H2NEW | Hydrogen from Next-generation Electrolyzers of Water

U.S. DEPARTMENT OF ENERGY

H2NEW: Hydrogen (H2) from Next-generation Electrolyzers of Water Overview

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DOE Hydrogen Program

2023 Annual Merit Review and Peer Evaluation Meeting

Project ID # P196

NREL/PR-5900-86490

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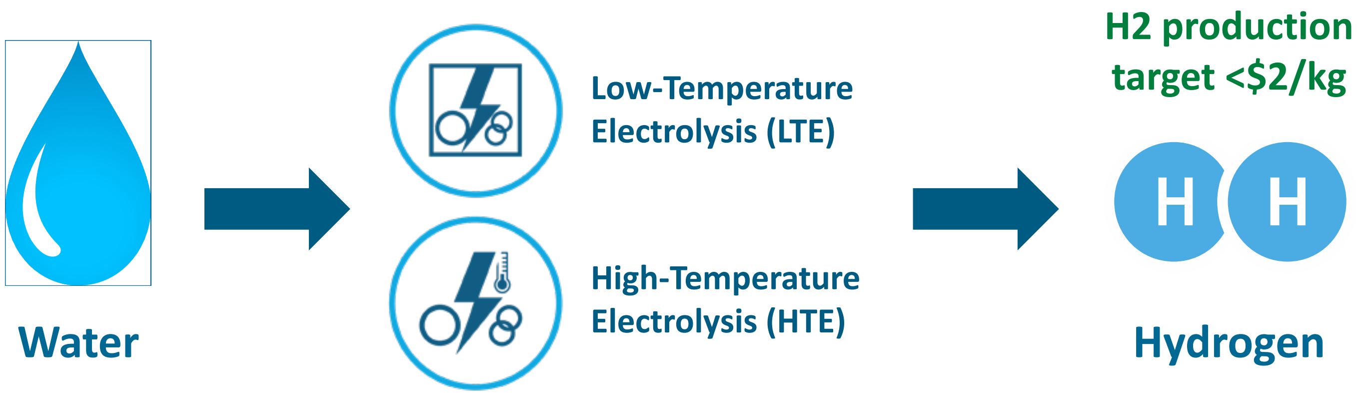
NREL Transforming ENERGY | INL Idaho National Laboratory | Argonne National Laboratory | Berkeley Lab Bringing Science Solutions to the World | Lawrence Livermore National Laboratory | Los Alamos National Laboratory | National Energy Technology Laboratory | Oak Ridge National Laboratory | Pacific Northwest National Laboratory

Project Goals

Goal: H2NEW will address components, materials integration, and manufacturing R&D to enable manufacturable electrolyzers that meet required cost, durability, and performance targets, simultaneously, in order to enable $2/kg hydrogen (by 2026 on way to H2 Shot target, $1/kg by 2031).



H2NEW has a clear target of establishing and utilizing experimental, analytical, and modeling tools needed to provide the scientific understanding of electrolysis cell performance, cost, and durability tradeoffs of electrolysis systems under predicted future operating modes

Overview

Timeline and Budget

- Start date: **October 1, 2020**
- FY21 DOE funding: **$10M (75% PEM, 25% O-SOEC)**
- FY22 DOE funding: **$10M (75% PEM, 25% O-SOEC)**
- FY23 DOE funding: **$28M (45% PEM, 20% LA, 35% O-SOEC)**

Detailed AMR posters on each task:

- **https://www.hydrogen.energy.gov/amr-presentation-database.html** (search H2NEW)

