. CSA Group writes product safety standards; it does not design codes. Design codes, which are often adopted by the authorities having jurisdiction as regulations that would include and apply this data, are published by ASME and SAE International (SAE) (and possibly National Fire Protection Association [NFPA] 497 in the future). NASA may have some interesting data also.
- The project should focus on characterization of polymers, not screening of polymers as acceptable or unacceptable for use. The key point is understanding hydrogen impact.

- This project should strengthen its collaborations with other stakeholders rather than mainly just national laboratories. This project should give more clear explanations for the parameters/test conditions set for testing or materials selected for testing.
- So far, the project is qualitative. Results have not been compared with corresponding results in the open literature. In addition, the project does not have even a single paper published in a referred journal.

Recommendations for additions/deletions to project scope:

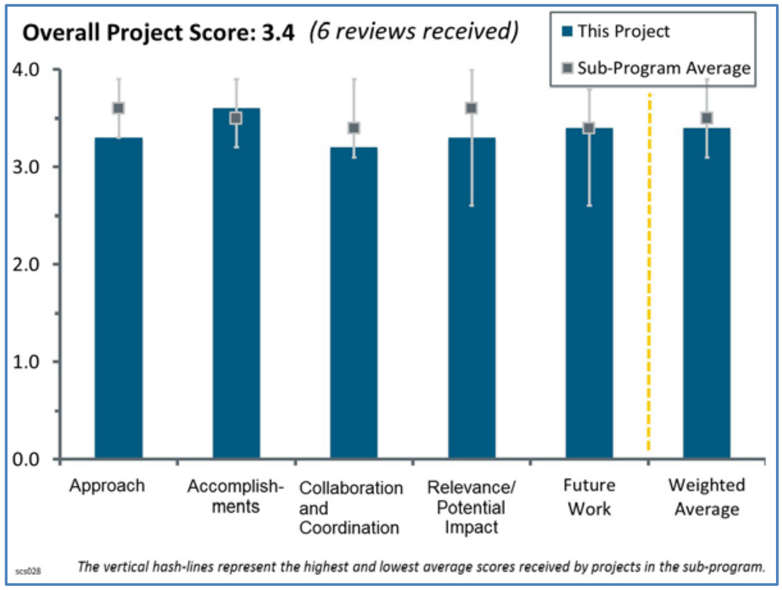
- Engineers will go to one of three sources for this information: ASME, SAE, and the Parker O-Ring Handbook. Publishing the data through all three venues would be of value.
- It is recommended that the project increase attention on identifying other critical areas or providing assessments/discussions of why this project primarily focuses on the effects of friction and wear. Collaborations should be improved with the research institutions in relevant areas, other stakeholders such as the industry related to high-pressure gas storage, and vehicle manufacturers heavily involved in hydrogen and fuel cell vehicles.
- So far the focus is on “normal” operative conditions, while there is also a strong need of studying beyond-operation behavior, for example at temperatures above 85°C, approaching the critical temperature of high-density polyethylene. Perhaps this will be not possible in the present project, but this aspect should not be underestimated.
- More quantitative results are needed. Testing devices and testing protocols need to be validated. There are no plans for such validation.

Project #SCS-028: Diode Laser Sensor for Contaminants in Hydrogen Fuel

Mark Paige; Southwest Sciences

Brief Summary of Project:

This project will construct and test a portable diode laser hydrogen contaminant detector for use in the laboratory and fuel stations. The detector will perform continuous measurements and provide real-time information, improving fueling station safety. The instrument will be capable of measuring several contaminants, including carbon monoxide, ammonia, hydrogen sulfide, water vapor, carbon dioxide, formaldehyde, formic acid, hydrogen chloride, and methane. As lack of technical data can hinder standards development, information generated by the detector could be used to enhance and revise various hydrogen standards.



Question 1: Approach to performing the work

This project was rated **3.3** for its approach.

- This appears to be a great approach—from the optics and sensitivity, to the overall size and ease of use (pushbutton).
- The approach outlined addresses the barriers of detecting contaminants in the fuel. The project is well laid out in the slides and was presented effectively.
- The project's modular approach, allowing customization, is welcome. The intrinsic safety of optical lasers will help to reduce risk and cost. One challenge may be realizing practical production cost in low quantities.
- The project team "knows their business"; the development approach is a tried and proven method.
- The approach is well planned and well presented.
- The project's approach does not allow for detecting all of the target contaminants at the SAE International (SAE) levels; however, the novel multi-gas sensing approach may yield interesting results. The technology used may not be cost-effective for wide-scale adoption, particularly if detection of hydrogen sulfide (H_2S) and formaldehyde is required.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.6** for its accomplishments and progress.

- The project seems almost perfect: the fact that the sensitivity exceeds the SAE J2719 requirements, that it is modular, and that it is safe (in terms of what the hydrogen is exposed to).
- Significant progress was made toward the DOE goals of safety and developing technical data in this project. The real-time data of contaminants in the fuel of various known chemicals and compounds will help ensure that fuel quality is maintained.
- Progress is excellent; when successful, this project is spot-on in meeting the DOE goals. The only place where the fundamental technology falls short is in the detection of sulfur, which does not really detract from the usefulness of this technology. If sulfur were to get into the fuel, it will most likely well exceed the concentration sensitivity of the detector.

- Accomplishments and progress are well defined and demonstrate consistency with the industry challenge to real-time measurement of contaminant species to a given standard (SAE J2719).
- This project is in early stages but is already showing some promise as a future fuel-quality-monitoring device. The technology used seems to be more appropriate for laboratory use than for use in the field.
- The project provides great data on COx sensitivity and repeatability. Although water is already proven, presentation of some water data (e.g., interference) for those who are unfamiliar would improve the report. The H_2S results are not impressive for fuel cell applications.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.2** for its collaboration and coordination.

- The project has established a collaboration team that covers topical areas needed to improve chances of success. The team is very appropriate.
- This project listed many collaborations with interested stakeholders. Interest from the Industry (Air Products and Measurement Laboratory) is a good sign. There is reference to the SAE J2719 standard; however, it was not clear whether there is any collaboration with SAE or oversight to the SAE work.
- Collaboration at this stage of the project is appropriately limited to DOE and the national laboratories, as well as the DOE Tech Team. At some point, further coordination with industry may be warranted.
- While this may not be "market-ready," it needs to be vetted/circulated among station developers so that they understand the kind of technology that is coming. There is a good deal of talk about in-line contaminant detectors, and it seems that it is very possible, but at a cost. People need to be ready for it.
- While it is still early in project, the opportunity for expanding collaborations with industrial gas companies, as well as several stations, may present itself.
- The team needs wider industry collaboration.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.3** for its relevance/potential impact.

- This is an imperative addition to commercial hydrogen fueling and customer experience; it could be revolutionary for fueling stations.
- The potential impact for this as a viable contaminant sensor is much higher than many of the proposed sensors.
- Fuel quality monitoring is critically important to ensuring that the fuel quality delivered to the vehicle meets the current standards.
- The project aligns well and should continue to be supported, as funding allows.
- H_2S is a challenge for fuel cell electric vehicles.
- The project is in early stages of hardware development. It is not yet clear whether the hardware will be able to meet the performance requirements in a cost-effective manner.

Question 5: Proposed future work

This project was rated **3.4** for its proposed future work.

- Southwest Sciences has extensive experience with weatherization of sensors used in outdoor, and even outer space, applications. Durability is another imperative piece to the value of this product and to the industry.
- The future work is appropriate.
- The slides and presentation outlined the remaining work clearly and concisely. It was not clear whether commercialization was feasible at a reasonable price point, even after market expansion.
- The team needs to recognize the significant challenge to the actual gas conditions. Temperatures vary from ambient (>30°C) to nearly -40°C. If temperature will affect the results, the team should clearly demonstrate

this in the laboratory prior to field tests. Overall, the project fails to articulate the specific technical hurdles that it faces and its plan to overcome those hurdles. Instead, it chooses to focus on past accomplishments, which suggests a lack of technical rigor or failure to scope the technical challenge of the application.
- It is important to be able to upgrade the system for outdoor use and add capability for other contaminants. At this stage, there is no discussion of cost-effectiveness.

Project strengths:

- Project strengths are many, including the size, ease of use, and modular aspect of the product; the stability of the electronics is a big plus. The knowledge and experience of the developer is impressive, as is the fact that it is near-commercial.
- Clear progress was made toward completion of the instrument. The remaining effort was well defined, and the responses to questions during the presentation were clear and concise. Partnering with the National Renewable Energy Laboratory and industry (i.e., Air Products) will provide useful information to address the remaining challenges. The size of the instrument (i.e., shoe box) is desirable for implementing in the fuel stations.
- This project is the only viable technical strategy to contaminant detection in the DOE Safety, Codes and Standards sub-program portfolio.
- This technology has very positive aspects for low risk, low maintenance, and customization.
- Project execution is admirable; the development of this sensor is impressive.
- The modular design of the system and ability to detect various contaminants are strengths.

Project weaknesses:

- The biggest down side is the cost; "you get what you pay for" may ring true in this case. This seems like a fantastic product, and it may be very well worth the investment if it cuts down on fuel-quality-related troubleshooting and maintenance. There is a need for this technology now to help improve customer experience, with retail stations coming on line.
- Although measurement accuracy is paramount, the comment that "if there's a cheaper method, you'll do it" was concerning. Consideration should be given to finding cost-effective solutions that industry can support. It was not clear how the sensor instrument will respond to contaminants—shut down, continue to fuel, etc. False positives of contaminants could have unintended consequences for stations and drivers.
- The detectability for sulfur does not meet the published standard. However, if sulfur is introduced into the fuel, it will most likely be introduced at levels that this technology will detect. So, while it is a weakness of this technology, it should not affect the usefulness of this detector technology.
- The project team did not demonstrate that it has an accurate scope of the technical challenge. Also, the team inaccurately identified that contaminants are related to safety. Contaminants are related to fuel cell performance, specifically, cost reduction of platinum group catalysts in fuel cells, thus fuel quality standards.
- Weaknesses include challenges on production cost, H_2S, and ammonia. The project would benefit from industrial collaboration.
- It is early in the project development. It may be some time before there is a sensor suitable for use at a hydrogen fueling station.

Recommendations for additions/deletions to project scope:

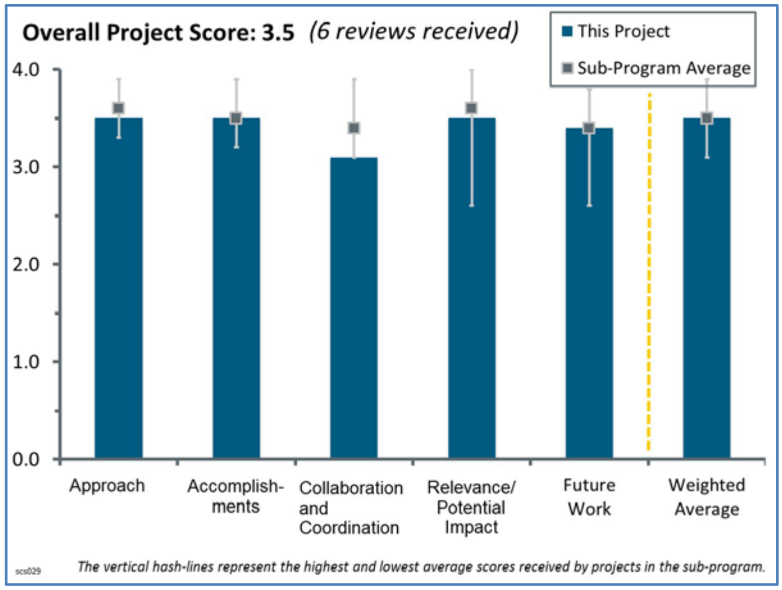
- The project should consider additional discussion regarding expanding multi-gas capabilities, for example, if the technology will allow the sensor to distinguish a hydrogen leak from the hydrogen in a passing diesel truck, if it will help reduce cost by increasing the market potential, and potential ways this expands the usefulness of the equipment.
  - Program Response: It should be clarified that the technology being developed is for hydrogen contaminant detection in the fuel stream and is not a gas leak sensor; however, the reviewer's recommendation to consider expanding the potential usefulness of the equipment will be taken into consideration.

- As the sensor will ultimately be used to measure contaminants in fuel for vehicles, the potential to involve vehicle manufacturers should be considered. The ability to detect poor fuel quality prior to causing harm to the vehicle is extremely attractive. However, any fault in the sensor that causes a shutdown response can harm the continued deployment. The project should expand on how this will be addressed in future work.

Project #SCS-029: Electrochemical Hydrogen Contaminant Detection

Trent Molter; Sustainable Innovations

Brief Summary of Project:



New hydrogen technologies and standards are driving the need for a cost-effective and reliable instrument that can sample hydrogen near the nozzle of a delivery pump, then certify acceptability or provide a signal to shut off the pump. The objective of this project is to define, design, fabricate, and verify operation of a hydrogen contaminant detector for use as a go/no-go sensor near the nozzle of a high-pressure hydrogen storage and dispensing system. Project efforts focus on (1) evaluating sensors with a larger list of contaminants, (2) identifying and developing materials for improved selectivity and response times; and (3) developing a field prototype.

Question 1: Approach to performing the work

This project was rated **3.5** for its approach.

- This project is early in its development. The approach—using a similar process to sense contaminants that poison the fuel cell to be protected—was good. It would be good to see a conscious effort to get the sensing element with the fastest time response possible. If the sensor time scale is on the order of one minute out of a four- to five-minute fuel tank fill time, then protecting the current fill may not be possible. However, catching a fueling contaminant fault for the subsequent fill is of value. Moreover, if this can be constructed to integrate the signal over time, and it should trigger with a fault signal that has been added over time (over several fills), then any one fill is probably acceptable. However, the integration of several fill triggers and the fills can be terminated without causing any one system to fail.
- The project is well structured, with an early and strong emphasis on real-world application of the device in hydrogen dispensers. It is suggested that the project establish more specific targets for sensor testing in highly dynamic temperature and pressure conditions.
- The problem definition is well characterized (e.g., reliability, pressure, temperature, operating range, location, and cost), and the project steps (define, design, fabricate, and verify operation to use as go/no-go) are clear and allow for efficient tracking of progress. It is a good approach: focusing on robust/simple hardware design elements (e.g., thermocouple) with innovative algorithms to allow for lower cost and better reliability/durability.
- The project slides and Annual Merit Review presentation were organized effectively. The approach was well defined and clearly indicated the prior and current efforts and results. The use of a timeline to show status is appreciated.
- Define, design, fabricate, and verify is a solid experimental development approach.
- The approach of using a thermocouple company and design is very resourceful.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.5** for its accomplishments and progress.

- The project has worked through a number of potential materials/configurations and is continuing to work on further refinements and other promising materials. Therefore, the researchers are potentially developing a good list of things that will not work and perhaps can focus in on one that will work. From this, the project has effectively narrowed the concept and design space to the "thermocouple" configuration. The focus on fast response time is very important, as well as acknowledging the importance of characterizing the performance of candidate sensor technologies at high pressure.
- The fact that this can be put into a pressurized stream seems to be advantageous in terms of placement at the station (i.e., not having to pull off a "sample"); it can be actual "real-time" sensing. The current ionomer coating configuration that is being optimized is promising, and the use of components that are already commercially available is also a plus. If this survives the high-pressure testing, it could be a real breakthrough.
- The presenter reviewed the accomplishments and progress of the sensor, and he noted an immediate response of the sensor was achieved, but with a degradation in the performance and durability. The work done and presented to address this issue was the "good news in disguise." The thought process of working on this project was evident from both the slides and presentation.
- The project has excellent progress and minimal spending to date. There has been a slight delay with electrolyte selection, although the lost time is expected to be recovered.
- An electrochemical sensor capable of detecting CO at 20 ppm is an excellent start. High-pressure detecting capability is equally important.
- This is a new project that is making the expected progress. When successful, this technology will prove to be very powerful in monitoring fuel quality under conditions of the fill, which will be a nice achievement.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.1** for its collaboration and coordination.

- The roles of the collaborators are described in the project plan, but their contributions to the specific deliverables could be described more clearly in the Accomplishments part of the presentation. The involvement of Duro-Sense Corporation as a commercial company focused on getting the results out of the laboratory and into commercial use was good.
- The team has a well-coordinated set of partners. It makes sense to start expanding collaborations internationally.
- The collaboration team is appropriate and powerful for this project.
- The principal investigator (PI) indicates limited feedback/agreement with station developers/industry on secondary contaminants. The project has had a strong emphasis on CO to date. It is recommended that the team have more formal communication with automakers, on-site production station operators, and industry organizations (e.g., the California Fuel Cell Partnership and the Fuel Cell & Hydrogen Energy Association). There is widespread interest in this subject, and the project team is likely to get helpful recommendations if the right individuals in industry are contacted.
- The list of collaborators is limited, although they seem to be key, so this may not be an issue. The collaborations could possibly expand as the project progresses.
- There were a few collaborators listed, but it was not clear from the slides or the presentation how the collaboration is being organized/coordinated.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.5** for its relevance/potential impact.

- The project is strongly aligned with the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan and represents a practical approach to much-needed in situ contaminant detection at low cost. The project addresses a barrier to widespread fuel cell electric vehicle deployment by offering automakers confidence that critical fuel quality parameters are maintained at sites with on-site produced hydrogen.
- The project is focused on a key technical need for selling hydrogen fuel. It is also well targeted to a specific part of the supply chain (i.e., the dispenser). Therefore, it is encouraging that the scope is well bounded and that the project is focused on a direct commercial need.
- As hydrogen for vehicle fueling increases, the need for verification of fuel quality will continue to grow. This project is on the way to finding a reliable cost-effective sensor that can be placed on the dispenser and detect contaminants at low levels at various pressures and temperatures. This project should continue to be funded.
- This project is cost-effective, and near-the-nozzle contaminant detection is critical to improving vehicle manufacturers' and users' confidence in fuel quality and control at the hydrogen refueling station.
- Real-time, in-line contaminant detection is necessary, important, and needed in retail hydrogen fueling for the success of fuel cell vehicles of all types.
- This technology is very relevant and critically needed to advance the deployment of polymer electrolyte membrane fuel cell technologies.

Question 5: Proposed future work

This project was rated **3.4** for its proposed future work.

- The proposed future work is clearly defined in the slides, and the work effort to date has shown good progress. Prioritizing the remaining work with the sensor options and optimizing the capabilities will be important.
- The future work is excellent for this young project.
- The project's future work is well defined and well articulated.
- The needed future work is well described at a high level, and the PI described the needs in some detail in the talk. However, it would be good to see more specificity of the plans for addressing these needs within the framework of the ~one year remaining in this project. For example, the detection algorithms are a critical part of this, but it is unclear what work needs to be done there in the next year. It is also unclear what specific testing needs to be done to get at least an initial indication of the applicability of the technology to other contaminants.
- The speaker said that "near-term market opportunity is questionable; long-term is more promising" and cited the petrochemical industry. This comment is confusing. It is unclear if that is because of the extent of the future work. This, and projects like it, should be aimed at as near-term as possible. This technology is key for retail hydrogen fueling and for potentially lowering costs of operation for hydrogen fuel station owners/operators. Current retail stations in California are required to have the SAE International (SAE) J2719 standard compliance fuel quality testing done four times per year, which is costly. The investment in one or two of these sensors, even at ≥$1,000 apiece, has the potential to save a station operator/owner money in the long run.
- Recent developments in the project highlight the need for a focus on software algorithms to manage sensor false detection during heavy transient conditions typical of hydrogen fueling (e.g., temperature change). The project does consider this barrier; however, more goals and targets should be defined to address this barrier to deployment, if achievable within the project budget.

Project strengths:

- This technology, if successful, will be the first technology of which the reviewer is aware that can actually measure contaminants in situ. The sensitivity appears to be adequate, and the response time (sensing element only) appears to be adequate (or can be made to be adequate). This is a nice project.
- The following are project strengths: inexpensive industry-standard installation, a logical approach using fuel cell catalyst materials as sensing elements, robust thermocouple design, multiple sensing elements with multiple contaminant detection algorithms, acceptable cost targets, and a design that addresses high-pressure design requirements.
- The diligence put into alternative options to address project obstacles is appreciated. If the low-cost strategy can be maintained for the duration, this is great for the industry. The project should keep up the focus on cost, while continuing to develop a sensor that meets the contaminant detection criteria. The presentation slides were concise and clear and very well organized.
- The team has a solid experimental development approach and a well-coordinated, collaborative team of partners with high-pressure capability.
- The project has very good progress to date with the configuration of the sensor, the use of commercially available components, and the pressure testing.
- The project is well scoped, working in a critical area, and collaboration is well positioned to transfer the technology to a commercial application.

Project weaknesses:

- No significant weaknesses were noted. The team is trying to solve a challenging problem.
- No real weaknesses were identified.
- It seemed that this sensor project has synergy with the fuel quality assurance research and development and impurity testing project being worked on at the Los Alamos National Laboratory (LANL) (Tommy Rockward). The acknowledgement slide shows LANL but not Tommy. It was not clear whether there is any collaboration with LANL that could help push both projects forward. Regarding collaboration, the frequency and format were not addressed. The schedule shows a considerable amount of independent activity. Unfortunately, reviewer question time expired before reviewers could get clarity about how the collaboration is being managed. Slide 3 incorrectly refers to SAE J7219; it should be SAE J2719.
- Project weaknesses include the following:
    - The project algorithms to evaluate the derivative of sensor signals may become complex.
    - The project does not currently test the full range of the SAE J2601-defined fueling conditions.
    - The project does not clearly address operability or troubleshooting of false detection (this must be easy to use by unskilled operators).
    - The project does not clearly define goals and testing targets for other contaminants beyond CO (recognizing that CO is a priority).
- CO detection of 20 ppm is a good start, but there is still a long way to go. The team also needs to reduce detection time.
- If possible, the project should focus on more near-term application.

Recommendations for additions/deletions to project scope:

- The slides and presentation both indicated a go/no-go sensor. If a contaminant is detected, it is unclear whether there will be unintended consequences or whether the station will stop fueling and leave a vehicle stranded. Consideration is needed to address how the sensor will be incorporated into the SAE standard, as well as other affected codes and standards. It was mentioned that the sensor “takes a minute or so” to detect contamination. The fueling could be complete before detection of poor quality fuel is known. Defueling bad quality fuel from the tank is not addressed in current codes or standards. Temperature and/or pressure deviations could cause false alarms and need to be identified differently from contaminant deviations. This will be a big challenge but should be considered as part of a revised scope.
- The project is well scoped in terms of focusing on a high-reliability, fast, and low-cost CO detector. However, since future work includes a look at other contaminants, it would be helpful to include a

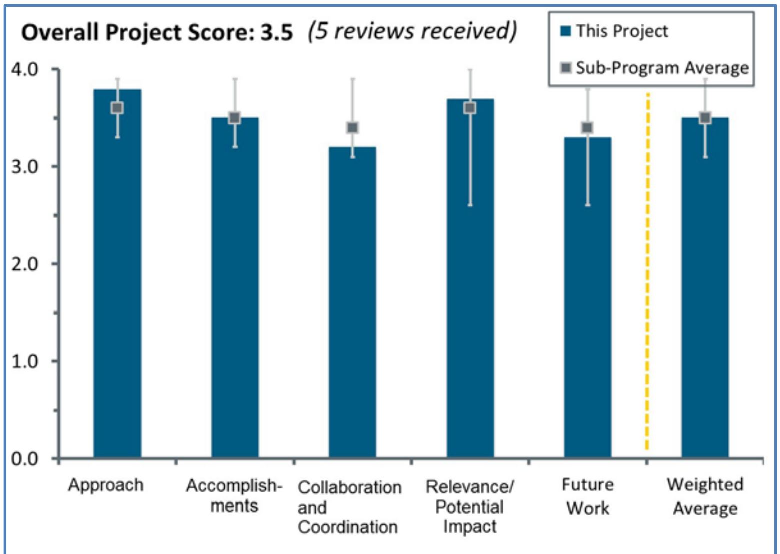
requirements framework for what contaminants need to be detected, at what levels, and how fast. That will, however, make the problem seem bigger and scarier.

- It is recommended that the project add targets to address false detection, especially under the harsh conditions of rapid temperature and pressure changes.
- The team should expand collaborations internationally.

Project #SCS-030: Advancing Fuel Cell Electric Vehicles in San Francisco and Beyond

Jessie Denver; City and County of San Francisco

Brief Summary of Project:



The vertical hash-lines represent the highest and lowest average scores received by projects in the sub-program.

One barrier to increased use of fuel cell electric vehicles (FCEVs) is the complexity of permitting and inspection processes among multiple jurisdictions. This project aims to address this challenge by updating and harmonizing best practices in permitting and inspection of hydrogen fueling stations among the San Francisco Bay area authorities having jurisdiction (AHJs). Additional project activities include (1) delivering hydrogen safety and best practice education to elected officials and planning, building inspection, and public safety officials in the area; (2) increasing community awareness of the availability and value of hydrogen and FCEVs; and (3) driving market demand for FCEVs through an established group procurement program.

Question 1: Approach to performing the work

This project was rated **3.8** for its approach.

- The approach is excellent, driving demand through better public awareness using education and outreach. This project is very well positioned in the project portfolio because it is, in essence, trying to apply all of the technical results of the other projects to enhance awareness and comfort of both AHJs and the public (a unique project focus). Also, the approach is to leverage a process previously developed; the presenter mentioned that it is based on a permit streamlining project previously developed/used for residential solar.
- Projects that provide outreach, such as this one, are needed to accelerate the deployment of hydrogen and fuel cell technologies. California and San Francisco both have a commitment to the deployment of zero-emissions vehicles (which includes greenhouse gas emissions). However, local jurisdictions are largely not familiar with or have misconceptions about hydrogen technologies. The outreach activities outlined in this project are well thought out to be effective in reaching the relevant AHJs and marketing entities to help accelerate the deployment.
- This project directly tackles the challenges faced in rolling out FCEVs and permitting hydrogen fueling stations. Interviewing AHJs who already have stations should yield valuable information to accelerate future permitting. Future reports on the lessons learned will be interesting. The planned community outreach does not mention local press; the team should consider inviting selected newspaper reporters to the outreach events to ensure the information reaches beyond those who participate directly in events or partner organizations.
- The approach is excellent, using partners to amplify education and awareness. The use of SunShare to support a group purchase is of high value.
- The approach for this project demonstrates the immediate benefit to the deployment of vehicles.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.5** for its accomplishments and progress.

- The project was launched just a few months ago; the accomplishments so far are mainly in organizing the project and setting up scheduled events and milestones. Next year, reviewers will see the results of the planned activities. The addition of FCEVs to the SunShare group procurement program is a unique approach that has already generated good results. Likewise, the commitment from Shell to use 100% renewable electric power at California Energy Commission-funded stations is important.
- The project is moving forward as planned, with progress to secure partners and provide education through workshops and special events.
- The project seems very effective for the target region, though the project team should consider including at least one key national conference within the outreach and education training schedule for presentation of results.
- This is a new project with good progress to date.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.2** for its collaboration and coordination.

- There is excellent, relevant coordination with both funded and unfunded collaborations. Upon completion of the project, the team should ensure results are available to regions that will follow suit. Also, the team should consider some level of collaboration with a national entity that can help ensure wide-scale dissemination and uptake of results. Publication of results in national newsletters that reach beyond the electric vehicle and California audiences could provide significant value to those who will be working toward similar goals in other regions. National organizations with similar goals include the Fuel Cell and Hydrogen Energy Association (FCHEA) and H_2USA.
- This project provides for collaboration with a unique group of organizations and so far seems to have been effective in leveraging them to achieve results in both consumer awareness and improved permitting. Having a large group of organizations that can all point to common permitting resources and training, for example, should be very helpful.
- The collaborators for this project are both funded and non-funded entities. The collection of collaborators is generally very good. However, this project should consider embracing more national-level collaborators, for example the regulation, codes and standards, and outreach activities of FCHEA, H_2USA, and possibly the international community of the International Association for Hydrogen Safety (HySafe) and the International Organization for Standardization (ISO).
- All of the project partnerships are good, and the link with the Bay Area Business Council on Climate Change (BC3) and the SunShare program. Some direct linkage with private businesses would be of additional value.
- This project should have higher visibility and more interaction with technical experts and industry participants.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.7** for its relevance/potential impact.

- Creating comfort with the technology on the permitting side and awareness on the public/customer side are critical to transitioning FCEVs and hydrogen fuel to commercial businesses where there is legitimate demand. This project is unique in that it works to create that "pull" through targeted outreach rather than solutions to specific technical problems.

- Education, awareness, and best practices will be key to market awareness and market demand to support fuel cell technologies. This topic has often been underestimated and should be reconsidered by DOE as a required element for other projects.
- The project has the potential to have a significant positive impact in the target region. Further consideration of methods to ensure information-sharing with other regions throughout the United States is encouraged to increase the potential impact nationally. The project should not target just the AHJs but should include other organizations in other regions that will be doing what this project is doing.
- This type of outreach is critically important to accelerating the deployment of FCEV technologies. Ignorance and misconceptions outside the hydrogen community are at a sufficient level that outreach from the hydrogen community to the AHJs, financial community, and general public is needed for deployment.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- Future work is consistent with the work plan and project management.
- Proposed future work is appropriate, but the collaborators should broaden to embrace the work of others in the community (H_2USA, FCHEA, HySafe, etc.).
- The project team should consider gearing at least one of the 30 planned workshops to educate representatives from other regions, specifically focused to assist participants who will be working on similar projects in other regions throughout the country. Nominations or recommendations for invited participants should be carefully considered.
- Getting to the go/no-go on the group buy program is the most innovative goal in the project and has potential for significant market impact. Some consideration should be given to how to share this work with other cities/other stakeholders to get the same sort of facilitation in other places (e.g., New York City and Connecticut)—this is one for Pete and DOE.
- Future work must include information regarding larger stations, specifically the challenge of permitting liquid hydrogen in urban areas such as the San Francisco Bay Area. This team must develop a collaboration with researchers and industry participants that are pursuing liquid hydrogen supply chains. Contact with national laboratories, such as Sandia National Laboratories in Livermore, California, will help facilitate this.

Project strengths:

- The project has a clear focus on educating AHJs and local communities in the San Francisco Bay Area, where FCEVs and hydrogen infrastructure are rolling out, and a focused set of collaborators with the potential to be very effective locally.
- Project strengths include the project partners, linkage with the SunShare program, and enthusiastic management.
- This project is just getting started but in a short period of time has embraced the talent of many relevant entities in the Bay Area (e.g., SunShare and BC3).
- The project’s strengths are in its unique leveraging of consumer awareness/demand and the potential to expand that process to other locations.
- This project focuses on a specific area of need that has relevance to urban areas nationwide.

Project weaknesses:

- There are no perceived weaknesses; this type of market support should be tied to other DOE initiatives to maximize potential for project success.
- No significant weaknesses were noted, though there appears to be a risk to future funding, given the stated priorities for DOE spending in fiscal year 2018.
- The project will clearly be valuable in the San Francisco Bay Area. Although permitting requirements are by no means consistent throughout the country, this project also has the potential to be very valuable to regions that may follow San Francisco in rolling out FCEVs and hydrogen infrastructure. There are

currently no plans to specifically share learnings with other national stakeholders to facilitate broader national relevance of the project, beyond California.
- The project would benefit from more industry collaboration, better visibility, and stronger technical connection to increase the value of outreach and education efforts.
- The team should consider broadening the collaborations to include other entities that have a long history in hydrogen behavior and safety (e.g., the Hydrogen Safety Panel, H_2USA, FCHEA, and ISO).

Recommendations for additions/deletions to project scope:

- The project is well scoped. The team should keep in mind the value of creating a template that can be used in other cities while reporting on the success of this project.
- The project team should add scope to share learnings with other national stakeholders, particularly entities with a similar role in the Northeast states, or more broadly outside of California.
- Replicating this educational program in other areas with other local organizations should be considered.

2017 – Market Transformation
Summary of Annual Merit Review of the Market Transformation Sub-Program

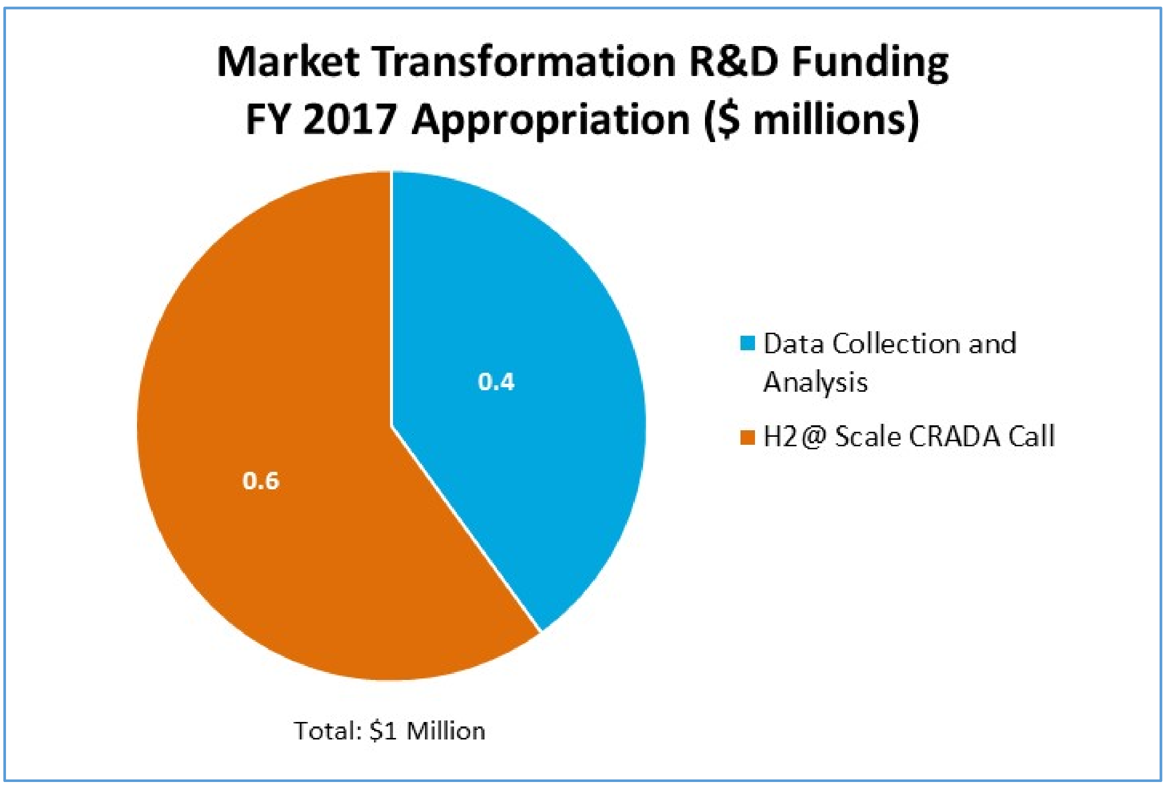
Summary of Reviewer Comments on the Market Transformation Sub-Program:

The purpose of the Market Transformation sub-program is to spur market introduction by demonstrating pre-commercial technologies in real-world applications. By doing so, this sub-program helps to identify and overcome market barriers to reduce the life-cycle costs of fuel cell power through technical and non-technical solutions. Six projects were reviewed this year, and these projects are highly leveraged, with more than half of the funds provided by the U.S. Department of Energy's (DOE's) partners. This substantial commitment of external resources shows the high level of interest in exploring applications and markets in which the hydrogen and fuel cell industry can expand, and the technologies can play a valuable role.

Reviewers generally shared positive comments about the sub-program's projects, with four of the six projects scoring at or above 3.1. The reviewers noted that there are appropriate targets for demonstration, good leadership, and good results. General recommendations involved developing additional information on economic systems analysis describing costs, value, and market potential.

Market Transformation Funding:

The fiscal year 2017 Market Transformation sub-program funding totaled $1 million. These funds were used primarily to support data collection and analysis for continuing demonstration projects and to support projects selected from the H2@ Scale cooperative research and development agreement (CRADA) call.



Majority of Reviewer Comments and Recommendations:

The Market Transformation sub-program's projects were rated above average to high, as overall ratings ranged from 2.8 to 3.5, with an average score of 3.2. The projects were judged to be relevant to DOE activities and to employ good or adequate technical approaches. Reviewers emphasized the need for data collection to develop technoeconomic reports that can be used to support further market expansion.

Airport Ground Support Vehicles: This project received an overall score of 3.5. Reviewers commented that significant progress has been made in moving to the prototype and advanced testing phase. They commented that the emphasis on drop-in-place technology resolves many of the system design requirements in this application. Reviewers commended the project's strong emphasis on safety, which is required for moving emerging technology to the marketplace. However, they expressed concern about the length of the project and suggested accelerating the implementation time for technology deployment. Reviewers asserted that since the team is five years into the project, there should be a complete dataset and determination of the value proposition.

Hydrogen Energy Systems as a Grid Management Tool: This project received an overall score of 3.4. Reviewers noted that the strategy to integrate motive power with grid management was excellent. However, they identified some areas that need attention, including utility involvement for controller operation and integration with grid operations; technical and economic investigation for design and/or selection of energy storage with battery, capacitor, or hydrogen production and storage; and refinement of controller management for economic dispatch of power products for energy, peak load management, capacity, and/or diversion for transportation fuel.

Maritime Fuel Cell Generator Project: This project received an overall score of 2.8 for its efforts to develop, design, and test a first-of-its-kind hydrogen fuel cell power generator for maritime applications. Reviewers commented that the design of the inverter appears not to match the project requirements and that downtime data analysis was not adequate. While collaboration with stakeholders was commended, a suggestion was made to develop a guide or information resource to enable easier permitting and acceptance for future projects.

Fuel Cell Hybrid Electric Delivery Van Project: This project received an overall score of 3.2. Reviewers stated that the project has realistic operational requirements for daily range, operation duration, and annual performance. Reviewers commended the project's approach to directly replace the electric vehicle's small combustion engine with a fuel cell, noting that this approach avoids a lot of integration work since most of the propulsion system has not changed. There was concern about the project's ability to meet safety barriers and challenges, as a safety plan has not yet been completed and the hazards and risks of the entire project have not been fully evaluated.

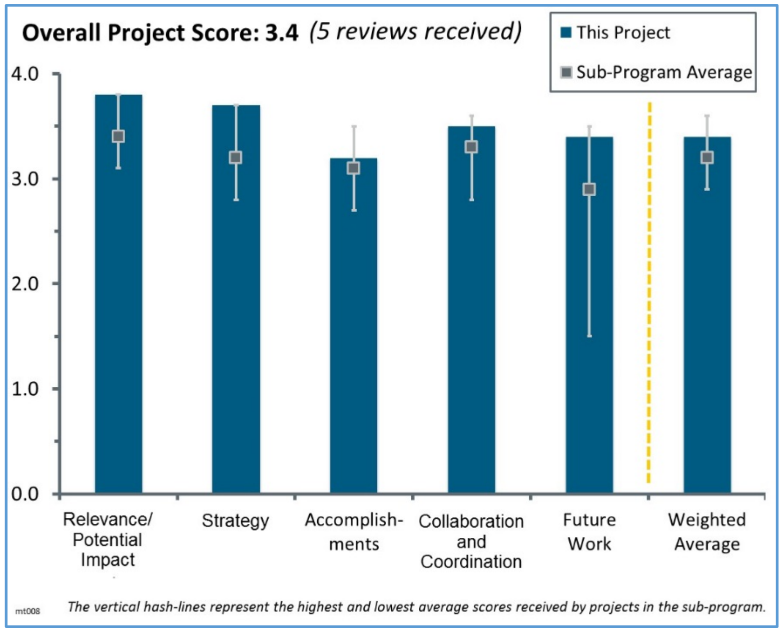
Fuel Cell Auxiliary Power Unit Project: This project received an overall score of 3.1. Reviewers supported the approach and commented that leveraging fleet operations to extend the value proposition of fuel cells and hydrogen will expand the use of fuel cells for transportation and related applications, paving the way for broader use. Suggestions included better explanation of the trucks' technical specifications and the potential commercial value proposition.

FCRx200 Development and Demonstration Project: This project received an overall score of 2.9. Reviewers suggested that the team should complete an economic assessment of this application and establish a duty cycle early in the project. Another comment was that safety planning and a hazard assessment needs to be completed with all participating partners before the operations testing phase starts.

Project #MT-008: Hydrogen Energy Systems as a Grid Management Tool

Mitch Ewan; Hawaii Natural Energy Institute

Brief Summary of Project:



The objectives of this project are to (1) support development of a regulatory structure for permitting and installation of hydrogen systems in Hawaii and (2) validate the performance, durability, and cost benefits of grid-integrated hydrogen systems. The validation entails three tasks: (1) dynamic operation of electrolyzers to mitigate the impacts of intermittent renewable energy, (2) demonstration of the potential for multiple revenue streams from ancillary services and hydrogen production, and (3) introduction of hydrogen fuel for shuttle buses operated by the County of Hawaii Mass Transit Agency and Hawaii Volcanoes National Park.

Question 1: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.8** for its relevance/potential impact.

- This project has very significant relevance in terms of the key elements of H2@ Scale. The combination of demonstrating grid frequency management using an electrolyzer as a load management device, creating a potential market locally for the oxygen produced (aquaculture), and supporting bus fueling with the hydrogen produced is very valuable for furthering development of the grid–hydrogen tie and creating a visible set of properties to encourage private investment in the technology. Codes and standards/permitting challenges were noted. However, it sounds like the project so far is also resolving those challenges, if not as quickly as desired, so those resolutions are also valuable in providing experience that will benefit future installations. Objectives include assessing electrolyzer durability under the transient demands of grid stabilization, looking at multiple revenue streams (aquaculture, grid service, hydrogen), and supporting fuel for hydrogen shuttle buses, as well as supporting development of regulatory structure for permitting of hydrogen systems in Hawaii—an important aspect.
- Conceptually, the use of the electrolyzer/fuel cell/hydrogen value chain is potentially a game changer to help manage intermittent load on the grid. With the introduction of more renewables to the grid, this value chain is a potential solution to the energy storage challenge.
- This is a relevant project to integrate values of zero-emissions vehicle transportation and grid management; however, these topics (fuel cell electric vehicle [FCEV]/hydrogen and grid management) are both complex and difficult projects to manage individually and even more so when combined. Nonetheless, the integration of the two areas is of high value.
- The project appears well aligned to the Market Transformation sub-program goals and objectives.
- Almost every fuel cell study hinges on the cost of the hydrogen. This project may offer a way to produce low-cost hydrogen. It also supports long-term use of renewables, which tend to destabilize the grid.

Question 2: Strategy for technology validation and/or deployment

This project was rated **3.7** for its project design, approach to addressing barriers, feasibility, and integration with other efforts.

- Having the central production facility at a state-of-Hawaii facility has allowed for strong political and financial support and good cost share. The incorporation of the pin-off application to try to use a pipeline to take hydrogen to the airport for ground support and to public hydrogen stations at airport entrances is an excellent opportunity to demonstrate the benefit of "aggregated demand." It would be very valuable to include some economic/cost analysis of what the project can demonstrate and lead toward in terms of hydrogen cost/price and investment opportunities. In addition, the modeling component—comparing operation of a 10 MW electrolyzer with operation of 1 MW battery (which is used in Hawaii) for grid stabilization—is expected to demonstrate the benefit of having both battery and electrolyzer. It would be helpful to understand the economics.
- The strategy for validation and deployment of the project for integration of motive power with grid management is excellent. Areas that need attention include increased collaboration with local officials for application of codes and standards and siting approval; utility involvement for controller operation and integration with grid operations; technical and economic investigation for design and/or selection of energy storage with battery, capacitor, or hydrogen production and storage; refinement of controller functions for cost-driven management in addition to frequency-driven management; and refinement of controller management for economic dispatch of power products for energy, peak load management, capacity, and/or diversion for transportation fuel.
- The modeling done to date provides a good idea of how this project can help solve some of the utility-scale challenges. The technology just needs to actually get into the validation stage.
- This is a strong project in that regard.

Question 3: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.2** for its accomplishments and progress.

- Progress and accomplishments are good, although there have been some delays—but not significant ones. Progress has been challenged by issues related to codes and standards, vendor selection, and the need to bring in the private sector and utilities for dispatch to the grid and/or use of energy products for transportation fuel. Project management is aware of these issues and is addressing them with potential solutions.
- The reported accomplishments in 2017 (developing the electrolyzer dynamic modeling tool, obtaining site permits from Hawaii County, starting site infrastructure installation by the Hawaii Natural Energy Institute [HNEI], getting equipment delivered, modifying hydrogen transport trailers to improve cascade fill utilization so that the trailers can deliver 90% of the hydrogen, and converting three buses) are significant steps toward the overall project objectives. It would be useful to see a timeline or Gantt chart of the tasks/milestones so that the reviewers can get a better idea of the overall project's complexity and the percentage complete.
- The project is behind schedule. However, it has managed issues well given the unpredictable setbacks and obstacles. The use of the booster pump and use of portable fuelers for station hydrogen supply were innovative.
- All progress is timely while at the same time facing the usual fuel cell infrastructure issues, i.e., locals not familiar with the fuel cell.
- There have been too many delays in the project to date. Some were unforeseen, but several could have been anticipated. This evaluation should rise in the next merit review because of accomplishments in installation and operation.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.5** for its collaboration and coordination.

- HNEI has done an outstanding job of engaging multiple stakeholders and agencies, especially with regard to gaining increased funding, and technical support from multiple sources. While the collaborators and their contributions are all noted, it would be helpful to show, possibly graphically, how they interconnect and which parts of the project are supported by each.
- Collaboration appears appropriate. The use of Boyd Hydrogen to interface with code officials is noted as a beneficial collaboration.
- Collaboration is good, but utilities and competitive suppliers need to be brought in for analysis of dispatch on cost and energy products.
- Although the progress has been slow, the expansion of the team and collaboration with stakeholders has been noteworthy.
- Coordination is good, but more interfacing with the electric utility Hawaiian Electric Light Company would be helpful.

Question 5: Proposed future work

This project was rated **3.4** for its proposed future work.

- The project has provided significant benefits beyond the scope of the project itself, specifically using lessons learned to write a request for proposals for the bus hydrogen station at Honolulu airport. Lessons learned were also transferred to Costa Rica in setting up a demonstration with an ex-Connecticut Transit fuel cell bus. Equally important are the potential future elements (such as tying into a hydrogen fueling station at the airport) that have been provided for in the project—it is very encouraging to see the planning for this project having a "multiplier effect."
- The project has very good potential and the manager is addressing issues.
- Proposed future work will demonstrate the value of the project. Since it is without further DOE funding, it will be critical to find a revenue stream to help support and continue the project.
- The future work appears consistent with needs to complete the project objectives.
- More is needed on economics, and discussions with utilities with large amounts of renewables on their system—such as Germany—would be useful.

Project strengths:

- The great strength of this project is the integration of multiple uses of the hydrogen and multiple economic drivers and aggregated demand for the same project (hydrogen supply to multiple uses such as grid ancillary services and oxygen for aquaculture).
- One of the real strengths is the engagement with many stakeholders and the collaboration among those players. Another is the concept of using the technology in providing grid management capability.
- Strengths include integrated value to combine zero-emission vehicle transportation, renewable dispatch, and a controller for multiple applications.
- This is a good technique for strengthening the grid as renewables become more prevalent.
- The principal investigator is committed.

Project weaknesses:

- More economic analysis/summary information would be very helpful; it is not clear how all the elements of the project are contributing to reaching a target price of hydrogen. This would be very valuable in helping quantify the investment, revenue, and price contributions of each element of the project.
- There have been some delays, although they are not significant. There have also been issues with codes and standards, issues with vendor selection, and a lack of direct utility and energy supplier participation.
- More outreach to domestic and foreign utilities would be beneficial.
- At this point, the lack of true field data after seven years under development is a weakness.

Recommendations for additions/deletions to project scope:

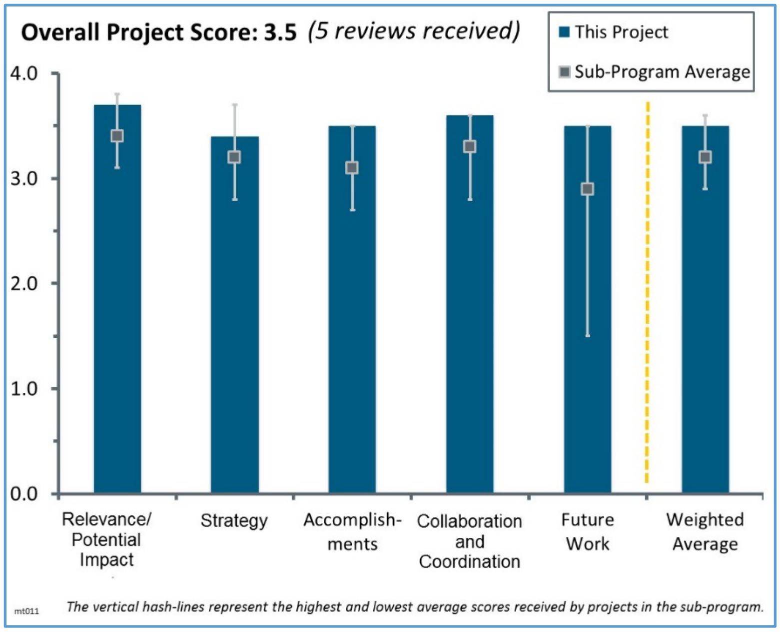
- The project should seek to involve utility and competitive energy suppliers; add cost as a driver for the controller to better understand if, when, and how much economic dispatch is possible; and consider a capacitor bank as a potential substitute for a battery.
- The project should press for the direct export of hydrogen to fueling stations using the FRP pipeline to supply a nearby location, if at all possible.
- The project should make sure the results from the implementation and operational phase are shared widely.
- More interfacing with utilities is recommended.

Project #MT-011: Fuel-Cell-Powered Airport Ground Support Equipment Deployment

Jim Petrecky; Plug Power

Brief Summary of Project:

The objectives of this project are to develop fuel-cell-powered ground support equipment that (1) is cost-competitive and more energy-efficient, (2) is lower in carbon emissions, (3) reduces consumption of diesel, (4) decreases energy expenditures, and (5) validates the value proposition. This project will deploy 15 fuel-cell-powered units for two years at Memphis–Shelby County Airport. The fuel-cell-powered cargo tractors will be located in Memphis, Tennessee, where FedEx Express has a fleet of 1,383 cargo tractors to manage 270 flights per day.



Question 1: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.7** for its relevance/potential impact.

- This highly relevant project establishes a pathway for research and development (R&D) efforts sponsored by the U.S. Department of Energy (DOE) to demonstrate their viability to meet the goals of the Fuel Cell Technologies Office (FCTO) and the overall DOE goals. With industry participation with both technology and cost share, this project demonstrates the diverse applications the FCTO-funded R&D products of the national laboratories, universities, and industry contribute to meeting environmental requirements and energy savings.
- Clearly, the objectives of the project to refine the value proposition and demonstrate technical performance are in line with FCTO/Market Transformation sub-program goals and objectives.
- The project's activities appear well aligned to the goals of the sub-program's market transformation activities. The project's learnings may be impactful to the DOE Hydrogen and Fuel Cells Program (the Program) and beneficial to similar projects.
- This seems like an ideal early application for a hydrogen fuel cell, with economics at $3,000 per kilowatt.
- This is an excellent topic for market transformation, with good potential for commercialization.

Question 2: Strategy for technology validation and/or deployment

This project was rated **3.4** for its project design, approach to addressing barriers, feasibility, and integration with other efforts.

- Using the airport hub for multiple users is an excellent approach. Identification of value areas (low noise, no idle, zero emissions, low maintenance, cost, and economics) is all good.
- The strategies for the multiple project activities are listed in detail as demonstration and commercialization requirements. Chart 8 details the value propositions, benefits, market drivers, and commercial benefits that will validate the fuel cell applications. The above-referenced requirements and the identified value propositions are the guidelines for the strategies for this project's successful conclusion.

- The length of this project points to a continuing need to reduce the implementation time for this technology's deployment. Five years into the project, data collection and determination of the value proposition are still not complete. While recognizing the delay with third-party vendor stacks, it still continues to point to maturity of the market and the industry supporting it. We should be able to get to a point at which project design/approval/construction is less than one year.
- While project barriers were addressed but not presented, this project helps remove barriers.
- All barriers have been addressed except for durability of the stack, which has a huge impact on economics.

Question 3: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.5** for its accomplishments and progress.

- Significant progress has been made with the development of fuel cell systems consistent with the application requirements of moving the fuel cell from the bench to prototype and advanced testing. The emphasis on drop-in-place technology resolves many of the system design requirements. A strong emphasis on safety demonstrates recognition of moving emerging technology to the marketplace.
- This project points specifically to the need to have backup plans for the technology. There is a need to develop a more robust "supplier" base, and that has been highlighted in the project. The project will be able to make an advancement in defining the value proposition for airport-type operations.
- The project did well at providing progress toward goals. Steps taken to address early fuel cell stack issues were impressive. The presenter suggested ideas for enhancing the value proposition of this application by expanding the approach to other services such as other airport equipment and delivery vehicles. To help DOE achieve its goals, it would have been good to see the project take this further to evaluate the potential for such activities.
- The accomplishments speak for themselves.
- There were some short-term delays associated with early selection of stack vendor and stack durability, but the problem has been solved.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.6** for its collaboration and coordination.

- Collaboration could not be any better.
- There are excellent partners, with public and private participants.
- Working with FedEx and tractor manufacturer local authorities seems to have been spot-on. The project team has managed through all aspects of the project so far.
- A strong project team was assembled.
- While basic collaboration was identified, deeper collaborations may be beneficial to the Program. For example, closer work with the Hydrogen Safety Panel and sharing of information from interactions with code and permitting officials could help future programs address roadblocks and barriers.

Question 5: Proposed future work

This project was rated **3.5** for its proposed future work.

- Future work looks very promising for commercialization. Preliminary findings (for high-duty cycle fleet use, single fuel use, need for financing, use of preferred vendors, education for service providers, need to provide economic justification, need to manage demand charge for electricity use, and use of mobile refueling to take fuel to equipment) are all very sound and provide good advice for future work.
- A well-organized statement of future work is provided. Future activities will resolve the value proposition and establish an operator maintenance program.
- Proposed future work appears appropriate for the remaining time and scope of the project. Perhaps the project team could formally document the learnings from the project to share with other projects.
- The focus should be on durability of stacks in application.

- There did not appear to be solid plans to perform the future goal of leveraging the infrastructure to support local fleet-type arrangements.

Project strengths:

- The project has chosen a good "captured" fleet environment to explore the value proposition. The large number of pieces of equipment offer the opportunity for increased usage and lower costs. This is a good testing ground to arrive at a successful value proposition.
- Strengths include the public–private team, excellent project management, and the focus on economic viability for commercial operation.
- The project has a well-experienced team that was responsive to changing project conditions and challenges. Learnings from the project are good.
- Strengths include project management by FCTO and Plug Power and the commitment of project partners such as FedEx.
- The good cooperation of many organizations is a strength.

Project weaknesses:

- Weaknesses include a lack of participation from utilities to resolve the demand charge issue, lack of participation from airport management for project implementation, and lack of input from state air regulators for Clean Air Act State Implementation Plan regulation of non-attainment areas with zero-emission equipment.
- There should be more emphasis on DOE barriers and activity from the project to address them, as well as greater collaboration with DOE and the Hydrogen Safety Panel to consider safety issues and document safety learnings.
- The length of time for the project and the delay created by the third-party stack supplier continue to point to a weakness in the supply/vendor chain.
- There is a need to advance the hydrogen infrastructure.
- Emphasis on stack durability is needed.

Recommendations for additions/deletions to project scope:

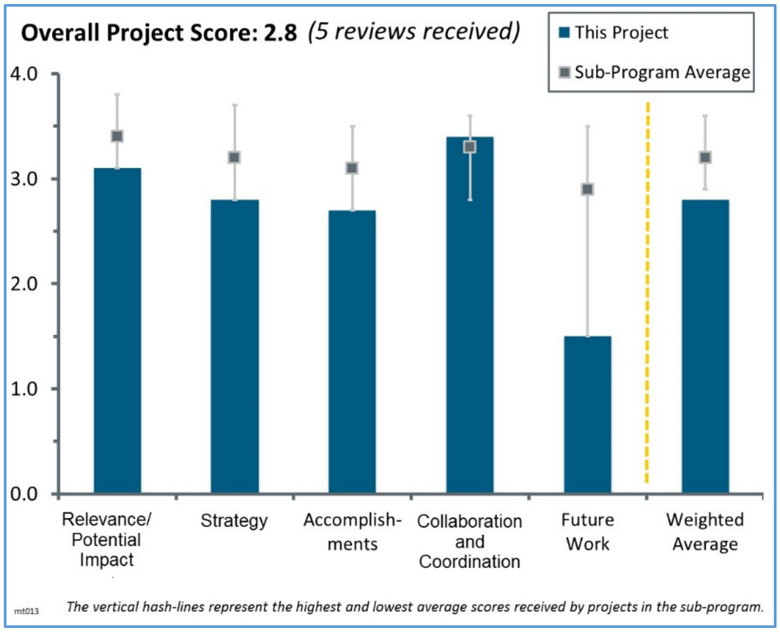
- The project needs to bring in utilities as participants to resolve the demand charge issue, airport management as a participant for project implementation, and state air regulators for Clean Air Act State Implementation Plan participation for regulation of non-attainment areas with zero-emission equipment.
- The project should look for other non-tractive airport applications of fuel cells, such as backup power to use some of the hydrogen.
- The project should define more explicitly the plan to expand and leverage for customers outside the airport—the last item in the project goals.
- Project learnings (including interactions with code officials) should be formally documented.

Project #MT-013: Maritime Fuel Cell Generator Project

Joe Pratt; Sandia National Laboratories

Brief Summary of Project:

The overall objectives of this project are to (1) lower the technology risk of future maritime fuel cell deployments by providing performance data on hydrogen polymer electrolyte membrane fuel cell technology in this environment, (2) lower the investment risk by providing a validated business case assessment for this and future potential projects, (3) enable easier permitting and acceptance of hydrogen fuel cell technology in maritime applications by assisting the U.S. Coast Guard and the American Bureau of Shipping to develop hydrogen and fuel cell codes and standards, (4) act as a stepping stone for more widespread shipboard fuel cell auxiliary power unit deployments, and (5) reduce port emissions with this and future deployments.



Question 1: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.1** for its relevance/potential impact.

- The project focuses on identifying new applications that can achieve high energy efficiency and a reduction in localized pollution using fuel cell systems and supports the Fuel Cell Technologies Office (FCTO) goals.
- Being able to design and deliver a cost-effective "modular" solution has applicability in many environments.
- One of the goals of the project is to enable market introduction of fuel cell technology. This project is relevant to that effort and could help to reduce barriers to further deployment of fuel cells.
- Based on the most optimistic of economics, the fuel cell case is, at best, worse than the baseline diesel case.

Question 2: Strategy for technology validation and/or deployment

This project was rated **2.8** for its project design, approach to addressing barriers, feasibility, and integration with other efforts.

- Barriers were well identified and addressed during the project. There clearly was a focus to understand and learn how to solve some of these barriers.
- The project did a good job evaluating all the barriers, permitting, etc. to any unit in this application, getting input from all the stakeholders.
- The strategy for this project should have been examined more closely before the project began. While ports seem to be a potential market for fuel cells, the economic analysis conducted by this project suggests that fuel cells are unlikely to be cost-competitive with diesel generators. Even if the fuel cell could somehow cost only $50/kW (unlikely to happen in the foreseeable future), the analysis shows that the fuel cell still has a higher life-cycle cost than a diesel generator. The principal investigator's response indicating that port

operators may adopt fuel cells because of some other intangible benefits was not satisfying. Individual consumers may make emotional decisions about finances, but businesses will not.

- The project does not appear to be well designed for deployment. The major problem is with partner Young Brothers, Ltd., which has a low interest in the project and appears to consider it a hindrance that interrupts the operation of its business. The prime contractor should have established an agreement for adequate support for this project from Young Brothers, and FCTO should have met with Young Brothers and other subcontractors to get their buy-in prior to funding the effort.

Question 3: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **2.7** for its accomplishments and progress.

- The project has good organization, identifying all the impediments and solutions, with the exception of economics.
- The project aligns wells with some of the FCTO/Market Transformation sub-program goals and objectives.
- It is not clear why maximum continuous run time is so low. The average gross power and the maximum five-minute gross power indicate low usage of the fuel cell power system's capability. The 30% efficiency gain is only at partial load; the gain at full load is unknown. Design of the inverter appears not to match requirements. The downtime chart (slide 13) does not give downtime over how many actual or anticipated days of operation and does not provide complete data analysis. Labor issues are a major problem.
- The project faced many challenges that prevented it from achieving its goals. The number of technical issues that caused downtime was too high, and the system never made it onto the barge as planned. This type of demonstration project should show potential customers that fuel cells are a viable candidate to replace incumbent technologies, but in this project, the high amount of downtime probably sent the opposite message.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.4** for its collaboration and coordination.

- One of the clear strengths was the collaboration among many different stakeholders.
- All the stakeholders were present; the project did a great job.
- The project had excellent collaborations.
- Labor/manpower issues are unacceptable and demonstrate poor choice of collaboration with Young Brothers (Foss Maritime).

Question 5: Proposed future work

This project was rated **1.5** for its proposed future work.

- Since the economics are poor, the project should attempt to identify and quantify other benefits.

Project strengths:

- Partners were good. Clearly a good deal of work went into this project.
- Collaboration among the stakeholder team was very impressive.
- The project has a good principal investigator and project collaborations.
- Identifying steps needed to get "it allowed" was good.
- It is difficult to tell what the project strengths are. Hawaii Natural Energy Institute and the Hawaii Center for Advanced Transportation Technologies appear to be the strongest collaborators.

Project weaknesses:

- No weaknesses were noted.
- Young Brothers (Foss Maritime) limited this project's success.
- Weaknesses include a lack of foresight about potential technical and non-technical issues and lack of a sound business case for the idea. A more detailed cost–benefit analysis should be performed before doing this type of deployment to determine whether the application makes economic sense.
- The economics are terrible, and there is no qualification of other benefits. Perhaps the project could ask the barge owners why they are interested in fuel cells.
- Sandia National Laboratories (SNL) did not identify strong collaborators that could contribute to the success of the project.

Recommendations for additions/deletions to project scope:

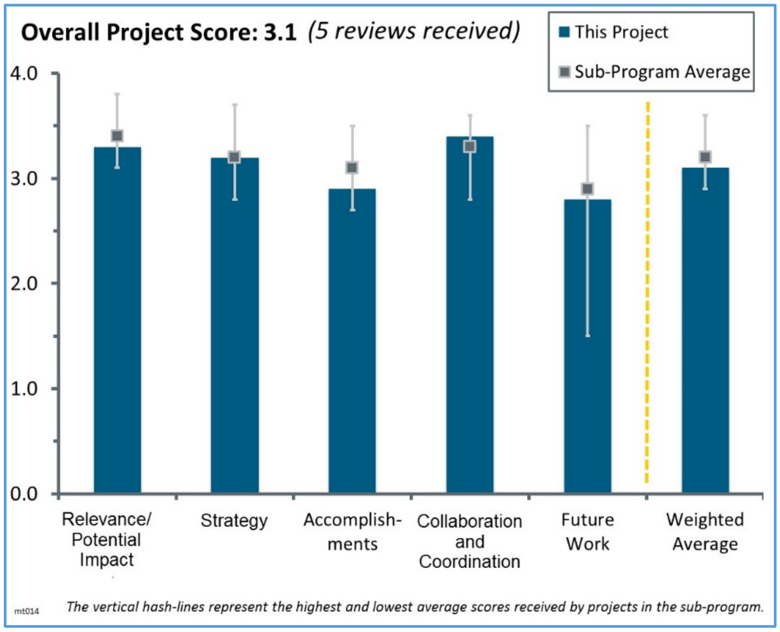
- Monitoring the progress of Hydrogenics in locating and selling to those who require modular power solutions should continue.
- Perhaps a guide or information resource could be developed to enable easier permitting and acceptance for future projects. If so, perhaps it could be shared on the H2Tools.org portal.
- FCTO should review with SNL management how the project was operated and how the proposal was developed. SNL should have an internal review of how projects that require strong contributions from collaborators are developed and proposed.
- Until there is some reason that this application can make sense, it does not justify continuation.

Project #MT-014: Demonstration of Fuel Cell Auxiliary Power Unit to Power Truck Refrigeration Units in Refrigerated Trucks

Kriston Brooks; Pacific Northwest National Laboratory

Brief Summary of Project:

The purpose of this project is to demonstrate the viability of fuel-cell-based transport refrigeration units (TRUs) for refrigerated Class 8 trucks using demonstrations and business case development. Two fuel cell systems will be developed and deployed in commercial operations. Investigators will assess system performance and analyze market viability.



Question 1: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.3** for its relevance/potential impact.

- Regarding relevance, this project has been/is useful to determining the market for auxiliary power units (APUs) to power truck refrigeration units. It looks like hub/spoke distribution with trucks returning to the central facility daily until there is widespread hydrogen fueling infrastructure available (following over-the-road truck applications). Some distribution centers already have hydrogen for forklifts. The project also needs to look at packaging/mass and continue to drive economics (very important). From the results reported, it looks like this will be an opportunity only in a market in which there are both emissions regulations restricting use of diesel TRUs and hydrogen-fueled forklifts so that there is aggregated demand to share the capital cost of hydrogen fuel. Perhaps there is an opportunity for designing a complete integrated TRU based on fuel cells. It seems like the need to produce 480 V three-phase power to satisfy existing refrigeration needs is driving cost/mass into the system.
- The project supports the development of new commercialization opportunities and brings in leaders in the fuel cell industry and the TRU industry. These should be good partners that can evaluate the adequacy of these applications. The business case analyses provide guidance for commercialization.
- The project has a good approach to solving the cost barriers of the hydrogen infrastructure issue. It also helps alleviate the problem of operating diesel APUs in environmentally constrained city systems.
- The project is attempting to leverage fleet-type operations to expand the value proposition for fuel cells and hydrogen. This continues to expand the consideration of using fuel cells for transportation and transportation-related scenarios, paving the way for broader use and introduction when the auto industry adopts fuel cells in a much bigger way.
- The project has a good topic and a good application for potential commercialization.

Question 2: Strategy for technology validation and/or deployment

This project was rated **3.2** for its project design, approach to addressing barriers, feasibility, and integration with other efforts.

- The approach to identifying the benefits and commercialization prospects is very strong. Barriers are addressed to minimize risk for investors and demonstrate the concept's feasibility for industry. Distribution concepts are identified, and costs relative to the existing technology (diesel engine) provide industry with information for making investment decisions. The project has a detailed approach for development of the fuel cell system and establishment of hydrogen infrastructure.
- The approach is as follows: develop and demonstrate, then assess performance, then analyze market viability. The use of the clear project phases (slide 5) and the use of the go/no-go assessment were good. Also, there was an honest assessment of the economics and, for one of the partners, the honesty to say "no-go." While the use of a "battery box replacement" approach to packaging a "diesel genset replacement" unit is understandable (as opposed to designing the complete refrigeration system around the fuel cell system), this may have hurt cost and mass.
- The project as designed explores the topic in a sound manner and way. There is a challenge: if the prime mover is probably still a diesel engine for the foreseeable future, you would have to support two fuel types. Most users would likely not see that as a desirable outcome.
- The true barriers are the environment under the truck and its impact on the fuel cell and the cost. Neither was sufficiently addressed. The project could simulate the air environment under the truck in a laboratory and not wait for the whole power plant to be constructed. Likewise, the project should assume that fuel cell cost of twice that of diesel was not optimistic enough.
- The hub-and-spoke strategy is good, but successful project development is questionable, with delay and change of business focus by a key participant.

Question 3: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **2.9** for its accomplishments and progress.

- The project made very good progress in identifying the fuel cell system necessary for the TRU application. Chart 12 clearly identifies the impact of low diesel cost for the competition. The high cost of fuel cell systems and the loss of the 30% federal Business Energy Investment Tax Credit were barriers that could not be overcome. However, these barriers were not the focus of the project.
- While specific project deliverables and milestones have been met, the project has gone very slowly.
- Progress is still a bit slow. The Nuvera team has yet to get the prototype in the field, and therefore, there is not much detail to report.
- Progress is questionable, with a change of the business focus by one of the key participants and a no-go decision by another key participant.
- There have been no great accomplishments.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.4** for its collaboration and coordination.

- The team organized by Pacific Northwest National Laboratory consists of leaders in both the fuel cell system arena and TRUs. The project was able to resolve many of the barriers as a result of this strong team.
- Being able to form two teams and trying to solve the problems was an interesting and noteworthy approach. It allowed for participation from several additional stakeholders.
- Despite the fits and starts with Nuvera (Nuvera/Thermo King have built hardware but not yet found a demonstration partner), Ballard/Carrier/Walmart seemed to work well together as a team. On the one hand, it may be prudent to have a completed design to show to prospective partners, but on the other hand, the complete execution and getting to the go/no-go point and an actual demonstration would have gone faster if

the demonstration partner had been on board at the beginning. It seems like some things could have been done in parallel.
- Collaboration with DOE and private businesses was excellent, but project management is challenged with a change of focus by a key participant and no-go decision by another key participant.
- More input is needed from manufacturers about the reason for their interest in the fuel cell.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- While the project needs to drive to the Nuvera go/no-go decision and get a demonstration underway if it is a go decision, it seems like there are further opportunities to hone the project more to find a niche where it would work commercially. Perhaps some thought should be given to doing further analysis, for example, on an emissions comparison with diesel (which might help to pinpoint a market in which there might be a pull) as well as a well-to-wheels-type efficiency comparison. Perhaps there is also a low-carbon fuel standard opportunity.
- The future work addressed design of the Nuvera fuel cell for field testing (it seems that a prototype is assumed). The safety assessment and demonstration efforts need more detailed descriptions.
- The work plan is good, but success of future work to meet project objectives will be difficult because of a change of focus by a key participant and no-go decision by another key participant.
- With the Ballard team's departure and the lack of an end user defined for the Nuvera team, future work and utility are unclear.
- More studies could be conducted on the impact of several fuel cell costs and laboratory tests of the impact of undercarriage air quality on fuel cell life.

Project strengths:

- Strengths include the project topic, early selection of team participants, focus on project value, and early identification of barriers.
- This project has a strong timing/execution plan, and the decision to have two teams to compare work/results is also a strength.
- The collaborators are the primary strength. They brought real-world operational experience to the project.
- Collaboration among developers and users is a strength.
- The project identified most issues.

Project weaknesses:

- The early work products are consistent with objective project evaluation; however, costs may be unreliable owing to a change in focus by a key participant that resulted in a no-go decision by another key participant. These changes have produced concerns for selection of platform design, with tank and fuel cell locations on the trailer underbelly subject to road damage, unreliable cost estimates, the questionable disparity of operational costs compared to conventional fuel vehicles, and high system costs that represent a major development issue. These issues will be difficult to overcome for an objective evaluation.
- The length of time to get the project to the demonstration phase is a weakness, along with the disconnect between the APU and prime mover fuel needs, which could be a barrier to adoption.
- There was no laboratory stack testing using a simulated air undercarriage environment. Also, the project was too pessimistic on fuel cell cost.
- The project perhaps did not ask enough questions or look at different levels of integration, so the opportunities to get to a viable "go" result are limited.

Recommendations for additions/deletions to project scope:

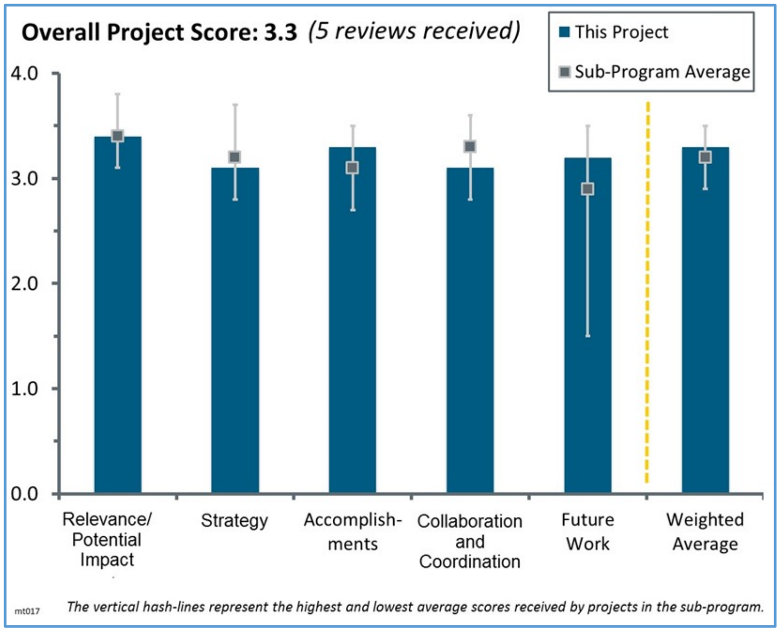
- It might be wise at this time to consider bringing in a new vehicle/system integrator that has a business focus for design and development of a motive fuel cell APU, and seeking to restart the evaluation with the user (Walmart).
- At this stage, quick selection of an end user for the Nuvera team is recommended. Also, comparison against other battery/electric solutions might be appropriate.
- Analysis of different systems integration approaches beyond just a direct replacement of a diesel genset might yield some potential configurations that do better on cost/mass.
- More parametric measures are needed on the impact of several fuel costs. Stacks should be tested at the laboratory level.

Project #MT-017: FedEx Express Hydrogen Fuel Cell Extended-Range Battery Electric Vehicles

Imran Ahmed; FedEx Express

Brief Summary of Project:

This project will demonstrate hydrogen and fuel cell technologies in real-world environments. Fuels cells are being integrated into 20 battery electric pickup and delivery vehicles. Those trucks will operate 10-hour shifts 260 days annually, amounting to at least 5,000 hours per truck for a total of 100,000 hours over 1.92 years. The project is expected to reduce diesel consumption by 100,000 gallons and prevent 270 metric tons of carbon dioxide.



Question 1: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.4** for its relevance/potential impact.

- Regarding relevance, the project is seeking to find the right technical solution for the range needed for the specific solution (“right vehicle, right route” concept) for zero-emission delivery. The focus is on using a fuel cell as a range extender for battery electric vehicles to get 150 miles or more of range (20,000–40,000 miles annually). This is good because the project team has done the sensitivity analysis on vehicle size, range, and hybridization balance.
- The opportunity to create a demand situation in these fleet-type roles is spot-on. The relative cost of this project seems a bit high based on some of the other funded projects, but if the value proposition is there, then a relatively quick adoption of the technology with FedEx is probable (at least where infrastructure to support might reside).
- This is an excellent topic for potential commercialization.
- For relevance, energy independence may no longer have the importance it did 10 years ago. The high cost of fuel cell systems without the federal subsidy may make total cost of ownership a difficult prospect. The on-board traction charger has been done for batteries. It is not clear what is unique about this system.

Question 2: Strategy for technology validation and/or deployment

This project was rated **3.1** for its project design, approach to addressing barriers, feasibility, and integration with other efforts.

- The Workhorse electric vehicle chassis has two battery packs (80 kWh) and a small combustion engine with 200 kW traction motor. The project is a direct replacement of the combustion engine with a fuel cell. This is a good approach because it avoids a lot of integration work since most of the propulsion system is not changed.
- The project has an excellent spoke-and-hub approach with realistic operational requirements for daily range, operation duration, and annual performance.
- The project has a well-organized approach to addressing milestones that meet strategy statements.

- The project has a straightforward approach to establishing the value proposition for the light- and medium-duty vehicle fleets. Because the initial deployment will be in the Albany area, the opportunity will not necessarily be replicated at other locations.
- “Unknown ability to meet safety” is identified as one of the barriers addressed by this project. As noted in the presentation slides, the project is 85%–90% complete for Phase I. It appears that a safety plan has not yet been completed for this project. Additionally, it is not clear whether the hazards and risks for the entire project have been fully evaluated. The principal investigator suggested that each project partner performs at its own risk analysis and that the vehicle is provided with substantial construction and a bumper. Given the location of the hydrogen storage tanks at the rear of the vehicle (with tank valves and manifold piping facing oncoming traffic), the answers do not suggest a strong technical basis for safe deployment of the vehicle. Other topics needing further safety consideration include evaluation of and basis for tank safety (SAE J2579 provides testing only for light-duty vehicles) and evaluation of vent paths for performance under overpressure conditions.

Question 3: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.3** for its accomplishments and progress.

- This timeline is perhaps the most aggressive of any reviewed within the Market Transformation sub-program. The project seems to have well-defined dates and, so far, has met each within reason. Design and build of the prototype reflects solid management.
- The project is well organized and has made significant progress in multiple subsystems (hydrogen storage, safety, cooling, vehicle interface). The demonstration/development vehicle is complete, if several months behind schedule.
- There was some early delay, but the project appears to be on schedule with good progress identifying and resolving barriers.
- Accomplishments are well described and demonstrate a well-organized project. It is unclear why the two fuel cells are operated individually or where the system prevents interaction between the independent fuel cells, e.g., perhaps if one fuel cell fails, the other fuel cell provides enough power to maintain battery charge. It appears that the on/off start point is a 20 kW operation; therefore, both fuel cells must be functional for the system to operate. Perhaps fuel cell system redundancy is a limit based on fuel cell manufacturers not developing a 20 kW fuel cell. The graph presented in Chart 17 indicates that the optimization (variable output) has not been demonstrated. It is not clear whether both fuel cells operate at the same operating point in variable operation or how this is controlled. What was done in Tasks 1 and 2 is also unclear. The fuel task list was not provided.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.1** for its collaboration and coordination.

- There are excellent partnerships with DOE and appropriate private businesses.
- Collaboration between the team and DOE is good.
- Collaborators include Plug Power, Workhorse, and Morgan-Olson (body builder), as well as DOE, the National Renewable Energy Laboratory (NREL), and Pacific Northwest National Laboratory.
- There was no indication of collaboration on safety planning or hazard evaluation.
- The difference between collaborators and sub-recipients is unclear, nor is it evident what work was done by Workhorse and Plug Power, e.g., whether Plug Power just delivered the fuel cell system.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- Planned work is consistent with the work plan and with expectations for a high-value product.
- The proposed schedule and planning appear on target.

- Getting to the completion of the first demonstration truck and going through the testing/demonstration phase will provide the critical output from the project. The cost share for the second phase (after the go/no-go gate, assuming the result is go) is not completely clear but might need to be more biased toward private cost share. It would be helpful for DOE/NREL to get the operational data from the 19 trucks but not necessarily pay to build/operate them.
- Future work is well organized up to Task 5. Phase II work is unknown.
- A complete project hazard assessment and safety plan involving all project partners should be an immediate focus. Failure to do this could have serious safety and potential cost implications.

Project strengths:

- This is a real near-term opportunity with a strong industry end user. This is the only project currently being reviewed for which the end user is the sponsor/advocate.
- Strengths include the team partnerships, appropriate private business participation, and thoughtful early identification of barriers to be resolved.
- The project has a clear project plan and good collaboration to complete multiple subsystems in parallel.
- FedEx, Plug Power, and Workhorse form a strong team.
- Strengths include experienced project partners.

Project weaknesses:

- No weaknesses were noted.
- More detail is needed on performance and cost of the project vehicle compared with the standard platform internal combustion engine (ICE) hybrid vehicle.
- It would be good to have more information about the project financials, particularly the Phase I/Phase II budgets and the expected operational costs.
- The presentation has a weakness because there was no discussion of Phase II.
- Safety planning and integration are weaknesses.

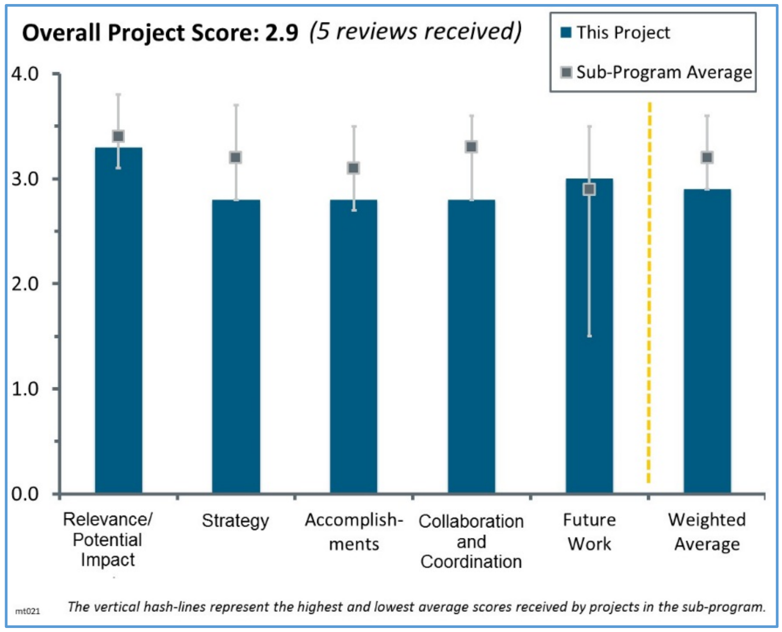
Recommendations for additions/deletions to project scope:

- The project team should discuss controls for two fuel cells working together to charge the battery. It is not clear how the system will operate if one fuel cell is operating at a different power point or with different efficiency. Next year, the project team should report on why this is not a weakness. There was no discussion of Phase II.
- It is important to keep focus on the key performance data. It is nice to have data from a large sample size, but the key here is to focus on metrics/data that are going to demonstrate the economics of building and operating the trucks in order to encourage private investment.
- Should the value proposition reflect good results, the project should identify expansion opportunities within FedEx.
- It might be helpful to have more detail on a performance and cost comparison of the project vehicle with the standard platform ICE hybrid vehicle.
- An immediate focus should be placed on safety planning and hazard assessment involving all team members.

Project #MT-021: Northeast Demonstration and Deployment of FCRx200

Abas Goodarzi; US Hybrid Corporation

Brief Summary of Project:



The project's objectives are to (1) design, develop, test, and demonstrate one fuel cell range-extended plug-in hybrid utility vehicle (FCRx200) at a commercial operator's site; (2) given the success of the initial prototype, receive approval to proceed with fleet development to deploy and operate a minimum of 20 FCRx200s for at least 5,000 hours or 30 months per vehicle, whichever occurs first, at the commercial operator's site; and (3) conduct an economic assessment, a payback analysis, a life-cycle cost analysis, an incremental capital cost per unit analysis, a fuel savings analysis, and a payback time analysis (concerning the use of hydrogen-fueled fuel cell range extenders in commercial fleets), as well as comments from the operator detailing the experience during operation. The economic assessment will be facilitated using data collected and submitted to the National Renewable Energy Laboratory on a quarterly basis. Upon project completion, the team will be able to make recommendations on the marketability of the FCRx200 vehicle.

Question 1: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.3** for its relevance/potential impact.

- The project looks into a new market segment, namely range extenders. One of the limitations of battery electric vehicles (BEVs) is range. By installing a small 5 kW stack, the range can be extended, and with that, a new application for fuel cells can be developed. Increased usage and sales volumes for stacks should lead to cost reductions and a more sustainable supply chain.
- The project supports the development of fuel cell system applications for vehicles. It addresses the development of fuel cell hybrid systems to increase the range of battery-powered delivery vans. The project advances fuel cells and hydrogen toward commercial systems.
- The project examines multiple possible uses of fuel cells, including transportation. This delivery van application further extends the scope of applications.
- This project seems to be more of an integration project than a technology demonstration/validation. Phase I involves the design, procurement, and integration of equipment for one prototype vehicle—which is fair enough, as this could provide some validation of the applicability of the balance between battery and fuel cell for the given size of vehicle and duty cycle. However, it does not seem that the further funding of 20 additional vehicles for demonstration breaks any new ground in terms of DOE goals.

Question 2: Strategy for technology validation and/or deployment

This project was rated **2.8** for its project design, approach to addressing barriers, feasibility, and integration with other efforts.

- The principle of using computer-aided design, simulation, and stack testing before putting it into a car is sound. Also, first building one car and then determining a go/no-go decision for the other 20 vehicles is good practice. However, doing the economic assessment at the end of the project is late; the assessment should happen earlier in the project, before going to 20-vehicle production. This technology is available in Europe, and there are more than a hundred BEVs with range extenders on the roads. The team should look at the experiences in Europe and try to reflect on those for the U.S. market. For example, Nissan and Symbio are working on the same technology for the eNV200. In Europe, this development with Nissan is not part of the Fuel Cells and Hydrogen Joint Undertaking funding. In the United States, Nissan works with US Hybrid to build the same system. It could be interesting to understand the differences in the economic models between the United States and Europe. During the presentation, it was mentioned that US Hybrid has no view yet on the road patterns and usage of the demonstration car. This is important information for designing the right stack performance. This is a very urgent action.
- Based on the project plan, the principal investigator (PI) has outlined a well-thought-out project. However, he should begin to consider economic issues quickly.
- The project is an evaluation of market viability (costs and meeting requirements) and acceptance (customer desire). The approach/project concept is to evaluate a light-duty fleet range extender for a BEV. Phase I is developing, building, and testing the prototype. Phase II is a two-year demonstration of 20 vehicles with fuel provided by the project (National Grid does not want to do it) for at least 5000 hours/vehicle. The specifications are 5–10 kW fuel cells with 2–3 kg hydrogen at 700 bar. The range is to increase from 100 miles (BEV only) to 250 miles. Also, since the project is in the Northeast, there is a significant cold weather component (heat recovery, freeze capable to -30ºC). The existing onboard charger will be used as an interface for the fuel cell system. It is unclear whether the project goals of determining cost viability and fuel cell durability require such a large fleet/funding. Other than any potential reliability problems that cause undue downtime/repair costs, the factors affecting cost viability will presumably be known at the outset. So while the goals of the project have some value, they do not seem to break any new ground in terms of DOE goals. The approach is simply to run 20 vehicles and see how much it costs and how long they last. This is not very novel and probably is not the most cost-effective way to get the information. It was stated in the question-and-answer (Q&A) session that DOE incentivized this project as a way of incentivizing (creating demand for) the 12 Northeast hydrogen stations. This may be an okay goal, but it was not stated directly in the project presentation.
- There is very little discussion of technology development in the objectives (Chart 7), yet Milestone 2 has fuel cell and balance-of-plant (BOP) design. Under accomplishments, the fuel cell stack and BOP were designed, but there was no discussion of that design.
- It is difficult to conclude that the project is well designed owing to the lack of information and the PI's response regarding safety planning and hazard assessment ("We have been operating [fuel cell electric vehicles] safely for 20 years"). Additionally, the inherent safety of the vehicle for operational and accident conditions can have an impact on market viability.

Question 3: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **2.8** for its accomplishments and progress.

- To the extent that one agrees that this is a valuable project, it is well organized and well planned, with clear milestones and deliverables. The go/no-go decision point works well as a process for managing projects of this size.
- The project has just begun, and progress is good so far; however, the tasks so far are easier than those in the future.
- Given that this project is just getting started, the accomplishments and progress appear appropriate.

- The project started just nine months ago. The project seems to progress well, although there is no Gantt chart available to judge that. Regarding the key performance indicators (KPIs), some were mentioned, but the discussion was very limited, and there was no mention of whether the prototype stack can meet the KPIs using simulations. Therefore, this point is not easy to judge objectively. It is recommended that the project team make a clearer plan and a more in-depth analysis of the state of play versus the KPIs that were set.
- There are very limited data and no discussion on fuel cell stack and BOP design. The stack result chart has no unit on the y-axis and legend. This is a very poor explanation of what was undertaken. It is not clear what the vehicle packaging boundaries are. There is no explanation of the thermal management system. This is a very poor discussion of accomplishments and progress.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.8** for its collaboration and coordination.

- Collaborator roles are well defined except that of the fueling stations, which was mentioned only tangentially in the Q&A session. It seems like there is more opportunity there to obtain infrastructure data and interface detail, even though they are planning to use retail stations. Argonne National Laboratory (ANL) will perform modeling, US Hybrid will provide drive-cycle input, and Nissan and National Grid will perform testing. ANL will provide final technical assessment and economic assessment (lifetime emissions, fleet ownership costs). Risk is decoupled from Nissan and National Grid. Fueling is anticipated at the 12 Air Liquide Northeast stations. National Grid has operations in Connecticut and New Jersey, and National Grid team members hope to be able to use one of those. (Pete Devlin says that project is incentivized—perhaps by DOE—to support those stations.)
- Each project partner task is clearly defined. Since we are still early in the project, not much collaboration is required. However, it looks like each partner is contributing its share. However, once the prototype part is integrated in the car, bigger challenges will come, and good collaboration between partners will be crucial for project success. During the presentation, it was revealed that there is still no contract in place with Nissan. This step is crucial to project success.
- Collaboration with Nissan and National Grid is good; however, the interface with National Grid should extend beyond the vehicle operators to system-level utility individuals to determine whether a fleet of zero-emission vehicles would save money by offsetting the cost of compliance in the organization's generation assets.
- Regarding the project concept and teams, Nissan and ANL should be very good.
- The PI indicated that a failure mode effects analysis will be performed for the fuel cell and storage equipment. Hazards originating external to the project equipment should also be evaluated for their impact on project equipment and its safety operation/performance in off-normal conditions. The PI indicated that vehicle performance in an accident is Nissan's responsibility and will not be considered by the project. Such an approach may result in potential safety issues for operation of the vehicle and should be considered collaboratively.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- At a high level, the project appears to have clear milestones and well-defined deliverables. In the Q&A session, it was discussed that there may need to be more focus on clear deliverables from the cost analysis portion of the project for Phase II to make sure that the desired outcomes of fully understanding cost viability are met. The remainder of 2017 includes final design, initiating procurement, developing the vehicle model, hydrogen storage selection, and integration and hydrogen fill interface. Hydrogen safety system and sensors (Phase I) in 2018 involves complete construction of the prototype vehicle, validating performance, and demonstrations with the operator. More cost analysis is needed in the process of planning for Phase II.
- Only one go/no-go decision point by DOE is foreseen, and this is after the first prototype car is made and tested, a logical judgment point. Unfortunately, there is no evidence of risk assessment or a potential

mitigation plan in the documents provided to the evaluators, so it is hard to judge this. The challenge in the third and fourth quarters in 2017 looks very challenging, and more time might be required for this step. The target seems to be a validated and demonstrated vehicle by end-2018, which looks realistic; however, it is advisable to have a more detailed plan and identify better potential risk. During the presentation, it became clear that Nissan had not yet signed a contract; this is a serious risk.
- The future work plan is good, but more substance is needed for the plans for economic evaluation.
- The list of activities for the last two quarters of 2017 is very large. No economic assessment was presented.
- Future work should include all project partners working together for hazard evaluations and hydrogen safety planning.

Project strengths:

- The project looks for new business chances and thus an increase of fuel cell production for US Hybrid, which is a local industry. The project can thereby create jobs and growth. If BEVs with range extenders are acceptable in the United States and make economic sense, this project would be a good way to increase the usage rate of hydrogen stations in the United States and, thereby, their reliability. In a way, BEV drivers can experience driving and refueling with hydrogen; maybe in the future, they will become fuel cell vehicle buyers. The way the project looked to optimize the heat generation and give it some value is very interesting.
- The planned fleet of 21 vehicles should yield a large body of statistically significant data on durability, reliability, and fueling.
- The engineering plan is good. The project has a good partner in National Grid, a worldwide utility with potential emission issues that a fuel cell fleet could possibly offset.
- The project team is strong. The approach to implementation and evaluation of equipment performance and value is reasonable.
- No project strengths were apparent.

Project weaknesses:

- The economic assessment is at the end of the project. This has the risk of spending a good deal of money to make 20 prototype cars to conclude maybe that it does not make sense, so it is better to start earlier and have a first assessment ready after the first prototype build. There is no clear build plan or risk management plan. Integration in a car is a big challenge and might cause serious delays and will need good partnering, especially as the Nissan e-NV200 will probably not be built in the United States but will instead include vehicles modified through aftermarket installation. It is noted that no U.S. automaker is part of the project and a contract is not yet signed with Nissan. Another weakness is that the design of stack performance is performed without knowing the customer profile in terms of daily routes, route profiles, and weight carried. In that sense, it looks like a 5 kW stack is too low and very risky. During the presentation, it was mentioned that a 10 kW stack might be possible. It is important to have a careful look into the right requirements; this will also have an impact on the economic model.
- There does not seem to be a well-developed up-front cost analysis/estimations, particularly for estimated maintenance costs. It seems like this could jeopardize project completion if those costs are high. Also, the project refers to learning about the duty cycle, but that needs to be understood beforehand to ensure vehicles get enough usage to accumulate 5000 hours of operation for the durability goals to be met. For the planned two-year demonstration, the vehicles would have to run eight hours per day, six days per week, to reach 5000 hours.
- The US Hybrid presentations were not very informative. Incomplete data were presented, and there was no discussion on thermal management. No economic assessment plans were presented.
- Hazard assessment and safety planning does not appear to be an integrated team approach.
- A weakness is the lack of economics.

Recommendations for additions/deletions to project scope:

- There should be an intermediate KPI check. A clearer and more detailed development schedule is needed that includes risk-mitigating measures (e.g., the lack of a signed contract with Nissan). The project should check experiences in Europe. The economic assessment should be started earlier; it should be part of the go/no-go decision. There is an urgent need to check the customer profile and route profile to define the right stack performance.
- This is an expensive project that has a high risk of not reaching the project objectives. The prototype phase should be expanded to obtain the reliability, customer acceptance, and durability data envisioned before building such a large fleet. It seems like those questions can be answered with perhaps three vehicles, greatly reducing the risk associated with building the large fleet and consuming a large amount of funding just running so many vehicles. If the prototype phase yields satisfactory information, then the second phase could be done later with much less risk and with much greater cost share from the non-DOE partners.
- The project should evaluate and analyze the safety of the system in an accident or off-normal condition.
- The project should be restructured with better organization and management.

2017 – Systems Analysis
Summary of Annual Merit Review of the Systems Analysis Sub-Program

Summary of Reviewer Comments on the Systems Analysis Sub-Program:

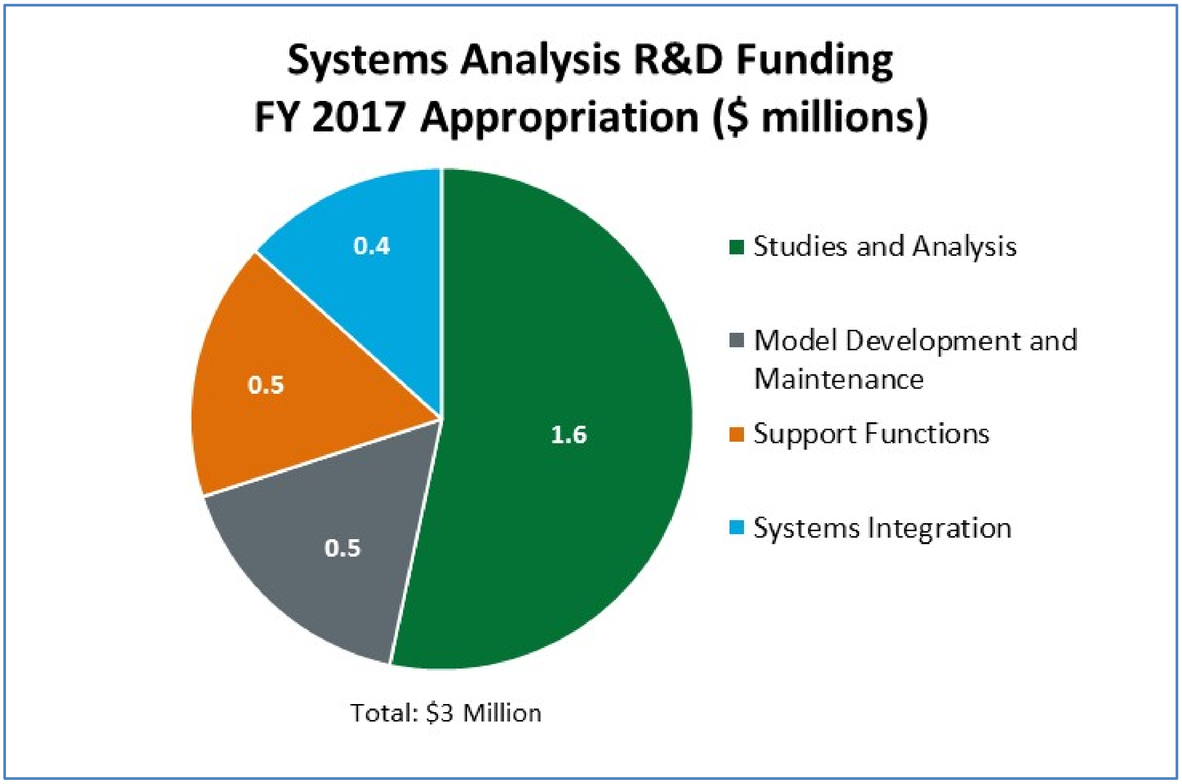
The reviewers considered the Systems Analysis sub-program to be critical to the U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program's (the Program's) mission and focused on the relevant issues that will enable cost-effective implementation of hydrogen fuel cell vehicles in a way that addresses national needs. In general, the reviewers noted that the Systems Analysis sub-program is well managed and the sub-program projects are diverse and focused on addressing technical barriers and meeting targets. Reviewers commended the sub-program for the excellent mix of near-, mid-, and long-term analyses as demonstrated by the assessment of hydrogen cost at low volumes for the current market, early-market infrastructure costs for the near term, and relevant activities to support H2@ Scale and assessment of medium-/heavy-duty transport and regional resources for the longer term. They said that one of the strengths of the sub-program was the extensive collaboration with industry, national laboratories, and academia to gather information from the entire value chain to conduct analysis. Overall, the reviewers commented that the sub-program's research and development (R&D) portfolio is appropriate and comprehensively addresses key technical aspects required to achieve the sub-program targets.

Some reviewers commented that the sub-program's broad portfolio of models and tools are adequate to address the issues and barriers facing the Program. They noted that the Systems Analysis sub-program links the results for all the pathways and technologies and adds a technoeconomic macro-level assessment of status and needs. Reviewers identified analytical activities as crucial in assessing the relevance of the technical progress. It was also noted that the analysis and model portfolio is balanced and enables the Systems Analysis sub-program to quickly respond to high-level assessments. In particular, when H2@ Scale was announced, the team was able to complete analysis tasks to assess market potential and economics using the current model portfolio.

Key reviewer recommendations for this sub-program include the following: (1) highlight the job impact assessment; (2) extend the analysis timeframe for the total cost of ownership assessment to 2040; (3) provide analysis of consumer behavior; and (4) provide risk analysis of sub-program targets to understand the impacts of meeting the overall objectives.

Systems Analysis Funding:

The fiscal year (FY) 2017 appropriation for the Systems Analysis sub-program was $3 million. FY 2017 funding focused on conducting analysis using the models developed by the sub-program. In particular, analysis projects concentrated on analysis of early market adoption of fuel cells, continued life-cycle analysis of water use for advanced hydrogen production technology pathways, the levelized cost of hydrogen from emerging hydrogen production pathways, employment impacts of hydrogen and fuel cell technologies, the impacts of consumer behavior, the cost of onboard hydrogen storage options and associated greenhouse gas emissions and petroleum use, criteria emissions from hydrogen pathways, greenhouse gas emissions from fuel cell medium- and heavy-duty trucks, and hydrogen fueling station business assessments.



Majority of Reviewer Comments and Recommendations:

The maximum, minimum, and average scores for the 12 Systems Analysis projects reviewed in the 2017 Annual Merit Review were 3.5, 3.1, and 3.4, respectively.

Infrastructure: The one analysis project reviewed in this topic area received an average score of 3.5 and focused on assessing hydrogen infrastructure development costs and understanding the hydrogen infrastructure costs.

Reviewers commented that the ***Hydrogen Financial Analysis Scenario Tool (H2FAST) Updates with Analysis of 101st Station*** project aligns well with the Program objectives of supporting infrastructure by providing options to focus effective research on cost reductions and insights to station network development. They noted that the model is comprehensive with the addition of the stochastic risk analysis capabilities for deployment of hydrogen infrastructure and incorporates excellent collaboration with stakeholders, including government agencies. The reviewers noted that the model would benefit from additional outreach and engagement with stakeholders to solicit customer feedback.

Model Development and Systems Integration: Five projects involving model development were reviewed, receiving an average score of 3.4. These projects received favorable reviews and were regarded as well aligned with the current sub-program goals and objectives.

Reviewers commended the ***Greenhouse Gas Emissions and Petroleum Use of Medium- and Heavy-Duty Trucks*** project for expanding the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model platform to include fuel cell applications for medium- and heavy-duty truck sectors. They agreed that the project is critical in emphasizing the benefits of hydrogen fuel cell applications for medium- and heavy-duty trucks, especially in communities that are disproportionally affected by heavy industrial activity. They commended the work for its effort to accurately assess engine and fuel cell performance in these truck sectors (including during idle engine operation) and for having excellent collaboration with stakeholders. Suggestions include validating the power assumptions, providing additional funding to continue this critical work, and adding health benefits from emission reduction.

Reviewers acknowledged the ***Life-Cycle Analysis of Air Pollutants for Refinery and Hydrogen Production from Steam Methane Reforming*** project for updating the GREET model platform to improve the model's accuracy and provide life-cycle data on criteria pollutants. They agreed that the project is addressing a sub-program gap and will enable critical evaluations of conventional internal combustion engine vehicles compared to zero-emission vehicles such as fuel cell vehicles in non-attainment areas. Suggestions include increasing collaboration with state agencies such as the California Air Resources Board (CARB) and California Energy Commission (CEC) to ensure the model has the most recent data and includes regional analyses to assess impacts on non-attainment areas.

Reviewers acknowledged that expanding the GREET model platform to include water-use life-cycle assessment and renewable hydrogen production pathways will address critical Program issues associated with hydrogen production and the comparative evaluation to conventional fuels. They agreed that the project has established a good fundamental understanding of water consumption associated with hydrogen pathways, which is essential for comparing multiple vehicle platforms, fuel pathways, and resource analysis. They commended the work for expanding the capabilities of existing modeling tools and for including county- and regional-level analysis of water consumption and potential for water stress. Suggestions include quantifying the net water impacts of fuel substitution or displacement, providing more context on water usage overall, considering the impacts of varying regional policies or economics affecting water use/cost, and increasing collaboration with/peer review by western state water authorities. Reviewers agreed with continuing the emphasis on completing and expanding regional analysis, especially in areas of the country where water limitations may be an issue.

Programmatic Benefits Analysis: Three projects were reviewed in the topic area of sustainability and employment impacts of hydrogen and fuel cell technologies, receiving an average score of 3.3.

Reviewers observed that the ***Benefit Analysis of Multi-Fuel/Vehicle Platforms with a Focus on Hydrogen Fuel Cell Electric Vehicles*** project's approach is good and uses well-regarded, industry-vetted models to generate results. They recognized the importance of estimating the benefits of DOE R&D but questioned the attribution of benefits to federal programs versus industry and others. They suggested that the model use an estimated market price of hydrogen versus the Hydrogen Analysis model (H2A)-calculated production cost, and criticized the five-year ownership period as being too short. Other suggestions included quantifying air pollutant reductions; adding medium- and heavy-duty trucks; conducting sensitivity analysis around vehicle ownership, vehicle resale value, and discount rate; evaluating the effects of different policy drivers; and increasing industry review and vetting of the work, possibly by adding an industry advisory or steering committee.

Reviewers commented that the ***Employment Impacts of Hydrogen and Fuel Cell Technologies*** project is based on the use of the well-regarded Regional Economic Model Inc. (REMI) model to understand job creation associated with the development of hydrogen infrastructure and production of fuel cell systems associated with automotive and stationary applications. They found the project to be very relevant and critical to examining the economic benefits and job impacts of an expanding fuel cell market, and useful in assessing complex scenarios of employment for a developing fuel cell market. The reviewers recommended expanding the work to include international competitiveness and medium- and heavy-duty fuel cell truck markets, although one reviewer was unclear about the value of the multimarket analysis and suggested that it be better articulated.

Reviewers emphasized the importance of a sustainability analysis tool to support technology evaluation and program decision making and noted the value of such a tool to the broader stakeholder community, including technology developers and end users. They appreciated the ***Sustainability Analysis: Hydrogen Regional Sustainability*** project's efforts to integrate existing data sets and models, noting that this increases the utility and capabilities of models already developed. Reviewers recommended that the project eliminate duplicative work being done by other projects (e.g., water use analysis and regional hydrogen supply analysis), provide additional clarification of input and output metrics, and engage a broader audience (through increased industry collaboration and education/outreach). They also made some specific suggestions about the model's assumptions regarding technology selections and hydrogen cost.

Studies and Analysis: Four analysis projects were reviewed, receiving an average score of 3.3. The projects covered a range of topics, including analysis of incentives and policy, and fuel cell storage cost analysis.

Reviewers generally agreed that the ***Cost–Benefit Analysis of Technology Improvement in Light-Duty Fuel Cell Vehicles*** project is extremely relevant in that it evaluates the value of future fuel cell and hydrogen storage technology improvements to consumers, which will help support R&D target setting and strategic planning. They praised the use of an established and well-respected modeling tool, and the use of assumptions that enable comparisons across component sizing options and vehicle platforms. Suggestions included adding an industry partner or gathering more outside feedback from industry and conducting analysis to evaluate the impacts of reaching various performance goals on total cost of ownership (e.g., fuel cell efficiency, platinum loading, etc.). They supported plans to conduct sensitivity analysis on hydrogen cost and to evaluate possible tradeoffs between cost and efficiency.

Reviewers noted that the ***Resource Availability for Hydrogen Production*** project's approach is technically strong and thorough and properly integrates new efforts with existing models and data. They agreed that updated estimates of regional hydrogen production potential are needed, given the availability of new resource data and technology improvements. They commended the plans to integrate the results into tools such as the Hydrogen Demand and Resource Analysis tool (HyDRA) and the Scenario Evaluation, Regionalization and Analysis model (SERA), which can be used to understand how supply chains may develop in different regions. Suggestions included adding uncertainty analysis for resource potential and production efficiencies; conducting analysis of relative cost, land use, and carbon dioxide emissions of various options; and increasing industry collaboration to vet key assumptions (such as hydrogen production efficiencies and ranges) and increase industry uptake and use of the results.

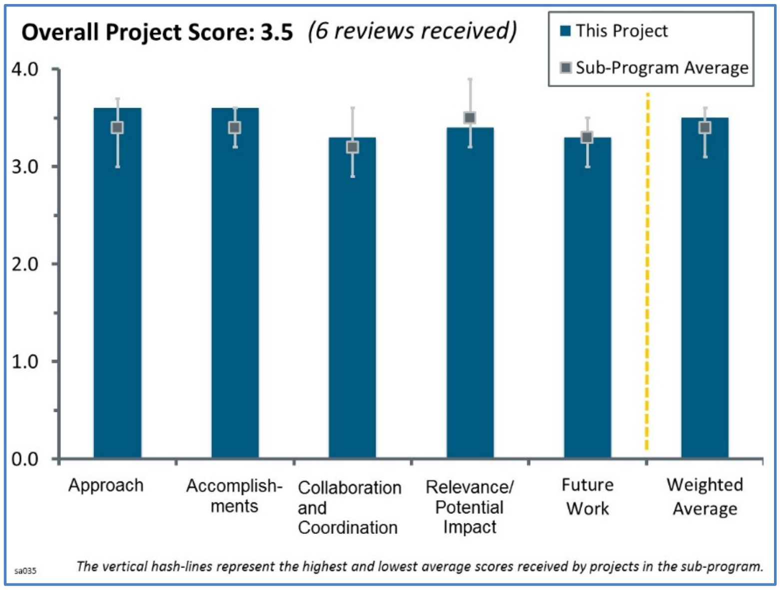
Reviewers commented that the ***Regional Supply of Hydrogen*** project provides data that is key to understanding infrastructure challenges and real costs, and commended its integration with other related analytical efforts. They agreed that the analysis is relevant and addresses options to provide hydrogen to various regions and accelerate the introduction of additional hydrogen refueling stations. Reviewers suggested that the project engage in more collaboration with state agencies such as CARB and CEC, vehicle manufacturers, and other industrial stakeholders. Other suggestions included comparing semi-central gaseous hydrogen with liquid hydrogen delivery and assessing costs for pipelines in urban areas.

Reviewers commented that the ***Hydrogen Analysis with the Sandia ParaChoice Model*** project has a good approach to using previously developed models as input and exploring uncertainties and tipping points. They noted that the project enables market segmentation and market assumption inputs to explore fuel cell vehicle market penetration. Reviewers suggested that the project be reviewed by a larger audience, including OEMs, and expand its collaboration with stakeholders, particularly additional collaboration with industry stakeholders and coordination with other models to minimize redundancy. In addition, the range of values assigned to key variables was unclear, and reviewers suggested these be articulated for transparency.

Project #SA-035: Employment Impacts of Hydrogen and Fuel Cell Technologies

Marianne Mintz; Argonne National Laboratory

Brief Summary of Project:



The objectives of this project are to (1) develop a consistent framework to estimate the impact of hydrogen infrastructure investments by the Fuel Cell Technologies Office (FCTO) and others; (2) develop a tool to address barriers/gaps in the FCTO analysis/ modeling portfolio; (3) evaluate impacts of alternative hydrogen and fuel cell infrastructure deployment scenarios; (4) provide input for evaluating FCTO research, development, and deployment (RD&D) targets; (5) work with stakeholders to develop robust, user-friendly tools with appropriate functionality; and (6) report analytical results to demonstrate benefits of the FCTO.

Question 1: Approach to performing the work

This project was rated **3.6** for its approach.

- The project made use of the Hydrogen Delivery Scenario Analysis Model, H2USA, and several other FCTO capabilities and activities in developing an industry scenario. The RCF Economic & Financial Consulting (RCF) employment modeling work is very well suited to the objective.
- The comprehensive framework was successfully used in 2008. The project makes good use of existing data sets, models, and projections.
- The approach is very impressive.
- The approach seems logical and thorough.
- It is encouraging to see that this work is seeking to avoid siloed modeling efforts and is making a concerted effort to incorporate and/or match several other models that provide key inputs. While the new Regional Economic Models Inc. (REMI) model discussed appears to have provided needed internal consistency, it is unclear what effect the model switch had on the final results, especially considering this appears to have occurred so late in the project’s total timeline. It is also good to see that several of the fundamental assumptions are being updated with today’s understanding and outlook of the fuel cell electric vehicle (FCEV) market, especially the expected rollout of FCEVs. This is important for the project to continue to provide realistic insights and expectations.
- The project uses models across multiple sources (the U.S. Department of Energy, U.S. Department of Commerce, regional sources, etc.), which lends credibility to the approach. The multi-market scenario does not really cover the major demand sectors for hydrogen outside of fuel cell connections; hydrogen generation via the pathways covered in the FCTO portfolio could generate additional employment as well. It should be clarified that these are or are not included in the presentation. The assumptions do consider the most recent and extrapolated oil prices as a single data point, which can shift the projections substantially from year to year. Doing a sensitivity analysis across a few scenarios would be helpful.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.6** for its accomplishments and progress.

- The project so far has answered several questions about the potential employment impact of hydrogen and fuel cell industries. The complexity of all the inputs involved makes this not a simple task, and the completion of such detailed modeling, especially with regional specificity, is a major accomplishment.
- The project represents analysis of a large number of data from various sources and synthesizes it into an understandable format. The dependence on geographic area is also an important element and could be compared to other manufacturing efforts in the United States to develop a strategy for states.
- There are very interesting results. The degree to which material flows are modeled explicitly is not clear. It is very good to be able to draw out distribution and sales jobs.
- The updating of the 2008 employment impacts study made good progress, including completing the development of the Base Case and Core Multi-Market Scenario, 75% completion of the REMI work, and economic analysis work.
- Progress appears to be good. A lot of work is planned for a relatively minimal budget.
- The project seems on track to deliver intended results.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.3** for its collaboration and coordination.

- The project made use of extensive collaboration through the advisory group, which includes industry members and others.
- It is good to see that the project is actively working with advisors and has a stakeholder workshop, given that the results are highly dependent on assumptions and projections. Industry validation and buy-in will also be important if policy decisions are ultimately based on project results.
- There are partners that have contributed to the project in the past, and it is planned that they will come back in future years for specific analyses. The project does discuss interaction with H2USA as an advisory group, but it was not extremely specific in terms of the review provided.
- Multiple parties have been effectively engaged in conducting this analysis work.
- The list of collaborators appears to be appropriate and thorough for the project scope.
- The project could use more industry participation, or academic expertise, in the automotive industry sector.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.4** for its relevance/potential impact.

- This project is absolutely relevant and critical to justifying and advancing the DOE Hydrogen and Fuel Cells Program goals by directly showing the effects on the U.S. job market. Recurring updates are, and will continue to be, critical because of the nature of the underlying projections, market changes, fuel cell technology evolution, and highly variable oil costs.
- The project directly addresses one of the objectives of Systems Analysis sub-program RD&D, and it does so with a thorough and rigorous modeling approach.
- The United States is falling short in meeting requirements of the Energy Policy Act of 2005 (EPAct), and this analysis is needed to quantify those impacts.
- This is a very relevant and important topic for analysis.
- This project is required by EPAct, and therefore, DOE has to complete it.
- While this should not be taken as criticism of the work being done, the relevance of jobs analyses in general is questionable. It seems intuitive that any technology taking market share in the light-duty transportation space will tie to employment. The more relevant question might be the effect on international competitiveness.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- Having a stakeholder workshop is key in providing feedback on the analysis. The groundwork laid already also provides a good foundation for the proposed expansions in scenarios and sensitivity analyses.
- The proposed future work includes tasks that are necessary to completing the study.
- Holding the stakeholder workshop and incorporating updates will be important.
- The future work was simply not stated with a great degree of detail. Overall, the goals seem appropriate, but it is difficult to gauge what the end products of the mentioned topics will be.
- Of the future work items listed, "workforce development needs" seems most actionable.
- There did not appear to be much detail on this topic, but presumably, the continuity to complete the scope and approach presented is the future work.

Project strengths:

- Distillation of a large number of data into a clear picture describing the positive impact fuel cells and hydrogen technologies can have and have had on job creation is a key outcome of this project, which is helping to quantify the benefits to U.S. manufacturing and employment.
- The strength of the project lies in the ability to assess such a complex scenario of employment for a developing market. Additionally, regional insights are valuable, and this may be the only work to date that provides such quantitative assessments of employment outlooks in the fuel cell and hydrogen industries.
- The project's strengths are its relevance and its synthesis of existing projections and data sets. It is, and will continue to be, critical to justify U.S. employment opportunities from continued federal investment into clean, advanced technology development and deployment.
- The Argonne National Laboratory and RCF team is well versed in this type of study, and the project appears to be on track to deliver what is required.
- Integration of both vehicles and fuels (eventually) is a project strength.
- The project is thorough in scope and approach.

Project weaknesses:

- No significant weakness exists.
- No major weaknesses were noted.
- It would be good to better understand the breakdown of contributions to net jobs. Also, if FCEVs become more competitive with conventional vehicles and hybrid electric vehicles, it is not clear whether they will create fewer jobs. It would be good to come away from this presentation with a clearer understanding of this issue.
- There was some difficulty following the presentation of how all the various associated models and data inputs correlated to one another within the project. It was especially difficult to gauge which input factor or model had a greater or lesser impact on output results.
- The team also needs to include medium- and heavy-duty markets in the analysis. Almost 11 million heavy-duty trucks were registered in the United States in 2014, according to the *Transportation Energy Data Book*. The project is missing a big opportunity to account for further job growth.
- The project is questionable in value. Job creation is certainly not the goal of advanced technologies. It is better to focus on workforce needs and the required supply base.

Recommendations for additions/deletions to project scope:

- In the context of H2@ Scale, it would be good to compare the other hydrogen applications on the list where water splitting could penetrate in the near term and the implication on jobs.
- The team should add medium- and heavy-duty vehicles to the project scope, if not already included.
- Sensitivity analyses are mentioned, although it is recommended that these focus on delineating how the various models' outputs feed into and affect the results of this project.

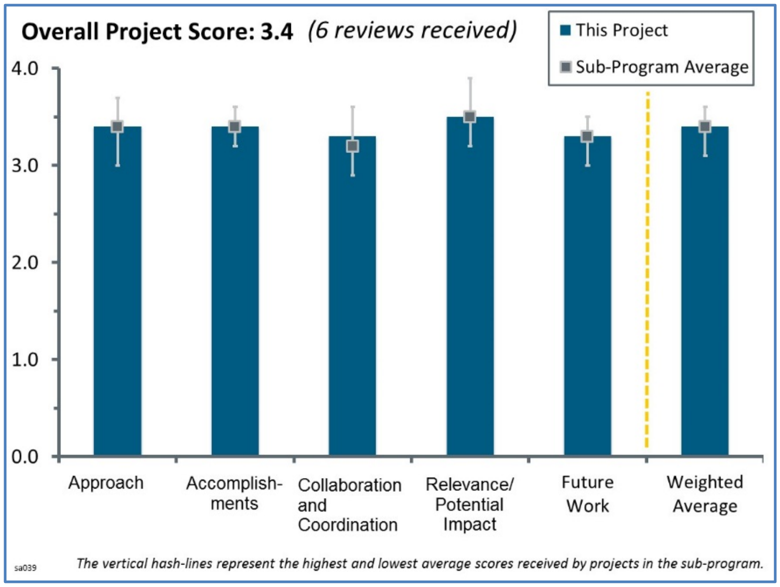
- It is recommended that the project team limit their efforts to the base case, unless the clear value of multi-market analysis can be articulated.