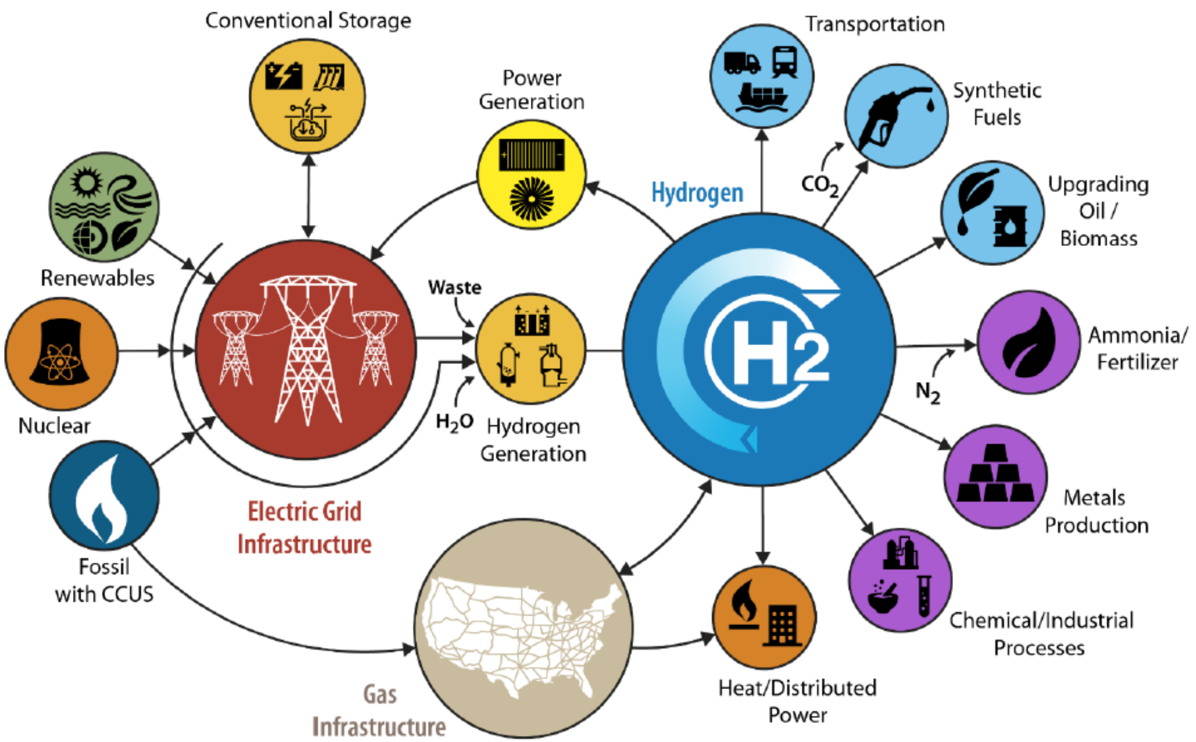
Consortium Team*

NREL, INL, Argonne, Pacific Northwest, Los Alamos, Berkeley Lab, Oak Ridge, NETL, Lawrence Livermore

- NIST, SLAC
- UC-Irvine
- Carnegie Mellon Univ
- Colorado School of Mines

* Expansion to include additional academic and industrial partners through FOA projects currently under review