Project #SA-039: Regional Water Stress Analysis with Hydrogen Production at Scale

Amgad Elgowainy; Argonne National Laboratory

Brief Summary of Project:

The Argonne National Laboratory (ANL) has expanded the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET™) model to include water consumption. ANL has (1) identified major contributors in the upstream supply chain to water consumption and (2) evaluated water consumption for the fuel production stage.



Question 1: Approach to performing the work

This project was rated **3.4** for its approach.

- The project has an excellent approach. It is not only addressing the needs of the project at hand but enhancing the capabilities of GREET overall.
- This project follows previous work expanding the GREET life-cycle analysis model to include water consumption and uses the revised model to understand water consumption associated with hydrogen fuels in comparison to other transportation fuels. The project team shows a very good understanding of water consumption aspects over the full fuel production and delivery chain. Use of the water consumption life-cycle analysis features of GREET allows for a consistent approach to assessing the impact of various transportation fuel and vehicle pathways on water resources.
- This is a very important topic for comparing hydrogen to other fuels. The approach is sound, given the limited data and ability to understand substitution or displacement effects across different water uses. Incorporating the water use associated with gasoline miles displaced would be an improvement to the current approach.
- This is excellent analysis, but it needs to be contextualized to water impact relative to current conditions. For example, it needs to reflect the fact that increased water consumption for hydrogen production really displaces two gallons of gasoline production and its associated water consumption. In this sense, western regions where water impact is crucial will show a relief by local hydrogen production, which yields net reduction in water consumption. In this context, it would be best to start producing hydrogen in California to alleviate water stress.
- Overall, the structure of the assessment is good, but it needs to put the water issue in better perspective. The project should compare it, for example, to water usage in a given area, including the major U.S. water usage, which is for agriculture.
- It is unclear how the water value is being calculated. The assumption is that the hydrogen will be produced in the same county it is used. This not a good assumption. It was not clear whether the Available Water Remaining (AWARE) index was invented by ANL or whether someone else devised it. While this addresses potential water stresses, it does not address available water. In many western states, the water rights have mostly been sold off; buying the water rights may substantially increase the cost.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.4** for its accomplishments and progress.

- The study makes important comparisons of the water consumption of various vehicle-fuel platforms and further breaks down water usage from different stages and processes, allowing a good understanding of what process elements drive water consumption. The preliminary county-level regional analyses of water consumption and water stress are excellent. The finalized results will be very useful in understanding how different hydrogen production technologies can be used regionally and how they will affect water resources.
- The initial studies attempt to identify the areas and counties that could be stressed by hydrogen production and others in which the hydrogen production may be a job source. Preliminary data does look very interesting. The areas where people wanted to put in solar (and wind) for water splitting tend to be the areas that are most susceptible to water stress factors.
- This is an excellent project, and ANL is doing a great job attributing and disentangling water consumption and stresses.
- Characterization of a stress index is very valuable. More details of supply chain component locations would improve on the assertion that fuel cell electric vehicle (FCEV) demand centers are driving water demand. Additional context around the economics or policies affecting water use in different regions or watersheds would also be informative.
- The analysis is well done, and results are clearly presented.
- There is good progress, but additional work is needed to better assess water usage overall. It is pretty clear that water usage in the first place is not a major issue/limitation for large-scale hydrogen production, but it needs to be confirmed/quantified.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.3** for its collaboration and coordination.

- The study team appears to have collaborated with the appropriate experts in the field, including water researchers from the federal government, national laboratories, and academia.
- Work has been coordinated with DOE H2@ Scale scenarios and draws from other DOE models such as the Hydrogen Analysis (H2A) model and VISION model.
- There are good collaborations. More policy and economic context may add value to these results.
- The collaboration is adequate.
- It would be prudent to include California water management entities in the process. These entities would have the right framework on how to think about producing hydrogen and reducing transportation water consumption. Also, it would be good if such entities would view this opportunity in terms of tackling their own targets.
- The project team has some collaborators and is using them. It is unclear how the team will validate the model. The industry partners could also make their voices heard.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.5** for its relevance/potential impact.

- These results lay the groundwork to begin to understand water usage and stress. Bringing them to final impacts in terms of economics or external costs—in dollar values—would allow water use to be monetized in a full social cost accounting framework.
- Because much of the focus on new hydrogen production is on water splitting with renewable power, it is important to understand which areas of the country have reasonable water supplies that could be used.

- This project helps expand life-cycle modeling to investigate water consumption associated with various vehicle and fuel technologies, including hydrogen FCEVs, which will be critical in the future.
- This is very relevant research.
- The project confirms a perhaps expected outcome: water usage is not substantial compared to other uses. The project does identify local areas where there may be an issue.
- Water stress is a good starting point, but the more relevant question might be whether access to water presents a barrier to hydrogen at scale. A good next step would be to estimate water costs in the high-stress regions and quantify impacts on end-user hydrogen fuel cost.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- These future work items flow naturally from the work done to date, and all items are important.
- Proposed future activities are appropriate. The continuing emphasis on completing and expanding regional data and regional analyses is critical, as consideration and concern regarding water resources are inherently regional in nature.
- The proposed future work is well-thought-out.
- The project does address the need to expand the evaluation to identify regions of the country where water limitations may be an issue, but it should provide an overall conclusion that, as a whole, water will not be a limitation to an expanded hydrogen energy system.
- It is suggested that the project team add an economics assessment. It is not clear what it takes to procure water in high-stress regions, whether the cost is significant, and which current users of water would likely be displaced.

Project strengths:

- There is continued interest in transportation sustainability. Policies regarding zero-emission vehicles such as FCEVs have been implemented to address air pollution concerns, but it is important to expand the understanding of the life-cycle impact of vehicles to include water resources. This project uses life-cycle modeling to investigate water consumption associated with FCEVs as well as other vehicle-fuel platforms.
- This project has an excellent purpose, a motivated team, and the expertise to quantify the water consumption impact of hydrogen transportation.
- The project has a good, strong team. The team lead is especially strong. The project has done a good job, given limited funding.
- It is great to have a consistent treatment of stress at the county level.
- The project highlights regional differences in water resources that could drive different regional approaches to hydrogen (or other alternative fuels) production.

Project weaknesses:

- The findings on water consumption and water consumption factors established within GREET would benefit from continued peer review. However, this is not necessarily a weakness because the project team is already collaborating with water researchers.
- Adding stresses along a supply chain geographically would be a significant improvement. Context around economics and policy/management issues could also add value.
- The project assumes hydrogen water use is incremental. If a region is truly stressed, displacement of other users seems more likely (assuming hydrogen is higher in value added per unit of water consumed).
- The project needs to put water usage in perspective as a whole by comparing it to existing usage, and identify portions of the United States where water limitations may impede hydrogen generation/ distribution.

Recommendations for additions/deletions to project scope:

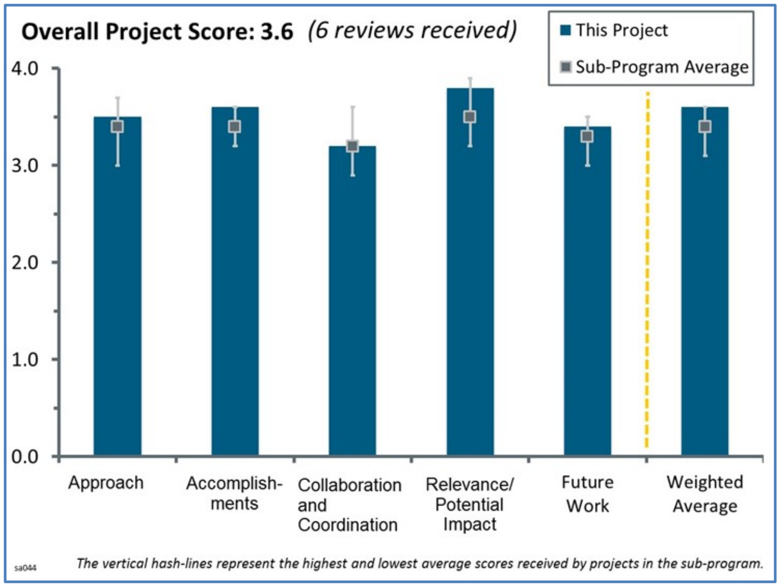
- It is important to try to address net water impacts if future FCEVs are displacing conventional vehicles or hybrid electric vehicles running on liquid fuels.
- The project should connect with southwestern state water management entities in order to ensure the right context of impact is being applied. It will make future interactions with these states smoother and may inform policies being considered by such jurisdictions.

Project #SA-044: Cost–Benefit Analysis of Technology Improvement in Light-Duty Fuel Cell Vehicles

Aymeric Rousseau; Argonne National Laboratory

Brief Summary of Project:

This project aims to quantify the impact of fuel cell system improvements on energy consumption and economic viability of fuel cell electric vehicles (FCEVs). The project will (1) analyze fuel cell stack, hydrogen storage, and fuel cell system improvements in terms of their impacts on the cost of driving FCEVs and (2) evaluate whether current fuel cell and storage technology targets are sufficient to make FCEVs viable.



Question 1: Approach to performing the work

This project was rated **3.5** for its approach.

- Multiple models, including comparisons to expert feedback, provide more grounding to the numbers, and make the work more relevant. Cost-performance benefits are important to help set research and development priorities and decide what "done" is (or what breakthrough needs to happen to break the cost curve).
- The project has a very good analysis framework.
- The approach and study goal are very sound and relevant.
- The project uses the well-known Autonomie model and input from the Office of Energy Efficiency and Renewable Energy (EERE), consistent with the project team's benefits analysis and planning studies.
- The clear description of assumptions was very helpful in understanding the results.
- A particular addition to the approach that could be valuable for the near term would be to add sensitivity to the cost of hydrogen, much the same way as there is a sensitivity to annual vehicle miles traveled (VMT). The $4.00 per gallon gasoline equivalent, while good for gauging long-term development requirements, is unrealistic in today's hydrogen market (and likely for some years to come). There may be opportunity to inform FCEV development in the short-term, but only looking at the cost–benefit tipping points for a hydrogen cost target that is so far in the future may miss other important factors. Otherwise, the approach is sound and the project provides fundamental assurance that U.S. Department of Energy (DOE) targets are valuable for the end consumer.
- The analysis seems rather idealized. It appears that a rather small number of variables were modulated or reported (e.g., efficiency and cost of storage). It is not clear whether there are assumptions on what it costs to achieve such gains. Automakers often use performance gains for improving other vehicle aspects, such as acceleration, range, and towing capacity, so they can compete better with other technologies. The analysis also would be more meaningful if it were contextualized against what may be feasible from other power train competitors (e.g., gasoline, electric vehicle, hybrid electric vehicle, compressed natural gas, and others).

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.6** for its accomplishments and progress.

- The accomplishments today seem to already be directly answering the broader questions in the project's scope. More specific insights may be provided with future work but important high-level messages are already being developed through this work.
- Modeling results demonstrate DOE targets provide a significant benefit if achieved, which is important in determining whether targets should be reassessed.
- The results presented show very good progress in identifying the costs versus benefits of the target points. The inclusion of the three annual vehicle miles scenarios was very helpful.
- There is good progress in setting up cost models and including key sensitivities.
- Apples-to-apples comparisons in terms of vehicle range make results more meaningful and show the impact of each change.
- These results are good in terms of establishing "fair" comparisons across component sizing options and vehicle platforms. However, fuel savings alone may not be the main criteria. It seems that market share is also an important criteria and one that depends upon more than just fuel price.
- A greater level of insight was expected from this application of Autonomie.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.2** for its collaboration and coordination.

- It looks like all of the right inputs and tools are being pulled into the analysis.
- There is a high degree of collaboration with other national laboratories and DOE-funded projects; however, an industry partner may help as particular questions representing gaps in industry knowledge may be posed and seem to be largely addressable through this work. This could increase the overall benefit of the project outcomes.
- DOE tools already developed were effectively used and input from the fuel cell systems team at Argonne National Laboratory (ANL) and industrial input from the U.S. DRIVE Partnership provide educated assumptions on the component and vehicle impacts. The frequency of interaction and method of providing input were not really described.
- There is a good network of collaborators. It is always valuable to get more industry input.
- The project relies on input and assumptions that have been used in EERE analyses for program records and Government Performance and Results Act (GPRA) reports.
- This project could greatly benefit from more input from industry and the fuel cell community. As partners, it appears that only internal resources were applied. It would, for example, be beneficial to include Strategic Analysis, Inc., (Brian James) or automotive companies' perspective behind non-disclosure agreements or even just in a reviewer capacity. It would also be helpful to evaluate various DOE technology development efforts and estimate their impact if they were successful (e.g., catalyst formulations, non-platinum catalysts, higher operating temperatures of stack, and smaller radiators and cooling systems).

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.8** for its relevance/potential impact.

- This project seems critically important as it not only moves toward DOE Hydrogen and Fuel Cells Program (Program) goals but also helps assess and define those goals.
- The project fully supports the Systems Analysis sub-program's mission of integrated analysis in support of various FCTO efforts for optimization purposes.
- The relevance is essential in guiding DOE activities for FCEV performance improvement.
- The project has a very important analysis and vehicle design question to address.

- This project helps to define whether the targets and objectives in the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan are even worth achieving by trading the direct benefits versus the other impacts on parts of the vehicle or system.
- A tradeoff analysis (planned for fiscal year 2017) should be used to provide guidance to technical programs and should be used in assessing overall technical progress. Allowable cost can be used to help screen projects and tradeoff analysis can be used to optimize system configuration in assessing overall program status (e.g., total cost of ownership).

Question 5: Proposed future work

This project was rated **3.4** for its proposed future work.

- The future work seems to address several of the gaps the reviewer identified in the completed work so far.
- The proposed work is necessary. For example, the impact of hydrogen prices and the tradeoff between efficiency and increased cost needs to be better ascertained.
- Plans through the end of project look good. It is important that the final report and tools be useful to FCTO teams.
- The project ends in two months and only has a few validation steps left.
- The proposed future work is fine but this type of modeling could be used to address a broader range of interesting questions. If vehicles are to be subsidized, such as through a "feebate" system that rewards high fuel economy and penalizes low fuel economy, it is not clear what types of vehicles would be "optimal." The effect of a carbon price signal is not clear. If vehicle ownership structures change and these vehicles belong to pools of vehicles that drive many more VMT per year than an average vehicle today, it is not clear what the affect would be. Each of these issues could be informed by this type of modeling.
- Sensitivity analysis parameter selection may stand to benefit from expert insight.
- It is essential to bring in external experts. It would have been better to bring them in at the beginning of the project.

Project strengths:

- The strengths are in combining the available systems-level modeling tools and existing target assumptions to analyze tradeoffs in weight, cost, and efficiency on life-cycle cost.
- Exploration of the design space available to FCEV engineers and the customer-based impacts of those decisions is an important perspective to have. The fact that this project provides an analysis from that perspective is its greatest strength.
- The systems approach and ability to assess cost tradeoffs in applying (or not applying) technical solutions are project strengths.
- Project strengths include the consistency of approach and is a good project goal.
- The project team and model are the same ones used on relevant EERE target-setting and GPRA analyses.
- The project leverages a good peer-reviewed model.

Project weaknesses:

- No major weaknesses are noted.
- The reviewer has no comments on project weaknesses at this time.
- There are no weaknesses, but the General Computational Tool may not be known to some in the audience and may deserve a brief description.
- The project could be broadened to address wider-ranging policy and market questions.
- The project needs more expert insight and industry competitive perspective.
- The presentation of materials needs to be simplified. Assumptions need to be made explicit.

Recommendations for additions/deletions to project scope:

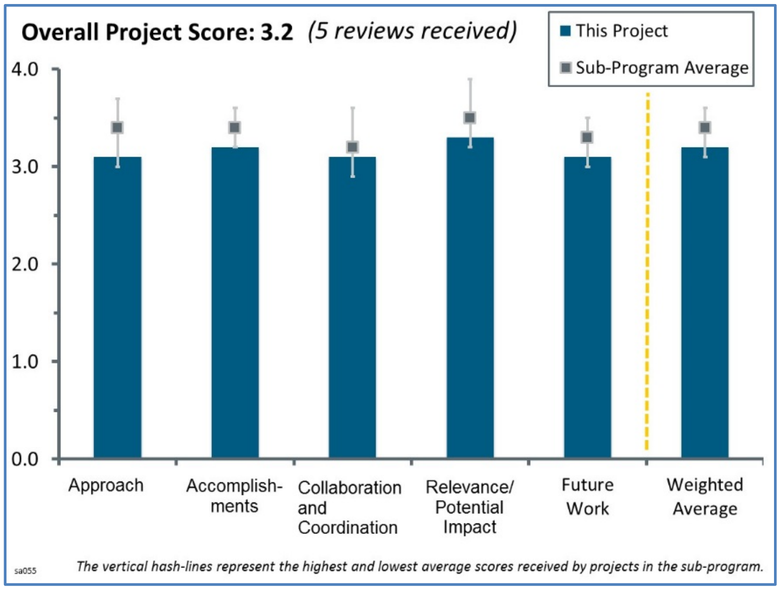
- In another project review, there was a comment that this project could help answer, or at least provide a stepping stone toward answering: a question regarding the cost-benefit effects of reducing platinum loading, at least in terms of the driver's total cost of ownership, as lower platinum loading may require higher purity hydrogen to ensure performance. A lower level of platinum represents a cost savings on a vehicle purchase price, but a higher purity requirement may add an incremental cost increase to operational fuel costs. It is unknown what would be the optimal point from the driver's perspective. This is important to understand: reducing component cost (a goal of the Program) should not result in increasing total cost of ownership. This project seems like it could be used to address a specific question such as this.
- It would be nice to see cost scenarios/tradeoffs incorporated into a single assessment tool with an intuitive user interface.
- A similar analysis would be highly worthwhile for related technologies where the targets exist at this level of detail.
- The project team should consider bringing in expert input external to ANL as soon as possible to improve framing and scope of analysis.

Project #SA-055: Hydrogen Analysis with the Sandia ParaChoice Model

Rebecca Levinson; Sandia National Laboratories

Brief Summary of Project:

The objective of this project is to understand changes to light-duty vehicle stock, fuel use, and emissions through analysis of the dynamic among vehicles, fuels, and infrastructure. ParaChoice parametric analysis will (1) identify trade spaces, tipping points, and sensitivities and (2) help researchers understand and mitigate uncertainty in data sources and assumptions.



Question 1: Approach to performing the work

This project was rated **3.1** for its approach.

- This work is taking an excellent approach to overcome the barriers associated with future market behaviors on fuel cell electric vehicles (FCEVs) and inconsistent data by performing system-level analyses leveraging well-established U.S. Department of Energy (DOE) sources, such as the MacroSystem Model (MSM); Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET); and Autonomie.
- The approach is generally good. The researchers are leveraging several other modeling efforts. There is some concern that they are comparing gasoline and other fuel prices with the levelized cost of hydrogen from the Hydrogen Analysis (H2A) model. The challenge with this approach is that gasoline and other fuel prices are set by the market, whereas the levelized cost does not include market considerations. It would be better if they provided a cost range.
- There is a very good team—including industry and public stakeholders—and good parameters are considered for modeling.
- The study team uses a rigorous approach using a set of well-developed models and analysis techniques to understand how different vehicle platforms might enter the market over time. A next step in strengthening the analysis would be to investigate how modeling and analysis assumptions affect the results. Sensitivities around such things as ownership time window (3 years versus 15 years), vehicle resale value, and consumer penalty for FCEVs would help better demonstrate the robustness of the results and show how sensitive the results are to analysis assumptions. More clarity is needed for the approach used for understanding how key parameters were arrived at by the study team. For instance, hydrogen fuel price is a key parameter used in the analysis. The presentation notes that hydrogen prices were taken from the MSM. The MSM is a modeling tool that allows users to exercise key DOE hydrogen and transportation models at the same time, including H2A, the Hydrogen Delivery Scenario Analysis Model (HDSAM), and GREET. It is not clear what input parameters and variances from the stock model reference cases were changed to develop hydrogen pricing. Stating that hydrogen pricing comes from the MSM does not provide enough transparency on how the study team developed hydrogen prices using the MSM tool.
- On slide 9, it says "Calibrated so national average price in 2015 is ~$12/kg." It is not clear what parameters were used to perform this calibration or what type of dollars those are (nominal/real). It is not clear how this matches with prices seen in California's commercial deployment. Slide 9 shows price drops from $12.00 to $6.25. As this chart spans 2050, it is important to state whether those are real or nominal dollars. It is not clear how the team arrived at $6.25. Slide 9 shows 50,000 kg/day units could serve neighboring states. The team may want to consider urban areas for better relevance of supply and demand estimation of number of units required.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.2** for its accomplishments and progress.

- Excellent progress was demonstrated this year, mainly on the areas around the 2050 hydrogen price projections based on natural gas and coal future prices as well as on the FCEV sales projections based on the analysis of market-driven hydrogen infrastructure.
- This project is progressing well, and the overall project framework is solid. The project is providing useful results, particularly in understanding how hydrogen FCEVs might enter the vehicle fleet over time in comparison to conventional internal combustion engine vehicles and other alternative vehicle platforms. Also, the ability of the ParaChoice model to highlight which parameters most affect vehicle adoption rates is very useful. It is unclear in some instances what was accomplished this year versus previous years. For instance, the business-as-usual sales fraction by vehicle type findings are important, but they were presented at the 2016 DOE Hydrogen and Fuel Cells Program (the Program) Annual Merit Review. Similar sales fraction analyses based on various levels of the Program's success would be an important addition.
- The sales comparisons are very interesting. For slide 15, a parametric analysis is used to predict hydrogen prices. This is very interesting. The only concern is the researchers are using projected coal and natural gas prices, which are generated based on current market prices, to compare a projected levelized cost, which is what H2A generates. It would be more accurate to say "2050 Pump Fuel Hydrogen Levelized Cost" rather than "Hydrogen Price." The projected penetration rates are very interesting. How the team vetted the numbers would be interesting to know. Given the current status of coal and the minimal development efforts in the United States for coal gasification, the projection of hydrogen from coal seems unlikely.
- Accomplishments are reasonably good. The team needs to include some realistic scenarios—particularly current higher growth of battery electric vehicles (BEVs) and emerging autonomous cars.
- Slide 11 shows a nice breakdown of total cost of ownership. The team should consider including BEVs with a 300-mile range (i.e., Tesla-type vehicles).

Question 3: Collaboration and coordination with other institutions

This project was rated **3.1** for its collaboration and coordination.

- The project has some very impressive unfunded partners. It needs to indicate how the partners provided reviews and inputs.
- Based on the interactions and collaborators listed, it seems that there is a good team and expertise available, although is not very clear what the contributions are from some of them, such as other national laboratories (Oak Ridge National Laboratory and the National Renewable Energy Laboratory) and Toyota, who is already entering the hydrogen FCEV market in California.
- The project leverages modeling capabilities and analysis efforts conducted for the Vehicle Technologies Office (VTO) and, based on that work, has collaborated with vehicle manufacturers such as Ford. The project would benefit from additional collaboration with FCEV and hydrogen fuel researchers and analysts. Such collaboration would yield improvements to the study approach and assumptions.
- The collaboration team is good. However, how the project benefits from them in the modeling and analysis should be explained.
- Collaboration could be improved by including technical reviewers from market leaders in FCEV development.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.3** for its relevance/potential impact.

- This project is very relevant to DOE's Fuel Cell Technologies Office because it provides an excellent analysis by including vehicle, fuel (by several production pathways), and infrastructure in the mix, which may provide an indication of possible future market behavior for FCEVs.
- These parametric studies may be able to provide some guidance and direction to hydrogen and fuel cell stakeholders on direction of development.
- The project seeks to provide useful insight into how key parameters such as hydrogen fuel price and FCEV vehicle price affect how FCEVs enter the market and how penetration rates of FCEVs compare to other advanced technology vehicles over time.
- At-home refueling (AHR) would have substantial economic and practical disadvantages because it provides very low utilization and the highest cost on a per-capacity basis. An at-home refueler has only about one fueling per week. While it may be a practical way to test vehicles, AHR would reside at the most unfavorable economics in terms of utilization, economies of scale, and codes and standards (e.g., set back distances and insurance). It is not worth considering AHR in the analysis. It might be more realistic to look at some resource pooling, such as fueling at an office building or campus.
- Distributed hydrogen from on-site solar photovoltaics or hydrogen from tri-generation are excluded, but they may be worth considering.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- The future work on including AHR as well as extending the analysis to include fuel cells in the heavy-duty space are great additions to the current work being performed.
- The project should consider dropping AHR. Heavy-duty FCEVs may be a great opportunity for focus. Interstate traffic congregates in tight corridors, requiring one-dimensional infrastructure coverage (along the highways) as opposed to two-dimensional coverage (along cities). Also, the scale of heavy-duty vehicles will allow economies of scale.
- The future work plan for this project looks appropriate. The study team should (if not already planned) provide vehicle market penetration results over time for a hydrogen FCEV success scenario, in addition to the baseline scenario results that have already been completed. It would be more appropriate in fiscal year 2018 to investigate uncertainty and sensitivity cases around passenger FCEVs to better understand the robustness of the findings than to begin work on heavy-duty FCEVs.
- The project team needs to identify preferred ways to make stations more competitive.

Project strengths:

- This project provides an important analysis of how FCEVs might enter the vehicle fleet and compete with other alternative vehicle platforms. The ParaChoice model helps show which vehicle/fuel parameters most affect the ability of FCEVs to penetrate the vehicle market.
- The project encompasses a wide consideration of competing technologies.
- The DOE sources and models used for the baseline of the work are project strengths.
- The project team is excellent.

Project weaknesses:

- The project needs more analysis to test out uncertainties, analysis assumptions, and the Program research and development (R&D) success cases would strengthen the overall analysis. For instance, investigating the response of FCEVs if no (inconvenience) penalties are assessed in the analysis, or where penalties are reduced to zero over time, would be important for understanding how great an effect that analysis

assumption has on the results. Similarly, analyzing consumer costs over a full 15-year vehicle lifetime or providing for a vehicle resale value assumption for the three-year analysis case are warranted.
- The project needs to benefit from the project team feedback—its latest experience.

Recommendations for additions/deletions to project scope:

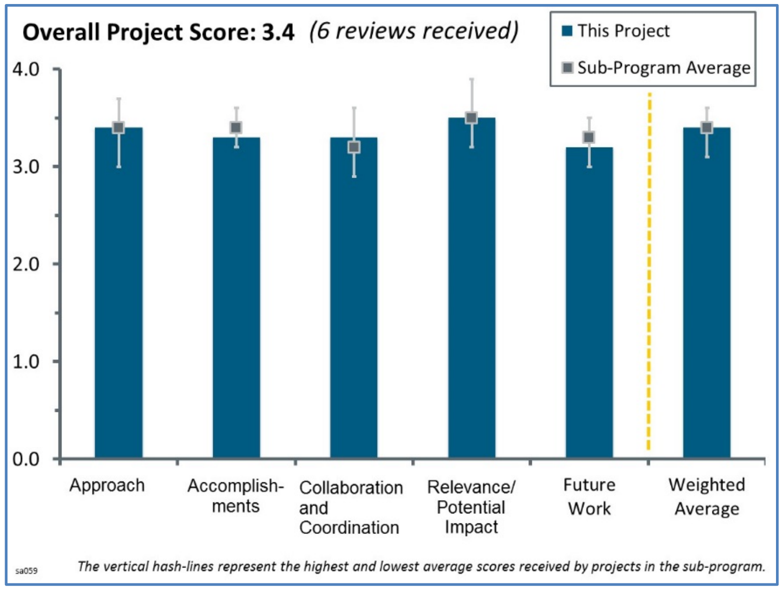
- The project team should make sure to include responses to reviewer comments. They did not seem to be in the presentation this year.
- Completing an analysis of a FCEV and hydrogen fuel R&D success case is a critical addition. Also, additional analysis of uncertainties, modeling assumptions, and sensitivities would provide insight into the robustness of the results.
- There is a good plan.

Project #SA-059: Sustainability Analysis: Hydrogen Regional Sustainability

Marc Melaina; National Renewable Energy Laboratory

Brief Summary of Project:

This project is conducting a sustainability analysis of hydrogen supply and stationary fuel cell systems using the Hydrogen Regional Sustainability (HyReS) framework. Investigators will develop regional metrics around upstream hydrogen supply chains, ensuring consistency with existing frameworks and tools used by engineering firms, the sustainable business community, and green investors. The project will leverage the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET™) model with the spatial detail of the Scenario Evaluation, Regionalization, and Analysis (SERA) model. Outcomes will include pathway cases, a beta framework, and a final public framework.



Question 1: Approach to performing the work

This project was rated **3.4** for its approach.

- Integrating the individual models together to create a single system that can provide a sustainability assessment is a significant benefit to the Hydrogen and Fuel Cells Program (the Program). This will allow a user to answer multiple questions relative to fuel cell vehicles and hydrogen. The only concern is that it is not clear what the final model will look like when the project is done, and what possible inputs and outputs would be. In the future, this should be clarified.
- Integration of the various models better facilitates industry use of the various U.S. Department of Energy (DOE)-sponsored models. The link of GREET and SERA is an outstanding connection.
- This project has a good approach with good collaborative efforts and incorporation of project partners' expertise.
- The project demonstrates good integration of existing data sets and models. It would be good to see an organized, consistent set of output metrics for sustainability that could be used to increase the utility of the tool(s) for a broad audience.
- This work builds upon some other models.
  - The team reinvents information that is available. For example, Argonne National Laboratory (ANL) is doing water analysis, and this project is doing water analysis. Since the ANL analysis is more advanced, this project should incorporate ANL's analysis rather than do its own.
  - The team is including several technologies that are not relevant or at least are not being developed by DOE and, to the reviewer's knowledge, by industry. For example, the team is using biomass gasification for hydrogen production. The Bioenergy Technologies Office program has essentially stopped researching this area. It would be better to use something like pyrolysis or hydrothermal liquefaction oil reforming.
  - The use of the Automotive Deployment Options Projection Tool (ADOPT) and FastSim is a good approach.
- The integrated assessment framework leverages key models such as SERA, GREET, and the Environmental Protection Agency's well-known models.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.3** for its accomplishments and progress.

- Progress is commensurate with time and spending; the case study results, the EV400 and fuel cell electric vehicle (FCEV) assessment, etc. were illustrative of good progress.
- The project's accomplishments are very beneficial. The project team needs further work in describing the accomplishments to a wider audience. There is too much detail in the accomplishments. The team should describe how the accomplishment is progressing toward a larger goal and why that accomplishment is important. The actual details of the accomplishment or how the accomplishment was achieved should be emphasized less.
- The project's analytical results are very useful and encouraging.
- The project's progress appears to be on track for the timeline.
- The water analysis work is duplicative of what ANL is doing, and ANL is further along in the analysis. The team should use ANL's analysis and use the saved funds for other areas. The regional supply of hydrogen is also being done on another project. The team really should coordinate with that work to prevent duplicative efforts. The team chose a biomass gasification pathway, which is not a good pathway. The project really should use something like pyrolysis oil or hydrothermal liquefaction oil reforming. It is presumed that ADOPT uses hydrogen price in its decision-making process. The project is using the Hydrogen Analysis (H2A) model for the hydrogen levelized cost. This hydrogen cost is not a price. Price is set by the market. The project should use hydrogen market prices and not H2A. If H2A is used, the researchers need to give a range. It is not really meant to project prices. ANL is in the process of updating GREET. The project should get the updated version of GREET, as the changes in the emissions GREET is calculating are substantial. At a minimum, the researchers should point out that they are using a levelized cost. This is especially important because the gasoline and other fuels have market-based prices.
- Although the slides claim that 63 indicators were identified in the literature and down-selected, it is not clear which ones were selected, how the selection process was done, and why the particular ones were selected. The team offered no clear path as to what they were trying to accomplish and when they are going to arrive. The goal should be to have the model be compatible with existing sustainability frameworks. It was not clear how or if that is being done.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.3** for its collaboration and coordination.

- The steering team includes a major FCEV manufacturer that is also a world leader in conventional and hybrid electric vehicles, the Institute for Sustainable Infrastructure—a world leader in sustainability ratings—and others.
- The project has excellent collaboration and coordination with proper institutions.
- The project's stakeholder involvement appears to be good.
- The team is collaborating with ANL for the GREET model. Therefore, the team should use the updated version of GREET and use ANL's water analysis work. The steering committee looks impressive, but it is not clear what direction the steering committee has provided.
- Industry participants are interested in this information. Toyota makes cars, not stations. It is unclear why there are no fuel providers collaborating in this effort.
- It would be good to describe what the project steering committee is doing for the team and how the team is using the committee's input and incorporating it into the approach.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.5** for its relevance/potential impact.

- The project is developing an evaluation tool that can help the Program show the sustainability of its technologies to decision makers and major stakeholders in a timely manner—when commercialization starts to pick up.
- This project fits well within the system analysis in evaluating technologies and pathways, including resource and infrastructure issues, guiding the selection of research, development, and demonstration (RD&D) projects, and estimating the potential value of RD&D efforts.
- The project is fundamentally relevant since it addresses environmental and economic sustainability.
- The work is very relevant and has potentially very good impact.
- The project's lack of broader industry collaboration is challenging the impact of this work.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- The proposed work is needed for the Program to have a good sustainability assessment capability, because the identified model integration and data updates will support the results defensibility.
- The team seems more interested in accomplishing technical objectives than making it relevant and useful. There must be a balance between science and education/outreach. This team should dedicate more time to education and outreach. The objective should be "additional steering team members *will* be added."
- The team should work with ANL to integrate the latest version of GREET into the system. The researchers should include ANL's water analysis rather than spend precious time and budget on performing their own.
- It is not clear what it means to "increase relevance to stakeholders by aligning with corporate practices." As described in future work, an important step forward is to automate the integration of simulation platforms and to demonstrate a comprehensive set of pathways.
- Future work appears to be needed but must stay focused on utility and ease of use for broad use and acceptance.
- The project's proposed work builds on good results, but further analysis is warranted.

Project strengths:

- The ability to tie the total cost of such things as water, carbon, system economics, and health to specific vehicles, hydrogen production approaches, and locations is critical to understanding the benefits and challenges of hydrogen and fuel cells. This project combines models together to answer multiple questions with the analysis they each provide. This will result in greater utility for the models already developed and expand their capabilities.
- Project strengths include inherent relevance and progress being made, given the complexity of the issue.
- The integration of complementary capabilities and data sources is the project's major strength.
- This project provides a much-needed analysis for the Program. The steering committee is good.
- This is very relevant and necessary work.
- The project team is the strength.

Project weaknesses:

- While there is no identifiable weakness at this time, the team should attempt to ensure the timely updating of results from the diverse models and projects whose funding may fluctuate in the future.
- This project duplicates the work being done on other projects. Where there is duplication, this project should stop its work and use the work being done by others. The team should not be considering biomass gasification for hydrogen production.

- It would be good to know how case studies are chosen, especially since it appears they are being used as a validation tool.
- One challenge is understanding the capabilities, inputs, and outputs of the model when it is complete and the steps that will be taken to get there.
- Input from operating experience and realistic initial data will improve the value of the analysis.
- The project has a lack of broad industry involvement and a means to provide feedback.

Recommendations for additions/deletions to project scope:

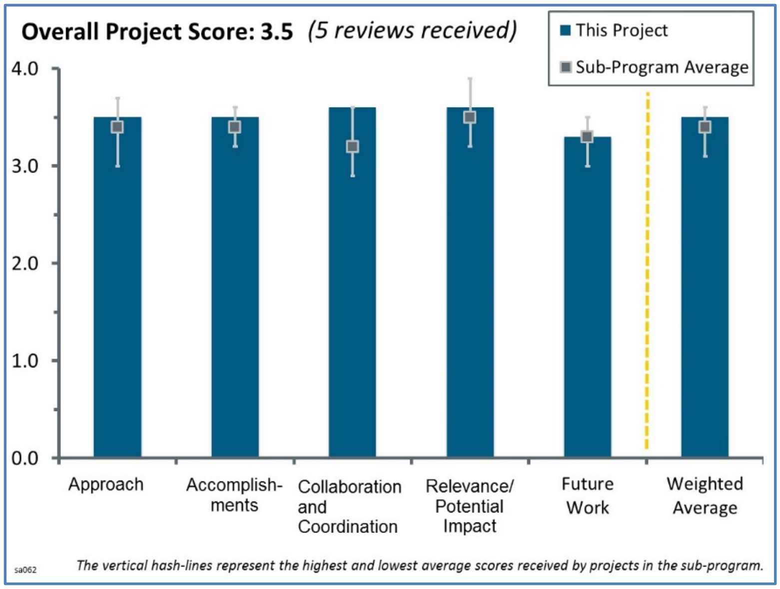
- Societal value and monetization of FCEVs is very important. This is a good start toward that. Continued efforts in this arena are needed for long-term sustainability.
- Framework output needs to be considered and optimized.

Project #SA-062: Hydrogen Financial Analysis Scenario Tool (H2FAST) Updates with Analysis of 101st Station

Marc Melaina; National Renewable Energy Laboratory

Brief Summary of Project:

The Hydrogen Financial Analysis Scenario Tool (H2FAST) enables detailed financial analysis for hydrogen infrastructure. This project is enhancing this tool with new capabilities to facilitate investments in hydrogen refueling stations and improve policy design decisions to support early hydrogen station and fuel cell electric vehicle market development. Examples of enhancements include improvements to usability, risk analysis for any input parameter, multiproduct configurations, multiple feedstock considerations, and expanded concurrent analysis of up to 300 hydrogen stations.



Question 1: Approach to performing the work

This project was rated **3.5** for its approach.

- The team has taken an excellent approach by employing very comprehensive models in addition to the risk analysis studies, which will serve as an enabler for the deployment of hydrogen infrastructure.
- The clear value and benefits of H2FAST are demonstrated. Industry collaboration demonstrates clear use of the model for informing current network development and planning.
- The project has a very good integration/utilization of available resources and models.
- The project has a very consistent and comprehensive approach and a good team.
- The project's work is progressing well, and the accomplishments are in line with what is expected of the model. Last year, the project was asked to provide additional outreach to socialize the software, but efforts to get this done were not seen in the presentation. It is important that the software is used by more than just a handful of stakeholders.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.5** for its accomplishments and progress.

- Cost analysis is critical to the success of advanced vehicles and associated infrastructure. It is necessary to know where research can best be used to improve technology and lower cost, and how cost compares in various areas in the country as a whole.
- Excellent accomplishments have been achieved on this project, mainly by incorporating H2FAST into the Scenario Evaluation, Regionalization, and Analysis model, as well as its use to evaluate real-world stations.
- The team's financial model strategy and parameters are very realistic and useful. Results can be used for commercial purposes for hydrogen stations.
- Each year the project determines new means for adding value to the analysis.
- The project's accomplishments are appropriate; however, it is important to socialize this software more to get additional exposure outside of just a handful of stakeholders.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.6** for its collaboration and coordination.

- Excellent collaboration with other entities to include government agencies, such as the Fuel Cell Technologies Office, the California Energy Commission, and industry partners through H2USA.
- The project has excellent collaboration with multiple institutions having a significant role in financial analysis. In addition, the project utilizes several models to provide a fully integrated assessment.
- This project is well known and well connected to ongoing industry and policy initiatives.
- The National Renewable Energy Laboratory team and collaboration team are excellent and well qualified.
- Coordination with outside stakeholders is appropriate to build the model and get it to run appropriately. However, the team needs to communicate with users to understand who they are, how they are using the model, what features are more useful, and what can be improved. Customer feedback is essential.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.6** for its relevance/potential impact.

- This project is very relevant, as H2FAST will help to provide investors and policymakers with a very comprehensive financial analysis, which will serve as an enabler to the initial rollout of hydrogen infrastructure.
- Financial analysis of various pathways/technology options provides a focus for effective research to best lower costs.
- The growth of stations and making them commercially viable is critical now. This effort is extremely valuable.
- As others have mentioned in previous years, industry will use in-house models to make investment decisions. At this point, it is not necessary to continue to invest resources in the model to improve it. The team should figure out whether customers find it useful and continue to socialize it.
- Beyond internal modeling, H2FAST provides key insights to much of the current station network development. Since site locations contain many variables beyond the H2FAST model, the actual network development is not clearly correlated to the model predictions.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- The project ends September 2017. The completion of planned work through then should provide an effective analysis tool.
- The proposed addition of fixed operating cost will be a great feature, which will further enhance H2FAST.
- The project's regionalization is okay, but it is not really necessary if the user can enter project-specific assumptions, which is already the case. It is a feature that is nice to have, but it is unnecessary. In addition, refining other assumptions is similarly good to have, but is also unnecessary since the user can specify those values.
- For California stations, 50 c/kWh cost seems to be unrealistic, but it was unclear why this estimate was so high. The team should check this estimate and identify solutions for peak hours, perhaps via energy storage. The team should examine the per kilowatt-hour costs of producing its own hydrogen polymer electrolyte membrane power. The project has a very nice work plan.
- The future work should focus on the various station sizes; specifically, the impact of substantial investments in hydrogen supply (liquefaction vs. pipeline). Connection to other models will be critical.

Project strengths:

- The project has a thorough use of existing models and extensive collaborations. A critical objective is to address re-implementation of advanced vehicles and research needs to lower costs.
- The project has a robust model framework, including a knowledgeable team and collaborations with experts.
- The project's team is very strong and suited for the modeling needed for 101st station.
- The great expertise provided by the principal investigator is a project strength.
- The project is very relevant and very useful.

Project weaknesses:

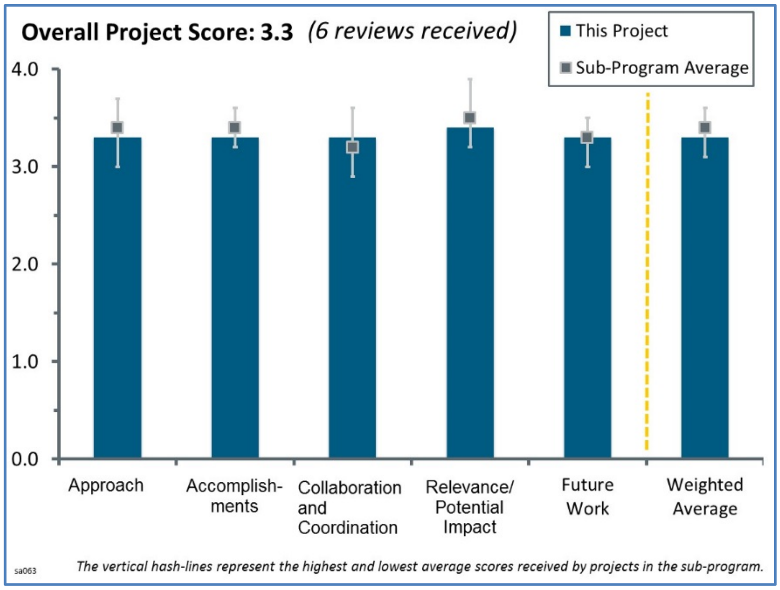
- There are no project weaknesses of significance, except that many assumptions are needed in such an effort. Thus, it is inherently challenging to provide firm financial forecasts.
- The project can operate in isolation far from the users. Better outreach and "customer experience" is needed. The senior leaders of industry are not the users of the model. The project team should use these connections to "dig deeper" into the industry organization to speak directly with the engineers and business analysts using this tool.
- One project weakness is the lack of outreach soliciting customer feedback.
- The project needs to develop scenarios that demonstrate profitable use cases.

Recommendations for additions/deletions to project scope:

- The team should spend more time socializing the model and making it useful to potential investors. There is no need to fine-tune assumptions if the model is flexible enough to accept user input.
- The team should use the model to validate cost estimates for high-capacity stations. The project has a good plan.

Project #SA-063: Regional Supply of Hydrogen

Marc Melaina; National Renewable Energy Laboratory



Brief Summary of Project:

This project aims to estimate existing hydrogen production assets and potential excess production capacity and provide enhanced forecasts for near- and long-term hydrogen supply chains. The analysis forecasts production capacity expansion requirements for the growing fuel cell electric vehicle market demand, simulates regional supply chain network dynamics, and incorporates market competition considerations.

Question 1: Approach to performing the work

This project was rated **3.3** for its approach.

- The researchers have shown an excellent approach, as they are building the work on a very strong and well-established tool: Scenario Evaluation, Regionalization, and Analysis (SERA). In addition, they are incorporating other key elements, such as economic drivers and market competition, for very comprehensive work.
- The project has taken a good approach to addressing the relevant questions and problems identified. By considering “semi-central” production along with compression, the investigators may have identified a new low-cost option for delivery and fueling.
- The key to understanding the infrastructure challenges and the real costs that will be incurred in transportation is the modeling of the existing hydrogen capacity and surrounding radius for delivery and where hydrogen will be used.
- This project’s much-needed study objective is well integrated with other related efforts to understand/optimize regional hydrogen provision for fuel cell electric vehicles (FCEVs).
- The team is using the Hydrogen Analysis (H2A) model to project the price. H2A generates a levelized cost and not a price. The price is set by the market. The team should use a levelized cost range in its analysis to compensate.
    - The team spent a lot of effort looking for hydrogen production numbers, when this information is available on the Hydrogen Analysis Resource Center (HyARC) website, which is now located on H2Tools.org. Other projects that were doing regional analysis used this data.
- The project approach is adequate. However, in the end, production networks will develop based on market conditions, including regulatory requirements, available incentives, and ease of permitting and resource availability, including land for pipelines. These considerations are not yet part of the model.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.3** for its accomplishments and progress.

- Setting up an accurate model for distribution is a large and complex task, which was done well in this project. The project shows the stress points geographically as hydrogen needs increase based on current production. One aspect that was not that clear was how “emerging” technologies were simulated at a centralized scale, given the huge extrapolations that would be required.

- Excellent accomplishments have been made, even on a limited budget. The accomplishments center mainly around the development of the modeling framework for semi-central production, which could serve as a near-term option for regional hydrogen supply.
- The team has made excellent progress towards the objectives, especially given the limited budget.
- The results are good for the level of funding allocated to the project.
- The findings reported so far are fairly obvious. Given the large refining capacity in the South and West, it is not surprising that those regions will have some capacity. Given the agricultural need for fertilizer and given the oil shale in the Midwest, it is not surprising that this area will not have a lot of stress. Finally, given that the Northeast has little in terms of refineries, less demand for fertilizer, and less oil shale, it would make sense that it will be the least stressed.
    - The pipeline rollout scenario of short pipelines seems unlikely. It is unclear that the cost in terms of time to gain permits and litigation fees is not included. It may take years to get the permits in place to put in a pipe and permission to actually start the installation. In this case, it is unclear why the team would do it for only a short couple-mile segments. Use of a natural gas pipeline is okay, but authorities having jurisdiction and the average person are used to natural gas. However, they are not used to hydrogen, which will cause concerns that result in delays, especially for installing a high-pressure line in the middle of a city.
    - The presenter did a good job talking with utilities about natural gas pipeline installation and about costs.
    - It is not clear that it will be utilities that put in hydrogen pipelines, which is assumed, at least in the discussions with the presenter.
- The project's progress is fine. The semi-central solution seems to be an interesting proposition to get hydrogen delivered at low cost. It is not clear how much the high-pressure pipeline would cost per mile, though. It seems that cost was calculated, but it cannot be compared against a traditional pipe with a 3-inch to 6-inch outside diameter.
    - The first and second objectives have not been met, and no information was presented to cover these topics. Nothing was seen in the presentation about calculating hypothetical excess capacity, which would have been interesting to review. Further, there was no information about how capacity expansion would happen to meet a growing demand for FCEVs.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.3** for its collaboration and coordination.

- The team has strong collaboration with numerous other institutions using available resources including past learnings, existing models, and relevant expertise.
- The investigators have worked with non-DOE entities and used varied data sources to carry out the work.
- The team can give good information. The team seems to be California-specific, with both the California Energy Commission (CEC) and the California Air Resources Board (CARB). Representatives from the Northeast would have been good.
- Collaboration with the CEC and CARB is crucial, but there is a need for additional collaborations to make the effort a true nationwide endeavor. Adoption of the results for state planning purposes would deem the project successful; however, these collaborations have not been fully established. There is a need to have the semi-central dispensing model assessed by a pipeline company.
- It would seem that a more collaborative dialogue with the vehicle companies and strategies for consumer preferences would be helpful to better understand how infrastructure and vehicles can be better matched. It was not totally clear why the *Oil and Gas Journal* was viewed as a more credible source than actually interacting with industry. It may be viewed as a neutral source that can provide unattributed data, which should be emphasized.
- Collaborating with the H2A and Hydrogen Delivery Scenario Analysis Model (HDSAM) experts at Argonne National Laboratory is key for this analysis work. It would be valuable to obtain more details on the external reviews mentioned on the presentation.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.4** for its relevance/potential impact.

- This analysis work is very relevant, as it addresses one of the Fuel Cell Technology Office's barriers in understanding future hydrogen market behavior. It will provide some guidance on how regional hydrogen supply, either centralized or semi-centralized, will have an impact on the demand and on the supply strategies.
- This project demonstrates a critical need; addressing how best to eventually provide hydrogen for all or most regions of the United States.
- If the "semi-central" production concept works out, it could have a large impact on the Hydrogen and Fuel Cells Program.
- Understanding the regional pipeline supply of hydrogen is important for DOE.
- The project could potentially help accelerate the introduction of additional hydrogen refueling stations, but it remains to be seen whether this project will remain purely as an academic exercise, or if it will actually be used to plan out expansion of hydrogen production and distribution networks. Collaboration and buy-in from regional planners is crucial to success.
- Understanding the different economic pathways and regional impacts is needed in collaboration with the vehicle companies to determine the most logical rollout strategy, as well as where to prioritize station deployment with distributed or centralized production.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- The proposed future work involves engagement with additional stakeholders and initiatives, which would tie the whole infrastructure story together.
- The incorporation of these concepts into the SERA model and full evaluation of total production and delivery costs is a good addition.
- The integration of the Hydrogen Regional Sustainability (HyReS) project, as well as the further opportunities with H2@ Scale, are very appropriate for the continuation of this work.
- The future work sounds like they are going to finish the model.
    - The team should include some form of validation. This could be a workshop or survey with industry and other stakeholders. They need to ensure there is a balanced participant list, and that one group, such as a state, does not have so much representation that it skews the results.
    - Other uses for hydrogen in addition to filling stations should be considered, especially if there is a pipeline present.
- Continuous updates and integrating results into other models is relevant. Integration of low-carbon fuel standard price signals and integration of non-FCEV markets are the most interesting next steps. It would be good to see additional collaborations with state and local officials to get their input and buy-in.
- The project team has a well-planned study with the right amount of consultation and use of existing resources at associated organizations. Plans for completion are focused correctly, but it is concerning that the budget will preclude sufficient future analysis.

Project strengths:

- The project team has done an excellent job planning, and it has accomplishments to date and plans for project completion with effective use of outside information and available models. In addition, the project has a strong list of proposed reviewers that includes the U.S. DRIVE Partnership Fuel Pathway Integration Technical Team.
- Project strengths include clear analysis of a complex infrastructure and demand system and consideration of several different models. The overall approach is sound and points out potential constraints and transition models.

- This analysis work is critical for understanding near-term and long-term future hydrogen supply strategies for the development of a cost-effective hydrogen infrastructure.
- The project builds on strong analytical experience and expertise. Identification of a novel production delivery scenario is a great development.
- The current SERA model is robust and is comprised of very comprehensive pathways and regional datasets.

Project weaknesses:

- There are no evident weaknesses, except there is a great budget needed for thorough completion.
- The project's compression model seemed a bit simplistic in transportation of high-pressure hydrogen. It is certainly true that centralized compression would save significant cost versus distributed compressors, but the capacity of the pipeline would be severely reduced, and the cost was only listed for the low-pressure option ($800/mile).
- This project has a difficulty of accessing business confidential data. This is always a problem in addressing commercial processes.
- The project does not address the hypothetical excess capacity question. It is unclear how semi-central gaseous hydrogen delivery compares with liquid hydrogen delivery pathways.
- The team needs to include some way of validating the work.

Recommendations for additions/deletions to project scope:

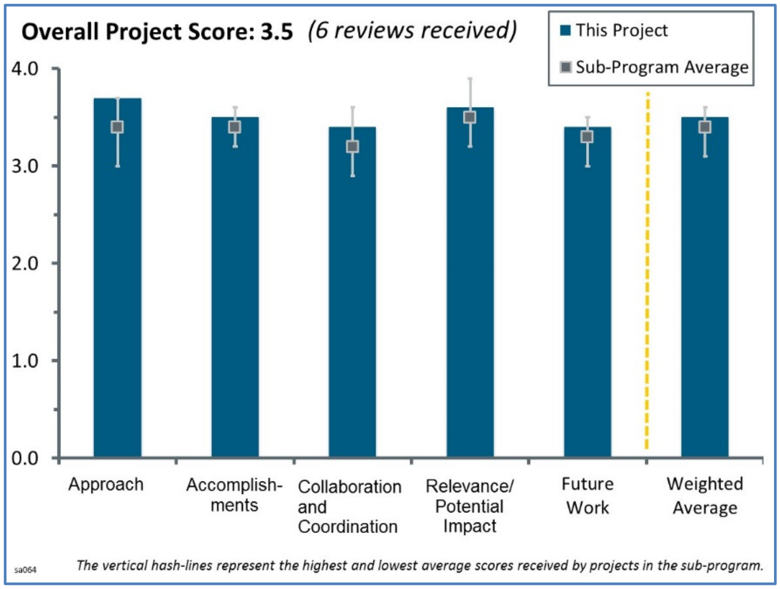
- The project's future work is well laid out. There are no recommendations for additional scope.
- The team should compare semi-central gaseous with liquid hydrogen delivery through the following:
    - Collaborate with state/local agencies to use SERA for planning purposes.
    - Have pipeline assumptions reviewed by a pipeline manufacturer/installer.
    - Assess the use of existing natural gas pipelines to move hydrogen molecules.
- The team should look into costs for pipelines in urban areas for semi-central scenarios.

Project #SA-064: Greenhouse Gas Emissions and Petroleum Use Reduction of Medium- and Heavy-Duty Trucks

Amgad Elgowainy; Argonne National Laboratory

Brief Summary of Project:

The objective of this project is to evaluate comparative petroleum use and air emissions of fuel cell electric vehicle (FCEV) technology and baseline diesel for diverse medium- and heavy-duty vehicles. A well-to-wheel accounting method is used to consider not only direct but also indirect emissions along the fuel supply chain. To conduct the analysis, the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model will be expanded to assess life-cycle petroleum use and air emissions of medium- and heavy-duty FCEVs compared to baseline diesel vehicles. The analysis is based on high-fidelity vehicle dynamic simulation, real-world idle fuel rates, and the most recent heavy-duty vehicle standards duty cycles.



Question 1: Approach to performing the work

This project was rated **3.7** for its approach.

- As noted in the presentation, the work is addressing a significant knowledge gap that currently exists in the FCEV industry. It is encouraging to see that significant effort was devoted to accurately assessing medium-duty vehicle (MDV) and heavy-duty vehicle (HDV) performance during idle engine operation, considering this is often the most pollutant-heavy operation mode of the vehicles, and it often occurs close to local communities. The use of the established GREET model is a good choice.
- It is good that analysis is assessed as an addition to GREET. The project effectively leverages past work. The project approach specifically answers the question of how much air pollution is reduced by fuel cell medium- and heavy-duty vehicles.
- The team uses results from the Fleet DNA Team at the National Renewable Energy Laboratory (NREL) and MDV and HDV components of Autonomie at Argonne National Laboratory (ANL) to improve on U.S. Environmental Protection Agency (EPA) modeling results. The nearly 500 vehicles in the Fleet DNA database provide a good source for selecting the appropriate data to use. The internally consistent Autonomie modeling approach enhances the results' credibility.
- This is a very thorough analysis of the emissions from a variety of vehicle types and original sources of fuels. It also ties to real-world data and fuel use to support the results.
- The project's approach is well-thought-out and addresses the key questions. Including the vehicle idling is extremely important in the applications the team is analyzing. The researchers should be clearer on how they estimated the fuel economy for baseline diesel and fuel cell medium- and heavy-duty vehicles. Simply stating that they used Autonomie to calculate it is not transparent.
- This project has a very nice combination of models and a strong team for collaborative analysis.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.5** for its accomplishments and progress.

- The assessment of fuel economy for multiple drive cycles is a good contribution. Assessing the impact of idling fuel consumption/impact is also a good contribution. Quantification of petroleum fuel reduction and greenhouse gas emissions with use of fuel cell trucks is a key achievement. Overall, the project has good accomplishments, given the size of the budget.
- The preliminary results look very interesting and make a strong case for the emissions side on why this is of interest. It is unclear how the fuel cell and battery power selection were validated. The EPA/National Highway Traffic Safety Administration cycle is a good start, and it was good to hear the project will be looking at other drive cycles. The use of the improved GREET model in the analysis is well done.
- The analysis covered a broad range of duty cycles, vehicle types, and regions. The models demonstrate the benefit of different vehicle types across a range of hydrogen sources.
- This is a very good analysis using models and input from team members, including industry and laboratories.
- The project's progress is very good for the allocated budget.
- One concern is that expansion of GREET to include MDV and HDV was listed as an accomplishment. However, it was unclear if this referred more to the exploration of Autonomie and Fleet DNA and the eventual incorporation of those results into GREET, or if there was some other separate work that was done within GREET specifically. If it is the latter, there did not appear to be any discussion of the validation of those additions. Quantification of criteria air pollutants for medium- and heavy-duty hydrogen fuel applications is also a major accomplishment, as this previously presented a significant knowledge gap.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.4** for its collaboration and coordination.

- Collaboration appears to have been a particular strength in this project's accomplishments so far. The one improvement that may be suggested is to find additional MDV and HDV manufacturers/system integrators to bring into the project. A single partner of this type may rely too heavily on a single market perspective.
- Leveraging of expertise of other groups, across vehicle types, was good. The description of each collaborator's role was clear. One element that might be missing is feedback from the vehicle companies, although the data collected from other consulting groups may already include that data.
- Pete Devlin (DOE Fuel Cell Technologies Office) has a drayage truck project. It would have been good to see collaboration with the industrial team developing those trucks. The industrial team could validate some of the performance assumptions.
- The collaboration with NREL, other ANL teams, industry, and university researchers is excellent.
- The interactions with other team members is very well organized and coordinated.
- The project has a good collaboration with the Autonomie team.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.6** for its relevance/potential impact.

- This project will be critical for emphasizing the benefits of hydrogen-powered MDVs and HDVs, especially in communities that are disproportionately affected by heavy industrial activity. In addition, the work of this project can help policymakers and local air quality agencies make informed decisions to more appropriately gauge and target investments in hydrogen-powered vehicles and infrastructure in order to meet their air quality and climate change goals.

- MDVs and HDVs represent an important and under-investigated sector. They contribute a substantial percentage of emissions. Thus, they are worthy of study to assess the potential savings if converted to fuel cell vehicles.
- Comparison with real-world data provided visibility into accuracy of different models and important parameters to consider.
- There is growing interest in using fuel cells for medium-/heavy-duty trucking. Therefore, this analysis is very relevant and timely. It might be interesting to see how fuel cells for trains, such as metro, would fare.
- As light-duty vehicle fuel consumption begins to stabilize in future years, the rapid increase in petroleum consumption by the HDV and MDV segments justify this project's relevance and impact on the mission of the DOE Office of Energy Efficiency and Renewable Energy (EERE).
- The work is very relevant to DOE plans, as it leads to societal and economic benefits of FCEVs.

Question 5: Proposed future work

This project was rated **3.4** for its proposed future work.

- The project has good plans that include consideration of battery-dominant fuel cell design strategies.
- The project's future work seems to be a logical extension of the existing program.
- The listed proposed future work is extensive and seems complete.
- The proposed work is highly relevant because it will use real-world duty cycles and provide a measure of uncertainty and variations in fuel economy as a function of operating conditions.
- The proposed work is built on good analysis so far; it is well coordinated with team members.
- The team is addressing the key problems.

Project strengths:

- The careful attention to accurate medium- and heavy-duty engine and fuel cell performance is a major strength of this project. In addition, the high degree of coordination with existing tools, and their own separate updates related to this project, is a necessary step for ensuring consistency across studies and data outputs going forward.
- The project makes comprehensive, methodical investigation of MDV/HDV emissions reductions possible with fuel cells. There is effective leverage of existing modeling platforms (GREET, Autonomie). The project has good collaboration and data collection from a variety of sources.
- The presentation as a whole was very informative and clear. The breakdown of the different results under different scenarios pointed out key points for specific conditions, such as idling or variation with season.
- This is a very well-designed and -executed project. The team has collaborators who can provide needed input.
- The use of well-known EERE-funded models and databases, and excellent collaboration and coordination among organizations, are major strengths.
- The project team is very strong and capable.

Project weaknesses:

- No significant weaknesses were noted.
- It appears that higher funding would, to a certain extent, allow more progress to be made in this highly relevant work.
- Adding health benefits from emissions reduction is critical in FCEV justification. It is not planned and, hence, not addressed.
- Validation of the power assumptions needs to be accomplished.
- There are no comments on project weaknesses at this time.

Recommendations for additions/deletions to project scope:

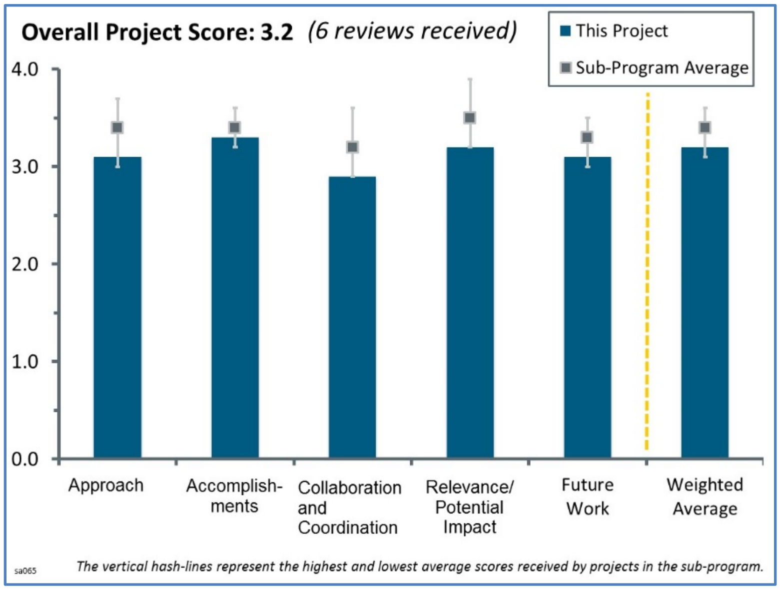
- It is recommended that battery-dominant architectures be considered to determine whether emission benefits differ substantively from those of fuel-cell-dominant architectures. The relatively high production of particulate matter $(PM)_{2.5}$ emissions due to steam methane reforming is not clear. Further clarification and explanation as to why these particulate emissions occur with a gaseous fuel would be of interest. In addition, future studies should consider whether these emissions could very easily be captured at the production plant.
- The project's work as proposed is very good.
- There is no additional scope recommendations beyond the planned future work.
- Considering the budget constraints, no recommendations are made now.

Project #SA-065: Agent-Based Modeling of Consumer Behavior

Marianne Mintz; Argonne National Laboratory

Brief Summary of Project:

This project explores the role of consumer choice in hydrogen technology adoption and infrastructure expansion and seeks to understand how the entire system might evolve through the decisions and behavior of individual actors. Existing agent-based models—which simulate the decisions and actions of individual players in the system—will be updated and extended with new data and lessons learned from vehicle and station owners in the Southern California market. Results of this work provide insight to other U.S. Department of Energy Fuel Cell Technologies Office analyses.



Question 1: Approach to performing the work

This project was rated **3.1** for its approach.

- The approach is based on previous work and appears to have been validated by the researcher continuing the work. The approach seeks to answer technically relevant solutions with a unique solution path. It will provide a very valuable balance to the "top-down" methods employed by other models.
- Agent-based modeling (ABM) is the right approach to gain additional insights that can help influence the deployment rate of new technologies and infrastructure.
- The project's overall concept is good and could provide needed insight into hydrogen fueling station network planning. However, as presented, there are several potential gaps in the input data knowledge base, and not really a definitive resolution determined yet for many of them. In addition to data issues already discussed in the presentation, others that may arise and were not discussed include:
    - The resolution, completeness, and degree of representation of consumer driving patterns, especially with geographical resolution
    - Seed points and resolution used for determination of station location by the infrastructure investment agents
    - Several of the key financial and business decision-making parameters, and metric values required to accurately simulate investor decisions
    - The method of quantifying inconvenience (not the translation into monetary values, but the actual factors and their quantitative metrics that are used to determine and quantitatively gauge inconvenience)
- The project's approach seems sound, but it is unclear to what degree sufficient data will be available to quantify some of the important feedback loops that have been identified. Many are real and important to the Hydrogen and Fuel Cells Program (the Program); however, if sufficient data are not available to tune the feedback loops, relative to each other, then this approach will result in only limited guidance for the Program.
- There is software available that does similar modeling of consumer behavior. It is unclear how this work differentiates from what is available. This work should be funded and done by industry. The comparison of only internal combustion engines (ICEs) and fuel cell electric vehicles (FCEVs) is too limited. There are a large number of existing and emerging technologies—hybrid electric vehicles (HEV), plug-in hybrid

electric vehicles, and battery electric vehicles, as well as compressed natural gas, diesel, and biofuel vehicles—that all could and should be included in this work to make it relevant.
- The project approach is good. However, it would be nice to work toward a tool that could be used by a wider audience to make economic, business, and policy decisions. In addition, it would be nice to see a validation step, such as using a historical case example to compare against actual empirical data (such as market growth).

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.3** for its accomplishments and progress.

- The project has not been in process for very long, but good first steps have been made. It is certainly worthwhile for the computing platform to be updated in order to take advantage of today's capabilities. Some of the collaborative work has started but does not seem to have progressed very far.
- This is just the beginning of the project. Therefore, the accomplishments to date are good but are relatively minor and theoretical. The accomplishments thus far do not yet reflect significant progress. For example, rather than a simple "refresh," the entire feedback loop structure of the model should be revisited and updated according to new conceptualizations of influences and relevant input data.
- This is early in the project, but it is almost a third complete.
- The project began in December 2016 and has not had much time. Considering this, progress is quite good.
- The accomplishments presented were reasonable, given the relative maturity of the current project.
- This project has been going for only a few months, and it has made acceptable progress in that time.

Question 3: Collaboration and coordination with other institutions

This project was rated **2.9** for its collaboration and coordination.

- The list of potential collaborators is complete and representative, although there was not yet a strong sense conveyed for how many are likely to eventually join the project. At the current moment, there is only one auto manufacturer collaborating, and this could be a significant problem for the project.
- At some point in the project, the collaboration network must be extended in such a way to collect feedback from the actual actors to be represented in the model. It will not be sufficient to collect feedback from just industry. For example, state agencies (other than California) and external investors (e.g., green banks) must also be included.
- The short time spent has not allowed for more significant collaboration, but the team intends to significantly increase its collaboration with appropriate entities in the near future.
- The project has an unnamed original equipment manufacturer. The researchers have plans for collaborating with others, but it is not clear if they have reached out to potential collaborators at this time.
- It was not clear that this project has made any attempts to develop collaborative partnerships with industry. Industry participation and collaboration, such as those identified in the presentation, are critical to relevance and accomplishment. The project team should have already started a steering committee or similar group to identify the correct industry contacts and relationships and begin the effort of collaboration with industry.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.2** for its relevance/potential impact.

- This project is extremely relevant. The project risks relevance issues and not meeting its potential through a lack of involvement from industry leaders.
- This project could greatly inform several ongoing efforts to help forecast the needs of a developing fuel cell vehicle market and economy. The project approach is unique among the several other projects that have

been occurring to date, and it has a high chance of providing new information and insights into the station network development work currently ongoing across the United States.

- The model relies on data for fueling station costs, hydrogen prices, FCEV prices and performance, drivers' fueling preferences, etc. These are very relevant to the understanding of factors that affect deployment.
- The potential impact of this project is significant, but the presentation has not focused in on the types of outputs that will be adding significant value to the overall systems analysis suite of models. The goal of "understanding how the system works" is too vague and broad. It seems unlikely that the model will be able to do this. Rather, it may be possible to improve understanding of a few specific feedback loops that can be calibrated using actual empirical data. The "whole system" will be far too complex.
- This work should be funded and done by industry. It is not clear how this will aid DOE in technical development of hydrogen and fuel cells. This seems to primarily aid industry in decision making.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- Items proposed for future work are important and highly relevant but also very ambitious and somewhat duplicative with existing systems analysis projects. A more streamlined approach to accomplishing these tasks by leveraging existing capabilities, rather than starting from scratch, would be most welcome.
- Future work is good, but it would be good to see validation, work toward a usable tool, and impacts of disruptive technologies considered, such as on-demand rides (e.g., Uber and Lyft).
- Given that this is a new project, much of the entire project's work remains as future work to be done. The approach seems sound and the process logical. The one area that could perhaps be described in greater detail is exactly what form of output the project partners are expecting to provide, and what kinds of recommendations for eventual application of the work may eventually be evaluated and reported.
- The proposed future work is to update the team's old model with new algorithms that are now available. The team plans to include other vehicles beyond ICEs and FCEVs. If DOE continues funding this work, the team needs to get other industrial feedback for this work.
- The proposed work includes looking at smaller fueling stations that are more relevant for the near term. Note that future stations could increase in capacity as more FCEVs are on the road.
- The proposed future work satiates the wants and desires of the researchers toward improving the model, but it is unclear to what end or whether it is relevant. No part of the future plans includes the extremely difficult process of collaboration, particularly as industry leaders will certainly provide various and sometimes opposing recommendations. Making a model is easy, but collaborating with industry to make that model relevant is difficult. The project should not do just the easy stuff. The project has a lot of potential, but only if the team does the hard stuff as well.

Project strengths:

- The greatest strength of this project is its implementation of an approach to hydrogen fueling and fuel cell vehicle market forecasting that is not replicated in many other places. This confers a high possibility of new insights to the outcomes of the project. A second strength is the use of a prior model to essentially gain a "head start" on an effort that would typically include significant effort across computer program development, observational data-gathering, and market research.
- This is a very interesting model approach and one that provides a very robust method to simulate the various strategies of market competitors, both station providers and car manufacturers. The model also provides the time-based dynamic changes in the network, which are often missing from simple linear forecast models.
- The strengths are the (still quite novel) bottom-up approach based on user decisions. The presenter provided a good explanation of ABM and input variables.
- Understanding actors within a broader systems context is a good goal. The ABM approach should be able to inform this research question.
- The team uses a model that was built to address this kind of issue, albeit updating it is needed. The planned emphasis on working with other entities, if funded, will be very helpful in making the model more credible.
- The team has an old program that was used over a decade ago. The project does have an industrial partner.

Project weaknesses:

- A significant project weakness is the potential for a skewed market picture based only on the input of a single auto manufacturer collaborator. It is strongly suggested that the project engage a wider range of auto manufacturers to inform this project. It is readily known that each manufacturer has a different target market and audience for its product offerings, different strategies, and therefore different views of the market. While this work is not meant to be predictive, there may still be some bias introduced in review and interpretation of market effects with only one auto manufacturer collaborating.
- It would be good to see more on model validation (understandably difficult here) and to see more on output data sets and products available.
- There is other software that does similar analysis to what is being done, and what is proposed to be done, in this project. This is work that industry, not DOE, should be paying for. The project has a very limited number of technologies it is evaluating.
- It will be difficult to calibrate decision-maker preferences and systemic feedback loops with empirical data.
- The team has a lack of involvement from industry.

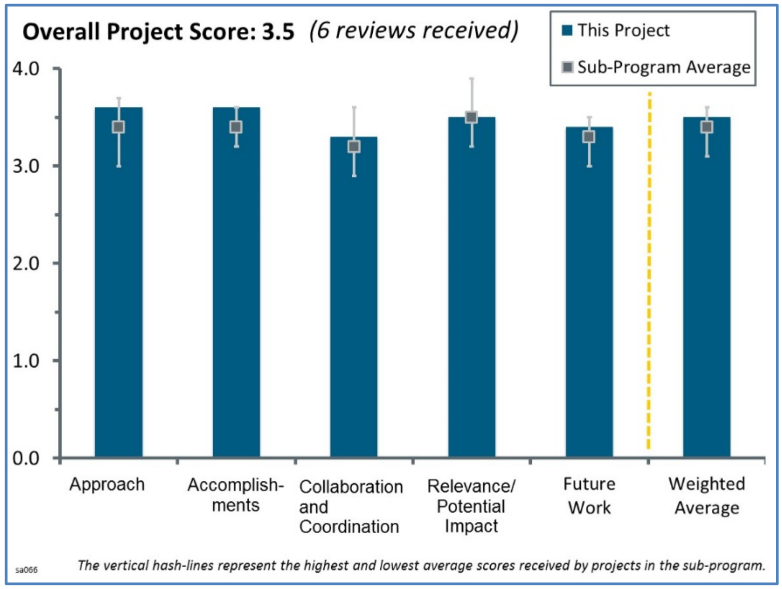
Recommendations for additions/deletions to project scope:

- It would be interesting to compare the insights of this model to the several other model outputs available through DOE and other entities' efforts, and to further compare these to the actual progress of hydrogen fueling network and fuel cell market development over time. A comparison of this type may provide insights to stakeholders on gaps or inconsistencies in their own understanding and forecasts of these two markets.
- The team should develop an effective tool for users to make economic, business, and policy decisions.
- Adding more FCEV types may not be a high priority in the near term.

Project #SA-066: Life-Cycle Analysis of Air Pollutant Emissions for Refinery and Hydrogen Production from Steam Methane Reforming

Amgad Elgowainy; Argonne National Laboratory

Brief Summary of Project:



The objective of this project is to provide life-cycle analysis (LCA) of air pollutant emissions for petroleum fuels and hydrogen production pathways. While fuel cell electric vehicles (FCEVs) have zero tailpipe emissions, there are upstream emissions resulting from hydrogen production, delivery, and compression. To conduct the analysis, emissions inventory and production data for petroleum refineries and steam methane reforming (SMR) hydrogen plants will be acquired, and emissions will be allocated to individual refinery products using flow schemes from linear programming (LP) modeling.

Question 1: Approach to performing the work

This project was rated **3.6** for its approach.

- This project takes a deeper dive into available data to improve the accuracy of the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model to provide life-cycle data on criteria air pollutants. Previous work used sparser secondary data on criteria pollutants to provide life-cycle air pollution estimates. The present study uses refinery data, LP modeling, and U.S. Environmental Protection Agency (EPA) emissions inventories to develop a robust set of data on refinery air pollution, which will improve GREET and enable better regional analysis. The project also takes a deeper dive into hydrogen production from SMR using emissions inventory data and national laboratory SMR facility data to more accurately develop combustion and non-combustion emissions factors for SMR production plants.
- The air pollutant data in GREET was outdated and is based on single point estimates. As criteria pollutants are becoming more relevant, it is necessary to have a better representation of their life cycle in transportation fuels. Argonne National Laboratory (ANL) is doing a good job of finding publically available information, cleaning up the data, and using an LP model to allocate emissions to different refinery products. There is very little room for improvement on this project.
- The use of the LP model to understand dynamics is excellent, especially with plans to expand the number of refineries beyond 11 to increase representativeness of input assumptions. The assumption to include only merchant plants is questionable; some future scenarios with high FCEV or other alternative fuel vehicle penetrations may result in reduced internal demand for hydrogen at the refineries. It is unclear what would happen to the refineries if total domestic gasoline demand declines. It is unclear whether some equipment would be repurposed. This would be scenario-dependent but is still worth examining, and probably not a major effort given the groundwork that has already been done for merchant plants. A corollary to this idea would be repurposing to refine biocrude. If that is worth pursuing analytically, repurposing for hydrogen should also be worthwhile.
- The project's approach is very good. The team used existing data available from DOE as well as industry surveys. It would seem that the EPA should have a lot of these data and have done a lot of this analysis. The team is trying to get data directly from industry rather than rely on inputs from others.
- This is a very nice study, just right in scope and level of detail.

- Use of LCA for this project's core objectives is definitely needed, and the insights the project is looking to create are important for industry and government to understand right now. However, there seemed to be some work that remains to be done with the presentation and interpretation of the data. While significant effort appears to have been put into the baseline emissions inventories and rectifying various sources, there still seems to be too few data available for statistical interpretation, especially considering the small number of data points that may exist in a single region. At least in the presentation, there also seemed to be something wrong with the presentation of the inner-quartile ranges on output emission factors. Therefore, it is difficult to really gauge their validity. Finally, the work as presently formulated seems to address only primary pollutant emissions (National Emissions Inventory, etc.) and does not include secondary pollutant formation. Thus, the total effect of SMR for hydrogen or petroleum is not yet captured for species such as particulate matter. Especially given that sulfur-containing species are also shown to be emitted, the potential secondary pollutant formations could be significant and would need to be accounted for in regional air quality planning.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.6** for its accomplishments and progress.

- The results of this project are very significant.
    - The substantial decrease in the emissions in the new data compared to the previous version of GREET was very important. This implies that many analyses were overstating the emissions from refineries.
    - The efforts to get primary data sources were well worth the work since it improved the accuracy.
    - From the results, it is obvious that this is a much-needed update to the GREET model.
    - The team needs to increase the sample size to the smaller producers.
    - The team should weight the data from the source. For example, data from larger plants and refineries should count more than data from the smaller ones. The reason for this is to prevent a few small dirty sites from skewing the data.
    - It would be interesting if the project would include projections to improvements in the refineries and gas production units.
- The project team has successfully revised GREET modeling of criteria air pollutant emissions from refineries and from SMR-based hydrogen production facilities. Previous criteria air pollutant estimates within GREET were based on secondary data sources and less rigorous emission factor estimations. The work in this study greatly improves the accuracy of GREET results to better estimate criteria air pollutants, both from refinery operations (and hence conventional internal combustion engine vehicles [ICEVs]) and hydrogen SMR production, better reflecting current-technology hydrogen FCEV life-cycle criteria air emissions. Based on this, the project team was able to better estimate well-to-wheels (WTW) criteria air pollutant emissions of conventional ICEVs compared to FCEVs.
- The amount of work that has been accomplished so far is clearly large and important. This work will have far-reaching impacts, especially in helping state and local governments determine the needs for air quality improvement programs and realistic expectations of the impact that can be achieved through SMR-based hydrogen applications. The project adds some degree of collaboration with state and local agencies to ensure that the outcomes and data are the correct pieces of information and in a readily usable form for those jurisdictions to be able to answer the questions they are currently facing. Right now, the project does not make reference to this, which is likely to be one of the most important real-world outcomes of the work.
- It is great to have updated results based upon new data. There is some concern about what may be a "tail" of high emitters that are far from "average" emitters. Perhaps there are other data sources on ambient pollution near refineries that can be used as validation for the overall emissions from particular refineries.
- The project's progress is good. The team is ready to input 2014 datasets to calculate refinery emissions, and the additional SMR data are yielding more accurate/defensible results.
- While it is important to quantify comparative emissions regarding gasoline and SMR hydrogen FCEVs for the United States as a whole, it is clear that FCEVs are substantially better in cities/congested suburban areas. Since current SMR hydrogen production would presumably give way to eventual electrolysis, or bio-

based, or possibly SMR with carbon capture and sequestration, this component should be assigned to any future work.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.3** for its collaboration and coordination.

- The project's collaboration and use of available information, models, and resources is excellent. However, the database is not always ideal with some information considered proprietary.
- The project would benefit from additional industry collaborations to vet criteria air pollutant emissions from refineries/SMR to ensure that data is still accurate within the uncertainty bands, given that public data has not been updated in a few years. Otherwise, collaborations have been appropriate.
- The team has some good collaborations with larger stakeholders. The project needs to increase the collaboration to get more information since the data is from a relatively small set of producers.
- This project was conducted by members of ANL's experienced GREET team, with input from consulting firms on refinery configurations and emissions, as well as national laboratory and industry researchers on SMR plants and process emissions.
- There is a significant gap from apparently not including state and local air quality management agencies as project partners. Industry and academia will likely have interest in the project outcomes, but government agencies are also likely to be major consumers of the data produced by this project. The perspective of the team's information needs related to this topic should be a high priority.
- There should be more data to draw comparisons, such as EPA regulatory data, case studies, and outlier data.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.5** for its relevance/potential impact.

- This project greatly expands data on criteria air emissions for refinery operations and hydrogen SMR production within GREET, improving the accuracy of GREET in presenting WTW emissions of criteria air pollutants for those pathways. This will enable much better evaluations of the local air pollutant emissions of conventional gasoline vehicles to hydrogen FCEVs in non-attainment areas, and in regions deploying zero-emissions vehicles (ZEVs). The updates to GREET also enable better regional analysis of local air pollutants.
- This project underscores fundamental reasons for the Hydrogen and Fuel Cells Program and has the potential to significantly inform several system-wide projects currently underway or potentially occurring in the future. In particular, the H2@ Scale work seems highly likely to benefit from this project, and any follow-on efforts that ensure emissions estimation for other hydrogen production methods are evaluated on an equivalent basis to what has been established by this project.
- As stated in the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan, one of the key benefits of hydrogen fuel cells is the reduction of air pollution. This project quantifies that benefit compared to the incumbent vehicle technology.
- This project provides a much-needed update to GREET.
- Refineries are a critical baseline comparison and source of hydrogen for early FCEV markets.
- SMR is likely the worst case in response to hydrogen generation emissions and is generally better than gasoline or certainly diesel. There is probably not much need to go further. Future lower CO_2 emissions generation processes should be better in response to air pollutants, with the possible exception of bio-based feedstocks.

Question 5: Proposed future work

This project was rated **3.4** for its proposed future work.

- All proposed topics for future work are important and will add value. The project's scope of impact assessment activity should be defined more clearly. Bringing calculations all the way to damage costs on public health would be a significant effort, and perhaps only worthwhile if equivalent comparisons can also be made to competing alternative fuels.
- Proposed future activities are appropriate. Expanding the current work to incorporate data from the 2014 emissions inventory will help improve the accuracy and reliability of data incorporated into the GREET model. Assessing the variability of data and emissions by region will allow for important regional analyses using GREET, particularly the ability to analyze emissions occurring within air pollution attainment areas versus emissions within air pollution non-attainment areas.
- It is suggested that the next public release of GREET rely on more than just journals for review. An effort should be made to reach out to the ultimate end users, especially local and state agencies, and incorporate their comments as appropriate into the review process. The regionalization effort is definitely a good choice, although it may necessitate some broadening of the project scope to include air quality modeling, depending on the ultimate goals for how many factors the regionalized data seeks to account for.
- Future work presents logical steps: adding 2014 refinery data, assessing regional variability, and updating GREET. Publication of results in a peer-reviewed journal is an excellent way to document results.
- The future work seems logical and well-thought-out. The team should include some validation work.
- Minimal additional work is suggested. Comparative emissions are adequately addressed already, except for any future bio-based processes.

Project strengths:

- The potential impact and the current need for the data that this project is developing are particular strengths. In addition, the methodical approach of LCA is a good choice for developing this knowledge base. The project team seems well composed for accomplishing this task.
- Improving GREET data and GREET accuracy for local air pollutant emissions will enable critical evaluations of conventional ICEVs versus ZEVs such as FCEVs—particularly in non-attainment areas.
- Consistent treatment of the entire integrated refinery system is a strength. The LP model seems to provide significant value.
- The project demonstrates strong knowledge of the industry and the GREET model. The team is experienced staff.
- Overall, this is a nice study using available resources and collaboration effectively.

Project weaknesses:

- No weaknesses are evident except that not all emissions data are reasonably available.
- Additional data on new refineries, as proposed in Future Work, is important.
- The largest weakness for this project is the lack of air quality management agency input. More input could help guide the formulation of input and output data products from the project so that the outcomes have the maximum possible impact.
- The database is not comprehensive. It is to be hoped that the 2014 database will be better. Refinery complexity varies, which is not well represented in the results.

Recommendations for additions/deletions to project scope:

- The team should consider presenting results of the LP model either by process unit or by refinery type (refinery complexity makes a big difference in the allocation of emissions). Results of hydrogen FCEVs should be compared not only to gasoline but also to battery electric vehicles, hybrid electric vehicles, plug-in hybrid electric vehicles, and diesel vehicles.
- It would be important to examine refineries under other than business-as-usual conditions, for example, with a greater use of bio-crude or heavier fossil crudes. Alternatively, greater reliance on alternative fuels

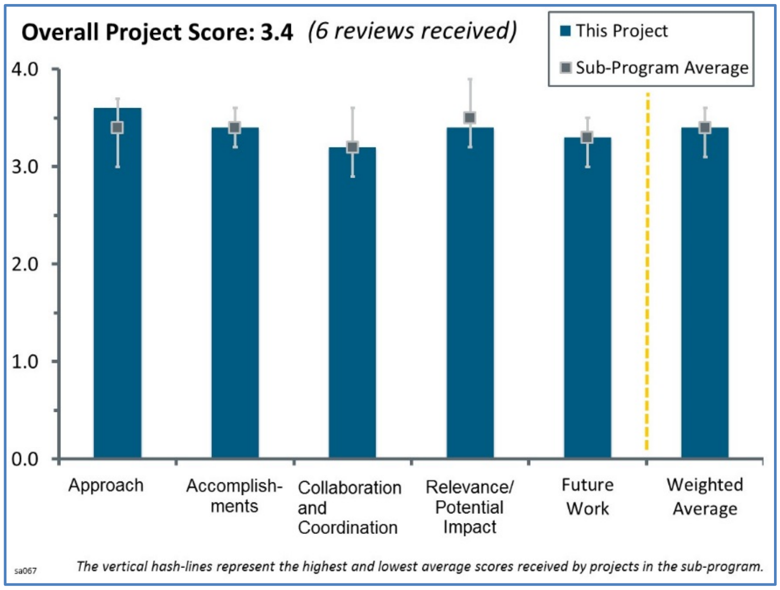
may reduce domestic demand for gasoline/diesel, but it is unclear how refineries might adapt. Perhaps they would export products, or perhaps more hydrogen production capacity could be freed up.

- The project scope seems well planned. The team might carefully consider how broad the modeling tools will need to be to truly capture all the possible information necessary for a regionalized analysis effort.
- It is suggested that the work not be pursued much further since conclusions are already adequate, unless bio-based generation becomes economically viable.

Project #SA-067: Resource Availability for Hydrogen Production

Marc Melaina; National Renewable Energy Laboratory

Brief Summary of Project:



This project seeks to provide insights into the long-term potential to develop a hydrogen infrastructure that is robust, resilient, and economically competitive by improving understanding of energy resource availability and diversity. Specific project tasks include (1) developing an estimate of hydrogen production required for potential future fuel cell electric vehicle (FCEV) demand; (2) updating estimates of hydrogen production potential from a wide range of energy resources, including natural gas, coal, uranium, biomass, wind, and solar; (3) comparing resource requirements for hydrogen to projected consumption in a future without significant FCEVs; and (4) determining resource availability spatially and on a per-kilogram-of-hydrogen basis.

Question 1: Approach to performing the work

This project was rated **3.6** for its approach.

- The approach is extremely valuable to industry and is the type of activity that is well suited to the national laboratories. The work is technically strong, and the approach ensures a clear start and end to the project objectives. The approach also outlines the integration of the new efforts to the existing network of models, along with clear collaboration and leveraging of ongoing co-collaborator models.
- The project is well designed to understand how supply chains may develop in different regions of the United States, depending on resource availability. The tie-in with SA-067 will make the information more usable and valuable. This update was important given the improvements in efficiency of photovoltaic, wind, and biomass technologies. The approach could be improved by including uncertainties.
- The approach was deemed excellent because it identifies a deployment scenario that is sufficient to evaluate the adequacy of resources for hydrogen, with updates to past resource estimates.
- The project is well designed. The project is reliant on, and makes effective use of, existing data from past National Renewable Energy Laboratory reports, H2@ Scale, and the United States Geological Survey (USGS).
- The investigator has used appropriate data, tools, and methods to address the problem.
- The project's basis for study is quite reasonable, but consideration should be given to relative cost and CO_2 emissions potentials of the various options.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.4** for its accomplishments and progress.

- The project has excellent progress from a technical aspect. It is not clear whether this project includes a steering committee or close partnerships, which would facilitate easy uptake of conclusions and guidance.
- This is a well-thought-out and -executed project. Consideration of availability of each individual resource is critical.

- The project's progress is excellent because the team has updated several major resources.
- The project has progressed well. It seems that most of the data have been gathered, and preliminary results are available. Once data are integrated into the Scenario Evaluation, Regionalization, and Analysis (SERA) tool, regionalization of the results will provide more useful information.
- Given the project budget, the investigator has done an excellent job of carrying out the tasks and producing a good product.
- The study itself is quite good using available resources, but it should include CO_2 emissions.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.2** for its collaboration and coordination.

- Collaboration through the use of USGS data is clear. Collaboration with H2@ Scale is not clear. The collaboration slide suggests that only future results will be coordinated with the H2@ Scale project team, implying that formulation and execution of the project so far has not been coordinated. It is the same with USGS.
- Product efficiencies are key model parameters. Collaboration with industry to generate distributions for these parameters would be valuable.
- There is a strong consultation/interaction with other relevant institutions—a nice effort in this regard.
- The investigator has worked with various data sources to assemble the information needed to address the problem.
- Collaboration with USGS, Idaho National Laboratory, and H2@ Scale (planned) was deemed very good.
- The team's collaboration with industry could be much stronger.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.4** for its relevance/potential impact.

- The project supports Multi-Year Research, Development, and Demonstration Plan objectives quite well by factually collecting information and displaying it in a uniform format for a variety of resources. Cross-resource comparisons are not always easy, given the differing reporting metrics and conversion efficiencies. Creation of a transparent and referenceable study on resource availability will enable data use for a variety of needs and other studies.
- This update is definitely relevant to ensure that subsequent analyses such as H2@ Scale, SERA, and the Hydrogen Demand and Resource Analysis (HyDRA) are accurate.
- New fuels need to be evaluated with respect to supply potential. This project is very relevant because it gives a basis to address potential inquiries from stakeholders, particularly through SERA.
- The project has significant potential for significant impact. The project needs to ensure that industry and policy developers are co-collaborators to ensure strong policies are feasible for industry.
- The work clearly shows the availability of relevant resources for regional hydrogen production.
- The study is important in terms of assessing availability of hydrogen generation resources around the United States, but should differentiate resources better in terms of cost potential and CO_2 emissions.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- The proposed work was deemed to be excellent, with a planned report and other output through the SERA model.
- The extension of the work to include transportation is a good direction. It would be interesting to begin to site hydrogen production (biomass gasifiers, solar electrolysis, wind production, etc.) and to begin to look at a technoeconomic analysis (TEA) of producing and delivering hydrogen to market.

- The proposed future work is basically finishing the report and using the results in other models. Additional work could be done to improve the usability of the information, including the following:
    - Provide variability ranges for production efficiencies
    - Assess potential land use from different renewable resources
    - Consider likely availability of resources, given the regional resource mix and available transmission lines
- The proposed future work (assuming funding is available) is very reasonable, but it should address cost projections as well as CO_2 emissions.
- Feeding resource information into SERA is a good move.
- Future work should identify the industry uptake and education steps beyond the creation of a report or list of conclusions.

Project strengths:

- The project has a number of different strengths, including the following:
    - Availability of data: resource potential in 2040, given anticipated technology improvements
    - People resources: researchers involved in original studies are updating information
- This is a well-conceived and well-executed study. Identification of percent-resources needed for hydrogen production is a good metric.
- This project has strong analysis, expertise, and tools. In addition, the project has effective consolidation of data from multiple sources.
- This project is very relevant to the long-term planning and considerations by all hydrogen energy stakeholders.
- The project involves a good overall assessment using available data and working with other institutions with relevant expertise.
- The use of appropriate data sources and the format of the results outputs are the project’s strengths.

Project weaknesses:

- There is a lack of economics. However, this was out of scope, and there certainly was not enough budget for it.
- The project has a lack of uncertainty assessments for resource potential and production efficiencies.
- The project should focus more on the relative cost of hydrogen generation options, as well as CO_2 emissions.
- The project lacks involvement from all stakeholders and industry in particular.

Recommendations for additions/deletions to project scope:

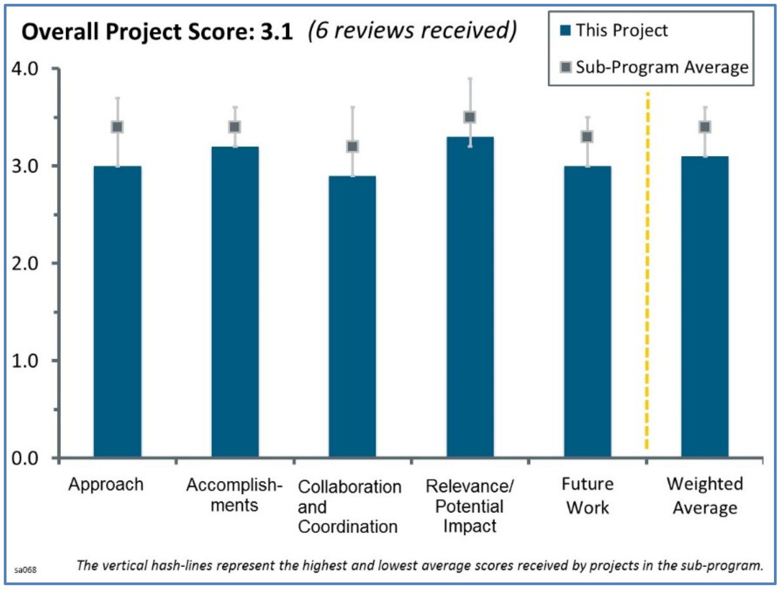
- Additional work could be done to improve the usability of the information, including the following:
    - Provide variability ranges for production efficiencies
    - Assess potential land use from different renewable resources
    - Consider likely availability of resources, given the regional resource mix and available transmission lines
- The hydrogen requirements for 50 million fuel cell vehicles is currently measured against each of the resources to assess the resources’ ability to supply the demand. However, in reality, the demand will be met by multiple resources simultaneously. Thus, the project should consider how this split might be implemented.
- The project should add hydrogen production at appropriate locations and scales and begin TEA for production and transportation.
- There should be a greater focus on the relative cost of hydrogen generation options, as well as CO_2 emissions.

Project #SA-068: Benefits Analysis of Multi-Fuel/Vehicle Platforms with a Focus on Hydrogen Fuel Cell Electric Vehicles

Tom Stephens; Argonne National Laboratory

Brief Summary of Project:

This project seeks to estimate potential future benefits attributable to the Fuel Cell Technologies Office (FCTO) Hydrogen and Fuel Cells Program (the Program), including petroleum use reduction, greenhouse gas emissions reduction, market acceptance of fuel cell electric vehicles (FCEVs), and economic impacts. The analysis utilizes data, models, and tools from various national laboratories and other entities, and synergies and interactions with the Vehicle Technologies Office (VTO) activities are taken into account. Two scenarios—with or without successful deployment of Program and VTO technologies—will be compared.



Question 1: Approach to performing the work

This project was rated **3.0** for its approach.

- The approach to investigate the benefits of FCEVs and other advanced vehicle platforms (including greenhouse gas [GHG] emissions and petroleum use) considering a business-as-usual case and a Program research and development (R&D) success case is very good. The project uses the well-regarded and industry-vetted models, such as Autonomie and Sandia National Laboratories' ParaChoice, to assess vehicle stocks over time, as well as vehicle prices. Additional analysis sensitivity cases would be informative, particularly sensitivities around vehicle ownership (e.g., 3-year, 5-year, 15-year), vehicle resale value, and applied discount rate.
- The approach is sound. This project provides an understanding of the potential societal benefits of the VTO and FCTO activities' meeting their targets, both separately and together, using existing models to predict costs of driving, reduction in fuel expenditures, and FCEV market share. It was good to see these predictions provided for the FCTO only as well as FCTO and VTO combined.
- It is great to have combined results from multiple consumer choice models. Attribution of benefits to Program vs. industry is something that could perhaps be made more nuanced in future work. Significant work has been done to understand the technology innovation process—some of that theory, those data, and/or those case studies should be able to inform these types of analyses.
- The project's approach is reasonably good. Different types of FCEVs—truck vs. bus vs. car—make a big difference.
- FCEV technology was pulled into the market as a result of California's Zero Emissions Vehicle mandate to address air quality. The project should consider including quantification of air quality benefits as part of the analysis. According to the California Air Resources Board, approximately 6,000 premature deaths annually are attributed to air quality; nationwide, this number should be larger. The project should consider monetizing carbon dioxide emission reductions. On slide 9, if the dispensed costs are per gallon gasoline equivalent, the hydrogen costs look a bit low, unless we are considering a pipeline distribution system.
- The following comments apply to the project approach:
  - The use of the Hydrogen Analysis (H2A) model costs as a price input needs to be reviewed. H2A estimates a production cost based upon its many assumptions; it does not include taxes or profit margins. The price is set by the market. The project should use hydrogen market prices and not

H2A whenever possible. Also, H2A was meant to give an apples-to-apples comparison. It has many assumptions specific to H2A that may or may not be correct for each application and region of the country, and it estimates a cost subject to those assumptions.
  - It is not clear whether the delivery cost is included in the hydrogen price.
  - The 5-year ownership period is very short; the project team should consider a 10- or (better yet) 15-year ownership. At 5 years, there is a resale value, especially for the fuel cell and the batteries.
  - For the ownership cost, a range should be used. The error bars seem much too small, given the number of assumptions and the uncertainty in some of the technologies being examined.
  - It is not clear whether policies are being used to encourage or accelerate the adoption of the vehicles. If policies are being used, they need to be spelled out, and a justification for why the policy will stay in place for 30 or more years needs to be given.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.2** for its accomplishments and progress.

- The project team has made good progress on evaluating vehicle ownership costs, projected on-road vehicle stock by powertrain, and GHG emissions for both the business-as-usual and Program success scenarios. Once finalized, these results will help show the benefits of R&D into FCEVs.
- One of the most useful metrics demonstrated is that, if the DOE goals can be met, the levelized cost of driving for an FCEV will be on par with the other vehicle classes.
- The progress is reasonably good, though it is not clear how the collaborative efforts are ensuring the quality of analysis and conclusions.
- On slide 11, it seems that most of the development for this technology is being attributed to the Program. This may be understating the effort and development done by auto manufacturers, states, and other stakeholders. Generally, in the absence of DOE, international efforts would continue. In the long term, technological leadership and profits made from FCEVs will be realized outside the United States, which may be the more significant cost impact of the Program. Regarding slide 13, it may be good to frame the slide as “National Energy Security Benefits.”
- If the projected on-road vehicle stock uses a 5-year ownership, then these numbers are questionable since most vehicles are on the road for 10–15 years. The petroleum savings are interesting; the researchers should consider including the work being done by Argonne National Laboratory (ANL) on medium- and heavy-duty trucks. It is not clear if they are using the most recent version of the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model with the improvements being developed by the other ANL team.
- The hydrogen price trend cited by the team seems very optimistic. It is nice to see attributions to FCTO specifically (slide 14), but it would be interesting to see how some VTO goals may also be helping improve the market competitiveness of FCEVs. Surely there are spillover effects that can be quantified and allocated to VTO targets using this same approach.

Question 3: Collaboration and coordination with other institutions

This project was rated **2.9** for its collaboration and coordination.

- The study team appears to have had appropriate collaboration with researchers from relevant national laboratories and consulting firms, particularly on the VTO side. It is not clear what level of collaboration the study team had with hydrogen and fuel cell vehicle researchers.
- The results have a stronger basis as a result of the project’s using multiple laboratories to develop market share projections. The results would be further improved if other collaborators were used and credited for providing estimates of the fuel economy in the no-FCTO/VTO program case.
- Teaming with other national laboratories is very good. However, industry review for this work is extremely important. An industry advisory or steering committee is recommended.
- Greater scrutiny and vetting by industry could add value.

- The team may want to include an economics institute to help frame the economic benefits. It may be good to have a California entity for this, as they are at the leading edge and have the most forethought on the subject.
- The team should provide more information about how the collaborative efforts produced effective analysis and useful conclusions.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.3** for its relevance/potential impact.

- This project provides information to decision makers as to the benefits of the FCTO and VTO to the development and acceptance of fuel cell vehicles.
- This project, once finalized, helps show the benefits that might accrue with continued R&D into hydrogen fuel cell vehicles.
- The purpose of the project is essential. However, the framing of the benefits could be improved. For example, the project needs to include air quality benefits, energy security impact from locally produced hydrogen, U.S. leadership in technology and manufacturing profits, and GHG emission reductions.
- This project will show the cumulative savings between the VTO and FCTO programs.
- It is important for the team to show market impacts and social benefits of FCTO R&D activities.
- Multifuel and impact-related goals and accomplishments are satisfactory but could be presented more clearly.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The project's proposed future activities are appropriate. The study will benefit from investigating uncertainties and developing sensitivity cases, though the presentation provided little detail on what uncertainties and sensitivities might be investigated. Analysis of study assumptions such as vehicle life, resale value, and discount rate would be particularly useful.
- Evaluating the fuel prices and hydrogen availability will provide a better understanding of the impacts of FCTO and VTO on FCEVs. A large increase in fuel prices or expansion of the hydrogen infrastructure will further strengthen the results. In contrast, low fuel prices and a retarded growth in infrastructure may significantly reduce the FCTO/VTO benefit.
- Examining selective side cases is important, but the team really should consider enlisting some industry and stakeholder input on their approach, assumptions, and results. The team also needs to include the updated GREET models to better understand the emissions, and include fuel-cell-powered medium- and heavy-duty trucks.
- It is important for the project to expand the scope to include medium- and heavy-duty vehicles. However, a proposal to make the overall approach address the innovation process itself more directly would also be welcome.
- It would be helpful to benchmark projections against other studies to understand any differences and considerations.
- The work is almost complete, and no new work is expected.

Project strengths:

- The project's investigation of the benefits of FCEVs and other advanced vehicle platforms (including GHG emissions and petroleum use), considering both the business-as-usual case and a Program R&D success case, is very good.
- This is a very useful project in supporting the benefits of the FCTO to the government and the public.
- This is interesting work that is looking at an important problem. The team has the right tools to accomplish the project goals.

- The project enjoys good consistency across components and vehicle platforms.
- The project's analytical models include reasonable parameters for FCEV and electric vehicle benefits and GHGs.

Project weaknesses:

- The team should consider involving industry to validate the assumptions and results. The team should also update the GREET model.
- The project team should conduct more sensitivity analyses to evaluate the impact of study assumptions to understand the robustness of the study's findings.
- The project may have underestimated the possible impact of non-federal funding (including state and industry) on progress toward the goals.
- The project has a somewhat simplistic approach to innovation and allocation of benefits.
- The project's quantitative parametric analysis may be inadequate.

Recommendations for additions/deletions to project scope:

- The project should consider putting a price on the benefits relative to the cost of meeting these targets. Estimates of cost benefits to health, carbon production, and oil savings, for example, would be useful. Other projects in the Systems Analysis sub-program have done that.
- The project could add more material around different policy drivers and how those may or may not influence FCTO R&D outcomes.

Attendee List: 2017 Hydrogen and Fuel Cells Program

The list below comprises those attendees who registered only for (or primarily for) the Hydrogen and Fuel Cells Program 2017 Annual Merit Review (AMR) (rather than the Vehicle Technologies Office AMR).

Last Name	First Name	Organization
Abbate	Luigi	NOHMs Technologies
Abbou	Sofyane	Michigan Technological University
Abe	Tadashi	The Association of Hydrogen Supply and Utilization Technology (HySUT)
Abraham	Judi	Alliance Technical Services (ATS)
Aceves	Salvador	Lawrence Livermore National Laboratory
Adams	Jesse	U.S. Department of Energy, Fuel Cell Technologies Office
Advani	Suresh	University of Delaware
Adzic	Radoslav	Brookhaven National Laboratory
Afzal	Kareem	PDC Machines
Ahluwalia	Rajesh	Argonne National Laboratory
Ahmed	Alauddin	University of Michigan, Ann Arbor
Ahn	Channing	California Institute of Technology
Akiba	Etsuo	Kyushu University
Alia	Shaun	National Renewable Energy Laboratory
Al-Jassim	Mowafak	National Renewable Energy Laboratory
Alkire	James	U.S. Department of Energy, Fuel Cell Technologies Office
Allendorf	Mark	Sandia National Laboratories
Alrashidi	Abdullah	University of Miami
Anderson	Art	National Renewable Energy Laboratory
Anderson	Everett	Proton OnSite
Anton	Donald	Savannah River National Laboratory
Antoni	Laurent	CEA
Araghi	Koorosh	NASA Johnson Space Center
Ardo	Shane	University of California, Irvine
Arges	Christopher	Louisiana State University
Asazawa	Koichiro	Daihatsu Motor
Atanasiu	Mirela	Fuel Cells and Hydrogen 2 Joint Undertaking (FCH2 JU)
Atanassov	Plamen	University of New Mexico
Atkins	Lance	Nissan Technical Center North America
Autrey	Tom	Pacific Northwest National Laboratory
Ayers	Katherine	Proton OnSite
Azra	Charly	PO-Celltech
Bae	Chulsung	Rensselaer Polytechnic Institute
Bahar	Bamdad	Xergy Inc.
Baker	Andrew	Los Alamos National Laboratory
Baldauf	Christoph	Heraeus Fuel Cells GmbH & Co. KG
Balema	Viktor	Ames Laboratory

Last Name	First Name	Organization
Banas	Charles	University of Connecticut
Bant	Roy	Air Liquide
Barilo	Nick	Pacific Northwest National Laboratory
Baronas	Jean	California Energy Commission
Bartolo	Robert	U.S. Department of Energy, Office of Fusion Energy Sciences
Baturina	Olga	Naval Research Laboratory
Beck	Andrea	Audi AG
Beckman	Michael	Linde LLC
Behling	Noriko	Kyushu University
Beliaev	Alexander	Pacific Northwest National Laboratory
Benjamin	Thomas	Argonne National Laboratory
Benn	Ellen	Johns Hopkins University
Berg	David	W. L. Gore & Associates
Best	Trevor	Syzygy Plasmonics Inc
Biebuyck	Bart	Fuel Cells and Hydrogen Joint Undertaking (FCH JU)
Bigelow	Erik	Center for Transportation and the Environment (CTE)
Blackburn	Bryan	Redox Power Systems
Boardman	Richard	Idaho National Laboratory
Borodin	Oleg	U. S. Army Research Laboratory
Borup	Rod	Los Alamos National Laboratory
Bos	Albert	HyET BV
Bose	Anima	University of Houston
Bouwkamp	Nico	California Fuel Cell Partnership/Frontier Energy
Bouwman	Peter	HyET BV
Bouza	Antonio	U.S. Department of Energy, Office of Electricity Delivery and Energy Reliability
Bowden	Mark	Pacific Northwest National Laboratory
Bowen	Laura	Oak Ridge Associated Universities
Bowman	Robert	Oak Ridge National Laboratory
Boyd	Erin	U.S. Department of Energy
Boyd	Robert	Boyd Hydrogen, LLC
Braaten	Jonathan	Carnegie Mellon University
Braithwaite	Daniel	Ardica Technologies
Brandau	Nils	Volkswagen AG
Bren	Kara	University of Rochester
Brinkman	Kyle	Clemson University
Broerman	Eugene “Buddy”	Southwest Research Institute
Brooks	Kriston	Pacific Northwest National Laboratory
Brouwer	Jack	University of California, Irvine
Brown	Craig	National Institute of Standards and Technology
Büchi	Felix	Paul Scherrer Institute
Burgunder	Albert	Praxair, Inc.

Last Name	First Name	Organization
Burke	Kenneth	NASA Glenn Research Center
Butler	Donald	Midwest Hydrogen Center of Excellence
Butsch	Hanno	National Organization for Hydrogen and Fuel Cell Technology (NOW GmbH)
Buttner	William	National Renewable Energy Laboratory
Byham	Stephanie	CSRA International
Calabrese Barton	Scott	Michigan State University
Campbell	Tom	University of Houston
Cannova	Catherine	The Boeing Company
Capuano	Christopher	Proton OnSite
Ceballos	Bianca	University of California, Irvine
Ceder	Gerbrand	Lawrence Berkeley National Laboratory
Chapman	Bryan	ExxonMobil
Chellappa	Anand	Intelligent Energy
Chen	Shuo	University of Houston
Chiba	Yutaka	Honda R&D Co., Ltd.
Chigusa	Sean	TATSUNO NORTH AMERICA, INC.
Childress	Anthony	Clemson University
Chiteme	Cosmas	Department of Science and Technology, South Africa
Choi	Wonbong	University of North Texas
Chou	Katherine	National Renewable Energy Laboratory
Choudhury	Biswajit	DuPont
Chow	Yachun	California Air Resources Board
Christensen	John	National Renewable Energy Laboratory Consultant
Christner	Larry	LGC Consultant LLC
Christopher	Daron	U.S. Department of Energy
Chu	Deryn	U. S. Army Research Laboratory
Chung	Hoon	Los Alamos National Laboratory
Chung	T. C. Mike	The Pennsylvania State University
Cole	James	CFD Research Corporation
Colella	Whitney	Gaia Energy Research Institute
Collins	Kevin	CP Industries Holdings, Inc.
Collins	William	WPCSOL, LLC
Colon-Mercado	Hector	Savannah River National Laboratory
Connelly	Elizabeth	National Renewable Energy Laboratory
Conrad	Kirt	Stark Area Regional Transit Authority
Coppage-Gross	Jacob	CertainTech Inc.
Corgnale	Claudio	Greenway Energy LLC
Cornelius	Chris	University of Nebraska
Crawford	Lalida	U.S. Department of Energy
Cresce	Arthur	U.S. Army Research Laboratory
Crum	Matthew	W. L. Gore & Associates, Inc.

Last Name	First Name	Organization
Cullen	David	Oak Ridge National Laboratory
Curry-Nkansah	Maria	Argonne National Laboratory
Dale	Nilesh	Nissan Technical Center North America
Dameron	Arrelaine	Forge Nano
Danilovic	Nemanja	Lawrence Berkeley National Laboratory
Das	Sujit	Oak Ridge National Laboratory
Datta	Moni	University of Pittsburgh
Daum	Johannes	National Organization for Hydrogen and Fuel Cell Technology (NOW)
Davenport	Rachel	Alliance Technical Services (ATS)
David	Thomas	WireTough Cylinders, LLC
De Castro	Emory	Advent Technologies, Inc.
de Valladares	Mary Rose	International Energy Agency – Hydrogen Implementing Agreement
DeCuollo	Gerald	TreadStone Technologies Inc.
DeSantis	Daniel	Strategic Analysis, Inc.
Deutsch	Todd	National Renewable Energy Laboratory
Devlin	Pete	U.S. Department of Energy, Fuel Cell Technologies Office
Dewey	Patrick	Bosch
Dickinson	Robert	Hydricity Systems Australia
Dillich	Sara	U.S. Department of Energy (retired)
Dimitrievska	Mirjana	National Renewable Energy Laboratory/National Institute of Standards and Technology
Dinh	Huyen	National Renewable Energy Laboratory
Dobbins	Tabbetha	Rowan University
Doerr	Thorsten	Heraeus Fuel Cells GmbH
Dornheim	Martin	Helmholtz-Zentrum Geesthacht
Dudney	Nancy	Oak Ridge National Laboratory
Durand	James	Midwest Hydrogen Center of Excellence
Ede	Rama	Plug Power Inc.
Edgecombe	Brian	Materia Inc.
Edwards	David	Air Liquide Advanced Business and Technologies
Ehrhart	Brian	Sandia National Laboratories
Eichman	Joshua	National Renewable Energy Laboratory
Elangovan	Elango	Ceramatec, Inc.
Elgowainy	Amgad	Argonne National Laboratory
Elrick	William	California Fuel Cell Partnership
Elvington	Mark	Savannah River Consulting
Elwell	Jessica	Ceramatec, Inc.
Epping Martin	Kathi	Alliance Technical Services (ATS)
Ermanoski	Ivan	Sandia National Laboratories
Esposito	Daniel	Columbia University

Last Name	First Name	Organization
Eudy	Leslie	National Renewable Energy Laboratory
Ewan	Mitch	Hawaii Natural Energy Institute
Fabian	Tibor	Ardica Technologies Inc.
Faivre	Laurent	Aperam
Farese	David	Air Products
Farhad	Siamak	University of Akron
Farmer	Richard	U.S. Department of Energy, Fuel Cell Technologies Office
Feng	Zhili	Oak Ridge National Laboratory
Fisher	Leah	CSRA International
Flowers	Daniel	Lawrence Livermore National Laboratory
Fong	Henry	SRI International
Fontaine	Joseph	Naval Undersea Warfare Center Division Newport
Forrest	David	U.S. Department of Energy, Advanced Manufacturing Office
Fortin	Stephane	ENGIE
Frisk	Joseph	3M Company
Frois	Bernard	CEA
Frost	Mary	Duke Energy
Fujita	Etsuko	Brookhaven National Laboratory
Fullenkamp	Patrick	GLWN
Fultz	Brent	California Institute of Technology
Funk	Stuart	LMI Government Consulting
Furusawa	Koichiro	Honda R&D Co.,Ltd.
Gagliano	Joe	California Fuel Cell Partnership
Gaillard	Nicolas	University of Hawaii
Ganesan	Prabhu	Greenway Energy LLC
Gangloff	John	U.S. Department of Energy, Fuel Cell Technologies Office
Gardiner	Monterey	BMW Group
Garland	Nancy	U.S. Department of Energy, Fuel Cell Technologies Office
Garsany	Yannick	EXCET, Inc.
Garzon	Fernando	University of New Mexico/Sandia National Laboratories
Ge	Qingfeng	Southern Illinois University
Geiman	Laura	W. L. Gore & Associates, Inc.
Gennett	Thomas	National Renewable Energy Laboratory
Gervasio	Dominic	University of Arizona
Ghezel-Ayagh	Hossein	FuelCell Energy, Inc.
Giles	Lauren	Energetics Incorporated
Gillette	Eleanor	National Institute of Standards and Technology
Girard	Francois	National Research Council Canada
Goodarzi	Abas	US Hybrid
Gordon	Bryan	Ivys Inc.
Goto	Risei	Sumitomo Corporation of Americas
Gottesfeld	Shimshon	Fuel Cell Consulting, Ltd.