Potential Impact – H2NEW connection to H2@Scale

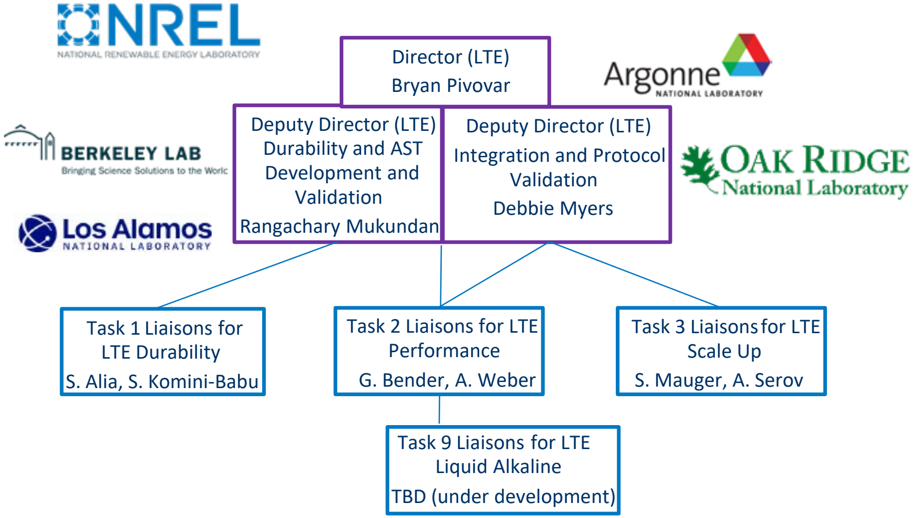


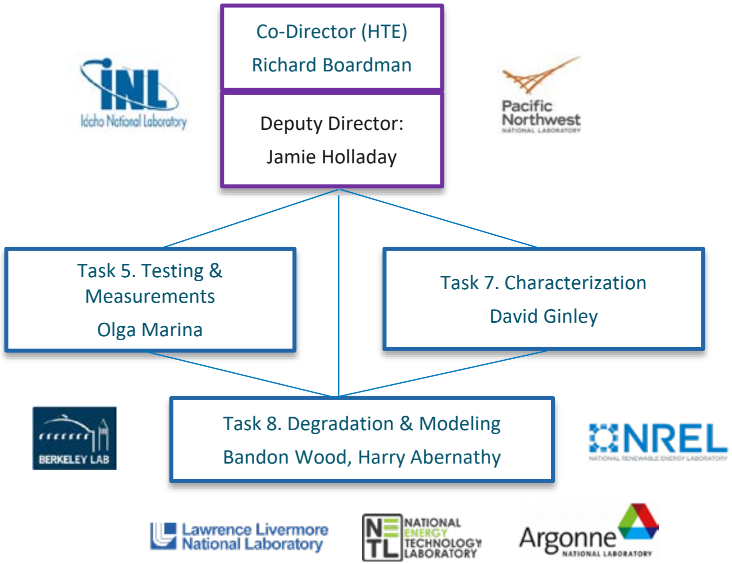
- Making, storing, moving and using H2 more efficiently are the main H2@Scale pillars and all are needed.
- Making H2 is the inherently obvious, first step to spur the wide-ranging benefits of the H2@Scale vision.
- Electrolysis has most competitive economics and balances increasing renewable generation challenges.

Illustrative example, not comprehensive

https://www.energy.gov/eere/fuelcells/h2-scale

Consortium Structure





- Well developed cross-lab structures for PEM and O-SOEC
- Liquid Alkaline efforts under development but will feed into LTE management structure

Collaborations and Coordination

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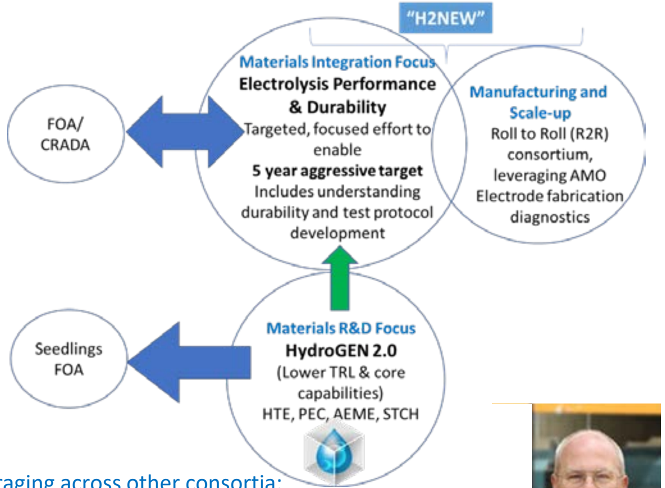
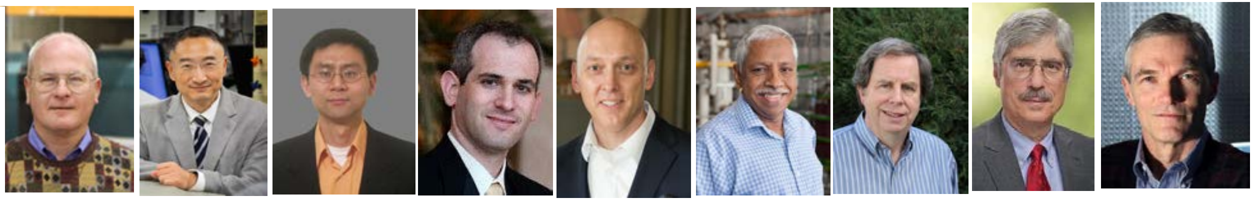


- Leveraging across other consortia:
- HydroGEN 2.0 (HFTO)
- ElectroCat 2.0 (HFTO)
- Million Mile Fuel Cell Truck (HFTO)
- Roll to Roll (Under development)
- Numerous industrial, academia, and international interactions: (IEA, ASTWG, materials suppliers, informal collaborations)
- Select group of advisors representing OEMs, Tier 1 suppliers, analysis and manufacturing interests.

PEM Stakeholder Advisory Board Members

Kathy Ayers	Cortney Mittelsteadt	Andy Steinbach	Jack Brouwer	Mark Mathias
VP R&D	VP Electrolyzer Technology	Specialist Materials Science	Professor	Consultant
Nel Hydrogen	Plug Power	3M	U.C. Irvine	retired (GM)

HTE Stakeholder Advisory Board Members



Scott Swartz	Xiao-Dong Zhou	Greg Tao	Bryan Blackburn	John Piatras	Elango Elangovan	Joe Hartvigsen	Tony Leo	Scott Barnett
Founder & CTO	Prof. Chem. Eng.	Vice President	Chief Tech. Officer	Sr. Principal Scientist, Group Leader	VP of Research	Co-Founder & CEO	Chief Tech. Officer & Exec. VP	Prof. Materials Sci. & Engineering
Nexceris	Univ. of Louisiana-Lafeyette	Chemtronergy	Redox Power Systems	Saint-Gobain	OxEon Energy	OxEon Energy	FuelCell Energy	Northwestern University

Liquid Alkaline Stakeholder Advisory Board (under development)

Associate Lab Director Board (in place)

H2IQ Webinar: https://www.energy.gov/eere/fuelcells/january-h2iq-hour-h2new-consortium-overview-electrolyzer-development-capabilities-0

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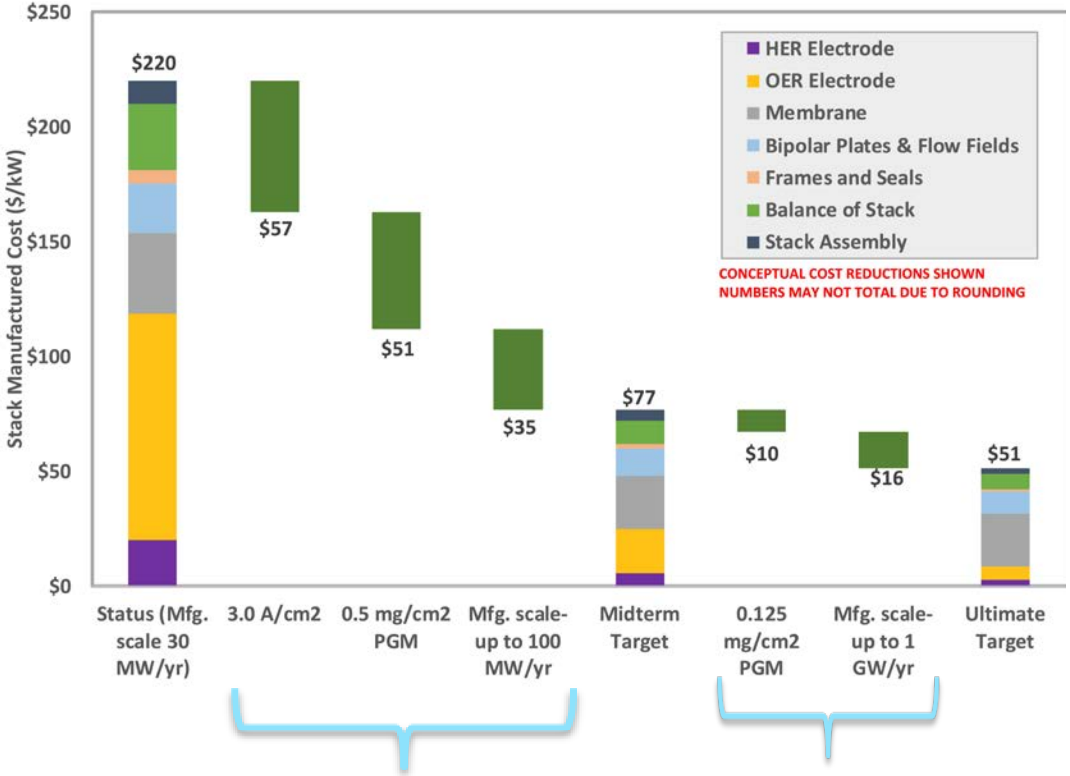
Potential Impact: Stack Costs (PEM)