Last Name	First Name	Organization
Graetz	Jason	HRL Laboratories
Grassilli	Leo	U.S. Department of the Navy, Office of Naval Research
Greene	David	University of Tennessee
Greenfield	Carl	International Technology and Trade Associates (ITTA)
Greenway	Scott	Greenway Energy LLC
Gross	Thomas	Consultant
Grot	Stephen	Ion Power
Groth	Katrina	Sandia National Laboratories
Gryniewicz	Anthony	U.S. Department of Energy
Gupta	Erika	U.S. Department of Energy, Fuel Cell Technologies Office
Gupta	Ram	Virginia Commonwealth University
Haak	Nico	SGL Carbon GmbH
Habibzadeh	Bahman	U.S. Department of Energy, Fuel Cell Technologies Office
Hamdan	Monjid	Giner, Inc.
Hamilton	Jennifer	BKi
Hancke	Ragnhild	Institute for Energy Technology
Hanlin	Jason	Center for Transportation and the Environment (CTE)
Hansen	Erik	Millennium Reign Energy
Hardy	Bruce	Savannah River National Laboratory
Harned	Alleyn	Virginia Clean Cities
Harris	Aaron	Air Liquide Advanced Technologies
Harris	Alexander	Brookhaven National Laboratory
Harris	Tequila	Georgia Institute of Technology (Georgia Tech)
Harrison	Kevin	National Renewable Energy Laboratory
Harting	Karen	Allegheny Science & Technology
Hartman	Brent	CSA Group
Hartmann	Kevin	National Renewable Energy Laboratory
Hartnig	Christoph	Heraeus Fuel Cells GmbH
Hatanaka	Tatsuya	Toyota Central R&D Labs., Inc.
Hato	Kazuhito	Panasonic Corporation, Advanced Research Division
Hatzell	Kelsey	Vanderbilt University
Haug	Andrew	3M Company
Hays	Charles	California State University, Los Angeles
Hayter	Dennnis	Intelligent Energy
Head-Gordon	Martin	University of California, Berkeley
Hebling	Christopher	Fraunhofer ISE
Hecht	Ethan	Sandia National Laboratories
Heffner	Rusty	Booz Allen Hamilton
Heller	Claude	Air Liquide
Hellstern	Thomas	Stanford University
Hennessey	Barbara	U.S. Department of Transportation, National Highway Traffic Safety Administration

Last Name	First Name	Organization
Heo	Tae Wook	Lawrence Livermore National Laboratory
Herring	Andy	Colorado School of Mines
Heske	Clemens	University of Nevada, Las Vegas
Hess	Richard	Idaho National Laboratory
Hibbs	Michael	Sandia National Laboratories
Hicks	Michael	H2PowerTech
Hill	Laura	U.S. Department of Energy, Fuel Cell Technologies Office
Hilliard	Samantha	Clean Horizon Consulting
Hilmi	Abdelkader	FuelCell Energy, Inc.
Hirano	Shinichi	Ford Motor Company
Ho	Donna	U.S. Department of Energy, Fuel Cell Technologies Office
Hobbs	Milton	Miltec UV International
Hofmann	Karsten	Continental Automotive GmbH
Holby	Edward	Los Alamos National Laboratory
Holladay	Jamie	Pacific Northwest National Laboratory
Holland	Wendolyn	Holland Consulting, LLC
Houchins	Cassidy	Strategic Analysis, Inc.
Hovsapian	Rob	Idaho National Laboratory
Hu	Leiming	Carnegie Mellon University
Hu	Shu	Yale University
Huang	Chiu-Ping	Industrial Technology Research Institute
Huang	Kevin	University of South Carolina
Hulvey	Zeric	U.S. Department of Energy, Fuel Cell Technologies Office (ORISE Fellow)
Hunter	Chad	National Renewable Energy Laboratory
Hurkmans	Ton	IHI Ionbond Group
Hurst	Katherine	National Renewable Energy Laboratory
Hussey	Daniel	National Institute of Standards and Technology
Huya-Kouadio	Jennie	Strategic Analysis, Inc.
Igarashi	Hiroshi	N.E. Chemcat Corporation
Iiyama	Akihiro	University of Yamanashi
Ikeda	Tetsufumi	The Association of Hydrogen Supply and Utilization Technology (HySUT)
Ilevbare	Gabriel	Idaho National Laboratory
Impullitti	Joseph	South Coast Air Quality Management District
Irwin	Levi	ManTech/U.S. Department of Energy, SunShot
Ito	Hiroshi	National Institute of Advanced Industrial Science and Technology (AIST)
Jacobson	David	National Institute of Standards and Technology
Jadun	Paige	National Renewable Energy Laboratory
Jakupca	Ian	NASA Glenn Research Center
James	Brian	Strategic Analysis, Inc.

Last Name	First Name	Organization
James	Rachel	Hawaii Center for Advanced Transportation Technologies
James	Will	U.S. Department of Energy, Fuel Cell Technologies Office
Jankowska	Joanna	University of Southern California
Jaramillo	Thomas	Stanford University
Jawahar Hussaini	Syed Mubeen	University of Iowa
Jaworski	Casey	Tanaka Kikinzoku International, Tsukuba Technical Centre (TKK)
Jensen	Craig	University of Hawaii
Jerram	Lisa	Navigant
Jhang	Shengshui	U.S. Army Research Laboratory
Jia	Hongfei	Toyota Motor North America, Inc.
Jiang	Rongzhong	U.S. Army Research Laboratory
Johnson	Terry	Sandia National Laboratories
Johnson	Webb	Pajarito Powder, LLC
Joseck	Fred	U.S. Department of Energy
Jung	Chiyoung	Korea Institute of Energy Research
Kakimoto	Seizo	Nissan Chemical Industries, Ltd.
Kanesaka	Hiroyuki	FC-Cubic TRA
Kang	ShinYoung	Lawrence Livermore National Laboratory
Karabacak	Tansel	University of Arkansas at Little Rock
Karathanou	Argyro	FCLAB
Kast	James	U.S. Department of Energy, Fuel Cell Technologies Office (ORISE Fellow)
Kato	Kei	Sumitomo Corporation of Americas
Keller	Jay	Zero Carbon Energy Solutions
Kent	Ronald	Southern California Gas Company (SoCalGas)
Kikuchi	Takamasa	Nissan Chemical Industries, Ltd.
Kil	Janet	Oak Ridge Associated Universities
Kim	Beomjun	Korea Institute of Energy Research
KIM	JUN YOUNG	KOLON Industries, Inc./KOLON Central Research Park
Kim	JuYong	J&L Tech Co., Ltd.
Kim	Kiyoung	ILSUNG
Kim	Sangil	University of Illinois, Chicago
Kim	Yongmin	Stanford University
Kim	Yu Seung	Los Alamos National Laboratory
Kimball	Brett	ADC
Kimura	Tatsusaburo	Sumitomo Corporation
King	Joel	Alion Science and Technology
King	Laurie	Stanford University
Klawitter	Jan	Anglo American plc
Klebanoff	Leonard	Sandia National Laboratories
Kleen	Greg	U.S. Department of Energy, Fuel Cell Technologies Office

Last Name	First Name	Organization
Klusky	Blaine	Ardica Technologies, Inc.
Knights	Shanna	Ballard Power Systems
Kocha	Shyam	National Renewable Energy Laboratory
Kollar	Lenka	NuScale Power
Kondo	Shinji	Sumitomo Corporation
Kongkanand	Anusorn	General Motors
Kopasz	John	Argonne National Laboratory
Koski	Brent	United Hydrogen Group
Kothavala	L.	Arizona State University
Kraigsley	Alison	National Institutes of Health, National Institute of Allergy and Infectious Diseases
Kramer	Matthew	Ames Laboratory
Krause	Theodore	Argonne National Laboratory
Kreutzer	Cory	National Renewable Energy Laboratory
Kumar	Amod	Nissan Technical Center
Kumaraguru	Swami	General Motors
Kuppa	Shashi	National Highway Traffic Safety Administration
Kuriyama	Nobuhiro	National Institute of Advanced Industrial Science and Technology (AIST)
Kuroki	Rentaro	Toyota Motor North America, Inc.
Kurtz	Jennifer	National Renewable Energy Laboratory
Kusoglu	Ahmet	Lawrence Berkeley National Laboratory
Kwon	Sunghyun	Pusan National University
Laffen	Melissa	Alliance Technical Services (ATS)
LaFleur	Chris	Sandia National Laboratories
Lakshmanan	Balasubramanian	General Motors
LaManna	Jacob	National Institute of Standards and Technology
Lantzakis	Mark	United Technologies
Lauer	Suzannne	Alliance Technical Services (ATS)
Lawler	Jeffrey	W. L. Gore & Associates
Leachman	Jacob	Washington State University
Lee	D-Y	Argonne National Laboratory
Lee	Seung Geol	Pusan National University
Lee	Sungchul	Hyundai Mobis
Lee	Uisung	Argonne National Laboratory
Lee	Won Yong	Korea Institute of Energy Research
Leick	Noemie	National Renewable Energy Laboratory
Leighton	DeLisa	Luxfer-GTM Technologies/IGX Group, Inc.
Lennon	Gregory	Mitsui & Co.
Levinson	Rebecca	Sandia National Laboratories
Levy	Michael Francis	Aaqius
Li	Gong Liang	NGK Spark Plugs

Last Name	First Name	Organization
Li	Wenyue	American University
Li	Yiju	University of Maryland Energy Research Center
Li	Zheng	Virginia Tech
Liang	Zhixiu	Brookhaven National Laboratory
Lichter	Kristopher	Ardica Technologies
Lindsay	Anthony	Gas Technology Institute
Linkous	Clovis	Youngstown State University
Lipp	Ludwig	eT2M
Litster	Shawn	Carnegie Mellon University
Litteer	Brian	American Fuel Cell
Litzelman	Scott	Booz Allen Hamilton
Liu	Bowen	GLWN
Liu	Chang	University of Virginia
Liu	Di-Jia	Argonne National Laboratory
Liu	Hong	Oregon State University
Liu	Xiaojun	American University
Liu	Yang	University of Maryland Energy Research Center
Lonnberg	Maria	Embassy of Sweden
Loosen	Suzanne	San Francisco Department of the Environment (SF Environment)
Love	Michelle	Oak Ridge Associated Universities
Lovik	William	Interpreter/Intern
Lu	Yunfeng	University of California, Los Angeles
Lu	Zifeng	Argonne National Laboratory
Lueking	Angela	National Science Foundation
Lundgren	Cynthia	U.S. Army Research Laboratory
Luo	Wei	University of Maryland
Luo	Yusheng	Idaho National Laboratory
Lyubovsky	Max	U.S. Department of Energy, Fuel Cell Technologies Office (ORISE Fellow)
Ma	Li	NIO
Mackanic	David	Stanford University
MacLeod	Bill	Retired
Maes	Miguel	NASA White Sands Test Facility
Magnusson	Lauren	National Renewable Energy Lab
Mahalik	Matthew	Argonne National Laboratory
Majzoub	Eric	University of Missouri – St. Louis
Maness	Pin Ching	National Renewable Energy Laboratory
Mansilla	Christine	CEA
Mao	ZongQiang	Fujian Snowman Co., Ltd.
Marcinkoski	Jason	U.S. Department of Energy
Marenco	Claudia	Fuel Cells and Hydrogen Joint Undertaking (FCH JU)

Last Name	First Name	Organization
Maric	Radenka	University of Connecticut
Markiewicz	Michal	National Center of Research and Development
Markovic	Nenad	Argonne National Laboratory
Martin	Josh	National Renewable Energy Laboratory
Martinez	Andrew	California Air Resources Board
Maruta	Akiteru	Technova Inc.
Marxen	Sara	CSA Group
Mason	Chad	Advanced Ionics
Masson	Julien	Plastic Omnium
Masten	David	General Motors
Matsumoto	Mitsuru	Toyota Central R&D Labs., Inc.
Matsunaga	Tomoya	Toyota Research Institute of North America
Matsutani	Koichi	TANAKA KIKINZOKU KOGYO K.K.
Matter	Paul	pH Matter, LLC
Matzger	Adam	University of Michigan
Mauger	Scott	National Renewable Energy Laboratory
Mayyas	Ahmad	National Renewable Energy Laboratory
McBurney	James	Rune Capital LLC
McCrory	Fredrick	Sandia National Laboratories
McDaniel	Anthony	Sandia National Laboratories
McKay	Brian	Continental Automotive Systems
McKeown	Kyle	Linde
McQuaid	Christine	Access Interpreting
McQueen	Shawna	U.S. Department of Energy, Fuel Cell Technologies Office
McWhorter	Scott	Savannah River National Laboratory
Medici	Ezequiel	Michigan Technological University
Meeks	Noah	Southern Company Services, Inc.
Melaina	Marc	National Renewable Energy Laboratory
Meneghelli	Barry	Vencore
Mertes	Catherine	RCF Economic & Financial Consulting, Inc.
Miller	Eric	U.S. Department of Energy, Fuel Cell Technologies Office
Milliken	JoAnn	Self-Employed
Mills	Michael	U.S. Department of Energy, Sustainable Transportation
Minagata	Hidetaka	Tokyo Gas Co., Ltd.
Minh	Nguyen	University of California, San Diego
Mintz	Marianne	Argonne National Laboratory
Mittelsteadt	Cortney	Giner, Inc.
Miyairi	Naomichi	HIOKI USA Corporation
Miyake	Aoi	Honda R&D Co., Ltd., Automobile R&D Center
Miyasato	Matt	South Coast Air Quality Management District
Moen	Chris	Sandia National Laboratories
Moffat	Thomas	National Institute of Standards and Technology

Last Name	First Name	Organization
Mohan	Ram	Planet Hydrogen Inc.
Mohanpurkar	Manish	Idaho National Laboratory
Mohanty	Debasish	Apple Inc.
Molter	Trent	Sustainable Innovations
More	Karren	Oak Ridge National Laboratory
Moreland	Gregory	CSRA International
Moretto	Pietro	Joint Research Centre (JRC) of the European Commission
Morgan	Brad	Tetramer Technologies
Morimoto	YU	Toyota Central R&D Labs., Inc.
Mosburger	Michael	Robert Bosch LLC
Motyka	Theodore	Greenway Energy LLC
Moulthrop	Larry	LMDesk LLC
Mtyelwa	Mandy Nompumelelo	U.S. Department of Science and Technology
Mukerjee	Sanjeev	Northeastern University
Mukoyama	Masato	DENSO International America, Inc.
Mukundan	Rangachary	Los Alamos National Laboratory
Mulder	David	National Renewable Energy Laboratory
Müller	Karsten	Friedrich-Alexander-Universität Erlangen-Nürnberg
Muratori	Matteo	National Renewable Energy Laboratory
Murphy	KP	Alliance Technical Services (ATS)
Murphy	Lilia	Alliance Technical Services (ATS)
Musgrave	Charles	University of Colorado Boulder
Mushtaq	Ali	EWII Fuel Cells
Myers	Charles	CSRA International
Myers	Debbie	Argonne National Laboratory
Nakahara	Hiroshi	EnerSys Advanced Systems
Nam	Sang Yong	Gyeongsang National University
Narayan	Sri	University of Southern California
Nawoj	Kristen	U.S. Department of Energy, Fuel Cell Technologies Office
Nelissen	Gert	Borit NV
Newman	Aron	Booz Allen Hamilton
Neyerlin	Kenneth	National Renewable Energy Laboratory
Nguyen	Nha	U.S. Department of Transportation
Nguyen	Tien	N/A
Nishii	Takumi	Tokyo Gas Co., Ltd.
Nishimura	Shin	Kyushu University
Nowak	Robert	RJN Associates
O'Brien	Chris	Ivys Energy Solutions
O'Brien	James	Idaho National Laboratory
O'Connell	Daniel	American Fuel Cell
Odgaard	Madeleine	EWII Fuel Cells

Last Name	First Name	Organization
Odom	Sara	Electricore, Inc.
Oesterreich	Robert	Air Liquide Advanced Technologies
Ogawa	Shohei	Carnegie Mellon University
Ogitsu	Tadashi	Lawrence Livermore National Laboratory
Ohnuma	Akira	Toyota Boshoku Corporation
Okawara	Jun	Sumitomo Corporation of Americas
Okazaki	Ken	Tokyo Institute of Technology
Olson	Greg	CSRA International
Oma	Atsushi	Nissan Motor Co., Ltd.
Onorato	Shaun	Allegheny Science & Technology Corporation
Orsino	Christina	Virginia Tech
Oshima	Yasuhiro	New Energy Industrial Technology Development Organization
Otani	Tetsuya	Sakai Trading New York Inc.
Ott	Kevin	Los Alamos National Laboratory (retired)
Paczkowski	Benjamin	U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC)
Paige	Mark	Southwest Sciences, Inc.
Pal	Narendra	United Hydrogen Group
Palm	David	Stanford University
Pan	Mu	Wuhan University of Technology
Papageorgopoulos	Dimitrios	U.S. Department of Energy, Fuel Cell Technologies Office
Parilla	Philip	National Renewable Energy Laboratory
Park	Andrew	National Renewable Energy Laboratory
Park	Gu-Gon	Korea Institute of Energy Research
Park	Seok Hee	Korea Institute of Energy Research
Parkan	John Michael	Providence Entertainment
Parker	Eric	Keylogic Systems
Parks	George	FuelScience LLC
Parysek	Karen	Praxair
Pasaogullari	Ugur	University of Connecticut
Pastel	Glenn	University of Maryland Energy Research Center
Patel	Pinakin	eT2M
Patil	Kailash	Giner, Inc.
Pecharsky	Vitalij	Ames Laboratory, Iowa State University
Pellow	Matthew	Electric Power Research Institute
Penev	Michael	National Renewable Energy Laboratory
Perry	Mike	United Technologies Research Center
Persson	Kristin	Lawrence Berkeley National Laboratory
Peters	Michael	National Renewable Energy Laboratory
Peterson	David	U.S. Department of Energy, Fuel Cell Technologies Office
Petitpas	Guillaume	Lawrence Livermore National Laboratory

Last Name	First Name	Organization
Petrecky	James	Plug Power Inc.
Petri	Randy	FuelCell Energy, Inc.
Petrie	Mark	SRI International
Phillippi	Scott	United Parcel Service (UPS)
Pietrass	Tanja	Los Alamos National Laboratory
Pintauro	Peter	Vanderbilt University
Pivovar	Bryan	National Renewable Energy Laboratory
Poerner	Nathan W.	Southwest Research Institute
Pollica	Darryl	Ivys Energy Solutions
Popovich	Neil	National Renewable Energy Laboratory
Pouy	Mark	Booz Allen Hamilton/Advanced Research Projects Agency – Energy (ARPA-E)
Prasad	Ajay	University of Delaware
Pratt	Joseph	Sandia National Laboratories
Pratt	Rick	Pacific Northwest National Laboratory
Prendergast	David	Lawrence Berkeley National Laboratory
Price	Rebecca	Energetics Incorporated
Priem	Thierry	CEA – LITEN
Prohaska	Robert	National Renewable Energy Laboratory
Qiao	Yun	University of Maryland Energy Research Center
Quackenbush	Karen	Fuel Cell & Hydrogen Energy Association
Quong	Spencer	Quong & Associates, Inc.
Ramsden	Todd	National Renewable Energy Laboratory
Randolph	Katie	U.S. Department of Energy, Fuel Cell Technologies Office
Read	Jeff	U.S. Army Research Laboratory
Rebollar	Dominic	Argonne National Laboratory
Reddi	Krishna	Argonne National Laboratory
Ren	Xiaoming	U. S. Army Research Laboratory
Renner	Julie	Case Western Reserve University
Renz	Tobias	Tobias Renz FAIR
Rice	Brian	University of Dayton Research Institute
Rinebold	Joel	Connecticut Center for Advanced Technology, Inc.
Ritzert	Nicole	Theiss Research/National Institute of Standards and Technology
Rivkin	Carl	National Renewable Energy Laboratory
Robertson	Denzel	Air Liquide
Robinius	Martin	Forschungszentrum Juelich GmbH
Rockward	Tommy	Los Alamos National Laboratory
Rodriguez	Miguel	U.S. Department of Energy, Fuel Cell Technologies Office (intern)
Ronevich	Joseph	Sandia National Laboratories
Rosseto Camiloti	Priscila	Ergostech

Last Name	First Name	Organization
Rossmann	Charles	Southern Company
Roychoudhury	Subir	Precision Combustion, Inc.
Rufael	Tecle	Chevron
Rupnowski	Peter	National Renewable Energy Laboratory
Rustagi	Neha	U.S. Department of Energy, Fuel Cell Technologies Office
Ruth	Mark	National Renewable Energy Laboratory
Sabarirajan	Dinesh	Tufts University
Sakurahara	Kazuo	Honda R&D Co.,Ltd.
San Marchi	Chris	Sandia National Laboratories
Sarikaya	Ayhan	Saint-Gobain
Sarkar	Reuben	U.S. Department of Energy, Sustainable Transportation
Sasaki	Kotaro	Brookhaven National Laboratory
Sasakura	Masaharu	The Institute of Applied Energy
Satyapal	Sunita	U.S. Department of Energy, Fuel Cell Technologies Office
Saur	Genevieve	National Renewable Energy Laboratory
Saxena	Ashok	Wiretough Cylinders
Schenck	Deanna	U.S. Department of Energy, Fuel Cell Technologies (ORISE Fellow)
Schlueter	Debbie	EWII Fuel Cells
Schneider	Martin	Hydrogenious Technologies GmbH
Schoenung	Susan	Longitude 122 West, Inc.
Schubert	Peter	Green Fortress Engineering
Schultz	Laura	George Mason University
Semelsberger	Troy	Los Alamos National Laboratory
Serov	Alexey	University of New Mexico
Serre-Combe	Pierre	CEA
Setzler	Brian	University of Delaware
Severa	Godwin	University of Hawaii
Shade	Willard	ACI Services Inc.
Shan	Xiaonan	University of Houston, Department of Electrical & Computer Engineering
Shao	Yuyan	Pacific Northwest National Laboratory
Sherwood	Stephanie	Oak Ridge Associated Universities
Shibata	Masao	Toyota Central R&D Labs., Inc.
Shikuya	Masayuki	Toyota Motor Corporation
Shimomura	Akira	Sumitomo Corporation of Americas
Shin	Kyusoon	Advanced Institute of Research, Dongjin Semichem Co.
Siddique	Luthfe	Johns Hopkins University
Siegel	Kay Kimberly	H2Safe, LLC
Sievers	Robert	Teledyne Energy Systems
Silva Botta Reis	Lívia	Ergostech
Simmons	Daniel	U.S. Department of Energy, Office of Energy Efficiency and

Last Name	First Name	Organization
		Renewable Energy
Simmons	Kevin	Pacific Northwest National Laboratory
Singh	Brij	John Deere
Sinsabaugh	Steven	Lockheed Martin
Smith	David	Oak Ridge National Laboratory
Smith	Edward	Volvo Group Trucks Technology
Smith	Owen	National Renewable Energy Laboratory
Smith	Thale	Sandia National Laboratories/University of California, Davis
Smith	William	Infinity Fuel Cell and Hydrogen, Inc.
Sneed	Brian	Oak Ridge National Laboratory
Snyder	Joshua	Drexel University
Soaper	Kimberly	BCS, Incorporated
Sofronis	Petros	University of Illinois
Soloveichik	Grigorii	Advanced Research Projects Agency – Energy (ARPA-E)
Son	Taeyang	Gyeongsang National University
Song	Liang	Brookhaven National Laboratory
Sookhoo	Ryan	Hydrogenics Corporation
Soto	Herie	Shell
Spendelow	Jacob	Los Alamos National Laboratory
Sprik	Samuel	National Renewable Energy Laboratory
Sproat	Vern	Stark State College (retired)
Srinivasan	Venkat	Argonne National Laboratory
Sriramulu	Suresh	CAMX Power
Stahl	Hans-Ulrich	BMW
Stamenkovic	Vojislav	Argonne National Laboratory
Stavila	Vitalie	Sandia National Laboratories
Steinbach	Andrew	3M Company
Steiner	Dr. Dietmar	Robert Bosch GmbH
Steiner	Nadia	FCLAB/Labex ACTION
Stetson	Ned	U.S. Department of Energy, Fuel Cell Technologies Office
Stevens	John	U.S. Department of Energy, Fuel Cell Technologies Office
Stewart	Eric	RCF Economic & Financial Consulting, Inc.
Stoots	Carl	Idaho National Laboratory
Stottler	Gary	General Motors
Strickler	Alaina	Stanford University
Stroebel	Raimund	Dana Incorporation
Studer	Sarah	N/A
Subbaraman	Ram	Robert Bosch Research and Technology Center
Suda	Kazuhiro	Honda Motor Co.,Ltd
Sun	Pingping	Argonne National Laboratory
Sun	Xin	Beijing China Automotive Technology and Research Center (CATARC) Data Technology Center

Last Name	First Name	Organization
Sutherland	Ian	General Motors
Swanborn	Rombout	HyET BV
Swartz	Scott	Nexceris, LLC
Swider-Lyons	Karen	U.S. Naval Research Laboratory
Tajima	Masaki	Tottori University of Environmental Studies
Tajiri	Kazuya	Michigan Technological University
Takaishi	Hideyuki	Takaishi Industry Co., Ltd.
Takeuchi	Susumu	Sumitomo Corporation
Tamburello	David	Savannah River National Laboratory
Tamez	Patricia	Shell
Tanaka	Kazuyoshi	Kyoto University, Fukui Institute for Fundamental Chemistry
Tanuma	Toshihiro	Asahi Glass Research Center
Tao	Ye	University of Maryland
Tartaglia	Katherine	Energetics Incorporated
Tarver	Jacob	National Renewable Energy Laboratory/National Institute of Standards and Technology
Tchouvelev	Andrei	A.V. Tchouvelev & Associates Inc.
Teprovich	Joseph	Savannah River National Laboratory
Terlip	Danny	National Renewable Energy Laboratory
Tesfaye	Meron	University of California, Berkeley
Thomas	Carlton (Sandy)	N/A
Thornton	Matthew	National Renewable Energy Laboratory
Thurston	Joanna	Withers & Rogers LLP
Timbario	Thomas J	Alliance Technical Services (ATS)
Tisack	Monica	Mississippi Polymer Institute
Tong	Jianhua	Clemson University
Townsend	Justin	Oak Ridge Associated Universities
Trejos	Vanessa	CSRA International
Trocciola	John	CSRA International
Tsai	Li Duan	Industrial Technology Research Institute, Material and Chemical Laboratories
Tsou	Yu-Min	Tongji University
Tsuchiya	Hiroshi	New Energy and Industrial Technology Development Organization (NEDO)
Uddin	Md. Aman	University of Connecticut
Udovic	Terrence	National Institute of Standards and Technology
Ulsh	Michael	National Renewable Energy Laboratory
Vacin	Gia	GO-Biz
Vanderborgh	Nicholas	Los Alamos National Laboratory (retired)
Veenstra	Mike	Ford Motor Company
Vela	Adriana	University of Guanajuato
Verduzco	Laura	Chevron

Last Name	First Name	Organization
Vetrano	John	U.S. Department of Energy, Basic Energy Sciences
Vickers	James	U.S. Department of Energy, Fuel Cell Technologies Office (ORISE Fellow)
Viswanathan	Vilayanur	Pacific Northwest National Laboratory
Vold	Jennifer	Access Interpreting
Vu	Cung	Self-Employed
Vukmirovic	Miomir	Brookhaven National Laboratory
Wagener	Earl H.	Tetramer Technologies, LLC
Wagner	Andrew	Mainstream Engineering Corporation
Wagner	Frederick	General Motors (retired)
Wakabayashi	Makoto	Nissan Chemical America Corporation
Walchuk	George	ExxonMobil R&E Co.
Waldecker	James	Ford Motor Company
Wang	Chao	Johns Hopkins University
Wang	Chengwei	University of Maryland Energy Research Center
Wang	Conghua	TreadStone Technologies Inc.
Wang	Haijiang	VICTRII
Wang	Hao	University of Delaware
Wang	Jia	Brookhaven National Laboratory
Wang	Junhua	University of Delaware
Ward	Patrick	Savannah River National Laboratory
Warren	C.	Oak Ridge National Laboratory
Watabe	Hiroyuki	Asahi Glass Co., Ltd.
Watanabe	Takahiro	Technova Inc.
Watari	Lulu	Ergostech
Weber	Adam	Lawrence Berkeley National Laboratory
Wegeng	Robert	Pacific Northwest National Laboratory
Wei	Max	Lawrence Berkeley National Laboratory
Weimer	Alan	University of Colorado
Weng	Baicheng	The University of Toledo
Werth	Chris	Allegheny Science & Technology Corporation
Wheeler	Douglas	DJW Technology, LLC
Whiston	Michael	Carnegie Mellon University
Whitson	Blake	Center for Transportation and the Environment (CTE)
Williams	Cherryl	Greenway Energy LLC
Williams	Mark	AECOM
Wilson	Adria	U.S. Department of Energy
Wipke	Keith	National Renewable Energy Laboratory
Woebkenberg	William	Aramco Research Center
Woehl	Taylor	University of Maryland
Wolfenstine	Jeffrey	U.S. Army Research Laboratory
Wood	Brandon	Lawrence Livermore National Laboratory

Last Name	First Name	Organization
Wood	David	Oak Ridge National Laboratory
Woods	Stephen	NASA White Sands Test Facility
Wu	Gang	University at Buffalo, State University New York (SUNY)
Wu	Haobin	University of California, Los Angeles
Wu	Qiyuan	Stony Brook University
Xie	Jian	Indiana University–Purdue University Indianapolis
Xie	Yingying	Shanghai Jiao Tong University
Xu	Hui	Giner, Inc.
Xu	Shaomao	University of Maryland Energy Research Center
Xu	Shicheng	Stanford University
Xu	Ye	Louisiana State University
Xue	Jisan	U.S. Department of Transportation, National Highway Traffic Safety Administration
Yamanashi	Fuminori	Nissan Motor
Yamauchi	Masaki	Panasonic
Yan	Yushan	University of Delaware
Yandrasits	Michael	3M Company
Yang	Bo	EWII Fuel Cells
Yang	Yong	Austin Power
Yang	Zhiwei	United Technologies Research Center (UTRC)
Yelvington	Paul	Mainstream Engineering Corporation
Yildirim	Mustafa Hakan	EWII Fuel Cells
Yim	Sung-Dae	Korea Institute of Energy Research
Yoon	Yoon JeYong	JNL Tech Co., Ltd.
Yoshida	Junichi	New Energy and Industrial Technology Development Organization (NEDO)
Yoshida	Toshihiko	Tokyo Institute of Technology
Yu	Hongbin	Arizona State University
Yu	Rujie	Beijing China Automotive Technology and Research Center (CATARC) Data Technology Center
Yuh	Chao-Yi	FuelCell Energy, Inc.
Yuzugullu	Elvin	CSRA International
Zawodzinski	Thomas	Oak Ridge National Laboratory
Zelenay	Piotr	Los Alamos National Laboratory
Zenyuk	Iryna	Tufts University
Zhang	Feng-Yuan	University of Tennessee
Zhang	Jianbo	Tsinghua University
Zhang	Lei	University of Maryland
Zhang	Ping	Beijing Nowogen Technology Co., Ltd.
Zhang	Sen	University of Virginia
Zhang	Wenqing	Shanghai University
Zhang	Xiaoyu	Old Dominion University

Last Name	First Name	Organization
Zhang	Xuyang	University of Miami
Zhang	Yi Heng Percival	Virginia Tech
Zhang	Ying	University of Maryland Energy Research Center
Zhao	Shuai	Giner, Inc.
Zhao	Yun	University of Delaware
Zhu	Huiyuan	Oak Ridge National Laboratory
Zhu	June	Beijing Nowogen Technology Co., Ltd.
Zidan	Ragaiy	Savannah River National Laboratory
Zimmerman	Jonathan	Sandia National Laboratories
Zou	Shouzhong	American University

Sub-Program Comments Provided by Reviewers

Hydrogen Production & Delivery Sub-Program Comments

1. Was the sub-program, including overall strategy, adequately covered?

- The sub-program was covered thoroughly, including hydrogen cost status and targets and the research, development, and demonstration (RD&D) strategies and framework—which addressed the leveraging of resources among stakeholders and cross-office and cross-agency collaborations. The production and delivery of hydrogen were shown to have been analyzed from a technoeconomic perspective. Several advances in research and development (R&D) were presented, e.g., a new photoelectrochemical (PEC) world record; an 875 bar hydrogen storage vessel designed to operate safely for more than 20 years and at a cost less than the target cost; and joint efforts with the Office of Science on catalysis for hydrogen production, hybrid perovskites, which are emerging as a new class of promising materials, and biomimetics for hydrogen activation. In addition, this year the price of hydrogen vis-à-vis low or high volume for early markets was thoroughly analyzed and compared with the ultimate target. In summary, the sub-program is a foundational part of H2@ Scale, which is a big national laboratory idea that will advance the U.S. Department of Energy's (DOE's) agenda toward energy security and economic growth.
- The presentation more than adequately covered the overall strategy and an overview of technical progress. This is a very well-balanced, well-thought-out sub-program that covers a very broad diversity of approaches to hydrogen production and distribution, ranging from collaborations with fundamental Basic Energy Sciences (BES) projects to foundational work done within the sub-program to applied materials and engineering work. This is a very well-integrated program, and it is apparently very well managed, as judged by outcomes.
- The overall strategy was clearly explained by the sub-program manager on slide 10. It is encouraging to see that the research is guided by the technoeconomics.
- Yes, but as in 2016, the overview presentation took too much time, making the end of the presentation challenging to follow. The presenter should focus on being concise because the individual project sessions explain all details. The real focus of this sub-program is \$4–\$7/gge—period. This is why the audience comes to listen to this overview.
- Yes. The sub-program was adequately covered. While Eric did a great job of explaining the department successes in the relative sub-programs, the "why" was still missing from the discussion. This has been, and remains, a challenge for the hydrogen community. While it is clear that 20 MMT hydrogen/year would be required to fuel 100 million fuel cell electric vehicles (FCEVs), an understanding and a vision for getting to 100 million FCEVs was missing. The H2@ Scale concept is helpful, but what is missing is the vision for how it functions and how we get there.
- Goals were presented, but clear, specific strategies for reaching economic goals were not described. Projects were described in generalities rather than specifics.
- Magnetic liquefaction work was not discussed.

2. Is there an appropriate balance between near-, mid-, and long-term research and development?

- This is one of the most diverse sub-programs the reviewer has encountered within DOE. The technical and scientific range of topics is quite large and diverse, and the range of timeframes the projects span is also quite large, ranging from near-term engineering studies and laboratory-scale demonstrations to longer-term foundational materials research, such as in the area of PEC generation of hydrogen. It is a sub-program that is well balanced, with a distribution of timeframes, technical risk, and technology readiness levels (TRLs).
- The sub-program has a balanced R&D portfolio, both on hydrogen production and hydrogen delivery vis-à-vis near- and long-term objectives. In fact, the sub-program should be commended for the thoughtful distribution of resources, e.g., on electrolysis, PEC, and solar thermochemical hydrogen (STCH), as shown on slide 11 and the technoeconomics of hydrogen and delivery costs.
- One of the key aspects of the sub-program's portfolio is the very good balanced to cover near- and long-term R&D. This is demonstrated for hydrogen production with a portfolio that covers near-term technology

options focused on fossil resources, while at the same time there is also some focus on long-term options on water-splitting technologies, such as STCH and PEC hydrogen production. On the delivery pathways, this is demonstrated by near-term efforts on tube trailers and tankers, while for long-term options, there are some efforts on advanced liquid carriers.

- The Hydrogen Production & Delivery sub-program definitely has a good balance between near-term technologies such as water electrolysis and being cognizant that future advances and early-stage research could make other technologies feasible. Going forward, there will be some challenges to maintaining this balance. It will be important for the office to continue great engagement with industry (end users) to understand their needs and design appropriately balanced research portfolios. Generally speaking, the vision of rolling out 60 MMT of hydrogen per year in the next 30 years—meeting this ramp-up—will require substantial investment in demonstrations, so while many early-stage/long-term technologies could be in the pipeline, later-stage/near-term technologies of those projects can add value to society's understanding.
- The sub-program has addressed fossil, biomass, and solar as near-, mid-, and long-term paths.
- It appears to be mostly mid- and long-term focused.

3. Were important issues and challenges identified?

- "Cost" was identified as a major challenge for both the renewables pathway and for refueling stations, which are both less technically challenging and more near-term. Earlier-stage technologies also had some technical issues identified. Maintaining stable and predictable budgets was also correctly identified as a major challenge for both later-stage and early-stage R&D. While solving the technical issues is a matter of really smart scientists working on a problem, overcoming the cost challenge is more difficult. The costs for electrical energy, which is outside the scope of the hydrogen program, represent 47%, while only 34% are for the system capital expenditure, which includes many components outside the scope of the electrolyzer stack. While the Hydrogen Production & Delivery sub- scope is limited as to its impacts on these other areas, it can have some influence. The work showing electrolyzer impacts to the grid can be quantified, and the impact of hydrogen energy storage + renewables on electrical energy prices can also be evaluated. Large-scale deployments of the technology can be utilized to drive balance-of-plant (BOP) and indirect costs down through scaling.
- Without a doubt, important issues and challenges were identified. Hydrogen generation's fairly foundational science challenges have been identified, and multiple approaches are being employed. Engineering challenges in delivery and distribution have been identified, and multiple mitigation strategies are being employed to obtain enhancements in reliability or durability or reductions in process intensity and energy efficiency, all of which will eventually play key roles in delivering hydrogen to consumers at competitive costs.
- All issues across the sub-program's portfolio were addressed, and the R&D challenges and framework were thoroughly defined, as demonstrated by slide 10.
- The issues and challenges for hydrogen production and delivery, as well as the strategies to address these, were clearly explained by the sub-program manager.
- Targets were presented, and brief explanations were given. "Early Market Target" is a good addition and was clearly explained.
- Production and delivery cost reduction is the main overarching challenge. While individual projects did bring up challenges, the overview presentation does not indicate what the highest-priority issues and challenges within the sub-program are that need to be addressed to achieve such cost reduction the quickest.

4. Are plans identified for addressing issues and challenges?

- New areas of emphasis are in new initiatives, e.g., the consortium HydroGEN and H2@ Scale, both of which will drive innovations to address challenges in hydrogen production and delivery. In addition, the sub-program has put in place collaborations with other agencies to leverage their work in production and distribution, such as the National Science Foundation (NSF)/BES, the emerging energy materials networks (EMNs), to name a few, where the Fuel Cell Technologies Office and this sub-program are reaching out to find leverage to accelerate the evolution of hydrogen fueling in the consumer segment.

- The well-balanced portfolio presented by the sub-program manager on slide 11 clearly demonstrates the plan for addressing the research challenges on both hydrogen production and hydrogen delivery.
- Strategies for RD&D were stated on the Strategy (slide 10), along with the national laboratory and interagency support framework and partnerships.
- Plans for addressing technical issues are identified, but addressing the cost challenges is not clear.
- Yes. Continued R&D is needed to reduce costs.
- Plans were given, but they lacked specificity.

5. Was progress clearly benchmarked against the previous year?

- A number of advances were presented that have clearly set the new benchmarks, e.g., the appliance-type refueling station for a small number of FCEVs at 700 bar, the steel-wrap approach to the stationary storage of high-pressure hydrogen, and the new world record on PEC.
- Several accomplishments were presented, and these were very impressive, such as the novel hydrogen technology option for the Delivery portion, as well as the new PEC record and the new HydroGEN consortium recently launched in the Production area.
- Goals were given at the beginning of the presentation, and metrics were presented throughout. However, there was no clear year-over-year benchmarking toward goals using the selected metrics. Qualitatively, several technical accomplishments were shown, which illustrates the quality of the work.
- The presenter clearly delimited the progress benchmarked against 2016. Significant progress was demonstrated across many near-term, mid-term, and longer-term R&D projects within the sub-program portfolio.
- Progress was clearly benchmarked in the project presentations attended but not in the overview presentation.
- No.

6. Are the projects in this technology area addressing the broad problems and barriers that the Fuel Cell Technologies Office (FCTO) is trying to solve?

- The ongoing activities in the sub-program portfolio are focused on addressing the main barriers within FCTO. It is really exciting to see the new HydroGEN consortium being launched, as it will bring projects and expertise to overcome some of the main materials challenges on water-splitting technologies.
- This sub-program, with its broad diversity of technologies and science being worked against near-term to long-term targets, is tightly focused on challenges and barriers that FCTO R&D is trying to breach, and with great success.
- Yes, the sub-program's projects do address the DOE targets in a balanced way among the alternative technologies. An example is the 875 bar storage vessel that addresses the storage target at a cost even less than the target cost.
- Yes, delivered cost of hydrogen and cost-competitive hydrogen from renewables are the broad barriers.
- The portfolio approach is good and certainly needs to be continued. However, the goals of 60 MMT hydrogen per year cannot be achieved through laboratory-scale demonstrations. Industry involvement in the technology deployment to answer key questions of scale, longevity, BOP, etc. is needed in the future to solve the problems and achieve the widespread deployment.
- Generally, yes. However, research of new (but previously explored, such as metal hydride) compressor technologies does not solve compressor challenges. In addition, for compressor challenges, it is not clear what the decision-making process within FCTO is in this area.

7. Does the sub-program appear to be focused, well-managed, and effective in addressing FCTO's needs?

- Overall, yes, but specifically, decisions on choices for R&D on specific topics should be more transparent, not a DOE FCTO "black box" approach. It is not clear whether all topics address actual industry needs and/or industry-identified challenges (instead they may address academic or [national laboratory] scientific challenges, separate from industry).

- While this broad set of technological and scientific topical areas might be difficult to manage effectively, that is not the demonstrated case here. This is a well-managed and efficient sub-program that has a history of success in challenging and breaking down technical barriers critical to FCTO Hydrogen and Fuel Cells Program needs.
- Liquid carrier work was examined early in the sub-program and specifically rejected as having little or no chance of meeting sub-program targets. It was formally written out of the delivery roadmap in 2012. It is not clear why carriers have resurfaced as a possible long-term option.
- Excellent management and an excellent support team are the main keys for the success and effectiveness of the Hydrogen Production & Delivery sub-program.
- The sub-program is well managed and focused and has many technical accomplishments across the portfolio. However, it is not clear how effective it is at addressing the key goals of sustainable hydrogen production at scale. This is principally because a vision and scale have been selected, 60 MMT H2/year, but there is no clear pathway on how to get there, and no go/no-go decisions based on drivers. (see answers to some previous review questions) In many cases, the program is tied up--doing the best that can be done with limited and uncertain budgets and DOE policy that is pushing for early stage research when the stated goal, 60 MMT/year, is a matter of scale up demonstrations with industry involvement.

8. What are the key strengths and weaknesses of the projects in this sub-program? Do any of the projects stand out on either end of the spectrum?

- A key strength is the continuous enhancement of sub-program elements; the sub-program is not static, e.g., bringing on HydroGEN and working with H2@ Scale. Another key strength is the leverage the program gains via communication and collaboration with entities such as NSF and BES, just as two examples. There are no key weaknesses.
- A key strength is the balanced portfolio on production and delivery involving short- and long-term efforts. The Sandia National Laboratories (SNL)/Pacific Northwest National Laboratory project on tribology in the presence of hydrogen is a promising approach to developing methodology and testing protocols for polymers operating in hydrogen. In addition, this year, fundamental science is addressed through joint projects with the Office of Science and NSF (slides 14 and 15).
- Strengths include an extremely well-balanced portfolio to address near- and mid-term challenges for both production and delivery, very efficient management and support, understanding of key barriers and how to address these, and external collaboration. There are no weaknesses.
- The key strengths of this sub-program are the breadth and depth of analysis that has been done on different scenarios and cost drivers for technologies, and many innovative technologies that have the potential to shift those cost drivers or modify the scenarios. The key weakness (this may sound contradictory) is the focus on technoeconomic analysis that really looks like economic analysis only. While it is good to baseline technologies and compare, technologies that are not "drop-in replacements" should not be evaluated only as such. Characteristics such as capacity factor, reliability, size, and connection to existing infrastructure (wires, gas lines, liquids pipelines and storage, water) need to be considered, as different technologies are unique and have been demonstrated at various scales. This is true of technologies within the hydrogen space, and also true of hydrogen vs. other technologies (such as hydrogen energy storage vs. battery energy storage or compressed air energy storage). The SimpleFuel demonstration and the PEC work are both very exciting and could change some of those costs/scenarios.
- The following are key strengths: most projects explore the challenges of producing and getting hydrogen as a fuel to vehicle drivers/operators, and liquefaction projects should receive increased emphasis because a pathway efficiency bottleneck exists here for which bench-scale solutions appear to hold promise. The following are key weaknesses: the sub-program has not clearly identified niche markets for hydrogen (as vehicle fuel or other use) that can help to scale up green hydrogen production (to at least thousands of kilograms per day); industry players are not sharing realistic cost numbers for delivery (assuming shorter equipment returns on investment than for existing industrial equipment in use); and long-term R&D focus is a given, but this does not do much to resolve current challenges with trying to achieve cost reduction (high-volume throughput can be calculated but has to be achieved first, which is a pipe dream if DOE does not focus on achieving this) to more acceptable levels (below $10 per kilogram dispensed).
- It is not clear that measurable performance benchmarks exist for early-scale research efforts. Even these projects need performance-based metrics for go/no-go decisions.

9. Do these projects represent novel and/or innovative ways to approach these barriers as appropriate?

- In many of the project areas, the technical and scientific competition is intense. For example, in the PEC generation of hydrogen, the competition is at the highest level; many of the world's best teams of scientists work in this area. Therefore, to remain competitive in this rapidly evolving area of science, they must provide innovative approaches to the problems that need to be solved. The DOE Office of Energy Efficiency and Renewable Energy's projects do that and compete successfully with scientists funded through BES, NSF, and other world-leading R&D organizations. In one specific sub-program element, non-mechanical gaseous hydrogen compressors, it was good to see that two teams working on competing technologies were in fact collaborating. This is a healthy indicator of how well sub-program participants can work together. It is heartening to know that in some instances, the technical outcome is more important than personal technical success.
- The sub-program has analyzed the technoecomics of hydrogen production from sustainable resources (see slide 4) and addresses this long-term challenge through a well-coordinated strategy (see slides 13, 16) and the newly launched HydroGEN consortium (slide 23). The program is similarly well balanced in its strategies for overcoming the delivery and storage barriers.
- Great representation of innovative ways to approach these barriers are as follows: for production, the discovery of new materials for water-splitting technologies, and for delivery, the innovative station design projects.
- The reformer/electrolyzer/purifier is an innovative use of existing technology. Magnetic and vortex-assisted liquefaction are both highly innovative with potential impact.
- SimpleFuel is a nice demonstration of packaging technologies for deployment and reducing cost. PEC research can address the cost of electricity by removing electricity production from the equation and relying directly on solar radiation. However, there is always a tradeoff because in any location the solar radiation can be used only once for its highest and best purpose (if the market's invisible hand is at work).
- Many do; some are a rehash of previous efforts (e.g., metal hydride compressors).

10. Has the sub-program engaged appropriate partners?

- The presentation laid out the strategy for collaborations among a set of other world-leading organizations, so yes, the sub-program has done an excellent job of partnering around the world and of course here in the United States.
- The sub-program has really excelled at engaging partners. All sectors and industries are fairly represented and have their viewpoints heard.
- The sub-program has an impressive collaborative program among national laboratories and interagency interactions, e.g., a joint funding approach with NSF.
- There is excellent collaboration with national laboratories, academia, and technology providers.
- There is good collaboration within DOE and other government agencies. Collaboration with commercial partners is limited.
- Overall, yes. However, large industry player engagement should be pursued more strongly.

11. Is the sub-program collaborating with them effectively?

- Ample evidence was given in the way of progress in many areas where collaboration was key to accelerating DOE R&D, and a good example was given entailing future strategies, e.g., the EMN interactions.
- Judging from presentations reported on slides 14 (Office of Science) and 15 (NSF), the collaborations can be deemed successful and serving the goals of the sub-program.
- There is very effective collaboration with the partners.
- The sub-program is definitely collaborating with partners. There may be some opportunity to engage more with end users and thereby help the sub-program understand the drivers better.
- It appears to be the case—this is not a specific project review.
- It was not possible to assess the effectiveness of collaboration from the presentation.

12. Are there any gaps in the portfolio for this technology area?

- There are questions around liquid hydrogen tanker trailer research; it is not clear what the limits are or whether the limits for over-the-road transport can be expanded. This would contribute to reduction of cost per kilogram delivered, owing to the ability to transport larger quantities. Another gap is underground compressed and liquid hydrogen storage solutions tanks. Renewable energy availability does not equal all renewable energy available for hydrogen production. Other gaps include assessment of all current oil and chemical industrial processes to explore potential for diverting hydrogen streams for higher-value purposes (than current uses), 700 bar dispensing for heavy-duty vehicle applications, and cryocompressed dispensing for heavy-duty vehicle applications.
- In the area of non-mechanical hydrogen compressors (electrochemical, metal hydride, hybrids, etc.), earlier attention to cost analysis could be beneficial to further focus the overall research effort. In these areas, the technology is somewhat mature, and there may be some advantage to focusing more on systems models that lead to cost (capital as well as operating) models, gaining some R&D efficiency in the process.
- Thermochemical conversion of biomass or biomass-derived liquids is not addressed. These may be considered as being mature enough not to warrant consideration.
- The biggest gap in the portfolio is scale. Reaching the 60 MMT/year is going to be challenging without a mechanism for technology to cross the valley of death.

13. Are there topics that are not being adequately addressed?

- The portfolio is well balanced. The addition of the HydroGEN consortium is very valuable to the sub-program.
- The development of strain-based mechanistic models of hydrogen embrittlement for specific steel microstructures (slide 19) is focused only on mechanical testing (PD-025). Although the work on mechanical testing carried out at SNL is state-of-the-art, it is not aiming at model development. Operation of metallic components for hydrogen applications require predictive models for safety and reliability, especially against fatigue.
- Yes: intermediate hydrogen production and delivery cost reduction goals at lower volumes should be addressed (the focus is on long-term goals at high volume).
- Scale of hydrogen production is not adequately addressed.
- The sub-program appears to be doing as much as it can under its limited budget.

14. Are there other areas that this sub-program should consider funding to meet overall programmatic goals?

- It is difficult to imagine where there is any "white space" the sub-program manager does not have covered—or if there is white space, there is a reason for it.
- Other areas include the following:
    - Liquid hydrogen tanker trailer research
    - Underground compressed and liquid hydrogen storage solutions tanks
    - Assessment of all current oil and chemical industrial processes to explore potential for diverting hydrogen streams for higher-value purposes (than current uses)
    - 700 bar dispensing for heavy-duty vehicle applications
    - Cryocompressed dispensing for heavy-duty vehicle applications
- These are a bit redundant, but if the goal is national deployment of sustainable hydrogen, there must be a DOE role in de-risking. Industry-led demonstrations with substantial support for large-scale demonstrations, which answer key questions, will be critical to rolling out this technology. Also, analysis that considers the unique benefits of hydrogen should be considered.
- Transportation of hydrogen from remote, renewable-resource-rich locations to high-demand locations does not appear to be given adequate attention.
- The sub-program should look into the state of R&D is for hydrogen compressors, an important component of refueling stations.

15. Can you recommend new ways to approach the barriers addressed by this sub-program?

- The sub-program manager is doing an excellent job, is highly knowledgeable, and is doing an absolutely stunning job of massing his attack on the remaining barriers.
- The sub-program should focus on one (1) hydrogen production "park" located adjacent to a location with excess renewable energy (photovoltaics, wind, and/or biogas) and existing pipeline or large storage accessible for injection at any time; all projects should be located here, not spread out over the whole country at a large number of difficult-to-access national laboratories. This could also include compressor projects and over-the-road distribution options. The sub-program should assess whether the TRL rating concept transfers directly to industry; DOE may be investing in the low-cost, easy-entrance conceptual part of the technology development spectrum, of which only 1 out of 100 concepts makes it to market (venture capitalist process).
- A key issue in the area of hydrogen delivery and infrastructure (e.g., materials for compressor technology) is hydrogen-accelerated fatigue of metals and alloys. SNL is successfully driving the codes and standards efforts, but fatigue is an issue that is still unresolved. Further, there are no mitigation strategies, and fatigue could be responsible for potential failure scenarios in the future. A joint program with NSF or the DOE BES is indicated. None of the projects with the Office of Science (slide 14) and NSF (slide 15) addresses this important issue of hydrogen-accelerated fatigue and mitigation.
- Cost barriers can be addressed only by scale, either scale at the site or manufacturing scale. As a market emerges, vendors will be able to better compete to reduce cost on components further.
- Continue industry engagements with the new HydroGEN consortium should be continued.
- No.

16. Are there any other suggestions to improve the effectiveness of this sub-program?

- The only suggestion is to include the university community on fundamental science issues, for example, in the area of fatigue mentioned in items 13 and 15. In summary, Dr. Miller has done a very fine job in shaping the sub-program into one that steadily advances toward the targets with an optimum allocation of resources serving short- and long-term goals.
- The sub-program should add an annual showcase of tangible DOE-funded project outcomes/products to create an emotional response about outcomes.
- There is no excuse for the presenter's not covering all the material in the allotted time. The presentation should be reviewed and "dry runs" carried out with colleagues before the Annual Merit Review. The presentation should be pared down if all the material cannot be presented in the allotted time.
- No.

Hydrogen Storage Sub-Program Comments

1. Was the sub-program, including overall strategy, adequately covered?

- The sub-program, including the overall strategy, was covered in a very good and professional way. An overview was given, and all the different storage options were considered. The goals and targets were presented and addressed very well. The sub-program is very well balanced. Those alternatives and technologies at a lower technology readiness level (TRL) and with higher ultimate potential to meet the final targets, but too low a TRL to be taken on by the industry itself, are given a special focus and should, in the future, be given an even higher focus.
- The overall strategy was well explained, particularly the explanation of the current status of commercially available fuel cell cars and how that has adjusted a few key technical targets for hydrogen storage.
- Yes, the objectives and strategy were very clearly and effectively explained. The sub-program presentation had very good content regarding the strategy and projects. In some cases, the materials-based storage included too much detail and did not highlight the linkage to improving a specific target.
- Yes. The strategy was well described and thoughtfully considered.
- Efforts in materials and physical storage were well described.

2. Is there an appropriate balance between near-, mid-, and long-term research and development?

- A very good balance between near-, mid- and long-term research and development (R&D) has been found, and all are addressed in high-pressure, cryocompressed, and physical storage means. Materials R&D, engineering R&D, advanced tank R&D, and analysis are covered. Concerning the final targets, only materials-based hydrogen storage has the theoretical potential to fulfill these. Especially as recently it is understood that volumetric storage density is more important than gravimetric storage density, the focus on materials-based hydrogen storage is correct. This sub-program, however, is not a continuation of old efforts in the area of hydrides but is following a new, much more knowledge-based approach by combining both experiments and computation in an unprecedented way that gives hope that researchers can either find and identify the right materials or answer why materials with high storage densities show unfavorable thermodynamic or kinetic properties at moderate temperatures and/or pressures. This approach has real chances if not taken halfheartedly. To be successful, the sub-program needs sufficient resources. With the current comparably low budget, there is the risk that the new methodologies cannot be fully exploited.
- Yes, the hydrogen storage team has a very good balance of projects associated with the near term (700 bar compressed) and the long term (cryocompressed and materials-based storage). In fact, there is an almost even split between the number of projects associated with the near term (advanced tanks, engineering, and analysis) and long term (materials), with a slight edge in funding to materials R&D, as highlighted in the presentation.
- Given the challenges entailed in reducing the costs and improving the performance of current and future hydrogen storage options, the balance across timescales is appropriate. The overall sub-program is focused on the appropriate topics as a function of timescale of the R&D vs. commercial efforts.
- Yes. It can be summarized as compressed gas in the near term and everything else as a longer-term R&D development.
- Too much is being spent on chemical and materials-based storage. This work has gone on for years, and materials-based storage is no nearer to meeting targets than it was 10 years ago. A lot of good work has been done on bad materials. It is time to cut this work significantly.

3. Were important issues and challenges identified?

- Yes, the most important issues and challenges are exceptionally well identified as costs of the fibers in high-pressure gas tanks, dormancy in cryogenic tanks, and especially the so far unsuitable combination of kinetics, thermodynamics, and capacities in case of materials-based hydrogen storage. There are many discovered metal hydrides with very nice properties at low working temperatures but with low capacities on the other side and other materials with high storage capacities but, for most applications, unsuitable slow kinetics or high working temperatures, but the reason is so far not at all understood. In the case of materials-based hydrogen storage, the sub-program aims at a comprehensive theoretical–experimental investigation of such materials and setting up the capabilities required for this. The sub-program has high potential to bring about a breakthrough; however, the rather low total budget could stop the full exploitation of the developed methods and the harvest of novel, more suitable materials through this knowledge-based approach.

- Certainly. A clear picture of current status emerged, and based on current status and trajectories, the challenges emerged and were presented in a logical fashion.
- New targets are appropriate and appear to have been justified through interactions with original equipment manufacturers (OEMs).
- Yes, the high-level barriers were identified on the strategy slide, along with further details in physical and materials storage activity sections. In the materials storage section, additional information could have been provided to highlight the gaps with materials-based storage on a system level prior to jumping into the materials' limitations.
- Yes. Barriers are clearly defined for each technology approach.
- The addition of dormancy targets is good.

4. Are plans identified for addressing issues and challenges?

- Both the challenges and the plans for overcoming those challenges are very well identified and addressed. Since materials-based hydrogen storage is the only option to reach the ultimate targets, the sub-program aims at the development of exceptional capabilities at different institutions, mainly the national laboratories. In contrast to earlier attempts to identify novel materials, the sub-program now takes the growing available computational power much more into account and aims at a very close and comprehensive experimental–computational effort to allow us to see, more clearly and with more of a knowledge base, which are the limiting material processes hindering their application, thereby enabling the search for proper future approaches to screen and/or design materials with the desired or necessary properties for mobile and stationary energy storage.
- Plans for addressing the substantial technical barriers in hydrogen storage were well presented and easily understood. An R&D portfolio that is designed to address the challenges in the short, medium, and long terms was clearly defined.
- The Hydrogen Storage sub-program plans for addressing challenges were included in the strategy slide and inferred by the project portfolio. The summary statements at the bottom of certain slides were very helpful in identifying the key message and R&D focus for addressing a certain issue.
- Carbon fiber cost reduction work is clearly laid out.
- In general, yes, but plans are identified only at a top level.

5. Was progress clearly benchmarked against the previous year?

- With the high-risk, high-reward individual projects, the Hydrogen Materials—Advanced Research Consortium (HyMARC) and its projects become really operative. Several other projects could be successfully finished. Also, impressive first demonstrations and applications in mobile applications such as unmanned undersea vehicles and forklifts could be shown demonstrating some of the beneficial outcomes of research work done in the field of metal hydrides, in addition to the knowledge gained through this type of research, which fertilized other technologically important areas such as battery development.
- Yes, in nearly every aspect of the R&D portfolio, progress against benchmarks and toward achieving the technical targets was clearly presented.
- Dry winding work was well described, but cost benefits were not quantified. Tank balance-of-plant (BOP) work was highlighted, but advances over last year's work were not clear.
- There was clearly progress being made within the sub-program, although it was not benchmarked from last year. A progression of key areas such as cost or other parameters would be helpful in evaluating the rate of improvement.
- In general, no, but advances were noted in many cases (just without reference to the previous level of performance).

6. Are the projects in this technology area addressing the broad problems and barriers that the Fuel Cell Technologies Office (FCTO) is trying to solve?

- Reductions in cost and improvement in hydrogen storage capacities, energy efficiencies, durability, etc. are an important piece of the puzzle that must be assembled that will lead to cost-competitive, large-scale implementation of hydrogen-fuel-cell-powered transportation. This Hydrogen Storage sub-program in FCTO is designed and is well managed to address the remaining barriers to practical onboard hydrogen storage systems.
- Yes, all the projects deal with hydrogen storage options and challenges and thus address one of the main barriers (hydrogen storage) of fuel cell technologies.
- The sub-program seems to have appropriate projects for addressing the broad problems and barriers. Most of the barriers on the strategy slide are being addressed by the projects in the portfolio. The sub-program may want to ensure complete coverage of the barriers by mapping the projects to the barriers. A barrier not being addressed is the system (material) cost for materials-based storage systems.
- Yes. The projects are well selected.
- It appears that the "ship has already sailed" in favor of physical storage, yet the sub-program continues to expend well over half its budget on materials-based solutions.