Stack Targets	Status	2026	Ultimate
Cell (A/cm^2)	2.0	3.0	3.0
Cell voltage (V)	1.9	1.8	1.6
Lifetime (khr)	40	80	80
Degradation (mV/khr)	4.8	2.3	2.0
Capital Cost ($/kW)	450	100	50
PGM loading (mg/cm^2)	3	0.5	0.125

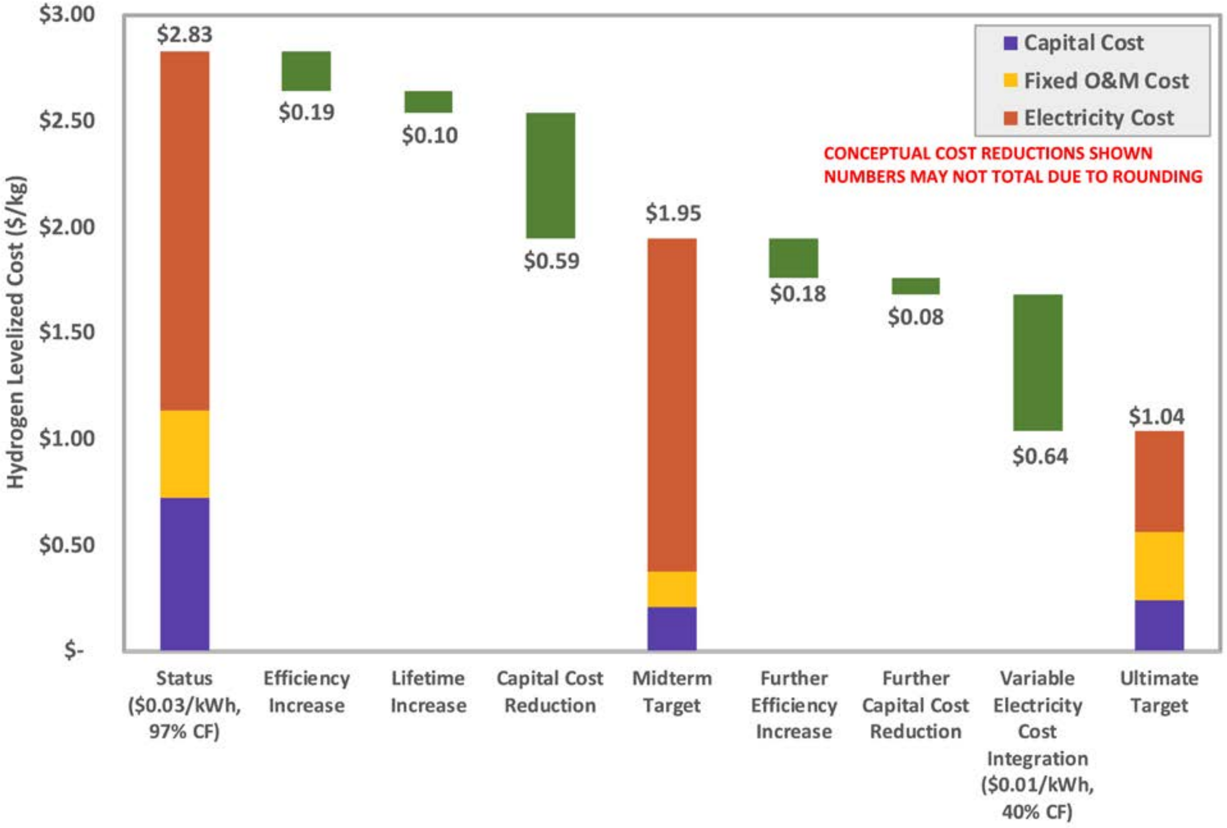
https://www.energy.gov/eere/fuelcells/technical-targets-proton-exchange-membrane-electrolysis

These 3 areas

1. Increased efficiency/current density
2. Decreased PGM loading
3. Scale-up

Are the strongest levers for addressing stack costs and primary focus of H2NEW.

Potential Impact: Hydrogen Levelized Cost

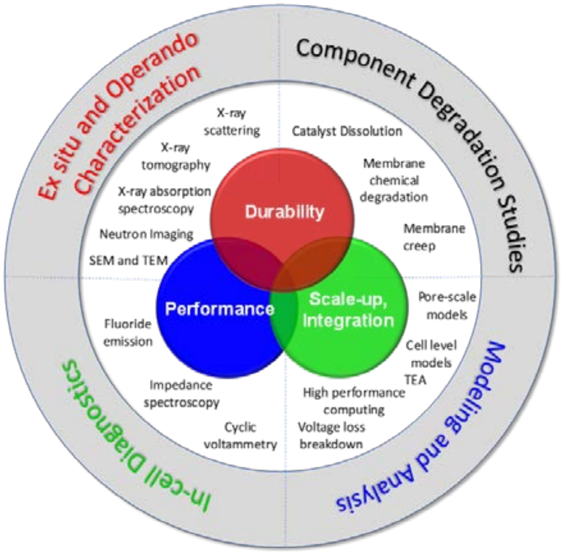


Select pathway to $2/kg and $1/kg identified.

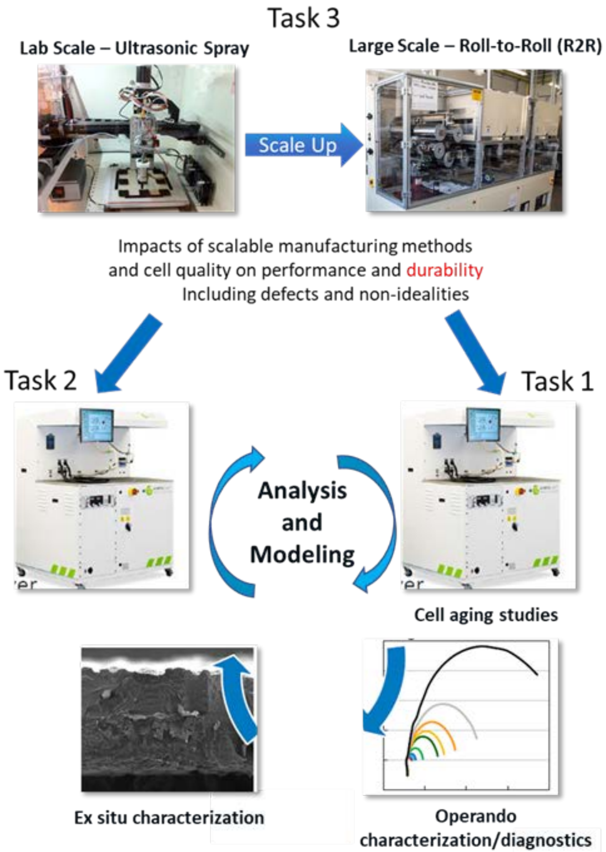
Much of HLC gains possible through greatly decreasing capital costs and enabling lower cost electricity through variable operation.

These advances can't come with compromised durability or efficiency, so all three areas are linked.