7. Does the sub-program appear to be focused, well-managed, and effective in addressing FCTO's needs?

- The sub-program appears very focused, well managed, and effective in addressing FCTO's needs, especially the new effort: HyMARC is going in the right direction by combining and developing key technologies to be able to bring about a significant impact. So far there has been a strong focus on automobile applications, which of course is good; however, hydrogen storage and fuel cell technologies are not limited to automobile applications. There is also a need for stationary applications, and so the planned efforts on H2@ Scale are welcome. However, the budget must be increased significantly to be able to include this new and, for the future, very important topic. The sub-program budget should be at least doubled to ensure good and recognizable activities and achievements and international visibility.
- The Hydrogen Storage sub-program has been and continues to be focused on key technology needs within the storage realm to address the barriers to cost-competitive hydrogen fuel cell transportation. The sub-program continues to be well-managed. Communication and collaboration are highly valued by the sub-program management, and this R&D environment has been effective in driving toward conquering the barriers.
- Yes, the sub-program is well managed and very focused on the FCTO needs. This sub-program has very effective and engaged DOE managers.
- Yes, the sub-program is well focused and well managed, and the presentation was delivered in a clear and effective way.
- The sub-program needs to come to grips with its failure to find adequate materials-based solutions and refocus on physical storage. It is not clear why the sub-program is working on alane for the U.S. Department of Defense.

8. What are the key strengths and weaknesses of the projects in this sub-program? Do any of the projects stand out on either end of the spectrum?

- A key strength has been in the layers of risk mitigation in the materials-based storage area. Multiple approaches that integrate experiment and computation, always with an eye to fairly stiff engineering requirements, engenders a very focused, well-balanced R&D program. A possible weakness is in the potential over-investment in the area of high-surface-area sorbents (e.g., metal–organic frameworks), where there appears to be significant overlap in several of the projects that include efforts to computationally predict hydrogen sorption isotherms to enable sifting through the now large databases of structure types. Another area that may not lead to progress toward enhancing foundational understanding of hydrogen storage is the area of binding of multiple hydrogen molecules on "naked" or coordinatively unsaturated non-transition metal cation sites. Binding of a single hydrogen molecule, much less multiple hydrogen molecules, to a "naked" Ca ion appears highly unlikely. Computational models that predict this need to be certain to include all potential reaction channels to avoid dropping into false minima that predict finding stable configurations.

- The sub-program has a good mix of basic materials development and engineering solutions, as well as a good mix of (large) national-laboratory-based consortium efforts (HyMARC) and small company innovative projects. The development of alternate metals is not justified based solely on the cost and mass reductions possible if the project is successful (as the savings will be quite small). However, there may be other applications or other features of the metal that make it applicable to a much wider range of applications. This should be explored.
- The comprehensive approach of HyMARC, together with the individual high-risk, high-gain projects, is unprecedented and should be strengthened and expanded. The main weakness is the comparably low budget when compared to some European countries, the European Union, and East Asian countries. The budget should be increased significantly.
- The overall strength of the sub-program is associated with an appropriate balance between near- and long-term research. The overall weakness of the sub-program is inability to filter technologies or projects without a clear path to achieving the targets or providing a value proposition over the incumbent technology. HyMARC is a strength to promote fundamental research, promote national laboratory collaboration, and assist individual materials-based projects in the portfolio. The sub-program should attempt to highlight the historical progression and provide future projections toward the system targets. The projects not related to transportation stand out as a weakness in this sub-program.
- The x-ray photoelectron spectroscopy (XPS) work on slide 21 proves *nothing* except that the investigators were working with a highly oxidized sample. The absence of titanium at the surface may be due to migration of Al to the surface under the oxidation of the sample due to inadequate handling of the sample before analysis rather than real surface chemistry of the active material. It has been over 25 years since the reviewer did XPS for a living, and the reviewer would have been too embarrassed to show this slide even back then.

9. Do these projects represent novel and/or innovative ways to approach these barriers as appropriate?

- The newly minted HyMARC consortium is one example of an innovative approach to removal of barriers, especially when coupled with the “seedling” project process. Gaining a better understanding of the foundational science involved in hydrogen storage materials is necessary to removing the few remaining barriers to practical application of materials-based hydrogen storage. Also, new organizational collaboration strategies among FCTO and parallel or similar activities at the National Science Foundation, Basic Energy Sciences (BES), the future energy materials networks, etc. represent new and novel ways to approach the problem by leveraging efforts across organizations and agencies.
- The comprehensive experimental–computational effort HyMARC, in particular, together with the individual high-risk projects, represents a novel, outstanding approach.
- Most of the projects are attempting to pursue novel approaches, although the innovation of the projects could be further highlighted if the principal investigators would identify the current state of the art and the specific innovation of their projects.
- Yes, there are numerous examples of novel materials/materials-synthesis and fabrication methods being pursued.
- Several of the projects do show novel approaches to the barriers.

10. Has the sub-program engaged appropriate partners?

- The programmatic collaborations of the FCTO effort with BES, Advanced Research Projects Agency–Energy (ARPA-E), the National Institute of Standards and Technology, the U.S. DRIVE Partnership (U.S. DRIVE) technology teams, and international activities such as the International Energy Agency’s Task 32 interactions are all valuable in helping the FCTO effort to maintain its focus and its reputation as the world’s leader in hydrogen storage.
- Yes, the sub-program has an excellent cross-section of industry, academic, and national laboratory partners. The relationship with the Institute for Advanced Composites Manufacturing Innovation was a great addition to the sub-program.

- The sub-program has engaged very appropriate partners. However, considering the really low budget, which is the main weakness, the sub-program should aim at strengthening international collaborations so that the United States is not falling behind Europe and East Asia.
- The sub-program needs to reengage with tank manufacturers and OEMs looking at novel storage methods such as cryocompressed.
- In general, yes.

11. Is the sub-program collaborating with them effectively?

- The Hydrogen Storage sub-program has a history of effective collaboration with a variety of U.S. and international organizations that engage in hydrogen storage or related research. The collaboration with the U.S. DRIVE technology team in hydrogen storage has helped keep the sub-program tightly focused on gaining outcomes that are impactful in the U.S. automotive industry. These collaborations are in part what has allowed the sub-program to maintain its reputation as the world-leading hydrogen storage program. All international activities look to the DOE sub-program as guidance for their own technical projects.
- Yes, the sub-program is collaborating with the partners effectively through various workshops, technical team meetings, and project reviews.
- It seems that there is excellent collaboration.
- Collaborations with national laboratories appear to be going well, but the effectiveness of collaboration outside DOE is questionable.
- Yes.

12. Are there any gaps in the portfolio for this technology area?

- It appears that where there might be gaps, the sub-program has effectively collaborated with other agencies to fill them. An example is the ARPA-E program in hydrogen storage in liquid carriers, e.g., ammonia, an area in which FCTO does not currently work.
- Hydrogen storage for automobile applications is very important, but automobile applications are not the only ones in which hydrogen will play a role in the future. Other mobile and stationary applications (with different targets and demands) should be considered as well.
- Storage system BOP components currently amount for a high fraction of system cost. Only the Sandia National Laboratories alternative metal project addresses this (and then only in a modestly impactful way). Additional BOP component cost-reduction or system-simplification projects should be pursued.
- The commercialization and cost analysis for materials-based storage is a gap in the portfolio. A basic understanding of selection of materials in relationship to their performance and affects on the infrastructure needs to be included in the sub-program.
- More work on physical storage is needed.

13. Are there topics that are not being adequately addressed?

- The constant vetting of the sub-program, and the close collaboration with U.S. DRIVE, assists the sub-program management with maintaining an adequate portfolio that addresses the topics that can help eliminate technical barriers to practical hydrogen storage systems.
- The fundamental research in HyMARC is helpful, although the linkage to the performance and properties is not clear, so there could still be gaps associated with the system. The relationship with the infrastructure needs to be further developed to ensure the heat rejection expectations of certain materials can be supported.
- Such topics include BOP component cost reduction and system simplification.
- Physical storage and analysis are such topics.
- No.

14. Are there other areas that this sub-program should consider funding to meet overall programmatic goals?

- Given the relatively limited size of the sub-program, the scope of the current portfolio is adequate. The strategy of having a core group of researchers, e.g., HyMARC, that then inform sub-program management of research areas that need to be addressed helps the sub-program management make the necessary adjustments and additions to the sub-program via the “seedling” process. This appears so far to be an effective strategy to maintain an appropriate balance and focus of the R&D portfolio.
- The sub-program could consider funding additional cost reverse engineering for materials-based storage systems to assist in guiding the materials research. There could also be funding for holistic integration analysis of the storage system into the vehicle (e.g., waste heat management) or holistic solutions for infrastructure (e.g., increasing temperature limitations or optimizing heat rejection).
- So far, the targets for hydrogen storage aim at automobile applications. Other mobile and stationary applications have different demands and therefore different targets. These have to be addressed as well.
- Funds should be moved from materials-based storage efforts to analysis, engineering, and physical storage.
- No.

15. Can you recommend new ways to approach the barriers addressed by this sub-program?

- The targets for hydrogen storage are formulated only for automobile hydrogen storage, which is only one part of the potential future application areas. The Hydrogen Storage sub-program should be set up broader to address also other mobile as well as stationary applications. In the field of hydrogen storage, more emphasis could be put also on the option to enhance volumetric storage densities of compressed gas tanks, even at much lower pressures, by developing hybrid compressed-hydride tanks. The approach of a comprehensive theoretical–experimental investigation, as in HyMARC, is very good.
- The sub-program could consider vehicle powertrain or platform variations and their effect on the system targets. For example, the sub-program could consider heavy-duty vehicles in terms of the volumetric density versus gravimetric density.
- Improvements to the vehicle (through lightweighting, aerodynamic improvement, etc.) should be considered as a way to reduce the requirement for hydrogen storage.
- There are no recommendations at this time. With the new consortium model now being productive, this should be monitored for efficacy, and perhaps adjustments could be made, but not at this time.
- No.

16. Are there any other suggestions to improve the effectiveness of this sub-program?

- The sub-program should examine its historical progress and be willing to make the tough choices to direct the portfolio toward the most promising solutions. There has been excellent work by many researchers over the years in this sub-program. An effort should be made to build on the past results, especially with the outcomes associated with the centers of excellence. The reverse engineering of materials targets should be utilized to a higher degree to guide and discontinue certain research. The evaluation of system parameters should be coupled with the infrastructure to provide a complete assessment of the hydrogen storage technology.
- The sub-program continues to be a well-managed and effective program, and so there are no further suggestions that would improve upon the sub-program at this time.
- The budget must be increased.
- No.

Fuel Cells Sub-Program Comments

1. Was the sub-program, including overall strategy, adequately covered?

- Yes.
  - The research and development (R&D) portfolio focused on polymer electrolyte membrane fuel cells (PEMFCs) but also includes longer-term technologies (e.g., anion-exchange membrane fuel cells [AEMFCs]) and higher-temperature fuel cells (e.g., molten carbonate fuel cells) for stationary applications.
  - Catalyst cost is projected to be the largest single component of the cost of a PEMFC manufactured at high volume; the strategy is to reduce platinum group metal (PGM) and improve performance.
  - Durability and cost are the primary challenges to fuel cell commercialization and must be met concurrently.
  - Brookhaven National Laboratory (BNL) demonstrated potential to develop low-cost Pt monolayer catalysts with noble metal free cores.
  - 3M perfluoroimide acid (PFIA) membranes meet most 2020 U.S. Department of Energy (DOE) targets.
  - 3M membrane electrode assembly (MEA) integration R&D leads to improved performance and decreased PGM content.
- Yes, the major goals of the sub-program area, their current status, new accomplishments, and current plans to achieve any unmet sub-program area goals were covered. Strategies for technology development were covered particularly well, especially through the consortium approaches that are now being implemented. The L'Innovator concept seemed interesting but was not exactly clear, and it seemed that a bit too much focus was placed on it. One potential change that could be recommended for the strategy is to assess whether another component or design feature could be a focus of near-term development in order to gain short-term progress toward the DOE cost targets. Platinum is projected as the long-term greatest cost contributor, and several projects are currently devoted to reducing platinum content as a means to reduce system cost. However, if another component would be a significant cost contributor at smaller production volumes, there may be a chance to impart more short-term impact by also focusing on improvements in that component or design feature now. Especially if solving the technical challenges of that component is more manageable than solving technical challenges of platinum reduction, the overall Hydrogen and Fuel Cells Program (the Program) may be missing an opportunity for at least short-term progress as a stepping stone by focusing only on the long-term problem of platinum content.
- Cost and durability are the major technical challenges. The sub-program's approach to identifying and addressing these issues is well covered and well structured, focused, and well managed. The consortia established by the Fuel Cell Consortium for Performance and Durability (FC-PAD) and Electrocat are really relevant for their potential to transform fuel cell technology.
- Yes, goals and objectives of the sub-program were adequately covered. The challenges were discussed, and the R&D portfolio identified focus areas.
  - Under focus areas, Performance and Durability – Mass Transport was identified, but the impact of catalytic activity was not identified, even though catalysts were identified under stack components. It is implied that catalytic activity is acceptable but not entirely clear.
  - Under Balance of Plant (BOP), there is no listing of critical components. This implies that all of the BOP components are a focus area.
  - Under Sensitivity Analysis, it is not clear what "Air Stoichiometry" refers to, whether air utilization, pressurization, humidification of the air, or something else. Also, if bipolar plate welding speed is important, it is not clear why bipolar plate coatings were left out. Bipolar plate coatings could be more time-intensive than bipolar plate welding.
- The presentation provided a good summary of current efforts and near-term plans. The overall strategy of the sub-program area was clearly presented and appropriate.
- Yes, the overall sub-program and strategy was clearly outlined.
- The presenter did an excellent job in covering the Fuel Cells sub-program.

2. Is there an appropriate balance between near-, mid-, and long-term research and development?

- Yes.
  - An ultra-thin-film (UTF) PtNi catalyst with 8.1 kW/g PGM was achieved, exceeding the 2020 DOE target.
  - UTF PtNiIr meets mass activity and hydrogen–air durability targets (A. Steinbach et al., 3M).
  - A PtCo/HSC-f catalyst exceeds targets for specific power and PGM loading (A. Kongkanand et al., General Motors)
  - Porous particles show lower Pt but higher Co dissolution, leading to accelerated performance loss.
  - A rotating disk electrode (RDE) testing protocol and best practices were disseminated, enabling procedural consistency and less variability.
- There is a good balance between near-, mid-, and long-term R&D in the Fuel Cells sub-program, at least for the main focus, which concerns MEAs.
- There is excellent balance between early applied R&D all the way to BOP and testing.
- The sub-program has a little bit of work in all time scales, though there is an apparent heavier focus on mid- to long-term R&D. The short-term development effort could be increased to effect more real-world impact of the advances made through these projects. Achievement of the technical capability to produce fuel cells meeting all targets through the sub-program will require years before those accomplishments are integrated into the commercial technologies. With the current balance that appears to de-emphasize near-term projects, there could be a risk of exacerbating the time it will take to transfer these advancements to commercial and consumer products. Consideration of a little more emphasis on near-term work should be made.
- The present sub-program has a good balance between near-, mid-, and long-term R&D. Upcoming budget pressures may force a concentration on long-term research, giving up the very substantial increase in effectiveness in the near- and mid-term work that has been achieved recently through the improved interactions between the national labs and between the national labs and industry that are exemplified by FC-PAD.
- Yes, in general, the focus on PEMFCs provides the nearer-term R&D, whereas the ElectroCat and anion-exchange membrane work provide longer-term activities. However, although the stated goal is to advance fuel cell technologies for transportation, stationary, and early market applications, the sub-program is very transportation-focused.
- A pathway for potential cost reduction and the 2020 target have been identified. Some of the 2020 research objectives are very difficult, e.g., reduction of bipolar plate cost since the sub-program does not include bipolar plate stamping. If the success of the Program depends on the discovery and development of PGM-free catalysts without the development of an alkaline membrane (not on the pathway), Program success will be very difficult. The DOE has funded PGM-free catalysis off and on for the last thirty years without success, with much of the work addressing Fe-N-C systems, similar to the current approach. The data given (chart 14) suggest mass transport limitations; hence, the objective might be the development of an electrode structure suitable to optimizing the performance of the PGM-free catalyst rather than the development of a PGM-free catalyst.

3. Were important issues and challenges identified?

- Yes. This group is doing excellent work on some of the key issues that are limiting the commercialization of fuel cells for automotive, stationary, and portable power applications. Most noteworthy are the advancements in core shell catalysts, the new PFIA membrane, the low-loaded catalysts, the UTF catalyst layer, and the progress on the alloy catalysts. For example:
  - 3M developed a 10 µm supported PFIA membrane with a chemical additive that meets the resistance target at 80°C for all humidities and at 120°C for the highest humidity, and meets mechanical and chemical durability targets.
  - R. Adzic et al. at BNL developed nitriding core components that can facilitate the development of high-performance Pt-ML catalysts with low-or no-noble-metal cores.
  - Steinbach and Kongkanand present the development of several advanced catalysts that approach the DOE 2020 targets.

These are not incremental advances on the same old materials that have been proven to have limitations in the past. These are newly developed materials and processes that have already shown superior properties to previous materials and continue to show the potential for significant further improvements. While further progress is required to meet ultimate durability and cost targets concurrently, significant progress has been made, important targets have been met, or at least approached, and new avenues for further improvements have been identified. In some cases, some of these new avenues of improvement are approaching the DOE targets. While the primary focus has been on polymer electrolyte membranes, developments in molten carbonate, AEMFCs, and electrolyzers are important improvements for those technologies.

- Yes, there is a clear focus on what technology improvements need to be made in order to meet the objectives and goals within the sub-program area. The use of the manufacturing cost analysis method as a basis for determining research needs to meet the cost target in particular is a very effective method of finding and targeting the appropriate challenges.
- Cost and durability targets met concurrently with cost targets are the major challenges. To reduce cost, PGM-free catalysts appear key and are well covered with the Electrocat project. The more classical approach to reducing cost by lowering the quantity of PGM in catalysts is also well covered. However, in that case, a study should be made to determine the minimum quantity of Pt content in an MEA to achieve performance, durability, and cost targets but still be compatible with Pt recycling of the MEA. Indeed, with a given amount of Pt, either technical or economical aspects will lead to losing interest in recycling Pt.
- The important issues and challenges were identified. Some of the severe challenges in meeting the DOE bipolar plate and catalyst cost targets could have been emphasized a bit more, and a resetting of these targets to more realistic levels, with subsequent revision of DOE planning in light of these, should be considered.
- Yes, the ability to concurrently meet both durability and cost has been appropriately highlighted as the most critical challenge. The cost sensitivity analysis provides further support for key challenges. However, although air loop cost and bipolar plate cost have significant impacts, these are not currently part of the R&D portfolio (although workshops on these topics were held).
- Improvements in multiple components simultaneously are required to meet 2020 targets.
- Yes. See charts 7, 8, 10, and 11.

4. Are plans identified for addressing issues and challenges?

- In general, yes, appropriate plans are in place for polymer electrolyte membrane (PEM) catalyst and MEA performance and durability. With respect to FC-PAD, a major initiative under this sub-program, the six component and cross-cutting thrusts have been well chosen to contribute to required fuel cell MEA advancements. The focus by FC-PAD on pre-competitive-level activities is appropriate and will provide significant support to industry, whereas the competitive-level work is appropriately carried out by industry-led projects. However, while the objective of evaluating/benchmarking different materials by FC-PAD is useful and appropriate, it is important that this does not merely duplicate work done under other DOE-funded work, i.e., benchmarking of DOE-supported material development.
- Yes. In addition to the R&D that addressed cost reduction, performance and durability enhancement of stack components including catalysts, membranes and MEAs, the establishment of ElectroCat with core capabilities to expedite the development of PGM-free catalysts and electrodes, and the addition of FC-PAD demonstrate the longer-range vision to establish the infrastructure that will be necessary for ultimate success. In this consortium, the focus should be on using a low-Pt-loading anode 0.05mg/cm^2 and non-PGM cathode. The study should be conducted on the MEA with a minimum of 25 cm^2.
- Yes, several strategies for coordinated development to address challenges in meeting the sub-program's challenges are clearly presented. Some of the details of those individual coordinated projects (such as the multiple consortia) are a little less clear, especially as concerns their overarching strategy. Some of the consortia projects appear to run along more of a "try everything" strategy than the overall sub-program's targeted and informed strategical methods. Also, as noted during the plenary, one of the major challenges being faced right now is how to meet the two remaining issues, cost and durability, at the same time. The sub-program seems to address both of these but as separate issues, even though there is explicit acknowledgment that they must be met concurrently. The expected method of meeting both together is not so clear.

- Plans have been identified for meeting the challenges. They could have been more specific in the case of the bipolar plate material cost issue. Plans for non-Pt catalysts are detailed, if not necessarily very realistic.
- Yes. Many collaborations and workshops are focused on resolution of issues.
- The current portfolio of projects is addressing these three main issues and challenges.
- No stepwise list of activities to address the issues was presented. There are many questions, for example, what the plans are to meet the mass activity targets, whether the composition will be changed, whether the Pt-to-Pt spacing will be changed, and whether there is an explanation for PtNiIr meeting oxygen reduction reaction mass activity at an atomic scale. There are similar questions for all the other approaches. Chart 20 offers no detail; it only requires our faith that core capabilities and consortia of industry and university partners will solve issues. More specifics would be helpful.

5. Was progress clearly benchmarked against the previous year?

- Yes, for several of the main projects and the sub-program targets overall, the progress over the last year (and in some cases, even over previous years) has been well documented. The consistency of maintaining focus on past accomplishments and gauging pace of development is a strength of this sub-program.
- Progress against the previous year was clearly benchmarked in most areas, including cost, high-current-density performance, and non-Pt catalyst performance in MEAs.
- Yes. Progress was reported for catalysts and alkaline membranes. Standard practice protocols appear to be in place.
- Yes. For example, the catalyst specific power of fuel cells improved to 10.6 kW/g_{PGM}, a more-than-three-times improvement from the 2008 baseline of 2.8 kW/g_{PGM} and exceeding the 2020 target of 8.0 kW/g_{PGM}.
- In general, significant progress has been made, and the accomplishment is solid and well coordinated.
- Fuel cell cost status was benchmarked based on catalyst research-level improvements, with power output per gram of Pt benchmarked year-over-year. However, durability was noted based on demonstration fleet operation—which speaks more to hours of operation as opposed to year-over-year technology advancements. PGM-free performance was provided with a statement on performance improvement, but the graph showed only current status and no assessment on longer-term ability to meet the DOE transportation targets, as is required by the waterfall chart.
- Yes.

6. Are the projects in this technology area addressing the broad problems and barriers that the Fuel Cell Technologies Office (FCTO) is trying to solve?

- Yes, the Fuel Cells sub-program is a core technology development program for meeting FCTO goals and objectives. The sub-program implements an impressive method for devising a research strategy specifically focused on the research needs and barriers within the sub-program, guided by quantitative analysis to build the overall strategy.
- Yes, for the most part, the projects in this technology area are well chosen with respect to the most critical challenges of PEMFCs. Performance and durability of the MEA are critical to meeting the long-term targets of fuel cell commercialization. These must be met at low cost. While the industry will focus on designing to appropriate trade-offs with cost, the FC-PAD consortium is focused on those activities that will enhance the understanding and provide the input to the industry to do so. However, the sub-program says little about stationary and early market applications and does not provide funding in the area of plates and the air loop.
- This is a well-focused and -managed sub-program that should lead to solutions to problems and barriers.
- Yes, the projects are addressing in detail the specific issues most relevant to the broad problems and barriers that FCTO is trying to solve.
- Yes, the different projects are well in line with the main barriers and challenges FCTO is trying to solve.
- Yes. However, the stepwise R&D was not fully discussed.
- Yes.

7. Does the sub-program appear to be focused, well-managed, and effective in addressing FCTO's needs?

- The sub-program appears to be focused, well managed, and effective. The FC-PAD consortium appears to be demonstrating the effectiveness of this new relationship between national laboratories and between the national laboratories, industry, and academia through improved integration of diverse capabilities. It is not yet clear whether the ElectroCat consortium will be as successful.
- In most cases, the research topics are clearly identified. The progress indicates the projects are well focused; however, detailed approaches for future work were not presented. The progress that was made last year and over the previous years would not have been possible without a well-managed sub-program, but it would be good to see more detail in the sub-program overview.
- Yes, the sub-program appears to be focused, well-managed, and effective in addressing FCTO's needs. There are only few orphan projects (intermediate-temperature solid oxide fuel cells, direct carbon fuel cells, redox flow batteries, and regenerative fuel cells), and regarding the budget evolution, their continuation should be reconsidered.
- Absolutely. This is one of the best-managed programs in DOE.
- Yes, the sub-program is well managed and focused on the most critical aspects with respect to transportation.
- In general, yes. The consortium approach does appear to need a bit more focus on the internal strategy between consortia. They do make important progress, but as of right now, the focus seems to be lacking a strategy or particular technologies around which developments should start coalescing.
- Yes.

8. What are the key strengths and weaknesses of the projects in this sub-program? Do any of the projects stand out on either end of the spectrum?

- The FC-PAD consortium seems to be making a step-change improvement in the targeting and coordination of national laboratory, industry, and academia efforts in improving fuel cell performance and durability. The personal fiefdoms of individual laboratories are breaking down, the complementary capabilities of the participating institutions are working together toward well-defined goals, and fuel cell developers are becoming more open about the true state of the art, allowing the DOE programs to address the true cutting edges of technology. The funding opportunity announcement (FOA) projects chosen under the consortium seem to address critical problems and finally align well with the activities of the national laboratories. The ElectroCat consortium seems less promising, though it may appear better after the projects chosen under its FOA have been announced. Restricting a consortium entitled "ElectroCat" to non-PGM catalysts seems inappropriate, given that the most promising paths to lower fuel cell cost (though perhaps not all the way to DOE's $30/kw target, which likely should be changed for planning purposes) lie with low-PGM catalysts. The large high-throughput component of the ElectroCat program seems particularly unrealistic. Non-Pt catalysts are highly dependent on processing details and less dependent on the compositional issues for which high-throughput methods are most effective. Some of the best non-Pt catalysts show no activity in RDE (and likely none in similar flow cells)—these catalysts must be evaluated in fuel cells. Scale-up of non-Pt catalysts is notoriously difficult. Synthetic efforts should therefore concentrate on fewer samples made at a scale of at least five grams so that activity, performance, and durability can be evaluated in fuel cells. With precursors being so much cheaper than for PGM catalysts, there is no need to work at the less-than-gram scale (though great attention must be paid to proper exposure of powders to gases during heat treatments).
- The projects cited in the overview show clear progress on reducing metal catalyst loading. The FC-PAD and ElectroCat consortium approach will increase coordination among national laboratories and with the FOA partners. Extensive national laboratory capabilities will be coordinated and applied in a synergistic manner toward PEM issues affecting durability and performance. The work by the national laboratories is generally conducted in a systematic manner, with extensive characterization to support hypothesis and models. The use of models is routinely used to help support understanding, and development of appropriate parameters will help others for use in industry models. The interactions with industry are expected to be positive and will help to guide the work, and will allow industry to access the very extensive national laboratory capabilities. The key progress achieved over the past several years is at the research level, and

despite many years of year-over-year progress, it is not clear how many of the advancements have made it into demonstration-phase or commercial-phase technology achievements. The sub-program office tends to support a couple of groups (industrial partners) on an ongoing basis, providing a significant advantage to those groups. On the other hand, there have been many advancements in the fuel cell industry demonstration-phase and commercial technology, so it must be assumed that the work supported by DOE is having an impact. Showing the linkages between research and technology deployment would be worthwhile, as well as showing the plans for commercialization of the technologies under development.

- The strengths are as follows:
  - The approach of coordinating the investigation of the performance and the durability of fuel cells or PGM-free catalysts through a consortium composed of the best available experts of national laboratories in a five-year project is excellent and represents the highest strength of the sub-program. This approach is allowing a deep understanding of the different mechanisms involved and the impact of novel materials or structures, and it ensures a long-term continuity of the knowledge. The addition of complementary projects with new industry and academia partners completes this approach in a very efficient way.
  - The L'Innovator approach is also a strength of this sub-program and should favor technology transfer to industry.
  - Mid- and long-term R&D on AEMFCs has to be considered a strength of the sub-program when considering the implementation of PGM-free catalysts.

  The weaknesses are as follows:
  - BOP components represent about half of the system cost, but no project is considering these components, even if air loop cost is the third most sensitive component.
  - Bipolar plates are also not really considered, although they represent about a quarter of the stack cost. Current base material appears too expensive to reach DOE cost targets. New base materials have to be considered.
- The key strengths are with the researchers conducting the individual projects. Many of the catalysts, PtNi and PtCo, have been around for many years, as evidenced in the patent literature. The strength in the catalyst research is the newer structures (morphologies) in which the catalysts are distributed.
- The Strategic Analysis, Inc., assessments of fuel cell system costs and drivers of those costs are particularly effective in having impacts sub-program-wide and ultimately on the fuel cell technologies that will, it is hoped, be in consumers' hands.
- One area of concern is slide 3 (in the 2017 presentation; slide 4 in the 2016 version), which suggests that the required development is almost done. This is wrong. Fuel cells are far from ready to challenge the internal combustion engine as the power source for automobiles. Fuel cells are marginally ready to challenge for niche markets. While the figures actually say that fuel cells nearly meet the six key targets, the gap between meeting those targets and commercial readiness needs to identified and addressed. The durability and catalyst degradation, as well as the mitigation strategy for the low Pt loading, are not solved. Non-PGMs are very far from being ready even for the accelerated stress test (AST).
- The work with 3M and General Motors (GM) stands out.

9. Do these projects represent novel and/or innovative ways to approach these barriers as appropriate?

- Yes, the ongoing work, especially to develop new catalyst ionomers, seems to be adept at reacting appropriately to ongoing advancements within and outside of this sub-program area. The work appears to always be building on recent advancements, rather than replicating them or finding unnecessary alternatives for most of the sub-program's efforts.
- A significant number of the projects are considering novel and innovative ways and appear relevant to contributing to achieving FCTO targets.
- The current range of projects covers a wide range of novel and innovative approaches to the most critical problems facing fuel cells.
- Yes, to some extent. There should be more data presented from manufacturers of fuel cell stack and systems. It would be nice to have Nissan Japan, Toyota Motors Japan, GM, and Ballard present in one session and give their view of the state of the art and the technical priorities that need to be solved for automotive application.

- No. The projects are making incremental progress toward success: ultra-thin layers have been proposed for over 15 years, PtNi and PtCo are over 20 years old, and high-surface-area supports are well understood. The progress is in understanding how performance/durability is limited and making incremental changes to improve the fuel cell system.
- Generally, yes.
- Yes.

10. Has the sub-program engaged appropriate partners?

- The sub-program has engaged appropriate partners, and the coordination between partners has recently improved through the organization of consortia. Industrial partners now seem to be more open to sharing detailed information, allowing DOE efforts to be more precisely directed to the cutting edge of fuel cell technology.
- Yes, this sub-program appears to have reached several key stakeholders in academia and industry to achieve the technology improvements at the core of its objectives. This is one of the sub-program's strengths.
- Yes. There are many national collaborations (inter- and intra-agency efforts), consortia, and focused entities, as well as industry partnerships.
- Yes, the portfolio of partners participating in the different projects appears appropriate, with members of industry, national laboratories, and academia.
- Yes, but Ballard or someone in Europe should provide an independent evaluation of these MEAs.
- The sub-program office tends to support a couple of groups (industrial partners) on an ongoing basis, providing a significant advantage to those groups. Other partners are supported on an irregular basis.
- Yes. See charts 16 and 13.

11. Is the sub-program collaborating with them effectively?

- Yes, strategies for collaboration, especially within the consortia, are well defined. The only exception is the concept of the L'Innovator program, and that was only because it was not entirely clear how the program was expected to work. This is likely just because it will be a new form of collaboration, but the concept seems like it either needs more details worked out or needs those details to be communicated more effectively.
- Yes, the consortium structure seems to be effective in formalizing and improving the collaboration between partners.
- The consortium approach should facilitate the collaborations.
- Based on the progress, yes.
- Yes (two responses).

12. Are there any gaps in the portfolio for this technology area?

- There seems to be a gap in identifying methods for cost reduction and durability improvement in the short- and possibly mid-term and developing technology improvement projects to meet those more near-term possibilities. Focus on cost and durability right now appears to focus more heavily on long-term solutions, though accounting for time to transfer technology to industry, even short- and mid-term solutions could actually become long-term in the eyes of the consumers. At least an investigation should be done into whether any possible technology improvement targets exist now for more short-term improvement with less research cost and effort.
- As planned, more detailed cost studies of roll-to-roll processing, PGM catalyst synthesis costs, and bipolar plate manufacturing are needed to check the realism of ultimate targets. Increased DOE roll-to-roll prototyping capabilities should be used to make slot-die-coated MEAs from novel catalyst materials as early in the development cycle as possible to reduce the use of unreliable RDE and flow-cell methods, particularly for durability and performance measurement, and especially for non-PGM catalysts.
- While the primary focus has been on PEMs, developments in molten carbonate, AEMFCs, and electrolyzers are important improvements for those technologies. Learning from IrO_2 anodes in PEM

electrolyzers should teach how to stabilize the carbon and what the important parameters to get a stable anode are.

- The sub-program is focusing on MEAs and sub-components (except gas diffusion layers) and on their performance and durability. Some gaps may be identified: too few projects on bipolar plates, and no project on internal gaskets, which may be an issue for durability in hot and cold cycling conditions.
- Nearer-term commercial challenges, plates, and BOP components are not well represented in the portfolio.
- Nothing was given on BOP, which was identified as a focus area.

13. Are there topics that are not being adequately addressed?

- For non-PGM catalysts, DOE should have an explicit sub-program to develop novel thick (100 microns or thicker) electrodes with designed distribution of porosity and/or other innovations to get improved high-current-density performance in air. Some group should be required to stick with a single reproducible catalyst and bang their heads against just electrode design to make better thicker electrodes in case no (highly unlikely) breakthrough in non-Pt active site density or activity is achieved by other groups.
- The sub-program identifies bipolar plates as the second-largest cost driver for fuel cell systems, and almost as significant as platinum cost. However, there does not appear to be very much research effort into this area, or at least not as much as catalyst and ionomer development. There was mention of an upcoming bipolar plate workshop, but it seems that significant acceleration in this area could be an effective way to ensure cost targets are more likely to be met by the time desired.
- MEA evaluation for both non-PGM and low Pt loading should be studied, as well as the mitigation strategy for degradation at the MEA level. Different process techniques for the catalyst and MEA manufacturing should be evaluated by an independent organization. An anode of 0l.3 mg/cm^2 should not be used in a study, as it does not meet DOE targets.
- BOP, gas diffusion layers, impurities, and seals are not adequately discussed.
- MEA operation in actual systems is not adequately addressed in the nanostructured thin film work.
- The investigated topics are adequately addressed.
- All topics are being addressed.

14. Are there other areas that this sub-program should consider funding to meet overall programmatic goals?

- Bipolar plate manufacturing and fundamental properties should be considered. With complex designs of bipolar plates that have been proposed, "thinning" of the metal will result in enhanced scrap or failure in operation. This is a fundamental problem. The flow of the metal during stamping or other processing needs to be thoroughly understood. With very thin plates, the size/depth of the welds becomes important, and there may be a fundamental limit in weld size and speed.
- Cost reduction activities outside of the catalyst area should be considered.
- More of the MEA study should be considered.
- There are no suggestions for new areas at this time.
- No.

15. Can you recommend new ways to approach the barriers addressed by this sub-program?

- Recommendations include:
    - Identification of degradation mechanisms and quantification of degradation on aged stack components (bipolar plates, electrodes, gas diffusion layers, membranes, cells, sealings, etc.) coming from demonstration projects. We cannot look only at RDE and MEA data.
    - Development of advanced in situ and ex situ characterization techniques and AST protocols, compatible to existing test station hardware, with the identification of transfer functions of the component degradation measured in an AST to real-world behavior of that component. For PEMFC technology, finalization and validation of the new single-cell design initiated by the working group should be coordinated with someone independent of the groups that are funded.
    - Development of models related to degradation mechanisms, implementing models describing degradation mechanisms into performance models, and mitigation strategy that is demonstrated at

MEA level. Evaluation of the capability of performance/degradation models to confirm and quantify the accelerating impact by adapting some operating or load profiles should be considered.

- The ElectroCat consortium should expand to include low-Pt electrodes (or, less desirably, its name should be changed to reflect its restricted subject area).
- Other than the potential addition of exploring more short-term solutions, there are no recommendations for new approaches.
- The ways to address the barriers are well defined and well managed.
- Overall, the approaches to solving the barriers are very good.
- No.

16. Are there any other suggestions to improve the effectiveness of this sub-program?

- This sub-program is well managed, and the results obtained again during this Annual Merit Review demonstrate its effectiveness.
- The BOP should not be forgotten. Some stack limitations can be resolved through system solutions. The history of fuel cells is that, in many cases, system solutions overcame fundamental property limitations of the fuel cell stacks.
- More understanding is needed from manufacturers and state-of-the-art technologies. Toyota has already produced a large volume of Mirai cars. It would be good to determine what we know from them and what they are willing to share with us.
- Steps should be continued to improve coordination of projects at the national laboratories with those in academia and industry. FC-PAD is a good prototype.
- No.

Manufacturing R&D Sub-Program Comments

1. Was the sub-program, including overall strategy, adequately covered?

- Yes. Manufacturing research and development (R&D) is needed to reduce the cost of hydrogen and fuel cell components so that they will be competitive globally. Quality control is critical to enabling low-cost manufacturing with reduced waste; defect morphology should be correlated with loss in performance (National Renewable Energy Laboratory [NREL], Lawrence Berkeley National Laboratory). The goal is to identify key factors determining U.S. competitiveness. Additional effort is needed by the U.S. fuel cell community: to maintain its current competitive position in gas diffusion layer (GDL) and membrane manufacturing, and to increase its capabilities in bipolar plate and catalyst production.
- The sub-program is well covered, and the proposed strategy seems very well adapted to reaching the objectives. The two investigated pillars are very important in enabling the hydrogen fuel cell technologies to be competitive at high-volume production.
- The strategy for the Manufacturing R&D sub-program was clearly laid out. The two main pillars were effectively described, with examples in each category.
- Yes, the sub-program was adequately covered. It was a bit hard to understand the funding situation for the sub-program, which was admittedly complex.
- Yes, the sub-program and strategy were well described.

2. Is there an appropriate balance between near-, mid-, and long-term research and development?

- Yes, there is a good balance. Some analyses are showing the current issues or weaknesses to overcome if the United States wants to stay in the top leading team for industrialization of hydrogen fuel cell technologies. Other analyses are investigating the impact of the future production routes. Quality control projects are providing information for near- and long-term developments. One project is investigating some new defect detection techniques and measuring their impact on the performance and the lifetime of fuel cells. One project is validating an optical technique, now with a packaging step, which may lead to mid-term application on industrial web lines.
- Manufacturing research by definition tends to be directed toward near- to mid-term R&D. Still, there is significant understanding needed for process effects and diagnostic tools that are more fundamental in nature that are being addressed. In this context, the balance between different stages of R&D is appropriate.
- To some extent. Local defects may have minimal impact on fuel cell performance initially but may have a huge impact later. NREL is developing advanced diagnostics for in-line detection of microsize manufacturing defects in fuel cell materials. But they are addressed only through defects. Novel roll-to-roll manufacturing technologies enable cost reduction, while investments in new materials and electrodes increase energy density, power density, and reliability. Regarding hydrogen delivery, a pipeline coupler that does not leak is needed.
- Yes, the balance between near-, mid-, and long-term R&D seems appropriate for a manufacturing project.
- This is a hard question to answer because this program is under-funded. Thus, achieving a proper balance is difficult, if not impossible.

3. Were important issues and challenges identified?

- Some of the most important issues and challenges, such as roll-to-roll processing and quality control therein, were identified. The project did the nation a service by identifying the United States' shortfalls in multiple areas of fuel cell manufacturing. For example, it would seem to be a national security issue that no major supplier of noble metal catalysts is now based in the United States. Perhaps too much of the sub-program has been supplier interaction meetings, which are not clearly of great value.
- Some issues and challenges have been identified:
  - The U.S. potential in stack manufacturing is broadly moderate to high, though with weaknesses in bipolar plate manufacturing and ionomers in the near term. U.S. original equipment manufacturers (OEMs) and other manufacturers need to re-start local development, as they have fallen behind Japan and Europe in bipolar plates, membranes, GDLs, and catalysts.

  - The domestic supply chain of hydrogen fuel cell components and systems should be expanded, and communication between OEMs and hydrogen and fuel cell component suppliers should increase.
- Highly important issues and challenges for manufacturing were identified, which clearly involved engagement from industry. These challenges included a range of topics from broad manufacturing capabilities and diagnostic techniques to specific critical components.
- There is very little new in either the 2016 or the 2017 presentation. Local defects have been a major concern for polymer electrolyte membranes (PEMs) for many years. There are test results using thermal imaging from about 10 years ago, both at the University of Connecticut and at the University of Central Florida. This process addresses only through failures; it will not find incipient failures, thin spots, foreign object damage, or chemical weak spots. This method has value, but only when coupled with a much more comprehensive integrated quality control (QC) process. DuPont, 3M, and many others are likely to have a much better understanding of what is needed to support a commercial effort. Very similar comments apply to roll-to-roll. Continuous processing is fundamental for meeting commercial production costs; however, successful continuous processes can be defined only after the production processes are fully defined, optimized, and fully understood. Academic studies at this level are useful only for long-range, order-of-magnitude projections that support funding decisions for development spending. They identify research needs but do not support manufacturing.
- The important issues and challenges being addressed were identified.

4. Are plans identified for addressing issues and challenges?

- There are some coordination activities planned to assist industry in supply chain considerations, and there are initiatives for laboratory collaboration. It is difficult to see how the objectives of the Manufacturing R&D sub-program will be met with no allocated budget, but that is not under the control of the team lead.
- The ongoing projects are addressing well the main points mentioned before.
- Yes, the plans are identified, but sufficient funding is not in place to properly execute them.
- The rationales behind current activities were given, but the presentation seemed not to have discussed plans for the future.
- No, this needs to be done with manufacturers.

5. Was progress clearly benchmarked against the previous year?

- Accomplishments of the past year were clearly laid out. It is difficult to say whether progress was clearly "benchmarked" without fully understanding the goals laid out for the year and metrics by which they were measured.
- Unfortunately, in some projects, it was difficult to clearly identify the progress, as many slides of this year were just a copy/paste of slides already presented last year or located in the back-up slides.
- Sufficient description was given of activities within the past year.
- Not much. Manufacturing companies could present what they had done and what their needs are.

6. Are the projects in this technology area addressing the broad problems and barriers that the Fuel Cell Technologies Office (FCTO) is trying to solve?

- The projects in this technology area are still very focused on fuel cells. To the extent that that has been the focus in rolling out commercial vehicles, it is probably appropriate that this is the case. Also, while the examples and applications are fuel-cell-focused, these areas are barriers for related problems that FCTO is trying to solve as well. Tying these projects to broader applications would further increase the value and impact of the work.
- Yes, the projects are addressing the main problems and barriers. An additional topics might be to address the manufacturing of embedded tanks.
- The projects in this technology area are rationally directed toward the broad problems and barriers.
- Some of the activities, such as the supplier chain meetings, may not have been very effective in advancing the field.

- Yes.
- No.

7. Does the sub-program appear to be focused, well-managed, and effective in addressing FCTO's needs?

- Yes. There is a significant diversity in the types of projects funded under this sub-program, but the individual projects are addressing FCTO needs.
- The sub-program is well managed within the budget limitations. To be more effective, additional engagement with industry is needed, across technology areas and the supply chain.
- The sub-program itself seems to be focused and well managed. Some of the efforts involving interactions with regional fuel cell promotion groups may not have been particularly effective.
- Yes, the sub-program is well managed and focused.
- No.

8. What are the key strengths and weaknesses of the projects in this sub-program? Do any of the projects stand out on either end of the spectrum?

- Strengths include the capability that is being developed at NREL for understanding of roll-to-roll processing considerations and in-line measurements to characterize defects. Understanding the detection limits for defect size, as well as speed, is essential in understanding the capability of the process. The global competitiveness study is also a key strength of the sub-program in assessing both where the United States needs to continue to advance technology and the overall maturity of the field.
- The following are strengths: (1) The analysis of the United States' position vs. other nations in fuel cells was very necessary, and the results should be stressed. (2) Projects that get information on roll-to-roll processing into the public domain and that provide pilot-scale roll-to-roll coating capability to developers of advanced materials will likely prove essential to advancing the field. Roll-to-roll-coated materials must be used for commercialization-relevant studies of fuel cell durability and performance. (3) The Advanced Manufacturing Office's (AMO's) roll-to-roll consortium, which this sub-program led to, could prove useful to the development of U.S. industrial installations in multiple areas of energy conversion and storage. The following are weaknesses: (1) It is not clear that the supplier chain meetings and workshops and the interactions with regional fuel cell promotion groups have provided significant benefits. (2) QC research needs to get out of the national laboratories and into real production environments to be of ensured value.
- The following are strengths: (1) different well-structured projects that are effective in reaching goals and milestones, (2) establishment of a clear supply chain for the main systems and components in hydrogen fuel cell technologies with efforts to communicate it to the hydrogen fuel cell community and with clear recommendations on the weaknesses to address, and (3) quality control of membrane electrode assemblies and identification of the impact of defects on performance and lifetime in order to avoid over quality. A weakness is the collaboration/communication between the ongoing projects, which is not very easy to see and should be improved.
- The effort to assess U.S. competitiveness in manufacturing of various fuel cell components is valuable in order to prioritize future FCTO investments. The work on the hydrogen pipeline coupler is important to ensure that the capability exists when it is needed. It is not clear how the work on QC and roll-to-roll process development will be transferred to industry. It is difficult to assess the value of the two projects related to supply chain development without some metrics related to actual matches made between suppliers and integrators (that result in actual component sales).
- These projects need to be addressed with stack and system manufacturing companies. UTC Power did the roll-to-roll process many years ago.

9. Do these projects represent novel and/or innovative ways to approach these barriers as appropriate?

- The QC, roll-to-roll, and pipe coupler projects appear to be innovative. By their nature, the analysis and supply chain development projects are not.

- As a manufacturing program, this activity properly deals more with the selection of the best available technology rather than the development of entirely new processes or materials. Some of the quality control methods being explored are at least partly novel.
- Yes, most of these projects favor innovative approaches to enable a more efficient manufacturing of hydrogen fuel cell components.
- Yes, but the projects could be expanded beyond fuel cells.
- No.

10. Has the sub-program engaged appropriate partners?

- The sub-program has a few defined partners through the Small Business Innovation Research and Small Business Vouchers (SBV) programs. For maximum effectiveness, it would make sense to engage more industrial partners. The component survey work is heavily engaged with industry and has done a good job of obtaining relevant information. R&D engagement is not as evident, likely because of the budget constraints.
- This is difficult to assess. It appears that individual projects have the right partners, but the overall sub-program is too small to have attracted a large number of engaged partners.
- Not enough. Academia should be engaged only when the industry identifies a key fundamental challenge.
- The current partners appear quite appropriate. Nevertheless, increase of the participation of industrial partners (component suppliers, Tier 1) would be appreciated, in particular by validating the technological devices developed and the different models of cost breakdowns.
- The sub-program has engaged appropriate partners (suppliers, developers, national laboratories) plus some partners of questionable appropriateness (regional fuel cell promotion agencies).

11. Is the sub-program collaborating with them effectively?

- The sub-program is collaborating effectively with the partners that have already been engaged.
- The sub-program is collaborating effectively with suppliers and national laboratories.
- The sub-program is collaborating to the extent necessary for the individual projects.
- No.

12. Are there any gaps in the portfolio for this technology area?

- Intensified attention to roll-to-roll processing, as planned under the AMO consortium, would seem appropriate. A number of the specific manufacturing issues that need further study and public discussion are being examined under the cost analysis function of the FCTO.
- On-board storage tanks remain a key element for the commercialization of fuel cell vehicles. The tanks are too expensive, and innovative manufacturing processes may be investigated to address this issue.
- Yes. Manufacturing of bipolar plates, catalysts, and GDLs should be addressed, as these materials and components have been identified as areas where the United States is relatively weak.
- There could be more interaction with product developers (stacks) to ensure relevance for the roll-to-roll processing.
- There are many gaps.

13. Are there topics that are not being adequately addressed?

- The impacts of fuel cell break-in procedures on costs should receive more attention. Internal combustion engines are now typically never fired up until they are in a completed vehicle. It would be useful to determine whether fuel cell materials and QC procedures can be developed to a similar level of confidence. Fuel cells have many parts working in series. This puts extreme pressures on QC that should probably receive more consideration and discussion than they have in the past.
- Most of the topics are very well addressed. Hydrogen refueling station trade flow mapping appears, however, not adequately addressed, with significant approximations to be corrected.
- Yes. Manufacturing of bipolar plates, catalysts, and GDLs should be addressed, as these materials and components have been identified as areas where the United States is relatively weak.

- Porous transport layer manufacturing is not addressed. Some QC measurements are included, but manufacturing development in the porosities and distribution needed, or how to make them, is not included.
- Yes.

14. Are there other areas that this sub-program should consider funding to meet overall programmatic goals?

- Components beside membrane electrode assemblies and catalyst layers are important and require additional focus somewhere in the FCTO Hydrogen and Fuel Cells Program. Manufacturing would appear to be the appropriate area. Also, some of the techniques for defect detection work for fuel cells but not other types of devices. Expanding the capability of these areas would be of benefit.
- Yes. Independent study and data from manufacturers should be considered.
- Manufacturing of on-board storage tanks may be one.

15. Can you recommend new ways to approach the barriers addressed by this sub-program?

- Improved connections between DOE and industrial personnel developed under the FCTO and AMO consortia should be exploited to get more complete descriptions of manufacturing, cost, and performance status into the public domain to guide policy development.
- Additional SBVs and funding mechanisms would be helpful in engaging with small businesses, which may not have the capability to invest in cooperative research and development agreements but could use this capability.
- More effective engagement of ultimate manufacturers in the Manufacturing R&D projects will be critically important.
- Yes. We should learn what has been done in Japan and Europe.
- The current approaches are well defined and effective.

16. Are there any other suggestions to improve the effectiveness of this sub-program?

- The diligent and capable efforts of the manufacturing team should continue to facilitate a hydrogen/fuel cell option in the United States' energy future.
- Additional funding is needed to balance the portfolio. The focus should be on where the U.S. manufacturing position is weakest.
- Yes. There should be more work with manufacturers.

Technology Validation Sub-Program Comments

1. Was the sub-program, including overall strategy, adequately covered?

- Yes, the sub-program has a clearly outlined strategy for addressing a wide array of technology data gaps. The sub-program is broad, and it is impressive how well managed the strategy is at addressing all subjects within the sub-program.
- Yes, the strategy is simple and clear: do what is needed to deploy technologies. The first few slides made clear how that is going to happen, and the slides that followed described how this strategy was rolled out through individual projects.
- The sub-program's overall goals and objectives were clearly stated; however, it is not clear that the strategies and barriers reflected on slide 2 are really aligned/up to date with the objectives (which are related to vehicle performance/station performance/stationary fuel performance). In addition, the budget slide then shows the largest budget item being H2@ Scale (which is a good thing), which is not directly linked to the Goal statement. It would helpful to get the goals, objectives, strategies, and budget more clearly aligned. This may mean it is time to update the objectives/strategies.
- The sub-program, including goals, objectives, strategy, and barriers, was well discussed. "Lack of [fuel cell electric vehicle (FCEV)] and [fuel cell electric bus (FCEB)] performance a durability data" as a barrier was a surprise, considering the extensive data collection by the National Renewable Energy Laboratory (NREL) over the past several years. Perhaps the previous data were not valid because of design changes in vehicles.
- The sub-program was explained, and the strategy was described, but the presentation could have benefited from specific examples of the impact strategic efforts would have on fuel cell adoption.
- Yes, goals, strategy, portfolio, issues, and accomplishments were well organized and well described.
- Yes, the strategy was clearly described.

2. Is there an appropriate balance between near-, mid-, and long-term research and development?

- Yes, as a technology validation program, the structure of the projects has been shown to be well balanced and appropriately weighted to near-term solutions. The requested budget for this sub-program is $0, and this would represent a significant loss to the momentum of efforts across the country to bring hydrogen and fuel cell technologies into the mainstream. The impact would be far-reaching and possibly cause delays of momentum for several years. The suggested elimination of the budget and elimination of the ability of any program within the Fuel Cell Technologies Office (FCTO) to focus on higher-technology-readiness-level (TRL) projects needs to be reversed. These programs will have some of the greatest impact in achieving the U.S. Department of Energy (DOE) and FCTO goals. Without them, it will be impossible to actually accomplish what has been set out in the Multi-Year Research, Development, and Demonstration Plan.
- Because of the nature of the sub-program, projects tend to be more near-term, but there are a couple of projects with longer-term implementation, such as H2@ SCALE. This balance is appropriate for the sub-program.
- At this point, it seems like it is time to reduce the effort on light-duty vehicles; they are in the market. Critical near-term goals seem like they should align with improving/facilitating infrastructure and mid- to long-term goals to H2@ Scale/Grid interaction. In general, things that were previously near-term are now commercial, and things that were previously mid-term are now near-term, etc. That said, the specific project focuses on, for example, dispenser reliability and hydrogen metering are important and well-focused on goals that were mid-term and are now near-term/urgent.
- Generally yes, with attention and appropriate flexibility to identify market changes that reflect consumer choice.
- Generally yes, although the timeline goes out only to 2020, which is not really long-term but is appropriate for the technology validation topic.
- By its nature, this sub-program focuses more on mid- and near-term work.
- Objectives only through 2020 are short-term but are well discussed. No objectives out to 2030 were recognized.

3. Were important issues and challenges identified?

- Yes, this sub-program in particular appears to be well informed by real-world experience and challenges being faced not only by companies but also by government agencies involved in hydrogen and fuel cell technology today. The Hydrogen Fueling Infrastructure Research and Station Technology (H2FIRST) program is a primary example of this appropriate focus on known and important issues in today's efforts.
- Yes, goals for range, operation duration, and production with validation strategy to support data-driven decision-making is very appropriate. Issues to resolve meter accuracy, siloxanes, and metal contamination were adequately addressed.
- Yes. Both fundamental issues (hydrogen metering, cryocompressed dispensing/storage) and practical issues (dispenser reliability, mobile fuelers) are driving well-founded work that is important to drive commercialization of hydrogen.
- Three barriers were identified, namely (1) lack of FCEV and FCEB performance and durability data, (2) lack of hydrogen refueling infrastructure performance and availability data, and (3) hydrogen from renewable resources. Given the types of projects that are undertaken by the sub-program, the following barrier should be added: lack of appropriate hydrogen station components (meters, pumps).
- Yes. They are listed clearly and succinctly.
- The program has identified the major challenges.
- Barriers are identified that appear to be equivalent to challenges. Since DOE makes up the questions, if the presenters used the same terminology, it would make it easier for reviewers.

4. Are plans identified for addressing issues and challenges?

- Yes, the sub-program exhibits a wide array of experimental, modeling, and analysis initiatives to address the largest unknowns in implementing hydrogen and fuel cell technology in real-world settings. The approaches used are well tailored to the information needs of the challenge being addressed.
- The challenges identified are lack of data and deployment of hydrogen from renewables. Lack of data is being addressed adequately, although it seems that there is less emphasis on validating hydrogen production from renewables outside of modeling efforts. It may be that DOE feels that this area is sufficiently well covered.
- For each of the activities in the project portfolio, there is a discussion explaining "why" the work is being done. In addition, Chart 3 has an impact statement along with the strategy statement that states what is being done and why. The detailed plans for how these activities are achieved are not presented. This may not be a good question for the projects in the Technology Validation sub-program, considering the limited timing for the presentations and the large number of activities in the sub-program.
- Generally yes, with project work that includes laboratory analysis, technology integration, validation, and testing with feedback for refinement.
- Some of the individual projects (e.g., cryocompressed) need clearer deliverables/dates. Some of the others (two delivery truck range-extender projects, for example) probably need to be looked at for possible redundancy and for relevance both to the "fundamental research" direction and to the focused goals. It is not clear that integration of range extenders is fundamental to either.
- Yes. However, since the primary challenge is a lack of data, the solution is (to a large extent) just to gather data.
- Yes.

5. Was progress clearly benchmarked against the previous year?

- Yes, projects within this sub-program clearly demonstrated the progress made over the past year. Some projects that had delays were candid about as much and provided convincing plans and strategies for recovering lost time over the next year. The discussion was logical, and the honesty was appreciated.
- The presentations showed significant increases in vehicles and stations. This is the result of original equipment manufacturers' (OEMs') and California's efforts. The sub-program appears to be taking full advantage of these efforts.
- There appeared to be an appropriate continuation of previous work with consistent progress.

- No. Accomplishments were given (and are impressive), but it was not clear whether these accomplishments contained information from the previous year. A crosscheck with the 2016 presentation identified some accomplishments that appeared to carry back to 2016. Clearer delineation of 2017 and 2016 accomplishments would help.
- No. Goals are stated at a high level for this and future years, but progress to goals that may have been stated last year for this year is not obvious. The individual project summaries include many significant accomplishments, but it is not clear whether those are directly planned deliverables.
- No, it is not obvious what changes happened between 2016 and 2017 without looking at last year's slides. Some of the projects are brand new, but it is not clear from this year's presentation alone.
- In general, no.

6. Are the projects in this technology area addressing the broad problems and barriers that the Fuel Cell Technologies Office (FCTO) is trying to solve?

- Yes, the projects in this sub-program ensure that demonstration of meeting the technology targets set out in the FCTO Hydrogen and Fuel Cells Program (the Program) are actually impactful. Validation of meeting the performance targets out in the field, and doing so with consistency and reliability, is necessary for the overall Program goals to have real-world impact. This sub-program successfully performs the work necessary for such a validation.
- Yes. This is a strong sub-program that is needed to make the transition from laboratory to prototype, leading to market transformation. Technology Validation is the sub-program, along with Market Transformation, that demonstrates that laboratory efforts can result in successful pathways to commercialization.
- In the infrastructure, H2@ Scale, and grid integration/energy storage areas, yes. In the vehicle areas, it seems like it is time to let industry integrate and commercialize; the projects in those areas seem to be working more on areas that are less fundamental. There is a caveat, however: in a couple of key areas, there is a need to execute a full-scale demonstration so that investors and stakeholders have something they can see and touch. The best examples of this are MT-008 (Large-Scale Electrolyzer for Grid Stabilization) and TV-039 (Advanced Technology Mobile Fueler). Both of these are hard to get industry to try without a full-sized demonstration.
- Yes, range, production, and durability are being addressed. Problems with meter accuracy and contaminants are appropriately targeted for action.
- The Technology Validation sub-program effort has expanded to include stationary fuel cells as well as vehicles. This is a move away from the traditional transportation focus, but it is appropriate.
- Yes, technology validation is critical to helping the industry transition out of the precompetitive stage, and DOE is well suited to performing that role.
- Yes. The projects are well selected.