Approach: H2NEW Cross-technology Methodology



- Durability
  - Establish fundamental degradation mechanisms
  - Develop accelerated stress tests
  - Determine cost, performance, durability tradeoffs
  - Develop mitigation
- Performance
  - Benchmark performance
  - Novel diagnostic development and application
  - Cell level models and loss characterization
- Scale-up
  - Transition to mass manufacturing
  - Correlate processing with performance and durability
  - Guide efforts with systems and technoeconomic analysis



H2NEW Poster Presentations*

- **Polymer Electrolyte Membrane (PEM)**
  - Task 1: Durability and AST Development: https://www.hydrogen.energy.gov/pdfs/review23/p196a_mukundan_2023_p.pdf
  - Task 2: Benchmarking and Performance: https://www.hydrogen.energy.gov/pdfs/review23/p196b_myers_2023_p.pdf
  - Task 3: Manufacturing, Scale-Up, and Integration: https://www.hydrogen.energy.gov/pdfs/review23/p196c_mauger_2023_p.pdf
  - Task 3c: System and Technoeconomic Analysis: https://www.hydrogen.energy.gov/pdfs/review23/p196d_badgett_2023_p.pdf
- **Liquid Alkaline (LAWE)**
  - Task 9: Liquid Alkaline: https://www.hydrogen.energy.gov/pdfs/review23/p196h_shviro_2023_p.pdf
- **Oxide-conducting – Solid Oxide Electrolysis (O-SOEC)**
  - Task 5: Durability and AST Development: https://www.hydrogen.energy.gov/pdfs/review23/p196e_marina_2023_p.pdf
  - Task 7: Cell Characterization: https://www.hydrogen.energy.gov/pdfs/review23/p196f_ginley_2023_p.pdf
  - Task 8: Multi-Scale Degradation Modeling: https://www.hydrogen.energy.gov/pdfs/review23/p196g_wood_2023_p.pdf

*Additional details found in associated 2023 AMR posters websites provided

H2NEW Activities: Low Temperature Electrolysis (LTE)

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Approach: Select LTE Milestones*

Milestone Name/Description	Due Date	Type	Status
Updated version of DFMA cost analysis report for HFTO and external stakeholder review (NREL)	12/31/2022	QPM	Complete
Define LAWE system configuration and identify all components of subsystems for gas and liquid control, hydrogen purification and electrical power supply. (ANL, NREL)	12/31/2022	QPM	Complete
Establish the correlation of the in-situ performance (polarization curve, EIS, CV) to the changes in morphology on the different break-in procedures. (LANL/ANL/ORNL/NREL)	3/31/2023	QPM	Complete
Model the stability of catalysts and separators based on ex situ and operando experimental data and support the development of accelerated stress tests (ASTs) (NREL, LANL, ORNL, ANL, LBNL)	6/30/2023	QPM	On Track
Complete durability testing under steady state operation and dynamic operation over 3 voltage windows. Validate the IrO2 dissolution model by comparing OER kinetic over potential increase observed in cell-level AST experiments to those predicted from dissolution-based models. Propose and validate at least one mitigation strategy to improve the durability of electrolysis cells under dynamic operation (NREL, LANL, ANL, LBNL)	9/30/2023	Mile-stone	On Track
Demonstrate LAWE single-cell performance agreement evaluated at 0.6 A/cm2, at less than or equal to 1.8V, and within +/- 50mV for at least three H2New labs at an operating temperature greater than or equal to 60C.	9/30/2023	Mile-stone	On Track
In coordination with HFTO, establish methodology involving analytical assumptions of electricity price, operating cycle, stack cost, performance and durability for evaluating hydrogen levelized costs and progress towards meeting the H2NEW target of $2/kg by 2026 and the Hydrogen Shot target of $1/kg by 2031. (all labs)	9/30/2023	Mile-stone	On Track

*Partial list, see associated 2023 AMR posters for additional details

Accomplishments

- 2023 AMR Select Highlights
  - Task 3c – Systems/Technoeconomic Analysis
    - Future electricity markets
    - Turndown ratio impact
  - Task 1 - Durability
    - Ir dissolution – Potential cycling
    - Establishing degradation baselines
    - Start/Stop – Reference Electrodes
    - AST Development
  - Task 2 - Performance
    - Benchmarking
    - Pressure effects
    - Test capability development
    - Cell modeling
  - Task 3 – Scale-up
    - Catalyst ink stability
    - R2R catalyst layer durability
  - PTL (cross task effort)
    - Novel tunable PTL/MPL development
    - PTL/CL interface optimization
    - Operando characterization of PTLs
  - Task 9 – Liquid Alkaline
    - Reference system
    - Benchmarking
    - Cell modeling
    - Initial performance testing

https://www.hydrogen.energy.gov/pdfs/review22/p196_pivovar_boardman_2022_o.pdf

Low Temperature Electrolysis (LTE)