7. Does the sub-program appear to be focused, well-managed, and effective in addressing FCTO's needs?

- Yes, the sub-program maintains focus on addressing the most immediate and pressing barriers to real-world deployment and demonstration of hydrogen and fuel cell technology potential. Varied efforts seem well coordinated with one another and emerging data needs in industry and field deployment.
- The sub-program is very well managed, based on the accomplishments and successes reported. The sub-program is highly effective in demonstrating the importance of the FCTO research and development activities. Technology validation activities do not report failures, and it is not clear why. Not all projects are successful, and identifying unsuccessful activities and making decisions to stop those activities are as important as identifying success.
- Yes, the sub-program appears to be using an appropriate approach, is well managed, and is well focused.
- Yes, the sub-program is accelerating the development and adoption of sustainable transportation technologies.
- Generally yes. However, with the future budget direction, there probably needs to be some refocusing on the most critical projects.
- Yes (two responses).

8. What are the key strengths and weaknesses of the projects in this sub-program? Do any of the projects stand out on either end of the spectrum?

- The strength of the sub-program's projects lies squarely in their immediate usability and their ability to address problems that are being faced right now by several efforts across the country to form the first seeds of wide-ranging implementation of hydrogen and fuel cell technologies. Particular projects that stand out as strengths include the National Fuel Cell Technology Evaluation Center projects on both hydrogen station and fuel cell vehicle performance and data collection, and the H2FIRST-related activities, especially hydrogen meter benchmark testing. The ongoing work for hydrogen fuel production integration with the electrical grid also stands out as projects that are well designed and are addressing significant gaps in knowledge that is in need today.
- The hydrogen metering effort is of great importance to widespread public dispensing stations. Benchmarking actual electricity consumption at electrolyzer stations is of importance to validating the actual usage against a string of subsystem computational models (electrolyzer, compression, cooling, dispensing). The integrated grid studies are important, but it is not evident that they are appropriately part of this fuel-cell/hydrogen-centered program. Fuel cell buses and trucks will play an important role, and their study is of great importance.
- The NREL composite data products are a great resource for information on vehicles and infrastructure and should be maintained and expanded.
- Strengths include the following: the ability to collaborate with OEMs in data collection and analysis of FCEBs, FCEVs, and hydrogen stations; and access to personnel and facilities to build and test supporting technologies, including sensors (i.e., flow meters) and models (i.e., real-time simulation of electrolyzers). A weakness is that, although one of the barriers mentioned was hydrogen from renewables, the only work in this area is through models. The Technology Validation team needs to initiate collaboration with utilities to test and implement their grid simulator models.
- The sub-program has appropriate focus on commercial goals and correction/resolution of problems, which is a strength. A weakness is that the economic factors from the systems analysis (Joseck) need to be identified to better target action for the most valuable markets that are ready for commercial development.
- A strength is the focus on key near- and mid-term enablers for commercialization. A weakness is a tendency to hang on to projects too long. Some projects have to be stopped before they are finished because the landscape changes and diminishes their relevance. That is a tough call but necessary in the context of budget pressure.
- The key strengths of the projects are the collaborations, specifically NREL activities and industry contributions. The weakness of the projects is not stopping (or announcing that FCTO is stopping) projects that do not meet commercial requirements.

9. Do these projects represent novel and/or innovative ways to approach these barriers as appropriate?

- Yes. In particular, several of the hydrogen fueling station equipment testing and characterization projects have developed entirely novel test stands and test methods that are not known to exist elsewhere. This includes several testing efforts within H2FIRST projects, as well as grid–electrolyzer interaction studies.
- The projects are novel and innovative, and the process for validation is objective and appropriate to promote commercialization and manufacture of U.S. technology, development of U.S. infrastructure, and appropriate utilization of U.S. resources.
- Yes, the sub-program is validating hydrogen station dispensing capacity by helping stations improve their performance through the flow meter, liquid pump, and component testing (contaminant evaluation) projects. The projects are actively speeding up the expansion of the industry by providing solutions to real-world problems.
- It is kind of a mixed bag—in some cases, yes (H2@ Scale, grid stabilization), and in some, no (truck range extender)—and in some cases, what is novel is that something that has been talked about for years (mobile fueler) is actually demonstrated. Some need better metrics (cryocompression) to ensure that the projects are continuing to deliver valuable results/milestones. The go/no-go structure is a good way to do this, as long as the decision criteria are clearly defined.

- The projects demonstrate that proper choice of commercial targets through collaboration of industry and the national laboratories results in incremental progress toward solving challenges and eliminating barriers, which will lead to successful results.
- The efforts are not particularly novel, but in this area, novelty is not as valuable as consistency, clarity, and comprehensive efforts.
- The approach is effective and appropriate, although not particularly novel or innovative.

10. Has the sub-program engaged appropriate partners?

- Yes. The sub-program appears particularly adept at responding to developing needs as identified by industry, government agencies, and others currently highly involved in the deployment of hydrogen and fuel cell technologies. Partnership and collaboration within this sub-program appear to be one of the major strengths.
- In general, each project lists a number of collaborators. These seem to be determined at the outset, which is fine, but it also seems like there are several projects for which it makes sense to bring in additional collaborators depending on how the project results unfold. It is not clear that the sub-program has the flexibility to do this. This may be related to how we define a "collaborator"—i.e., perhaps a collaborator has to be a contractor or provider of funds/services to a project—it is not clear.
- Yes, all listed and described partners including industry, laboratories, universities, and government are very appropriate participants. There would be value to better understanding more precisely the players, the level of participation, and the specific contributions from each of the partners.
- The Technology Validation sub-program is working with a number of commercial entities, in addition to the typical interactions with the national laboratories.
- There is appropriate collaboration by the laboratories and OEMs, but additional collaboration with utilities to vet and utilize the grid integration models is suggested.
- In general, yes.
- Yes.

11. Is the sub-program collaborating with them effectively?

- In general, yes. The "typical" collaborators (DOE, national laboratories, long-standing corporate participants, universities) are all very familiar with working in this environment and so respond well to structuring and working within a project framework. The sub-program might look for opportunities to draw in unconventional collaborators who might bring new perspectives.
- Yes, the transportation data collection and analysis is the best example of this collaboration. Data continue to be gathered and analyzed confidentially.
- Yes. This is a major strength of the sub-program.
- It appears so; however, more information on the level of participation and contributions from each of the partners would have been helpful.
- Yes, based on accomplishments.
- Yes (two responses).

12. Are there any gaps in the portfolio for this technology area?

- *From two respondents:* There are no obvious gaps.
- There is significant need right now to understand how to test and validate claims of hydrogen station fueling capabilities, especially claims of daily fueling capacity, back-to-back fueling capability, and simultaneous fueling capability. The Hydrogen Station Equipment Performance (HyStEP) device has been a good first step toward validating station performance with respect to codes and standards, and may be a good stepping stone for launching an effort into validating performance characteristics that are not necessarily related to a standard or a protocol.
- FCTO has been doing work in other sub-programs to understand the technoeconomic aspects of tube trailer refueling, thus avoiding on-site compression. It would be good to see this technology being validated through this sub-program.

- No, although the grouping of projects/topics is not really consistent within the presentation material (slide 4 vs. slide 20). It seems there is a need to ensure H2@ Scale, vehicles/infrastructure (with the most emphasis on Infrastructure at this point), and grid/energy storage are covered as the main groupings.
- There are no apparent gaps, but a better identification of costs and values with some information on the market potential and economic value for specific project areas would have been helpful.
- There is some uncertainty about actual hydrogen compressor efficiency. This merits further examination.

13. Are there topics that are not being adequately addressed?

- No. The work that is currently ongoing seems to be overall covering a good breadth of the related issues, with their respective objectives and technical challenges being addressed.
- No, the presentation effectively addressed the main topics for stationary, motive, and hydrogen production.
- There is concern that venting losses (even at 3.6% project future levels) are too high.
- Projects that do not project commercial success should be eliminated.
- No (two responses).

14. Are there other areas that this sub-program should consider funding to meet overall programmatic goals?

- The area integrating stationary power with controller technology for dispatch, storage, integration of renewables, cost management, and demand response is an area that could be ripe for commercialization through competitive suppliers and/or utilities. This is an interesting focus area that should be continued.
- In response to the budget's being eliminated for the next year, all funding needs to be restored to at least the previous year's levels. Elimination of all funding for this sub-program is unacceptable.
- Emphasis should primarily be within the H2@ Scale and energy storage areas. Infrastructure reliability, energy usage, and cost also remain important.
- There are innovative hydrogen production technologies that are not included in the Program, and the Technology Validation sub-program could benefit from expanding the scope of activities.
- Validation of tube trailer dispensing should be considered.
- No (two responses).

15. Can you recommend new ways to approach the barriers addressed by this sub-program?

- Given the budget situation, and acknowledging the development of hydrogen and fuel cell industries broadly across several states, there may be an opportunity to try to convene a states' coalition for identifying on-the-ground technology deployment issues and information needs. Perhaps efforts under such a consortium approach can help identify new opportunities for ongoing work.
- Where possible, participation and collaboration with private industry should be increased, with identification of individual contributions. Regulators should be engaged to better understand the process to integrate stationary power with controller technology for dispatch, storage, integration of renewables, cost management, and demand response for commercialization through competitive suppliers and/or utilities. Integration of technical work with economic systems analysis (Joseck) should be increased, where possible.
- The Technology Validation sub-program has the mandate to study, test, and validate actual performance of systems and components. It would be good to see a clear linkage between findings from the sub-program's efforts and the follow-on efforts to capitalize on the information. For instance, if hydrogen meters are inadequate, it would be good to know what specific research and development programs are addressing the gap. This linkage is implied, but a direct connection should be identified.
- Barriers are listed as lack of FCEV and FCEB performance and durability data, lack of hydrogen refueling infrastructure performance and availability data, and hydrogen from renewable resources. The first two are pretty well taking care of themselves. Projects supporting hydrogen from renewable resources could be a focus area to support several of the strategies.
- The sub-program could test and collect data from home/community refueling stations. There was an H2Refuel project at the poster session; the sub-program could collaborate with them to test/validate the technology's durability under different conditions.

- No, data accumulation from California and other projects should be kept up.
- No.

16. Are there any other suggestions to improve the effectiveness of this sub-program?

- Overall, this is a valuable and well-managed DOE sub-program. Increased private industry participation and identification of contributions, integration with economic systems analysis, and collaboration with utility regulators and competitive power suppliers would be of value. Concise white papers on sub-program accomplishments targeted for non-technical energy industry stakeholders (utilities, power suppliers, marketers), policymakers, and government officials might also be an area to show sub-program value.
- There is no excuse for the presenter's not covering all the material in the allotted time. The presentation should be reviewed and "dry runs" carried out with colleagues before the Annual Merit Review. The presentation should be pared down if all the material cannot be presented in the allotted time.
- The sub-program should try to look at which projects may need to end due to changing priorities and resources so that the remaining projects or new ones can be resourced for maximum effectiveness.
- Funding should be increased, but this does not appear to be possible with the new administration.
- There are no suggestions at this time.
- No.

Safety, Codes and Standards Sub-Program Comments

1. Was the sub-program, including overall strategy, adequately covered?

- The overall strategy of the Safety, Codes and Standards (SCS) sub-program is well-thought-out. The sub-program is focusing on areas that need support for enabling the deployment of hydrogen infrastructure and the further reliability aspects of it. Some examples of these are (1) the work in establishing scientific-based data for enabling the reduction of safety distances, given that footprint requirements for station deployment are currently a barrier for integrating large-capacity hydrogen fueling stations into a retail environment; and (2) the number of projects for the development of an in-line fuel quality analyzer that will enable highly reliable operation of hydrogen fueling stations.
- Yes. Mr. James provided a thorough and well-organized review of the SCS sub-program. He identified the key focal areas and barriers and the strategy for addressing challenges, and he provided a deeper look at the progress and accomplishments made over the past year. The focal areas of this sub-program are all needed for helping to accelerate the hydrogen and fuel cells market. It is also a well-balanced portfolio that addresses technical needs, outreach, and identification of future needs.
- Yes, for years, this area has had a clear overarching goal and multi-annual objectives, and these are tackled structurally and in a complete way.
- Yes, it was an excellent overview on focus areas, barriers, and objectives to address barriers.
- Goals and Strategies are stated; however, they are not referred to consistently through the first part of the presentation. Slide 2 shows Goals/Objectives in two areas, slide 3 shows budget in three different areas (maybe slide 2 is a "vertical" cut, while slide 3 is "horizontal"), and slide 5 then shows five focus areas with barriers and another set of objectives. These can be organized better so that there is a clear flow of objectives to focus areas to deliverables to resources.

2. Is there an appropriate balance between near-, mid-, and long-term research and development?

- The balance of near- and long-term research and development (R&D) seems appropriate. For the near-term needs, the sub-program is heavily focused on station reliability by supporting several projects on the development of in-line fuel quality devices, in addition to the support of critical stakeholders on hydrogen safety best practices; whereas in the long term, the sub-program seems to be focused on liquid hydrogen and therefore larger-capacity fueling stations by supporting work that will have an impact on the required safety distances (or footprint) for the deployment of larger stations.
- Yes. The sub-program is focused on R&D and information dissemination for challenges that we face currently. It is also working on issues we anticipate becoming (and are seeing become) more prominent as the market grows. Finally, the Inter-Laboratory Research Integration Group (IRIG) was developed to identify future needs.
- Yes. Safety research is critical for enabling near-term standards and facilitating construction. Sensor research is an important medium-term effort, and materials research supporting safe/reliable/cost-effective infrastructure is a good longer-term effort.
- Yes, the sub-program covers all of what is needed for filling gaps in safety knowledge and data; it naturally integrates the underpinning scientific foundation at the service of standards and permitting tools and processes.
- Yes.

3. Were important issues and challenges identified?

- Yes. The issues being addressed under the sub-program, once solved, will help reduce space and cost challenges (e.g., separation distances, safety sensors, and fuel quality)—both currently limiting factors in hydrogen station development.
- Yes. Gaps in codes and standards (also in safety) are continuously analyzed and prioritized. The process for achieving this is based on a broad coalition of stakeholders and experts.
- Main issues and barriers were clearly identified by the sub-program manager, as presented on slide 5.
- Yes, challenges are identified for each major area of effort.

- Yes.

4. Are plans identified for addressing issues and challenges?

- Yes. The presentation focused on sharing progress within each focal area, and each focal area is designed to meet specific objectives that will address larger barriers. Future plans for each focal area were not outlined specifically; however, the progress is being demonstrated, and the path forward can be seen.
- Yes, and not only the plans—the mechanisms for their successful implementation are also properly designed on the basis of previous experiences (for example, the CSCI and the IRIG instrument).
- Slide 5 clearly identified the main objective for each of the barriers identified, and throughout the talk, the sub-program manager showed in detail the corresponding projects that will address the main barriers and how to overcome these.
- Yes. The funded projects represent well-planned efforts to address the challenges identified.
- Yes. Plans were also clarified during individual project sessions.

5. Was progress clearly benchmarked against the previous year?

- Yes, progress was clearly presented, with some of the main highlights being the techniques for understanding liquid hydrogen release behavior, the release of the Hydrogen Risk Assessment Model (HyRAM) 1.1, and the patent application for the fuel quality sensor.
- It was. Mr. James devoted a slide to outlining progress since last year. There could have been an opportunity here to highlight progress more here to underscore the value and importance of this work, for example, by showing in each focal area the status in 2016, what was achieved in 2017, and what is left to be done. That said, Mr. James still did a good job of sharing the solid progress that has been made.
- It is not clear what "benchmarking" is supposed to mean in this context. Quantitative improvement indicators are not possible for this area of the sub-program. However, certainly a multi-annual mapping of the achievements were given, allowing the assessment of the progress toward SCS gap filling. A part of the activities in this area consists of maintaining, improving, and disseminating (safety) knowledge datasets. Also, for these aspects, quantitative indicators do not exist, but there is clear evidence that improvement in respect to last year's status was achieved.
- Yes, key areas of progress for each project since the 2016 Annual Merit Review were clearly stated and summarized.
- Yes, the overview slide was a good summary of progress.

6. Are the projects in this technology area addressing the broad problems and barriers that the Fuel Cell Technologies Office (FCTO) is trying to solve?

- Absolutely. For example, setback distances are a persistent challenge for station development in highly populated urban areas (much of California), and bringing down the cost of safety sensors and hydrogen purity monitors will help bring down overall station costs, which will enable more infrastructure development and may help spur more private investment in the market. Additionally, safety education is still very much needed, and the safety outreach efforts are fantastic. H2Tools is an excellent resource that this reviewer values firsthand and has heard the same from many others.
- Yes. It appears evident that this area is well integrated with the rest of the FCTO Hydrogen and Fuel Cells Program and reacts well to the needs of the other areas. Examples are the focus on safety in tunnels to answer urgent needs for the deployment of the technology in the Northeast, and the need for fundamental understanding and facts related to liquid hydrogen (storage) behavior to address one of the most critical enablers for full-scale deployment.
- Yes, given that the speed of acceptance and implementation of infrastructure is being hindered by lack of clear codes, familiarity, and understanding of hydrogen properties and rules, SCS is one of the most critical areas of FCTO work. It is critical to keep an eye on how the objective of "R&D to provide critical data and information needed to define requirements..." can be very quickly brought to bear to support resolution of emerging issues such as the bridge and tunnel problems. For example, while the facilities and work at Sandia National Laboratory to quantify liquid hydrogen spill behavior are valuable long-term assets, they were not able to respond quickly enough to affect the immediate revision cycle of the National Fire Protection Association's Hydrogen Technologies Code (NFPA 2).

- Very clearly. Even with a very limited budget, the sub-program is well balanced to provide support for addressing the main barriers around safety, reliability, and code implementation.
- Yes, the projects are addressing the development of a foundation of safety knowledge and codes & standards needed and widespread sharing thereof.

7. Does the sub-program appear to be focused, well-managed, and effective in addressing FCTO's needs?

- Very effective management has been the key for the success of the SCS sub-program. Management is always engaged with the external community and does a good job disseminating the advances of the sub-program.
- Yes, although the current projects will need to be clearly prioritized in light of the new budget and focus/ direction realities. This may mean that some projects may need to be stopped to provide resources for critical new needs that arise.
- Yes. However, it is challenging to keep up with the changing needs on a limited budget for this topic area.
- Absolutely.
- Yes.

8. What are the key strengths and weaknesses of the projects in this sub-program? Do any of the projects stand out on either end of the spectrum?

- Key strengths include the following:
    - The work on tunnel safety is very important for enabling market growth in the Northeast.
    - Reducing separation distances and costs for safety sensors could also help accelerate the market in the United States and internationally.
    - Assuring adherence to fuel quality standards is also an emerging need.
- The following are key strengths: a strong and dedicated group/network of collaborators, both national and international; alignment with industry needs; and the H2tools.org website as global resource. The following are key weaknesses: H2tools.org's dependence on U.S. Department of Energy (DOE) funding to continue operations, and the SCS sub-program's dependence on the annual budget-making process.
- Among other excellent projects, HyRAM should be mentioned as a most successful international attempt to offer to stakeholders a one-stop shop on safety design.
- One of the key strengths is that the projects have been well targeted to meet real-world immediate needs such as setback data and sensors for service facilities. It is, perhaps, a weakness that the economic objectives of all the projects are not clearly stated at the beginning. For example, after showing very promising sensing results, the principal investigator of the laser diode sensing project, when asked about cost, said in effect that the technology is extremely expensive and that it is unlikely that someone would choose to use it because of that.
- Strengths include sub-program management and significant engagement with national and international codes and standards organizations. Weaknesses include a limited budget and perhaps the lack of work on fueling protocols (this might be due to the limited budget).

9. Do these projects represent novel and/or innovative ways to approach these barriers as appropriate?

- In some cases, yes (such as SCS-029, in which an existing instrument technology is being adapted for a new use with novel algorithms). In some cases, it is more a matter of just identifying and prioritizing the critical work that needs to be done (which is important and okay to do).
- The most characteristic and appreciated aspect of the SCS sub-program is its integrated approach to the challenges, trying to engage with all types of stakeholders and experts. This is perhaps not successful in all cases, and sometimes industry presence and input could be better, more intense and continuous, as admitted also by the sub-program manager. However, this issue is very much out of the manager's control and is a characteristic deficiency of similar international programs.
- This is clearly demonstrated by the fact that scientific-based data are used to support the proposed modifications to codes and standards.

- Yes.

10. Has the sub-program engaged appropriate partners?

- Yes. The sub-program has engaged U.S. and international partners, enabling us to leverage learnings from (and contribute to) other countries while also being grounded in specific needs for U.S. market development. Partners also exist across sectors—government, industry, academia, non-governmental organizations—and within these sectors, the sub-program has partnerships with the "right" key organizations.
- Very extensively. The continuous interactions with the codes and standards technical bodies is probably one of the main strengths of the sub-program.
- The most characteristic and appreciated aspect of the SCS sub-program is its integrated approach to the challenges, trying to engage with all types of stakeholders and experts. This is perhaps not successful in all cases, and sometimes industry presence and input could be better, more intense and continuous, as admitted also by the sub-program manager. However, this issue is very much out of the manager's control and is a characteristic deficiency of similar international programs.
- Yes, the SCS umbrella involves/requires engaging a wide array of collaborators and partners to obtain, develop, and disseminate information and data. One concern (broader than just SCS) is that DOE projects do not often bring in new partners/collaborators mid-stream through a project. It seems like cultivating the ability to do this would be very valuable, as it is often not known at the outset what direction project results are going to go.
- Yes.

11. Is the sub-program collaborating with them effectively?

- It appears so. The reviewer cannot speak to all collaborations, but from those organizations that the reviewer is involved with that partner with this sub-program, the answer is yes. Lines of communication are open, market needs are being identified and addressed, and the hydrogen fuel cell community is benefiting from this sub-program's projects.
- Absolutely. This in part speaks for the success of the sub-program's activities.
- Yes, although the ability to have flexible collaboration arrangements that change over the duration of the projects is needed.
- Yes, very well.
- Yes.

12. Are there any gaps in the portfolio for this technology area?

- This portfolio does a good job of addressing current key challenges to enable market expansion of hydrogen and fuel cells.
- Gaps include heavy-duty hydrogen vehicle fueling and underground hydrogen storage (direct burial) codes and standards (including setback/separation distances).
- An increase in budget will greatly help to support R&D work on fueling protocols.
- No gaps were noted.
- No.

13. Are there topics that are not being adequately addressed?

- Absolutely not. However, the area of detection/sensors could profit from some clarification to avoid confusion. Under this name, a broad set of technologies is used for two very different goals. Safety hydrogen sensors are critical for the safe operation of all installations. Hydrogen impurity detection is critical to guarantee gas quality and to avoid fuel cell degradation, a very critical aspect of the whole technology chain. It is obvious that common competence in gas detection is required in both goals, but the approach to solutions is different in the two cases. This does not appears very clear from slide 5, where a general barrier typical for safety sensors is coupled to an objective specific for impurity detection, where a fully developed technology solution is not yet even available.

- For in-line hydrogen quality sensor efforts, it would be good to know what the progress is with assessing the real cost for these sensors, not just the replacement cost.
- The development of innovative fueling protocols should be taken into consideration.
- No.

14. Are there other areas that this sub-program should consider funding to meet overall programmatic goals?

- Other areas include heavy-duty hydrogen vehicle fueling, underground hydrogen storage tanks in hydrogen fueling station safety testing, limits for over-the-road liquid hydrogen transportation (whether limits can be expanded), and transport of liquid hydrogen by rail.
- Other needs that the sub-program could consider funding include (1) a Hydrogen Station Equipment Performance (HyStEP)-type device to enable third-party fueling protocol verification systems to be validated and 2) development of medium- and heavy-duty fueling protocols to enable acceleration of the medium- and heavy-duty fuel cell market.
- Whether the field of hydrogen impurity detection and measurement receive enough funding could be considered. This technology covers a critical role in the whole technology chain and deserves the most urgent attention. There could be also a need to join forces (resources, competences) with other sub-programs.
- In light of the fact that funding will likely not continue to be available for everything on which FCTO is currently working, it would be helpful to conduct a priority review of projects/resources underway so that critical projects can continue to be fully resourced and so that resources can be allocated if/when new critical priorities arise.

15. Can you recommend new ways to approach the barriers addressed by this sub-program?

- There is a very small suggestion for improvement in the specific area of safety sensors as a key technology for preventing/mitigating measures. It is still not possible to offer a simple and cheap methodology for the proper installation of detecting devices in complex/difficult spaces, so the work initiated in 2017 on dispersion and detection in an electrolyzer container will not be enough to answer this question in a general sense, to determine what industry would like to have. There are algorithms and novel approaches to this, which should use three-dimensional computational fluid dynamics only in the validation phase, and later on offer easier and cheaper methods to be applied, as already adopted for other gas industry areas.
- It would be very impactful if our outreach/education projects can create opportunities for stakeholders/ students to visit existing hydrogen facilities to see firsthand what safety systems are in place, how codes are applied, and how safety systems (passive and active) work. This would increase the already very helpful momentum that has been achieved in meetings, seminars/class sessions, and webinars. Likewise, perhaps some of the web content could provide suggested facilities/contacts for viewers to consider visiting facilities that showcase examples of the material being studied.
- This sub-program could be integrated with the DOE Office of Fossil Energy safety area (if there is such a thing).

16. Are there any other suggestions to improve the effectiveness of this sub-program?

- It would be very impactful if our outreach/education projects can create opportunities for stakeholders/ students to visit existing hydrogen facilities to see firsthand what safety systems are in place, how codes are applied, and how safety systems (passive and active) work. This would increase the already very helpful momentum that has been achieved in meetings, seminars/class sessions, and webinars. Likewise, perhaps some of the web content could provide suggested facilities/contacts for viewers to consider visiting facilities that showcase examples of the material being studied.
- Particularly in light of the recent budget cut announcements, it seems that working more with industry to both ensure research is actually filling key needs and information gaps and to encourage/leverage private investment is now more important than ever.
- The work should be kept up, whether under DOE FCTO or elsewhere.
- The budget should be increased.
- No.

Market Transformation Sub-Program Comments

1. Was the sub-program, including overall strategy, adequately covered?

- *From two respondents:* The sub-program, including the overall strategy, was adequately covered.
- The sub-program was discussed in great detail, and good progress was being made in the acceleration of technology for hydrogen fuel cell systems. The success generated by the prior efforts on materials handling with the continued sales of forklift trucks without the federal subsidy validates the efforts of the Fuel Cell Technologies Office. The strategy was not specifically identified, and since this question always gets asked, a chart with "strategy" would be helpful. The objectives appear to define the strategy and are consistent with meeting the Market Transformation sub-program goals.
- Yes, markets, demonstrations, and targets were well organized and accurately presented. There is good leadership with thoughtful management.
- Although the reviewer was not able to attend the presentation in person, a review of the slides presents a very firm picture of the efforts and overall strategy for the Market Transformation sub-program.

2. Is there an appropriate balance between near-, mid-, and long-term research and development?

- Yes, sub-program objectives to investigate use of fuel cells for stationary and motive power with baseload, back-up, and supplemental use (range extension) for practical and affordable market transformation are being objectively demonstrated for short- and long-term development.
- The balance between near-, mid-, and long-term research and development is very reasonable, considering the mission of the Market Transformation sub-program.
- There is an appropriate balance between near-, mid-, and long-term research and development.
- There is an appropriate balance in the two areas, but the funding is not sufficient to accomplish as much as is needed in both areas.
- No specific timeline for the projects was presented. Some projects were established in separate phases (Project Scope), and progress was demonstrated on all projects. However, the presentation did not allow for a determination as to whether the project(s) were on schedule. Some delays were identified, e.g., the marine project, but not necessarily because of poor technology—more because of permitting issues.

3. Were important issues and challenges identified?

- Operation, durability, and applications are being identified and tested. Performance and other issues are being identified appropriately for correction.
- Important issues and challenges were discussed adequately in spite of the limited time allocated to the presenter, although the time constraint meant that reviewers should be somewhat familiar with the sub-program's technologies and markets.
- Important issues and challenges were identified.
- Under challenges, four specific projects were listed. The challenges chart did not identify any specific details for each project. Later in the presentation, some targets were given, e.g., the availability of airport cargo tow tractors and drivetrain specifications for battery-electric-vehicle–fuel-cell parcel delivery trucks.
- Whether major issues or challenges were encountered could not be detected from the slides.

4. Are plans identified for addressing issues and challenges?

- Yes, plans are identified where applicable. For example, the transport refrigeration unit (TRU) and auxiliary power unit slide shows the next step: integration of the inverter and TRU.
- Plans for addressing issues were not specifically discussed. Project highlights and accomplishments were given. The Project Scope slide identified project activities but not specific issues the activities were resolving.
- The research process appears to be adequate to identify issues and challenges for correction.
- Yes, plans have been identified for addressing issues and challenges.

5. Was progress clearly benchmarked against the previous year?

- Yes, the movement in the forklift and back-up power segments were quite impressive.
- Progress appears to be consistent with the work plan and goals. Benchmarking to identify annual progress is adequate.
- Accomplishments and progress were clearly identified and assumed to be from this year. A cross-check with last year's presentation identified that many of project accomplishments were for this year.
- Yes, progress was clearly benchmarked against the previous year.
- Slides show new accomplishments to help the audience see progress compared to the previous year.

6. Are the projects in this technology area addressing the broad problems and barriers that the Fuel Cell Technologies Office (FCTO) is trying to solve?

- The projects clearly aim at addressing barriers to enable faster market penetration of fuel cell and hydrogen technologies in appropriate markets that benefit the broader national goals for fuel cells and hydrogen, plus battery deployment goals.
- Yes, market transformation demonstrations (lift trucks, back-up power, marine power, air transport) appear to be appropriate targets to address problems and barriers for successful commercial deployment.
- Yes. Most of the projects are demonstrating the viability and acceptance of fuel cell power in industrial and consumer applications. A few projects are just starting or have identified problems associated with permitting or acceptance of technology.
- The major hurdle for broader fuel cell introduction is the value proposition and the lack of infrastructure. More money and dedicated effort are probably required to move the needle here.
- Yes, projects in this technology area largely address the broad problems and barriers that FCTO is trying to solve.

7. Does the sub-program appear to be focused, well-managed, and effective in addressing FCTO's needs?

- The sub-program focuses on both industry and inter-governmental needs and is well managed and effective in addressing FCTO's needs. For example, it catalyzes key program activities and partnerships and provides technical assistance to end users.
- Team leadership appears focused, with proper management of the sub-program. Sub-program outcomes will clearly address FCTO needs.
- Yes. Sub-program managers selected competent partners, and partners are moving the projects forward.
- The Market Transformation sub-program appears to be focused, well managed, and effective in addressing FCTO's needs.
- Yes, although a greater level of funding would allow more engagement.

8. What are the key strengths and weaknesses of the projects in this sub-program? Do any of the projects stand out on either end of the spectrum?

- Strengths include strong partnerships with appropriate industrial and government entities and leveraging the resources available in the private sector and agencies. There are no weaknesses.
- Strengths include appropriate targets for demonstration, good leadership, and good results. Weaknesses are as follow: (1) additional information on economic systems analysis (Joseck) would be helpful to understand costs, value, and market potential; (2) additional project reporting for non-technical stakeholders is needed; and (3) specific contributions from participants need to be identified.
- Collaboration is the strength of the sub-program. Focusing on those technologies and solutions that are near market-ready is a strong goal. The primary weakness is the inability to make broader movement on several fronts to assist market adoption. The auto industry is probably the key to making a significant dent in the infrastructure and cost challenges, and the U.S. Department of Energy/FCTO/sub-program is just not there with enough resources to help advance that consideration across the nation.

- The primary key strength is the project partners: Plug Power–FedEx, Nuvera–ThermoKing, Hawaii. A weakness is some of the project partners: US-Hybrid had a delay with a technology ownership change (UTC sold technology to US-Hybrid).
- A key strength is the creativity of the Market Transformation sub-program personnel in trying to make things happen. Weaknesses include funding and also the over-focus on funding of the laboratories, an effort that very much seems to undercut real progress toward stated FCTO goals.

9. Do these projects represent novel and/or innovative ways to approach these barriers as appropriate?

- The projects are in themselves novel and innovative; the sub program process is well suited for project demonstration and objective technology evaluation.
- These projects are breaking ground for new polymer electrolyte membrane fuel cell applications and are demonstrating the benefits of fuel cell systems.
- The projects represent novel ways to address barriers, largely because they involve commercial or government end users with a vested interest in achieving collaborative success at minimal cost.
- No, projects do not always represent the most innovative approaches to barriers, in large part because it appears that some creative projects from industry that might offer real advances are overlooked in favor of projects from the laboratories, so one can wonder if the FCTO program is designed to focus on advancing fuel cells or keeping the labs alive. That said, the Market Transformation sub-program office seemed to do a better job than other offices, as only 2 of 6 projects presented were from labs (while 10 of 13 Technology Validation sub-program oral presentations were from labs).
- Not many novel and/or innovative ways to approach these barriers were presented.

10. Has the sub-program engaged appropriate partners?

- There is a large number of partners and collaborations, as listed in chart 15. However, the reviewer missed reporting on Proton OnSite, General Motors, and Toyota. It would be interesting to see a table with names of collaborators and an adjacent column with activities.
- Yes, all partners appear to be appropriate; however, identification of the particular roles and contributions of each partner would be helpful.
- Yes, there is a good collection of fuel cell manufacturers, hydrogen producers, and end users identified and collaborating.
- Yes, the partners are appropriate, and their cost sharing is significant.
- Yes, the sub-program engages appropriate partners.

11. Is the sub-program collaborating with them effectively?

- Yes, there are extremely effective collaborations with Plug Power, Hydrogenics, FedEx, Workhorse, and others.
- Yes, the use of limited funds seems very effective.
- Yes, absolutely.
- It appears that private industry is engaged. However, the specific roles and contributions should be identified.
- Yes, collaboration is effective.

12. Are there any gaps in the portfolio for this technology area?

- No significant gaps are apparent, but identification of the cash flow and economic viability for each project would be helpful.
- There are no gaps, but expanding the effort to new applications and partners would be beneficial.
- The key to broader introduction across all areas is the auto industry and adoption. If the solution comes in that industry area, then others can rapidly follow thanks to infrastructure improvements and cost reductions.
- No significant gaps exist.

- Yes, but the portfolio is budget-constrained.

13. Are there topics that are not being adequately addressed?

- No, the selected topics are appropriate, but each project should be analyzed with systems analysis tools, benchmarked with comparative and/or conventional alternatives, reviewed with appropriate market information, and assessed with an economic analysis.
- The cost of the fuel cell systems for the different applications would be beneficial, specifically with comparison to U.S. Department of Energy costing analysis.
- No topics immediately come to mind.
- Yes.

14. Are there other areas that this sub-program should consider funding to meet overall programmatic goals?

- The topics are appropriate and justified. Additional areas of consideration might include more support for renewable hydrogen; application clusters (i.e., multiple vehicle refueling for lift, light-duty, bus, and ground support vehicles at targeted locations, e.g., the airport); and demand response with hydrogen production and storage for utility and competitive supplier applications.
- If more funds were available, it might be helpful to have more competing teams with the existing portfolio rather than looking at additional areas.
- If dollars existed, stronger play with the auto industry might be valuable.
- Yes, there are other areas, especially in hydrogen delivery.
- There are no other areas that are obvious.

15. Can you recommend new ways to approach the barriers addressed by this sub-program?

- Partners all appear appropriate, but additional private industry involvement should be welcomed to help identify barriers and solutions. All projects should be analyzed with systems analysis tools, benchmarked with comparative and/or conventional alternatives, reviewed with appropriate market information, and assessed with an economic analysis. Each successful project should require additional reporting and outreach to present results to non-technical stakeholders, policymakers, and government regulators to help support the next steps in commercialization.
- The use of workshops to focus the discussion of challenges and identification of mitigating and solution strategies is a worthwhile process.
- No, the sub-program has a well-developed approach to the barriers.
- No, but the next round of Multi-Year Research, Development, and Demonstration Plan updates may identify new ways.
- No.

16. Are there any other suggestions to improve the effectiveness of this sub-program?

- The sub-program is well managed, has good leadership, and has made excellent progress, especially with lift truck commercialization. Progress and program value should be better promoted with an education initiative to industry, government regulators, and policymakers; specific participant involvement should be identified to highlight public–private partnerships and to keep private businesses engaged; and each project should be assessed with systems analysis, market benchmarking, and an economic analysis.
- Probably the important suggestion is the identification of resources to more boldly attack the challenges. Work related to unmanned aerial vehicles was mentioned on slide 5, but nothing on the slides dealt with that initiative. Also, slide 7 did not reflect the correct team participants.
- There should be more publicity regarding successes.
- The sub-program should get away from the laboratories and reach out to business more.

Systems Analysis Sub-Program Comments

1. Was the sub-program, including overall strategy, adequately covered?

- The Systems Analysis sub-program presentation covered annual updates on fuel cell markets, products and patents, and models that are available and are being developed. The purpose and direction of the sub-program were discussed. Most of the work being performed this year by the projects was included, although a few projects presented at the Annual Merit Review were not specifically discussed in the overview presentation.
- Yes, it is clear that this sub-program collaborates with all other areas of the Fuel Cell Technologies Office (FCTO) to ensure consistency and transparency.
- The sub-program manager clearly explained the overall strategy and the main foundation elements of it, as stated in details on slide 4.
- Yes, it was very well covered, and all relevant topics are being addressed.
- Yes (two responses).

2. Is there an appropriate balance between near-, mid-, and long-term research and development?

- There is excellent balance on near- and long-term activities. This is clearly demonstrated, for example, on near-term activities: the assessment for hydrogen cost for low volumes for the current market; early market infrastructure analysis, where for the long term some of the relevant activities are around the support to H2@ Scale; increased focus on medium- and heavy-duty transport; and regional resources analysis.
- The H2@ Scale provides the opportunity to perform long-term research and development. Most of the other models being developed look at both near- and long-term results.
- It is clear that as long as the other FCTO programs continue to exist, there will be a need to tie together assumptions, results, goals, and technology innovation through analysis.
- The assessment of the total cost of ownership (TCO) in 2040 is appropriate, but it would be interesting to also assess the transitional stages, e.g., how the TCO will compare in 2020 and 2030.
- The sub-program addresses current and future technologies with an appropriate balance.
- Generally yes, although the studies seem to utilize long-term assumptions most dominantly, i.e., the analyses assume a 2040 analysis year with the achievement of target cost/performance.
- Yes. Analysis spans near term to long term and low to high volume.

3. Were important issues and challenges identified?

- This sub-program assesses barriers across the entire Hydrogen and Fuel Cells Program, quantifying them and directing efforts to surmount barriers.
- The focus of the Systems Analysis sub-program portfolio clearly speaks for the main challenges and how these are addressed.
- One of the areas that reviewers bring up again and again is the need to have the models validated and vetted with industry. This should be a significant component of every project within the Systems Analysis sub-program.
- Important issues were discussed, but challenges were (generally) not described in terms of target metrics.
- No, issues and challenges were not identified.
- Yes.

4. Are plans identified for addressing issues and challenges?

- Generally, yes. But given that this is systems analysis, the plans are buried as analysis assumptions. They were not openly called out as pivotal targets/metrics.
- The sub-program has a clear strategy for addressing issues.

- The very well-thought-out and diverse portfolio, the interactions with external experts, plus the models, tools, and expertise provided by the national laboratories are definitely great ways to address the critical issues.
- In one of the last slides, Fred identified upcoming activities, which include achieving sub-program targets and addressing economy-wide challenges such as energy security and sustainability metrics. Those are overarching challenges that will be tackled by the sub-program. Specific issues/challenges that will be addressed by the program were not mentioned.
- For each presentation, it would be beneficial to see how the work is different from what was done previously and how it complements other projects that are ongoing. This would help the reviewers and also the researchers themselves to articulate how their work fits into the big picture of the sub-program.
- Yes.

5. Was progress clearly benchmarked against the previous year?

- Significant accomplishments and progress presented for this year include analyses on energy security, market segmentation, resource, employment, H2@ Scale, medium- to heavy-duty, and criteria emissions, among others.
- Data were provided on the increased number of fuel cell electric vehicles (FCEVs) and refueling stations and the price of hydrogen relative to last year. It is assumed that the graphs and data presented for fiscal years 2016–2017 highlight demonstrates progress from last year.
- Analysis focus areas were identified. Benchmarking against the previous year is probably not applicable to this analysis work.
- Progress was benchmarked for only some of the projects. Other projects are too new to have a 2016 benchmark.
- 2017 accomplishments in several areas were clearly highlighted.
- In general, no.

6. Are the projects in this technology area addressing the broad problems and barriers that the Fuel Cell Technologies Office (FCTO) is trying to solve?

- The broad portfolio of models addresses most of the issues facing the Hydrogen and Fuel Cells Program. The one area that is not adequately addressed is consumer choice and behavior. This probably lies outside the expertise typically found in national laboratories. The sub-program might seek to engage original equipment manufacturers and consultants to better understand consumer choice, but often this data is tightly held.
- Yes, in fact, the sub-program helps tie together results for all pathways and technologies, adding a technoeconomic macro-level assessment of status and needs.
- Yes. This analysis is crucial in assessing the relevance of technical progress within the FCTO project portfolio.
- The sub-program has a broad portfolio of projects that clearly focus on addressing the main FCTO barriers.
- Yes, the projects are addressing the problems and barriers as specified in the Multi-Year Research, Development, and Demonstration Plan for Systems Analysis.
- Yes. The projects are well selected.

7. Does the sub-program appear to be focused, well-managed, and effective in addressing FCTO's needs?

- The sub-program is very broad, which is understandable given that it envelops a diversity of projects that range from job creation to comparing the sustainability benefits of advanced vehicle options. Despite its breadth, it is focused, as it follows the developments and needs of other programs and provides the level of assessment needed to understand their overall impact. The sub-program is adequately managed for the reasons described above and because it has been able to incorporate relevant technical expertise from the national laboratories. As analytical issues arise, the System Analysis sub-program has been able to quickly respond with high-level assessments. A case in point is H2@ Scale, which was announced last year, and now there is a Systems Analysis project looking at market potential and economics.

- Excellent management has been the key for the excellent and valuable analysis work completed by the sub-program.
- There were no issues identified in the management and focus of the work. It is good to see the analysis being used to drive research and development in the other sub-programs.
- Yes. In additional to being well focused and well managed, the presentation was delivered in a clear and effective way.
- Yes. The sub-program has been responsive to suggestions from reviewers and other outside input.
- Yes.

8. What are the key strengths and weaknesses of the projects in this sub-program? Do any of the projects stand out on either end of the spectrum?

- The Systems Analysis sub-program serves as the "honest broker" integrating all topics. The government team is viewed as open-minded and willing to consider new ideas. The TCO and truck investigations are particularly noteworthy.
- Strengths include the following: strong management, a well-balanced portfolio, world-class experts and tools from the national laboratories, and extensive industry engagement. Weaknesses include a limited budget.
- Strengths include strong analysis expertise and tools and dogged efforts to obtain the data needed to assemble and validate models.
- Key strengths include strong analytic capability and good support from the laboratories. Weaknesses include promotion/use of the analyses by planning agencies at the state and local levels to develop roadmaps for deployment of infrastructure and development of incentive plans. The TCO for FCEVs, battery electric vehicles (BEVs), and buses is very material at this point, given the early penetration of the technologies.
- A key strength is economic analysis that puts technical progress into context. The weakness is only that some analysis seems questionable in value (jobs impacts and county-by-county resource mapping).
- There is a concern that the jobs creation discussed as part of this sub-program is not necessarily all new jobs but, in some cases, may be just job replacement (e.g., if people are buying FCEVs, they are not buying traditional internal combustion engine vehicles). There is a need to evaluate the difference between these two.

9. Do these projects represent novel and/or innovative ways to approach these barriers as appropriate?

- With many individual models having been developed for various purposes, it is good to see exiting models being integrated together to address larger-picture issues. This may not be extremely novel, but it is the right approach relative to developing entirely new models. The existing models have been vetted and are recognized. It would be good to see fewer models that are more versatile instead of more models.
- The assessment projects reflect innovative technologies and alternative pathways to conventional energy/fuel/transportation pathways.
- Yes. Projects are assessing FCTO technologies from multiple vantage points such as economic viability and environmental impact. It helps to frame a complete picture of the value/endgame.
- The approach is solid, effective, and appropriate.
- Yes. Inclusion of agent-based models for consumer choice is a good example.

10. Has the sub-program engaged appropriate partners?

- Yes, this particular sub-program involves all other areas by default as it gathers information from the entire value chain to conduct analysis. Further, national laboratories and industry have been involved in conducting analyses and validating results.
- The sub-program has engaged many entities in industry to obtain information needed to construct and validate models.
- Yes, the sub-program is working with key laboratories that have constructed and operate a strong portfolio of modeling tools.

- One of the strengths of the sub-program is the extensive engagement and collaboration with industry.
- The collaboration with each project to assist in the development of the models and analysis seems adequate, although in some cases it is difficult to appreciate what contribution the collaborators are making.
- In general, yes.

11. Is the sub-program collaborating with them effectively?

- Yes, there seems to be an open line of communication, as the models are updated constantly with results from the laboratories and the other sub-programs. Further, the results also incorporate industry achievements.
- There is very effective two-way interaction with industry partners.
- Yes, modeling and analysis experts are directly engaged.
- It would be helpful to understand who is using these models outside of the U.S. Department of Energy (DOE) and whether the users found the models to be useful. Those that download the models should be periodically queried to provide feedback.
- Additional communication within FCTO would aid in project effectiveness.
- Yes.

12. Are there any gaps in the portfolio for this technology area?

- The sub-program is doing a great job with its funding level.
- Additional funding will greatly help.
- In life-cycle cost analyses, alternative fuels should be stress-tested against low petroleum prices (the Energy Information Administration's Low Oil case). While oil prices may go high at times, the actual production costs of oil-based liquid fuels are quite low.
- TCO should be compared for other vehicles; for light-duty vehicles, diesel, hybrids, and plug-in hybrids should be included. For buses, liquefied natural gas (LNG) should be included.
- One gap is greenhouse gas (GHG) targets to compare results across technologies on a GHG-abated/dollars-invested basis.
- No.

13. Are there topics that are not being adequately addressed?

- It was good to see that the Systems Analysis sub-program has expanded to include buses and trucks. Work has been underway within FTCO for many years in this area. It would be better if the sub-program led out on the evaluation of new technologies or evaluated them as they are identified rather than waiting for years to include them in analyses.
- Current status in TCO assessment should be included; analysis is for the 2040 timeframe. It would be good to know where we are today and how we will get to 2040 numbers.
- TCO should be compared for other vehicles; for light-duty vehicles, diesel, hybrids, and plug-in hybrids should be included. For buses, LNG should be included.
- Consumer behavior is perhaps an example, but work such as agent-based modeling is a first step in remedying that.
- In the TCO analysis comparing BEVs and FCEVs, it is not clear that the infrastructure differences (relative pros and cons) between charging and fueling have been comprehended. These could be factored in as generalized cost attributes, or they could also be used to restrict the addressable market in some cases.
- No.

14. Are there other areas that this sub-program should consider funding to meet overall programmatic goals?

- No gaps were obvious. Of course, with more funding, the sub-program could do more. The impression is that there are enough valuable projects on hold that additional funding could be quickly deployed effectively.

- The current set of projects seems adequate. H2@ Scale analysis (planned for 2018) will be important.
- The sub-program's portfolio is very strong.
- Regarding energy security analysis, it would be good to know how much FCEVs are contributing given the shift in energy sources in the United States. It would also be good to know where FCEVs will make more of an impact, and what the potential is for this technology to reduce expenditures by DOE, the U.S. Department of Defense, and others.
- No.

15. Can you recommend new ways to approach the barriers addressed by this sub-program?

- The current approach seems adequate.
- A risk analysis of not meeting DOE technical targets would be beneficial to the sub-program. This risk analysis should address which targets are most important to meeting the overall objectives of FCTO. This would be beneficial to the sub-program.
- The possibility of using hydrogen for long-distance freight transport (perhaps as a range extender), as well as using hydrogen for maritime transportation, could be assessed.
- No (two responses).

16. Are there any other suggestions to improve the effectiveness of this sub-program?

- Supporting H2@ Scale and the analysis for medium- and heavy-duty transport are great additions to the Systems Analysis sub-program portfolio.
- State and local city planners should be invited to provide feedback and propose new projects.
- No (three responses).

Research and Development Project Evaluation Form

This evaluation form was used for the following Hydrogen and Fuel Cells sub-program review panels: Hydrogen Production and Delivery; Hydrogen Storage; Fuel Cells; Manufacturing R&D; Safety, Codes and Standards; and Systems Analysis.

Evaluation Criteria: U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program Annual Merit Review

Please provide specific, concise comments to support your evaluation. It is important that you write in full sentences and clearly convey your meaning to prevent incorrect interpretation.

1. Approach

To performing the work – the degree to which barriers are addressed and the project is well designed, feasible, and integrated with other efforts. (Weight = 20%)

4.0 - Outstanding. Sharply focused on critical barriers; difficult to improve significantly.
3.5 - Excellent. Effective; contributes to overcoming most barriers.
3.0 - Good. Generally effective but could be improved; contributes to overcoming some barriers.
2.5 - Satisfactory. Has some weaknesses; contributes to overcoming some barriers.
2.0 - Fair. Has significant weaknesses; may have some impact on overcoming barriers.
1.5 - Poor. Minimally responsive to project objectives; unlikely to contribute to overcoming the barriers.
1.0 - Unsatisfactory. Not responsive to project objectives; unlikely to contribute to overcoming the barriers.

- ☐ 4.0 - Outstanding
- ☐ 3.5 - Excellent
- ☐ 3.0 - Good
- ☐ 2.5 - Satisfactory
- ☐ 2.0 - Fair
- ☐ 1.5 - Poor
- ☐ 1.0 - Unsatisfactory

Comments on Approach to performing the work:

2. Accomplishments and Progress

Toward overall project and DOE goals – the degree to which progress has been made and measured against performance indicators, and the degree to which the project has demonstrated progress toward DOE goals. (Weight = 45%)

4.0 - Outstanding. Sharply focused on critical barriers; difficult to improve significantly.
3.5 - Excellent. Effective; contributes to overcoming most barriers.
3.0 - Good. Generally effective but could be improved; contributes to overcoming some barriers.

2.5 - Satisfactory. Has some weaknesses; contributes to overcoming some barriers.
2.0 - Fair. Has significant weaknesses; may have some impact on overcoming barriers.
1.5 - Poor. Minimally responsive to project objectives; unlikely to contribute to overcoming the barriers.
1.0 - Unsatisfactory. Not responsive to project objectives; unlikely to contribute to overcoming the barriers.

- ☐ 4.0 - Outstanding
- ☐ 3.5 - Excellent
- ☐ 3.0 - Good
- ☐ 2.5 - Satisfactory
- ☐ 2.0 - Fair
- ☐ 1.5 - Poor
- ☐ 1.0 - Unsatisfactory

Comments on Accomplishments and Progress toward overall project and DOE goals:

3. Collaboration and Coordination with Other Institutions

The degree to which the project interacts with other entities and projects. (Weight = 10%)

4.0 - Outstanding. Close, appropriate collaboration with other institutions; partners are full participants and well coordinated.
3.5 - Excellent. Good collaboration; partners participate and are well coordinated.
3.0 - Good. Collaboration exists; partners are fairly well coordinated.
2.5 - Satisfactory. Some collaboration exists; coordination between partners could be significantly improved.
2.0 - Fair. A little collaboration exists; coordination between partners could be significantly improved.
1.5 - Poor. Most work is done at the sponsoring organization with little outside collaboration; little or no apparent coordination with partners.
1.0 - Unsatisfactory. No apparent coordination with partners.

- ☐ 4.0 - Outstanding
- ☐ 3.5 - Excellent
- ☐ 3.0 - Good
- ☐ 2.5 - Satisfactory
- ☐ 2.0 - Fair
- ☐ 1.5 - Poor
- ☐ 1.0 - Unsatisfactory

Comments on Collaboration and Coordination with other institutions:

4. Relevance/Potential Impact

The degree to which the project supports and advances progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan. (Weight = 15%)

4.0 - Outstanding. Project is critical to the Hydrogen and Fuel Cells Program and has potential to significantly advance progress toward DOE RD&D goals and objectives.
3.5 - Excellent. The project aligns well with the Hydrogen and Fuel Cells Program and DOE RD&D objectives and has the potential to advance progress toward DOE RD&D goals and objectives.
3.0 - Good. Most project aspects align with the Hydrogen and Fuel Cells Program and DOE RD&D objectives.
2.5 - Satisfactory. Project aspects align with some of the Hydrogen and Fuel Cells Program and DOE RD&D objectives.
2.0 - Fair. Project partially supports the Hydrogen and Fuel Cells Program and DOE RD&D objectives.
1.5 - Poor. Project has little potential impact on advancing progress toward the Hydrogen and Fuel Cells Program and DOE RD&D goals and objectives.
1.0 - Unsatisfactory. Project has little to no potential impact on advancing progress toward the Hydrogen and Fuel Cells Program and DOE RD&D goals and objectives.

- ☐ 4.0 - Outstanding
- ☐ 3.5 - Excellent
- ☐ 3.0 - Good
- ☐ 2.5 - Satisfactory
- ☐ 2.0 - Fair
- ☐ 1.5 - Poor
- ☐ 1.0 - Unsatisfactory

Comments on Relevance/Potential Impact:

5. Proposed Future Work

The degree to which the project has effectively planned its future in a logical manner by incorporating appropriate decision points, considering barriers to its goals and, when sensible, mitigating risk by providing alternate pathways. Note: if a project has ended, please leave blank. (Weight = 10%)

4.0 - Outstanding. Sharply focused on critical barriers; difficult to improve significantly.
3.5 - Excellent. Effective; contributes to overcoming most barriers.
3.0 - Good. Generally effective but could be improved; contributes to overcoming some barriers.
2.5 - Satisfactory. Has some weaknesses; contributes to overcoming some barriers.
2.0 - Fair. Has significant weaknesses; may have some impact on overcoming barriers.
1.5 - Poor. Minimally responsive to project objectives; unlikely to contribute to overcoming the barriers.
1.0 - Unsatisfactory. Not responsive to project objectives; unlikely to contribute to overcoming the barriers.

- ☐ 4.0 - Outstanding
- ☐ 3.5 - Excellent
- ☐ 3.0 - Good
- ☐ 2.5 - Satisfactory
- ☐ 2.0 - Fair
- ☐ 1.5 - Poor
- ☐ 1.0 - Unsatisfactory

Comments on Proposed Future Work:

Project Strengths:

Project Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Technology-to-Market Project Evaluation Form

This evaluation form was used for the following Hydrogen and Fuel Cells sub-program review panels: Market Transformation and Technology Validation.

Evaluation Criteria: U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program Annual Merit Review

Please provide specific, concise comments to support your evaluation. It is important that you write in full sentences and clearly convey your meaning to prevent incorrect interpretation.

1. Relevance/Potential Impact

The degree to which the project supports and advances progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan. (Weight = 15%)

4.0 - Outstanding. Project is critical to the Hydrogen and Fuel Cells Program and has potential to significantly advance progress toward DOE RD&D goals and objectives.
3.5 - Excellent. The project aligns well with the Hydrogen and Fuel Cells Program and DOE RD&D objectives and has the potential to advance progress toward DOE RD&D goals and objectives.
3.0 - Good. Most project aspects align with the Hydrogen and Fuel Cells Program and DOE RD&D objectives.
2.5 - Satisfactory. Project aspects align with some of the Hydrogen and Fuel Cells Program and DOE RD&D objectives.
2.0 - Fair. Project partially supports the Hydrogen and Fuel Cells Program and DOE RD&D objectives.
1.5 - Poor. Project has little potential impact on advancing progress toward the Hydrogen and Fuel Cells Program and DOE RD&D goals and objectives.
1.0 – Unsatisfactory. Project has little to no potential impact on advancing progress toward the Hydrogen and Fuel Cells Program and DOE RD&D goals and objectives.

- ☐ 4.0 - Outstanding
- ☐ 3.5 - Excellent
- ☐ 3.0 - Good
- ☐ 2.5 - Satisfactory
- ☐ 2.0 - Fair
- ☐ 1.5 - Poor
- ☐ 1.0 - Unsatisfactory

Comments on Relevance/Potential Impact:

2. Strategy for Technical Validation and/or Deployment

Rate the degree to which barriers are addressed, the project is well designed, and it is feasible and integrated with other efforts. (Weight = 20%)

4.0 - Outstanding. Sharply focused on critical barriers; difficult to improve significantly.
3.5 - Excellent. Effective; contributes to overcoming most barriers.
3.0 - Good. Generally effective but could be improved; contributes to overcoming some barriers.
2.5 - Satisfactory. Has some weaknesses; contributes to overcoming some barriers.
2.0 - Fair. Has significant weaknesses; may have some impact on overcoming barriers.
1.5 - Poor. Minimally responsive to project objectives; unlikely to contribute to overcoming the barriers.
1.0 - Unsatisfactory. Not responsive to project objectives; unlikely to contribute to overcoming the barriers.

- ☐ 4.0 - Outstanding
- ☐ 3.5 - Excellent
- ☐ 3.0 - Good
- ☐ 2.5 - Satisfactory
- ☐ 2.0 - Fair
- ☐ 1.5 - Poor
- ☐ 1.0 - Unsatisfactory

Comments on the Strategy for Technology Validation and Deployment:

3. Accomplishments and Progress

Toward overall project and DOE goals – the degree to which progress has been made and measured against performance indicators, and the degree to which the project has demonstrated progress toward DOE goals. (Weight = 45%)

4.0 - Outstanding. Sharply focused on critical barriers; difficult to improve significantly.
3.5 - Excellent. Effective; contributes to overcoming most barriers.
3.0 - Good. Generally effective but could be improved; contributes to overcoming some barriers.
2.5 - Satisfactory. Has some weaknesses; contributes to overcoming some barriers.
2.0 - Fair. Has significant weaknesses; may have some impact on overcoming barriers.
1.5 - Poor. Minimally responsive to project objectives; unlikely to contribute to overcoming the barriers.
1.0 - Unsatisfactory. Not responsive to project objectives; unlikely to contribute to overcoming the barriers.

- ☐ 4.0 - Outstanding
- ☐ 3.5 - Excellent
- ☐ 3.0 - Good
- ☐ 2.5 - Satisfactory
- ☐ 2.0 - Fair

- ☐ 1.5 - Poor
- ☐ 1.0 - Unsatisfactory

Comments on Accomplishments and Progress toward overall project and DOE goals:

4. Collaboration and Coordination with Other Institutions

The degree to which the project interacts with other entities and projects. (Weight = 10%)

4.0 - Outstanding. Close, appropriate collaboration with other institutions; partners are full participants and well coordinated.
3.5 - Excellent. Good collaboration; partners participate and are well coordinated.
3.0 - Good. Collaboration exists; partners are fairly well coordinated.
2.5 - Satisfactory. Some collaboration exists; coordination between partners could be significantly improved.
2.0 - Fair. A little collaboration exists; coordination between partners could be significantly improved.
1.5 - Poor. Most work is done at the sponsoring organization with little outside collaboration; little or no apparent coordination with partners.
1.0 - Unsatisfactory. No apparent coordination with partners.

- ☐ 4.0 - Outstanding
- ☐ 3.5 - Excellent
- ☐ 3.0 - Good
- ☐ 2.5 - Satisfactory
- ☐ 2.0 - Fair
- ☐ 1.5 - Poor
- ☐ 1.0 - Unsatisfactory

Comments on Collaboration and Coordination with other institutions:

5. Proposed Future Work

The degree to which the project has effectively planned its future in a logical manner by incorporating appropriate decision points, considering barriers to its goals and, when sensible, mitigating risk by providing alternate pathways. Note: if a project has ended, please leave blank. (Weight = 10%)

4.0 - Outstanding. Sharply focused on critical barriers; difficult to improve significantly.
3.5 - Excellent. Effective; contributes to overcoming most barriers.
3.0 - Good. Generally effective but could be improved; contributes to overcoming some barriers.
2.5 - Satisfactory. Has some weaknesses; contributes to overcoming some barriers.
2.0 - Fair. Has significant weaknesses; may have some impact on overcoming barriers.
1.5 - Poor. Minimally responsive to project objectives; unlikely to contribute to overcoming the barriers.
1.0 - Unsatisfactory. Not responsive to project objectives; unlikely to contribute to overcoming the barriers.

- ☐ 4.0 - Outstanding
- ☐ 3.5 - Excellent
- ☐ 3.0 - Good
- ☐ 2.5 - Satisfactory
- ☐ 2.0 - Fair
- ☐ 1.5 - Poor
- ☐ 1.0 - Unsatisfactory

Comments on Proposed Future Work:

Project Strengths:

Project Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

List of Projects Presented but Not Reviewed

Project ID	Project Title	Principal Investigator Name	Organization
ARPAE17	A Novel Intermediate-Temperature Fuel Cell Tailored for Efficient Utilization of Methane	Meilin Liu	Georgia Tech
ARPAE18	Nanocomposite Electrodes for a Solid Acid Fuel Cell Stack Operating on Reformate	Tom Zawodzinski	Oak Ridge National Laboratory/ University of Tennessee, Knoxville
ARPAE19	Low-Temperature Solid Oxide Fuel Cells for Transformational Energy Conversion	Bryan Blackburn	Redox Power Systems
ARPAE20	Solid Acid Fuel Cell Stack for Distributed Generation Applications	Calum Chisholm	SAFCell
ARPAE21	Fuel Cells with Dynamic Response Capability Based on Energy Storage Electrodes with Catalytic Function	Yunfeng Lu	University of California, Los Angeles
ARPAE22	A Bifunctional Ceramic Fuel Cell Energy System	Kevin Huang	University of South Carolina
ARPAE23	Development of an Intermediate-Temperature Metal-Supported Proton-Conducting Solid Oxide Fuel Cell Stack	Tianli Zhu	United Technologies Research Center (UTRC)
ARPAE24	Intermediate-Temperature Hybrid Fuel Cell System for the Conversion of Natural Gas to Electricity, Liquid Fuels, and Chemicals	Ted Krause	Argonne National Laboratory
ARPAE25	Dual-Mode Intermediate-Temperature Fuel Cell: Liquid Fuels and Electricity	Carl Willman	FuelCell Energy
ARPAE26	Intermediate-Temperature Electrogenerative Cells for Flexible Cogeneration of Power and Liquid Fuel	Greg Tao	Materials and Systems Research, Inc.
BESH2020	Tailoring Hydrogen Evolution Reaction Catalysts for Operation at Specific pH Values	Bianca Ceballos	University of California, Irvine
BESH2022	Hybrid Perovskites and Non-Adiabatic Dynamics Simulations: Catching Realistic Aspects of the Charge Recombination Process	Joanna Jankowska	University of Southern California
BESH2023	Nano-Bio Systems for Light-Driven Hydrogen Production	Kara Bren	University of Rochester
BESH2024	Mechanistic Investigations on Hydrogen Catalysis by [FeFe]-Hydrogenase	David Mulder	National Renewable Energy Laboratory

Project ID	Project Title	Principal Investigator Name	Organization
BESH2025	Reversible Conversion between CO_2/H_2 and Formic Acid by Molecular Catalysts	Etsuko Fujita	Brookhaven National Laboratory
FC109	New Fuel Cell Membranes with Improved Durability and Performance	Michael Yandrasits	3M
FC115	Affordable, High-Performance, Intermediate-Temperature Solid Oxide Fuel Cells	Bryan Blackburn	Redox Power Systems
FC116	Smart Matrix Development for Direct Carbonate Fuel Cell	Chao-yi Yuh	FuelCell Energy
FC117	Ionomer Dispersion Impact on Polymer Electrolyte Membrance Fuel Cell and Electrolyzer Durability	Hui Xu	Giner, Inc.
FC129	Advanced Catalysts and Membrane Electrode Assemblies for Reversible Alkaline Membrane Fuel Cells	Hui Xu	Giner, Inc.
FC148	New High-Performance Water Vapor Membranes to Improve Fuel Cell Balance of Plant Efficiency and Lower Costs	Earl Wagener	Tetramer Technologies, Inc.
H2REFUEL	H2 Refuel	Darryl Pollica	SimpleFuel
MN018	Roll-to-Roll Advanced Materials Manufacturing Lab Consortium	Claus Daniel	Oak Ridge National Laboratory
PD103	High-Performance, Long-Lifetime Catalysts for Proton Exchange Membrane Electrolysis	Hui Xu	Giner, Inc.
PD118	New Metal Oxides for Efficient Hydrogen Production via Solar Water Splitting	Yanfa Yan	University of Toledo
PD119	National Science Foundation/U.S. Department of Energy Solar Hydrogen Fuel: Engineering Surfaces, Interfaces, and Bulk Materials for Unassisted Solar Photoelectrochemical Water Splitting	Tom Jaramillo	Stanford University
PD120	Accelerated Discovery of Advanced RedOx Materials for Solar Thermal Water Splitting to Produce Renewable Hydrogen	Charles Musgrave	University of Colorado Boulder
PD121	Tunable Photoanode–Photocathode–Catalyst Interface Systems for Efficient Solar Water Splitting	G. Charles Dismukes	Rutgers University

Project ID	Project Title	Principal Investigator Name	Organization
PD123	High-Performance Platinum-Group-Metal-Free Membrane Electrode Assemblies through Control of Interfacial Processes	Katherine Ayers	Proton OnSite
PD124	Solid-Oxide-Based Electrolysis and Stack Technology with Ultra-High Electrolysis Current Density (>3A/cm_2) and Efficiency	Randy Petri	FuelCell Energy
PD148	HydroGEN: A Consortium on Advanced Water-Splitting Materials	Huyen Dinh	National Renewable Energy Laboratory
ST014	Hydrogen Sorbent Measurement Qualification and Characterization	Phil Parilla	National Renewable Energy Laboratory
ST114	Next-Generation Hydrogen Storage Vessels Enabled by Carbon Fiber Infusion with a Low-Viscosity, High-Toughness Resin System	Brian Edgecombe	Materia
ST135	HySCORE: Technical Activities at the National Institute of Standards and Technology	Thomas Gennett	National Renewable Energy Laboratory
TV038	Overview of an Integrated Research Facility for Advancing Hydrogen Infrastructure	Michael Peters	National Renewable Energy Laboratory
TV040	High-Temperature Electrolysis Test Stand	Richard Boardman	Idaho National Laboratory
TV044	Introduction to H2@Scale	Bryan Pivovar	National Renewable Energy Laboratory

2017 Annual Merit Review Questionnaire Results Summary

Following the 2017 U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program Annual Merit Review (AMR), all participants were asked for feedback on the review process and meeting logistics. This appendix summarizes the results of that feedback and is organized by type of respondent, as follows:

1. All Respondents
2. Responses from “Attendee, neither Reviewer nor Presenter”
3. Responses from Reviewers
4. Responses from Presenters

1. All Respondents

1.1. What is your affiliation?

	Number of Responses	Response Ratio
U.S. federal government	17	7.8%
National/government lab, private-sector or university researcher whose project is under review	57	26.3%
Non-government institution that received funding from the office or program under review	56	25.9%
Non-government institution that does not receive funding from the office or program under review	39	18.0%
Government agency (non-federal, state, foreign government) with interest in the work	3	1.3%
National/government lab, private-sector or university researcher not being reviewed	26	12.0%
Other	16	7.4%
No Responses	2	<1%
Total	216	100%

“Other” Responses

- *From four respondents:* Industry
- *From two respondents:* Local government that received funding from the office or program under review
- International government
- Foreign university researcher with interest in the work
- Tier I supplier
- Service provider
- Energy company
- IP counsel
- 501(c)(3) non-profit
- Media
- Sub-contractor providing support for the Office of Energy Efficiency and Renewable Energy (EERE)
- Independent consultant

1.2. The Joint Plenary Session was valuable in providing an overview, including the purpose and scope of the Annual Merit Review (answer only if you attended the Joint Plenary on Monday).

Top number is the count of respondents selecting the option. Bottom % is percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
3	2	23	69	50
2%	1%	16%	47%	34%

36 Comments

- The presentations by General Motors (GM) and Shell were informative and useful. It was beneficial to receive an industry viewpoint. The presentations by the Vehicle Technologies Office (VTO) and the Fuel Cell Technologies Office (FCTO) were useful.
- The overview was good. Presentations from Shell (Joe Powell) and FCTO (Sunita Satyapal) were especially informative.
- The fireside chat presentations, especially the one from GM, were excellent for showing industry interest in DOE-funded research.
- This was a great session. There was a lot of good information, and the interactive portion moderated by Rueben Sarkar was especially interesting.
- The fireside chat was new this year, and I enjoyed it.
- It is critical that the technical community understands the target vision of DOE in both areas.
- It is always useful to hear the priorities at the highest level.
- It gave a broad and wonderful perspective.
- Love the panel discussions.
- Very well done.
- I am missing some pieces of this, such as how DOE and the U.S. Environmental Protection Agency communicate and arrive at common goals. I will be looking for further background about that. From industry, I can see that partnering with these large projects to review results could make these endeavors valuable.
- There was a nice variety of viewpoints and yet a more or less aligned vision of where to take the sub-programs. I noticed that an understated concern about the impact of funding cuts seems to permeate them all. I hope Congress gets that message.
- I liked the idea of the fireside chat but would like to see the audience get more incorporated into the discussion.
- This was a good high-level review, but there was no attempt to determine long-term strategy, though I understand the current administrative situation may make that difficult.
- “Highly disagree” for the initial Welcome Remarks, “Agree” for Keynote remarks, and “Agree” to “Strongly Agree” for the two Hydrogen and Fuel Cells Overview presentations.
- The outside speakers provided interesting insights. The “fireside” chat did not.
- The information on the sizable EERE cuts in the President’s budget for 2018 was very troubling. Transparency, if such a consideration exists at all, requires open discussion by the leadership in such a forum. It is indeed basically a technical, not political, meeting, but the top government administrators should not hide behind broad positive statements while deeply cutting the budget.
- Some remarks were poorly prepared and reflected lack of understanding of what was actually being reviewed at the meeting.
- *From eighteen respondents:* I did not attend.

1.3. The two plenary sessions after the Joint Plenary Session were helpful to understanding the direction of the Hydrogen and Fuel Cells Program and/or Vehicle Technologies Office (answer only if you attended the Hydrogen and Fuel Cells and/or Vehicle Technologies plenary sessions on Monday afternoon and/or Tuesday morning).

Top number is the count of respondents selecting the option. Bottom % is percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
3	0	22	59	65
2%	0%	15%	40%	44%

30 Comments

- The plenary session set a technical tone for the whole conference and provides important linkage to sponsored technical projects.
- The presentations by GM and Shell were informative and useful. It was beneficial to receive an industry viewpoint. The presentations by the VTO and FCTO were useful.
- Under normal circumstances, I would say that the plenary sessions are very valuable to get an idea of what future funding and directions are. DOE is in an understandably difficult position with regard to giving information about future budgets. So this year, with all of the uncertainty, it was a little less informative. Still, it is a very useful presentation and should continue to be given.
- A great occasion to have an overview of all of the Hydrogen and Fuel Cells Program.
- Great job by the FCTO Director!
- It laid out the context for the individual projects.
- Not so much for me, because I know the direction well, but it would level up those who do not have regular contact with DOE.
- While the downsizing of the budget was disappointing, it was of value to see the strategy going forward.
- The direction of Hydrogen and Fuel Cells under the new administration was not clear from the presentations. The message was mixed. On the one hand, the talks described the importance of the work and all the great progress made, and that we are marching toward targets set for commercialization (assuming a certain level of funding). However, the message from the budget was quite different, with large funding cuts but no changes in the timeline for the targets.
- I attended the VTO plenaries. There was good detail but no real planning for new organization and focus areas for limited future funding.
- It was mainly a discussion about existing sub-programs.
- It would be great to have a summary of all the projects that each sub-program sponsors to show the research portfolio.
- I think these overviews could have been a little more detailed. It would have been good to see explicitly how the sub-programs were broken out in terms of objectives, funding, and funding horizons.
- It was interesting that nobody said anything about fiscal year 2018 budgets and the uncertain future of the whole Office.
- *From sixteen respondents:* I did not attend.

1.4. Program overviews were helpful to understanding the research objectives (answer only if you attended one or more Program overviews).

Top number is the count of respondents selecting the option. Bottom % is percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
6	0	8	78	85
3%	0%	5%	44%	48%

23 Comments

- Excellent high-level summaries of the sub-programs. I recommend that these remain part of the AMR and that the presenting (sub) program managers (continue to) devote attention to high-quality summaries. I found this year's FCTO summaries to be quite valuable.
- The overviews are critical to the success of the individual sessions. Those presentations provide the context into which the rest of the Hydrogen and Fuel Cells Program fits.
- It is important to have an overview so that the principal investigators (PIs) understand where and how their respective projects fit and to see how else they might be able to contribute.
- I learned about programs that were relevant to my area of research that I would not have otherwise known about. Also, best practices and lessons learned were helpful for my research efforts.
- The overviews focus all attendees on critical targets and short-term/long-term objectives of technical programs.
- The presentations by GM and Shell were informative and useful. It was beneficial to receive an industry viewpoint. The presentations by VTO and FCTO were useful.
- I especially enjoyed the overview "Electric Drive/Grid/Charging R&D Overview." A nice summary for a non-subject matter expert of how many of the challenges were being addressed.
- The Safety, Codes and Standards presentation was especially helpful.
- The multiyear plans are more valuable; please continue making those available and easy to find.
- The descriptions were well defined. It helped put everyone on the same page.
- It laid the context for the individual projects.
- All did a great job!
- Very informative.
- I think all of the reviews were done very clearly and professionally. There is not much time for background, so I think they would be clearer, but it would likely be upon the reviewer to study in advance. I think it would be helpful to have a clickable bibliography that must be looked through prior to attending the review.
- Energy Efficient Mobility Systems (EEMS) was of particular interest, but after reviewing many projects, some questions remain about the overall strategy regarding simulation research and level of tool maturity to accurately predict market penetration and oil displacement impact.
- They would have been more helpful if the budget had been clearer.
- Sometimes they steal the thunder of the talks.
- *From six respondents:* I did not attend.

1.5. What was your role in the Annual Merit Review? (Check the most appropriate response—if you are both a presenter and a reviewer and want to comment as both, complete the evaluation twice—once as each.)

	Number of Responses	Response Ratio
Attendee, neither Reviewer nor Presenter	100	46.2%
Presenter of a project	72	33.3%
Peer Reviewer	43	19.9%
No Responses	1	<1%
Total	216	100%

2. Responses from “Attendee, neither Reviewer nor Presenter”

2.1. The quality, breadth, and depth of the following were sufficient to conduct a meaningful review:

Top number is the count of respondents selecting the option. Bottom % is percent of the total respondents selecting the option.

	Highly Disagree	Disagree	Neutral	Agree	Highly Agree
Presentations	1	0	6	49	34
	1%	0%	7%	54%	38%
Question and answer periods	1	0	7	53	28
	1%	0%	8%	60%	31%
Answers provided to programmatic questions	1	0	15	52	21
	1%	0%	17%	58%	24%
Answers provided to technical questions	1	0	9	53	24
	1%	0%	10%	61%	28%

9 Comments

- The standardized format of the presentation and slides is very helpful in ensuring that important details are discussed and challenges are clarified.
- There were times some more technical discussion of methods and assumptions was warranted, but reviewers do a fairly thorough job. Most PIs were available for more in-depth discussions, which is helpful.
- I think that there is a nice balance of technical and programmatic information and questions. It would be nice if the reviewers could send questions to the presenters in advance. Some questions could be addressed in the presentation.
- Very good content. There is one concern: the totality of “mobility systems” with respect to energy efficiency has large breadth and may not be sufficiently represented in this AMR program. I feel the program content was primarily focused on “ground-based on-road connected and automated cars/trucks.” I suggest some wordsmithing to align with the content on VTO’s website—“About us” and “Mission”—to represent this focus of mobility.
- These were wonderful days for polymer electrolyte membrane fuel cells. A good deal of content is included in a presentation. It is hard to understand all of it well without past AMR technical information. For example, there were many acronyms and abbreviations: PFIA, SOAMEA, and so on.
- Many presentations were good; some were too “top-level” and lacked sufficient information.
- I am not sure if presenters are directed to pack their slides with tons of text and graphics, but some were outrageously dense and distracting. I would recommend asking presenters to pare down the content in some of their slides.
- Many projects/presentations included multiple parts, making it difficult to present in a single 20-minute presentation. Analysis projects do not fit well in the AMR presentation template.
- Some presentations do not go into the work deeply enough. The summary is too high-level without proof of work progress.

2.2. Enough time was allocated for presentations.

Top number is the count of respondents selecting the option. Bottom % is percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
0	3	5	47	35
0%	3%	6%	52%	39%

5 Comments

- There is a good balance between the technical presentation and enough time for reviewer questions. In the sessions I attended, all allocated question-and-answer (Q&A) time was used.
- I think the talks really need an additional five minutes. There are so many required program slides that they really take away valuable time that should be spent on results.
- Too much time was spent discussing funding and timelines. Presentations should be allowed to focus on the technical aspects.
- Where time ran short, I generally believe the presenters could have been more concise in their discussion and material.
- I feel that some topics could have been discussed more and some topics less.

2.3. The questions asked by reviewers were sufficiently rigorous and detailed.

Top number is the count of respondents selecting the option. Bottom % is percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
0	2	18	49	23
0%	2%	20%	53%	25%

7 Comments

- It seemed that some of the reviewers had only a very basic understanding of the technical areas they were reviewing. This clearly caused problems for the presenters.
- Some projects clearly do not have the right reviewers with the right backgrounds even to ask any questions.
- Some presenters received no questions or only one question—this seems an insufficient level of review.
- The answer is highly dependent on the reviewer. Some reviewers asked pointless questions.
- Some of the questions were not really helpful in understanding the work.
- Could be more rigorous at some times.
- Some are more rigorous than others.

2.4. The frequency (once per year) of this formal review process for this Office or Program is:

	Number of Responses	Response Ratio
About right	83	38.4%
Too frequent	3	1.3%
Not frequent enough	3	1.3%
No opinion	3	1.3%
No Responses	124	57.4%
Total	216	100%

3 Comments

- Less frequent reviews would miss shorter projects and allow too much time to pass without feedback/ redirection from industry.
- This is a good schedule to monitor progress.
- I suggest that more depth could be presented on individual tasks within a large project if the task reviews were staggered. The large project as a whole could be reviewed annually, but more emphasis could be placed on individual tasks within the project, rotating the emphasis to other tasks in the subsequent year.

2.5. Logistics, facilities, and amenities were satisfactory.

Top number is the count of respondents selecting the option. Bottom % is percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
1	3	8	33	46
1%	3%	9%	36%	51%

18 Comments

- *From three respondents:* The conference rooms were too cold.
- The Wardman Park is a much better location than Crystal City.
- The hotel, food, and refreshments were excellent.
- I thought the logistics of the conference were handled exceptionally well.
- Excellent—this was the best meeting.
- EEMS track attendance was underestimated; the room was too small, with people standing in back, and too warm for the space. It was a nice hotel, closer to the airport. Wayfinding signage was good. Food/refreshments were a plus.
- The new strategy of allowing people to plug into the USB-on-a-string to get the program review files is a little scary, from an IT security perspective. I think it would be wise to return to the old policy of handing out individual USBs or go completely to an online download system.
- Some rooms were crowded, and doors in many of the rooms slammed when people entered/exited during presentations, which was distracting. Noise from the hallway disrupted some sessions when other rooms were released prior to all sessions completing for the break.
- The poster session hall was adequate but quite cavernous. The Lincoln 5 room was remote and difficult to find. The downstairs presentation rooms were long and narrow—not great for the audience.
- Free Wi-Fi only in the lobby is inadequate. Wi-Fi is needed in meeting rooms; I like to look up information related to the presentations.
- When the only option for food served during the poster sessions needs a plate and fork, this makes it difficult for those presenting to be able to eat and awkward for those trying to view the posters.
- Satisfactory, but the Crystal City location was probably better. There is more overflow hotel space nearby there.
- The hotel did not have rooms. Locating rooms in the area was difficult.
- The room for Fuel Cells R&D was too small for the plenary overview but okay for the sessions. Please hold the plenary overviews in the larger room.
- The chairs could have been spaced farther apart; it was very uncomfortable to sit in a crowded session squeezed in between two other people.
- More tables are needed. It was difficult to take notes on my lap.

2.6. The visual quality of the presentations was adequate. I was able to see all of the presentations I attended.

Top number is the count of respondents selecting the option. Bottom % is percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
2	10	11	35	31
2%	11%	12%	39%	35%

24 Comments

- *From four respondents:* The rooms were the wrong ratio—too long and narrow—for the audience to see the presentations.

- *From three respondents:* The screens were not large enough (and/or raised high enough), especially in the long rooms.
- *From three respondents:* Some of the presentation fonts, especially on graphs, were too small for such large rooms.
- The EEMS room presentations were overcrowded, and it was hard to see the presentation over others seated in the next row. When I could see it, the projection quality was very good.
- There was standing room only in a few presentations in Washington Room 3. It was great that there was so much interest, but it was also really challenging to hear and see.
- Overall, it was good, but some presentations were crowded.
- The fonts on some of the slides were different (too big, off the screen) from the ones sent to the presenters for review before the AMR. Someone needs to check these slides on the big screen, not just on a little tablet or computer screen.
- I would like to have received a physical copy of all the presentations on a thumb drive or disk to keep as a separate item rather than just file downloads.
- Some PowerPoint standards in regard to minimum font sizing would help with the “readability” of the slides and reduce the amount of content on each slide for the benefit of the audience.
- There was a lot of information on the slides; they were often hardly readable.
- It was hard to see the screens from the back of the room. The fact that the presentations will be available alleviates that somewhat.
- The screens are not adequate for the size of the rooms. Extra monitors should be included toward the back.
- Presentations in the basement, particularly for Hydrogen and Fuel Cells, were difficult to see and hear.
- Washington 5 was not well organized. It was difficult to see the slides from the most of audience seats.
- Washington 3, especially, was a nightmare of a presentation room.
- The battery room was a little bit big.

2.7. The audio quality of the presentations was adequate. I was able to hear all the presentations I attended.

Top number is the count of respondents selecting the option. Bottom % is percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
0	2	5	36	48
0%	2%	5%	40%	53%

3 Comments

- There were a couple of blips in the beginning. You should test out the equipment before the session begins and make sure that the speakers know how to use it. Toward the end, presenters were using the mouse instead of the laser pointer, and that worked flawlessly.
- Most speakers had microphones, but for a few presentations, I was unable to hear the speaker.
- In some of the smaller rooms, the sound was weak.

2.8. The meeting hotel accommodations (sleeping rooms) were satisfactory.

Top number is the count of respondents selecting the option. Bottom % is percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
0	1	17	21	30
0%	1%	25%	30%	43%

16 Comments

- *From nine respondents:* I did not stay at the hotel.
- *From two respondents:* The hotel was too expensive, so I decided to stay elsewhere.
- The hotel was booked, so I stayed at the nearby Churchill Hotel near Embassy, which was also very good and an acceptable walking distance (less than a mile).
- The hotel is good, only there are several reports of bedbugs in customer reviews of the hotel that make the stay there a little scary.
- The meeting hotel offers a rate higher than the DOE allowance. I hope this is adjusted in the future. Note: I have gotten a complaint from my group leader in the past about this.
- I was unable to secure a room at the government rate at the meeting hotel.
- The hotel was expensive.

2.9. The information about the Review and the hotel accommodations sent to me prior to the Review was adequate.

Top number is the count of respondents selecting the option. Bottom % is percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
0	0	10	41	36
0%	0%	11%	47%	41%

4 Comments

- A big thank you to the organizing team for helping with hotel stays.
- A bigger block of rooms is needed. The discounted rate was unavailable well before the deadline.
- Maybe I missed something, but it would be helpful to have short summaries of the research to accompany the presentation titles. Some of the presentations were not what I expected.
- I have attended many large symposia; however, for some reason, the program here was particularly confusing. I am not sure why, so I apologize for just complaining without offering constructive feedback.

2.10. What was the most useful part of the review process?

44 Responses

- *From six reviewers:* The presentations.
- *From two respondents:* Networking.
- *From two respondents:* The Q&A.
- Learning the status of the projects and highlights of the roadmap of future technologies driven by DOE. I was able to understand the various collaborations between the private and public sectors. All activities of participating national labs with respect to various areas, including vehicle technology, energy source, grid management, and infrastructure, were very helpful.
- Seeing all of the topics presented within the same field was extremely helpful in seeing how each complemented the other. While I was aware of many of the topics, I was still able to meet new people doing interesting work.
- I found the poster sessions very helpful as an opportunity to have more in-depth discussions. They helped me to better understand concepts that were introduced earlier and provided great interaction opportunities with key project personnel.
- Meeting with team members from other institutions. Meeting with reviewers. Meeting with program managers. Meeting with industry. This is an excellent venue for solid technical discussions.
- Understanding other projects in which I have no direct involvement/awareness and how they can relate. There could be a tie-in for next-generation products. That insight is invaluable.

- For me, it was the networking with new/existing connections, as well as getting a sense of where DOE VTO is going with EEMS.
- The social networking part, in which key people in the field are gathered in the same place to exchange progress and lessons learned.
- The opportunity to discuss the presented topics with the experts face to face and to get an overview of the sub-programs.
- Getting updated with the latest developments and challenges. Meeting peers with similar interests.
- The quality of the presentations and the networking opportunities. I enjoyed the technical focus of the talks.
- The ability to learn, all in one venue, the breadth of programs and technology areas under investigation by DOE.
- Overall, I felt reviewers were giving constructive criticisms/suggestions/comments, which is very welcome.
- The meeting of many of the key researchers all together at same time.
- Having a chance to see work similar to our own projects.
- The reviews were by knowledgeable personnel.
- The project accomplishments and how they help DOE targets to be met.
- Seeing how government funding was being used in an accountable way.
- The project review in the plenary session is effective.
- The insight provided by GM and Shell in the plenary.
- The program overview was very informative, especially this year.
- Plenary sessions that provided an overview of the vision.
- Understanding the direction of R&D.
- Sub-program presentations and Q&A sessions.
- Learning about the state of the art in hydrogen energy technologies.
- Having the presentations available for download at the kiosk.
- The depth and breadth of the various sessions.
- The wide variety of content.
- The process was quick and to the point.
- H2@ Scale.
- Both presentations and posters.
- The presentations and Q&A sessions.
- The presentation structure.
- Open discussion.
- Meeting people. More room is needed for networking events during the review.

2.11. What could have been done better?

35 Responses

- *From five respondents:* Nothing comes to mind. The AMR was well done.
- There is so much information, and the event was well structured. I am sure it would be challenging to gauge interest in certain sub-programs; however, if there were a way to better assign room space to topics that would have higher traffic that would be good. It would be a challenging feat, but perhaps a worthwhile one.
- Honestly, I am not sure, as I just wish I could have attended more of the sessions.
- I noticed several similar activities are being conducted by various participating parties. It seemed they were to accelerate development, which accounted for the redundancy. There were a few that seemed too repetitive. Some consolidation would be better, especially in the areas of connected automated vehicles and batteries. Also, the food could be better. There were fewer options for vegetarians.
- We had reviewers drop out because of conflict of interest (COI) five minutes before a presentation. The COI questionnaire should include the subs on the project to minimize reviewers dropping out at the last minute.
- There were too many reviewers for each presentation. This is overly taxing for the organizers and reviewers of presentations. A more focused group that includes more reviewers with outside perspectives (e.g., industry) would be more effective and valuable.

- The two-hour blocks of presentations can be a bit long, honestly. Having even a five- to ten-minute break would be nice every hour or hour and a half. Two hours is okay in places, but all day for several days in a row becomes a bit daunting.
- The timing in the rooms was off. In some of the rooms, when a presentation ended early, the moderators would move right on to the next one. This caused the rooms to be running on different schedules and made it difficult to switch between rooms. Moderators need to be told to pause if a session ends early and not to start the next session until the appropriate time.
- The VTO overview sessions on Monday should allow questions from the audience. In addition to reviewer scoring, DOE should consider allowing the audience to give public review scores to projects. I think it is appropriate to weigh public opinion, as the general public is not involved in the reviewer selection process.
- Eliminate repetitive slides. Adjust presentation times according to the amount of material being presented. Keep the room temperature slightly higher; there was too much of a cold draft all day.
- I would have been interested to see more posters/exhibits on combustion and after-treatment topics. It would be interesting to see more industry participation.
- I am not overly fond of the huge sit-down multicourse lunches. Less formal lunches with an opportunity to sit and talk would be helpful. The large lunch room environment was chaotic and difficult to manage. Maybe eating in the meeting rooms would be good.
- I would like to have received a physical copy of all the presentations on a thumb drive or disk to keep as a separate item rather than just file downloads. During the breaks, it would be good to have sections organized by main topic areas, specifically with the recent presenters nearby to congregate and meet with people.
- Presentations should be available online during the AMR meeting. Thumb drive copy was available, but I have very high concerns about viruses. Also, my company would have encrypted the drive once I used it on my computer.
- Please explain the DOE numbers for the projects. I thought they were chronological, but it appears not. I want to know what the latest projects are. I asked multiple people, and nobody knew.
- An opportunity to meet/network with VTO staff. Also, it was impossible for me as a general attendee to be at the AMR the entire week. That is okay, but I missed out on some things as a result.
- Better quality control on the posters is needed. Posters with too-small text are unprofessional and do not serve the purpose of the AMR.
- Sound and lighting could have been better in the poster rooms. The northern room had better lighting and ceiling tiles, while the more southern room did not.
- Rooms should be sized to demand. Many rooms were much larger or smaller than optimal for the number of attendees.
- Mostly changing the rooms so that we could see the screens better. Also, gluten-free food was not available for the poster sessions.
- Hold sessions in wider rooms rather than long skinny ones.
- Panel discussion for each section (e.g., for SSB, or Si anode, or high-voltage electrolyte).
- Every presentation was given the same time (30 minutes). Perhaps it is possible to allocate time depending on the budget or size of the projects.
- There are too many presentations. Focus on the projects that have specific achievements or remarkable results.
- The presentations should have simpler slides and less text/fewer graphics.
- Do not start on a Monday.
- Wait until Thursday to serve ice cream during the afternoon break.
- There should be parking validation or a discount.
- Facilitated networking.
- Lunches.

2.12. Overall, how satisfied are you with the review process?

Top number is the count of respondents selecting the option. Bottom % is percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
0	0	2	50	39
0%	0%	2%	55%	43%

3 Comments

- This is a very good one-stop shop for meeting many of the key researchers.
- I am satisfied. However, I am concerned that having the reviews open to the public may jeopardize our intellectual property and competitive edge—on a national level. It may be best to limit participation.
- Some of the reviewers were quite engaged (asked incisive questions). Ideally, all would be.

2.13. Would you recommend this review process to others?

	Number of Responses	Response Ratio
Yes	86	39.8%
No	1	<1%
No Responses	129	59.7%
Total	216	100%

6 Comments

- It provides a unique opportunity for industry/academia/national labs (bringing a different perspective from that of the presenting PI) to provide input on DOE's project portfolio to adjust and improve the projects and results.
- I am neutral about this. The process has its pros by providing a broad set of information to make people more aware. However, the scale, planning, coordination, cost, and stress that goes into such a meeting seems unnecessary to receive feedback on projects. This could be done more effectively by project or in small groups through webinars or small-scale meetings as needed.
- A yearly basis seems too frequent, but otherwise the process seemed to run smoothly.
- Yes, except for its being open to the public.
- Maybe—the content seems to have too much replication.
- If the presentations are just going to be posted on a website, I may not be as willing to attend this AMR.

2.14. Please provide comments and recommendations on the overall review process.

20 Responses

- Overall, I felt I learned a lot about all the various ongoing activities, especially in my area of interest—vehicle technology. I see the push from DOE for future innovation in the areas of autonomy, connectivity, powertrain, etc. With the persuasion of various cities and national labs, the future looks promising.
- The team at the Marriott was exemplary: the long days that they worked to provide support in the presentation rooms, ensuring timeliness of the presentations; keeping the rooms clean; providing directions and help as needed; and ensuring we all had food and great snacks. They were a really incredible team this year, and I was grateful. Please extend my thanks.
- It is very good to share every achievement of almost all the projects every year.
- Open discussion is quite important to creating new innovation.
- Very organized; moderators and presenters stayed on schedule, and the flow appeared to have worked.
- I was very impressed; the review process was highly systematic.

- The quick turnaround of providing reviewer comments to the PIs was good.
- It was a productive meeting. Thank you very much.
- A good networking opportunity.
- I think this was slightly better than the U.S. Department of Transportation review.
- Keep up the good work.
- This should be done every year.
- Do not cancel it.
- Excellent.
- Everything was fine.
- It was adequate.
- I am satisfied. However, I am concerned that having the reviews open to the public may jeopardize our intellectual property and competitive edge—on a national level. It may be best to limit participation.
- Overall, it was really well done—with the exception of the poor presentation layout in the basement rooms.
- Availability of presentations immediately after the meeting is critical for accurate and effective use by media. In the future, perhaps it would be possible to provide a USB stick to media representatives. I travel without a laptop and use an Android tablet, so the arrangement this year was not helpful.
- Everyone attending is dedicated to increasing energy efficiency, yet everything is so far disconnected from the environment that everyone is working so hard to protect. It was gorgeous weather, and everyone was stuffed into a hotel basement, acting like that is a normal or sustainable process. Perhaps future meetings could be more connected to the environment.

3. Responses from Reviewers

3.1. Information about the sub-program(s)/project(s) under review was provided sufficiently prior to the review session.

Top number is the count of respondents selecting the option. Bottom % is percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
2	2	2	21	15
5%	5%	5%	50%	36%

11 Comments

- I looked at each of my items several times before the review and had enough time to familiarize myself with them.
- There was plenty of time to review presentations and last year's AMR report.
- I did receive a couple of new projects shortly before the review. However, this did not present a problem.
- PDFs were available for download prior to the meeting. However, I would have liked an entire inventory of presentations, as in prior years, when I arrived at the meeting.
- Individual project information was provided in advance. The overview presentation came in only the night before, however.
- It would be good to obtain access to technical presentations two to three weeks in advance. We all have very busy schedules and need to find extra time to examine technical materials in advance.
- Two weeks before is too short. One more week would be appreciated.
- The presentations were not made available with sufficient time prior to the meeting for a thorough review.
- The presentation that I downloaded from the PeerNet website was not the same as the actual presentation delivered. There must have been a last-minute change. It was upsetting.
- My assignments changed a few days before the review.
- If anything, pull back on the reminders.

3.2. Review instructions were provided in a timely manner.

Top number is the count of respondents selecting the option. Bottom % is percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
0	2	1	15	23
0%	5%	2%	37%	56%

7 Comments

- Everything was very easy to do. I had no problems.
- I have been a reviewer before, but the webinar is still a useful reminder.
- Clear as always.
- No issues.
- I suggest distributing the confirmed reviewer agenda ahead of time.
- I was unable to attend the two PeerNet trainings and was unprepared for the software changes, which I see as a step backwards from the original version.
- I had trouble accessing the reviewer webinar on Thursday.

3.3. The information provided in the presentations was adequate for a meaningful review of the projects.

The top number is the count of respondents selecting the option. The bottom number is the percentage of total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
0	2	5	21	9
0%	5%	14%	57%	24%

16 Comments

- This is a good way to provide information needed for reviews of projects.
- The time limitations make it difficult to know the whole background; however, I think it is about the best we can do.
- There is plenty of information in the presentations, but it is not enough to conduct a thorough review, so the presentations are very important.
- The presentations could not cover everything. The opportunity to ask questions resolved any uncertainties.
- One of the major work products is a summary report that was linked to (generally) in the presentation.
- For the most part, this is true. I noticed that, in particular, the presentations by Oak Ridge National Laboratory were well organized and utilized a format (template) that made it easy to fill out the reviews. If there is some template like this, I would highly encourage *all* presenters to follow that format.
- In general, this is so. A few presenters just have trouble with the format, but with so many projects, that is natural enough.
- In general, the information was very useful for rating the project. However, more content related to the technical aspects of the project would be preferred over the boilerplate slide requirements.
- Suggestion: Allow presenters to include a much more expanded backup for reviewers and others interested in more technical detail. (Maybe this is already the case, but reviews would benefit from more than the ~20 slides to adequately assess a project.)
- There was some inconsistency in how the various projects structured their presentations vis-à-vis the reviewer question format. For example, some projects did not use a “Future Work” slide, instead scattering that information across the presentation.
- I agree, but only when the presenter followed the template. I would “highly agree” if they would all follow it.

- Information provided varied between various projects.
- Some yes, some no.
- There was no information provided in the presentations to answer the review question about adequacy of funding. Where models (especially predictive models) were the end result, these models were not often provided, even in preliminary form.
- Most projects had the money received and the duration of the project, but the final "end" goal of the project was not always clear, so it was difficult to assess whether projects were on schedule.
- There was a lack of clear project planning schedules, and sometimes key performance indicators vs. DOE targets were missing.

3.4. The evaluation criteria upon which the review was organized (see below) were clearly defined. (Note that slightly different criteria are used by each office. Some of the criteria below do not apply to every project.)

Top number is the count of respondents selecting the option. Bottom % is percent of the total respondents selecting the option.

	Highly Disagree	Disagree	Neutral	Agree	Highly Agree
Relevance/Potential Impact	0	1	1	24	15
	0%	2%	2%	59%	37%
Approach	0	0	2	23	16
	0%	0%	5%	56%	39%
Technical Accomplishments and Progress	0	0	1	21	19
	0%	0%	2%	51%	46%
Collaboration and Coordination	0	3	1	23	14
	0%	7%	2%	56%	34%
Proposed Future Research	0	0	2	29	10
	0%	0%	5%	71%	24%
Resources	1	1	8	21	6
	3%	3%	22%	57%	16%
Strategy for Technology Validation or Deployment	0	1	16	10	7
	0%	3%	47%	29%	21%
Alternative Fuel Market Expansion and/or Petroleum Reduction Potential	0	1	14	11	6
	0%	3%	44%	34%	19%

10 Comments

- The evaluation criteria are clearly defined, though there may be the need to tweak criteria based on some project focus areas, i.e., deployment versus strict research.
- Budget cuts made this an unusual situation, stretching to discuss the future.
- I did not review any deployment projects, so I cannot comment on those. As for the review questions, typically all projects are relevant, and there is rarely any discussion about sufficiency of funding, so those questions do not appear all that critical. As for the overview presentations, there are too many questions, they do not really seem to ask several of the key questions that arise, and several appear duplicative. Twelve well-developed questions should be sufficient.
- Regarding relevance and potential impact, it would have been helpful to list the desired set of impacts with the questions so that every review is reviewing based on identical criteria/interpretations of the criteria. Collaboration is a difficult criterion for review. One had to struggle with interpreting what was being sought. For instance, it is not clear whether the contribution of a sub-contractor is on a par with that of a partner. In many instances, PIs listed sub-contractors as collaborators, or at least implied that they were.

- The definition of "good" collaboration is not clear, i.e., whether it means a lot of collaborators or very involved collaborators or collaboration with industry. The resources question, which just asked yes or no, was not useful.
- The resources question was difficult to address. It was not clear whether this meant adequate going forward. Many projects did not indicate what future funding would be available.
- *From four respondents:* I did not rate, or marked as neutral, criteria that did not apply to the sessions I attended.

3.5. The evaluation criteria were adequately addressed in the presentations. (Note that slightly different criteria are used by each office. Some of the criteria below do not apply to every project.)

Top number is the count of respondents selecting the option. Bottom % is percent of the total respondents selecting the option.

	Highly Disagree	Disagree	Neutral	Agree	Highly Agree
Relevance/Potential Impact	0	2	5	22	11
	0%	5%	13%	55%	28%
Approach	0	0	3	23	14
	0%	0%	8%	58%	35%
Technical Accomplishments and Progress	0	1	2	24	13
	0%	3%	5%	60%	33%
Collaboration and Coordination	0	3	4	24	9
	0%	8%	10%	60%	23%
Proposed Future Research	0	1	7	25	6
	0%	3%	18%	64%	15%
Resources	1	4	11	15	3
	3%	12%	32%	44%	9%
Strategy for Technology Validation or Deployment	1	6	11	11	4
	3%	18%	33%	33%	12%
Alternative Fuel Market Expansion and/or Petroleum Reduction Potential	0	1	18	9	3
	0%	3%	58%	29%	10%

17 Comments

- Obviously, it is the responsibility of the presenters and PIs to review weightings and criteria, but many presentations went long, so it was hard to provide appropriate scores for some later items if there was no chance to ask particular questions.
- Collaboration and Coordination: For each review, I would like to see *how* the collaboration is going to benefit the project or if other collaboration is felt to be required. For instance, I do not see other agencies generally mentioned. I also rarely see how the results will be collaborated on to provide a valuable outcome or result. Resources: I cannot see the detailed budget for each project, so I cannot tell how the funds are being used.
- Collaboration and Coordination was often fuzzy—sometimes referring only to a request of the listed organization to review some aspect of the work, or the names of organizations of which the PI was a member, even if the project was not being discussed or coordinated with that entity.
- I did not review any deployment projects, so I have no comments on those. All these projects are relevant, or they would not be done, so that is not that critical a question. As for funding, the sufficiency is rarely discussed.

- Not all presentations provided clearly stated "Proposed Future Research" sections. The "resources" information was confined to the current fiscal year, which does not provide clarity for projects projected to end in a future fiscal year.
- No information was provided in the presentations to answer the resource question: no matrix for the ratio of money spent and work done, no information on money left, and no information on the effort level required to complete the work.
- Not all speakers explained the underlying purpose of their project or showed how it was relevant to energy security or petroleum displacement.
- I do not recall much discussion of technology validation. For example, most presentations did not talk about the statistical significance of the results.
- Uncertainty about future DOE budget funds available for basic studies makes comments regarding future plans/resources impossible to judge.
- There should be more emphasis on technical accomplishments and the technical pathway.
- Project arrangements are often made by people's connections/acquaintances rather than based on expertise. I get the impression projects are applying for funding to use their fancy/expensive equipment and facility, ignoring easy ways to answer the question.
- I agree, but only when the presenter followed the template.
- This varied widely by presenter.
- Some yes, some no.
- *From three respondents:* I did not rate, or marked as neutral, criteria that did not apply to the sessions I attended.

3.6. The right criteria and weightings were used to evaluate the programs/projects. (Note that slightly different criteria are used by each office. Some of the criteria below do not apply to every project.)

Top number is the count of respondents selecting the option. Bottom % is percent of the total respondents selecting the option.

	Highly Disagree	Disagree	Neutral	Agree	Highly Agree
Relevance/Potential Impact	0	1	5	24	9
	0%	3%	13%	62%	23%
Approach	0	1	5	25	8
	0%	3%	13%	64%	21%
Technical Accomplishments and Progress	0	0	4	26	9
	0%	0%	10%	67%	23%
Collaboration and Coordination	0	2	7	23	7
	0%	5%	18%	59%	18%
Proposed Future Research	0	0	8	23	8
	0%	0%	21%	59%	21%
Resources	1	0	10	17	5
	3%	0%	30%	52%	15%
Strategy for Technology Validation or Deployment	1	1	12	11	5
	3%	3%	40%	37%	17%
Alternative Fuel Market Expansion and/or Petroleum Reduction Potential	0	1	13	10	5
	0%	3%	45%	34%	17%

7 Comments

- Collaboration is important only if the project benefits from it; some projects seem to be inclusive just for the collaboration's sake. Foundational research strategy is missing in many projects. Younger researchers are marching forward, unchecked by overall program management. Researchers are commenting that they are using immature techniques and missing critical data—but they go forward anyway to attempt to meet milestones.
- I do not recall any discussion about whether adequate resources were provided. There was little insight into what the collaboration section means. The relevance was mostly mother and apple pie. There was no real discussion about what it even means to be relevant.
- I do not think I can answer this one. I think we are missing a big one, and that is future value and vision for how the results will be used.
- This question would be easier to answer if the assigned weights were available to refresh my memory. I already submitted the reviews and do not recall the exact weights.
- It really depends on the area and the details. This question is somewhat meaningless.
- Funding sufficiency is probably irrelevant at this point.
- I did not fill in criteria that do not apply to sessions I reviewed.

3.7. During the Annual Merit Review, reviewers had adequate access to the Principal Investigators.

Top number is the count of respondents selecting the option. Bottom % is percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
0	2	9	19	11
0%	5%	22%	46%	27%

11 Comments

- Ample opportunities were available for interaction between presenters and reviewers. A sit-down lunch was also valuable for additional discussion.
- This is one of the great things about the AMR.
- There was access for sure for poster sessions but not always for speakers. However, that is not the fault of the AMR; it is the schedules of busy people.
- Yes, largely so.
- Suggestion: Perhaps set a short time for the presenters to meet with reviewers only (this almost happens in poster sessions, when reviewers can directly introduce themselves and get walked through the poster, but not in the oral presentations).
- Some reviewers were keeping their seats even after their sessions. As a result, I lost my chance to raise questions.
- Often a PI was not there. Obviously, that is fine if there is a family emergency, but perhaps the PI should call in for questions if the budget does not allow for his/her travel.
- There was very limited time, and some PIs do not stay after their presentations, making it difficult to have further discussion.
- Some PIs were not available (not attending or attending only during a specific session).
- A few arrived immediately before, and left immediately after, their presentations.
- There was not enough time to ask all my questions.

3.8. Information on the location and timing of the presentations was adequate and easy to find.

Top number is the count of respondents selecting the option. Bottom % is percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
0	0	3	21	18
0%	0%	7%	50%	43%

4 Comments

- Fine, as always.
- It would be great if an invite to the calendar can be set up to trigger notifications.
- The timing and location of this meeting conflicted with competing conferences. More consideration should be given to making sure overlap with other popular meetings does not present a conflict. Also, for reviewers, blocks of hotel rooms should be reserved so that booking the event does not become a problem.
- A portion of one session was suddenly relocated, which I found disruptive.

3.9. The number of projects I was expected to review was:

	Number of Responses	Response Ratio
Too many	4	1.8%
Too few	4	1.8%
About right	34	15.7%
No Responses	174	80.5%
Total	216	100%

11 Comments

- This was my fault. I should have offered to do fewer. I was interested in them all, but I could have done a better job sticking to four or five.
- The reviewers should be given an opportunity to preview the presentation materials ahead of time so that they can decide whether they are sufficiently competent or knowledgeable to review the issues. I was assigned to review a presentation that was totally out of my subject matter expertise.
- I received only two assignments at first, which I found to be too few to justify the trip to Washington, DC. I asked for more and was finally given twelve, which was much better.
- There were too many, but not way too many, and anyway, I am used to it.
- Well, it was a lot of work, but someone has to do it.
- I was assigned ten reviews in advance and another four during the meeting.
- I reviewed seven. More would have been difficult.
- I reviewed only one project and would have been willing to review up to five.
- I did two. Three might be better.
- I could have handled more.
- I could have done a few more.

3.10. Altogether, the preparatory materials, presentations, and the question & answer period provided sufficient depth for a meaningful review.

Top number is the count of respondents selecting the option. Bottom % is percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
0	2	2	26	11
0%	5%	5%	63%	27%

10 Comments

- A 20-minute presentation with 10 minutes of Q&A is just right.
- I think the Q&As were right-sized.
- There were good follow-up discussions during the sessions I attended.
- It is generally well run, allowing for meaningful reviews.
- No issues.
- For the EEMS presentations, it would have been nice to have a slide that explained (or an introductory slide that included) which pillar was supported by the work and how it fit into the overall pillar goals/objectives.
- I would like to see separate, closed sessions of reviewers, PIs, and DOE folks for direct interactions. Then the PIs can present to the public.
- Perhaps a few more minutes for some of the higher-value projects would be worthwhile. A $5 million project gets the same time as a $50,000 one.
- Especially for multimillion-dollar projects, half an hour is too short.
- Not in all cases.

3.11. Please provide additional comments.

15 Responses

- The annual AMR conference is a critical technical conference where attendees can learn about future technology trends and new approaches to problem-solving, meet old colleagues, interact with/coach newcomers, etc. There is *no* other U.S. conference addressing all these activities. *Keep it going, and do not change the format.*
- This is a well-organized, effective use of time. Even the posters had good detail and enthusiasm from presenters.
- Overall, the review process seems to work well.
- Overall, the event went well.
- Thanks for all that you do.
- My main goal is to learn how these very valuable projects and datasets can be applied to industry to help obtain the results that are desired by DOE.
- I liked the lunch format, but the food was not great.
- It will be interesting to justify the expense of coming to this meeting next year, if Hydrogen and Fuel Cells Program funds are cut.
- DOE publishes comments by reviewers often many months after the meeting, leaving the PI only a few months to adjust. The release of the report should be more timely. Additionally, for the comments to have a lasting influence, it should be required for the PI to respond to the comments in a more substantial way, whether public or not.
- There were not enough reviewer computers available during the presentations. There were *no* computers during the VTO overview Monday afternoon, and there were only two available in the meeting rooms. I do draft reviews in the PeerNet system as the projects are being presented, and there were two other reviews where I could not get one of the two in the room.

- As a reviewer (at least in my case), I spend many hours and travel at my own cost. DOE should consider providing travel cost reimbursement or a voucher for a tax credit as a public service. All those presenters are reimbursed through their funding, and so are DOE officers.
- The revised PeerNet is terrible. I do not like the one-question-per-page. Sometimes I could not type in the dialogue boxes and had to reload them. The Internet connection was intermittent in some rooms.
- To ensure reviewers are available for the meeting, conflicts with other conferences should be minimized. Also, major conventions in other industries were competing for hotel rooms, which caused booking issues.
- Two hours per session is too long. Raise the screen about a foot so those sitting in the back can see the whole slide.
- The room sizes were too small for most of the Delaware B reviews.

4. Responses from Presenters

4.1. The request to provide a presentation for the Annual Merit Review was provided sufficiently prior to the deadline for submission.

Top number is the count of respondents selecting the option. Bottom % is percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
2	3	1	26	32
3%	5%	2%	41%	50%

7 Comments

- *From five respondents:* The deadline is too early. In the two months prior to the meeting, work is done that cannot be covered in the presentation, and the data is old by the time it is presented.
- I would recommend providing a minimum of four weeks for a presenter to develop slides before submitting them to DOE. Gathering all information in the two-week timeframe is taxing, particularly with projects that include multiple organizations.
- Requests were way late this year, though we assumed the timing from the past.

4.2. Instructions for preparing the presentation were sufficient.

Top number is the count of respondents selecting the option. Bottom % is percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
1	1	1	22	29
2%	2%	2%	41%	54%

5 Comments

- *From two respondents:* Very clear.
- I do want to comment that many presentations did not follow the directions on font size and content. Many presentations were unreadable on the big screen.
- The link to download the instructions was hidden within the email. A more prominent link would be useful.
- To a fault.

4.3. The audio and visual equipment worked properly and were adequate.

Top number is the count of respondents selecting the option. Bottom % is percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
2	0	1	17	44
3%	0%	2%	27%	69%

7 Comments

- The audio/visual equipment was amazing—very clear.
- Inclusion of a laser pointer for presenters was very helpful.
- I encountered a software issue during my presentation that caused confusion throughout the delivery and cost several minutes of my allotted time. There is not enough space here to explain in detail, but the issue could have been anticipated and overcome if the speaker ready stations had used the same dual-screen Presenter View configuration that is used for the actual presentations, rather than using just a single screen. In the future, please use dual screens at the speaker ready stations.
- It would be nice if combination slide advancer/laser pointers were available so we did not have to use laptops to advance the slides.
- We had split presenters, so an additional microphone for questions might have been useful for some questions.
- This is not a big deal, but having a full-size mouse would make it easier for the speaker.
- Some of the presenters were hard to hear if you were sitting in the back.

4.4. The evaluation criteria upon which the Review was organized were clearly defined and used appropriately. (Note that slightly different criteria are used by each office. Some of the criteria below do not apply to every project.)

Top number is the count of respondents selecting the option. Bottom % is percent of the total respondents selecting the option.

	Highly Disagree	Disagree	Neutral	Agree	Highly Agree
Relevance/Potential Impact	2	0	2	41	17
	3%	0%	3%	66%	27%
Approach	2	0	5	33	22
	3%	0%	8%	53%	35%
Technical Accomplishments and Progress	2	0	2	35	23
	3%	0%	3%	56%	37%
Collaboration and Coordination	2	0	4	40	16
	3%	0%	6%	65%	26%
Proposed Future Research	2	0	7	36	17
	3%	0%	11%	58%	27%
Resources	2	2	11	28	12
	4%	4%	20%	51%	22%
Strategy for Technology Validation or Deployment	1	3	14	20	10
	2%	6%	29%	42%	21%
Alternative Fuel Market Expansion and/or Petroleum Reduction Potential	0	3	17	17	9
	0%	7%	37%	37%	20%

2 Comments

- Clearly defined. I have no idea how it is used or if it is appropriate for all projects under review.
- Neutral responses indicate the criterion did not apply to my project.

4.5. Explanation of the questions within the criteria was clear and sufficient. (Note that slightly different criteria are used by each office. Some of the criteria below do not apply to every project.)

Top number is the count of respondents selecting the option. Bottom % is percent of the total respondents selecting the option.

	Highly Disagree	Disagree	Neutral	Agree	Highly Agree
Relevance/Potential Impact	2	0	2	35	23
	3%	0%	3%	56%	37%
Approach	2	0	4	31	24
	3%	0%	7%	51%	39%
Technical Accomplishments and Progress	2	0	3	32	23
	3%	0%	5%	53%	38%
Collaboration and Coordination	2	1	2	35	20
	3%	2%	3%	58%	33%
Proposed Future Research	2	1	3	32	21
	3%	2%	5%	54%	36%
Resources	1	0	8	27	13
	2%	0%	16%	55%	27%
Strategy for Technology Validation or Deployment	1	2	11	21	11
	2%	4%	24%	46%	24%
Alternative Fuel Market Expansion and/or Petroleum Reduction Potential	0	3	13	15	10
	0%	7%	32%	37%	24%

1 Comment

- I was not sure what was meant by approach, so I consulted with a colleague with AMR experience to clarify.

4.6. The right criteria and weightings were used to evaluate the project/program. (Note that slightly different criteria are used by each office. Some of the criteria below do not apply to every project.)

Top number is the count of respondents selecting the option. Bottom % is percent of the total respondents selecting the option.

	Highly Disagree	Disagree	Neutral	Agree	Highly Agree
Relevance/Potential Impact	2	0	6	33	15
	4%	0%	11%	59%	27%
Approach	2	1	6	30	17
	4%	2%	11%	54%	30%
Technical Accomplishments and Progress	2	1	5	31	17
	4%	2%	9%	55%	30%
Collaboration and Coordination	2	2	7	30	15
	4%	4%	13%	54%	27%
Proposed Future Research	2	1	9	29	15
	4%	2%	16%	52%	27%
Resources	1	1	12	25	8
	2%	2%	26%	53%	17%
Strategy for Technology Validation or Deployment	1	1	14	20	8
	2%	2%	32%	45%	18%
Alternative Fuel Market Expansion and/or Petroleum Reduction Potential	0	1	16	13	8
	0%	3%	42%	34%	21%

1 Comment

- I have no idea of the weightings.

4.7. Please provide additional comments:

9 Responses

- This is my second time presenting, and I find it very helpful to self-evaluate my research in the process of developing the presentation.
- Well-organized event. High-quality meals. I made some new connections. Overall, I am satisfied that I attended.
- Great meeting; great progress is being made in several areas. I am looking forward to next year's meeting.
- Outstanding review; all was great.
- Excellent meeting.
- Based on past experience, PIs should not expect to receive feedback on the project presentations for about six months after the AMR, which is more than eight months after preparing the review material. This lag is too long to have substantive impacts on the project going forward. It would be better to target getting compiled review comments to the PIs in two months or less.
- Some attendees' questions were hard to understand. I do not know what could be done to improve them technically. It was mainly issues with accents. Maybe the facilitator could restate the question so it could be clearer and understood.
- Uneven reviewer quality over the Hydrogen and Fuel Cells Program duration was a problem.
- The presentation should focus more on objectives and accomplishments.