Task 3c: Analysis (more content in AMR Poster P196d)

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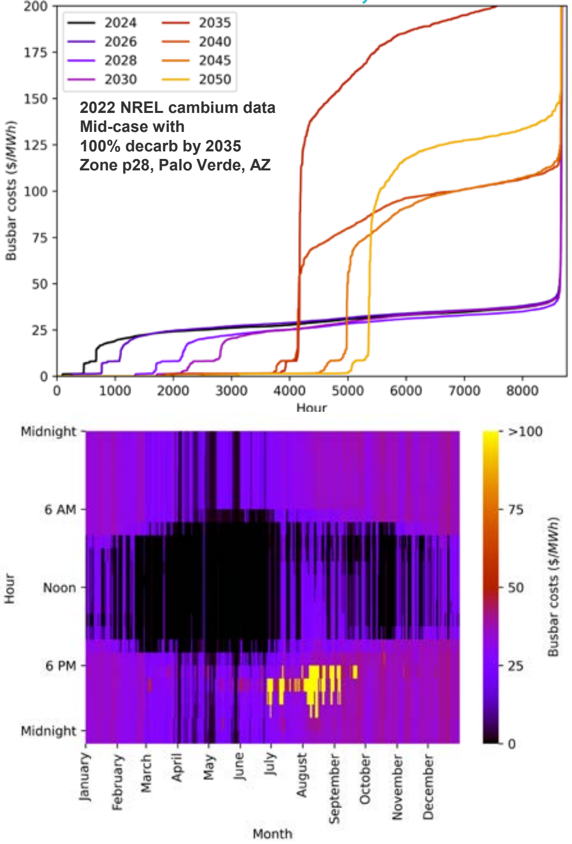
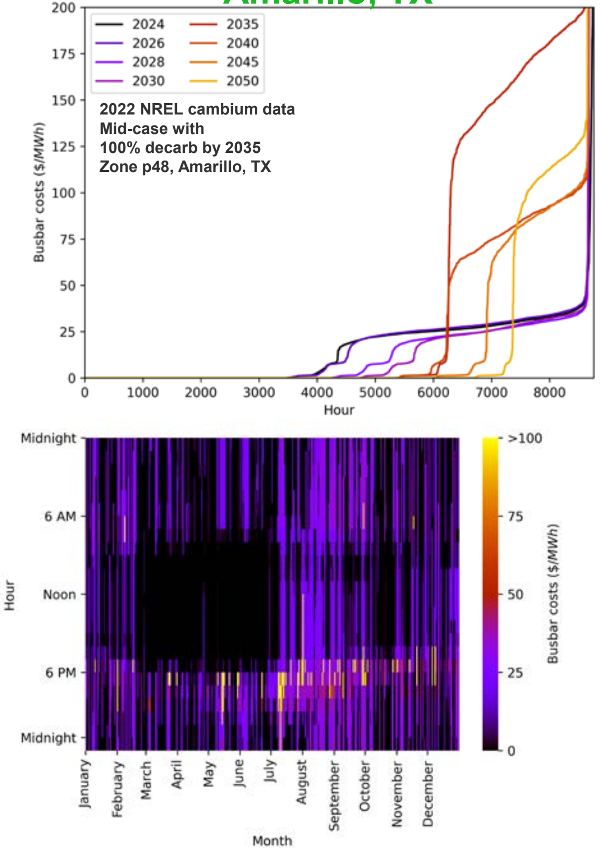
Accomplishment: Analysis of projected marginal electricity costs by location

- We have expanded our analyses to explore “projected” electricity costs.
- We have chosen select locations to highlight the impact of grid mixes.
- Price structures directly influence optimal operating strategies.
- Explores the impact of “chasing” cheap electricity.
- Ignores the impact that electrolysis can have on electricity price structure.

Palo Verde, AZ



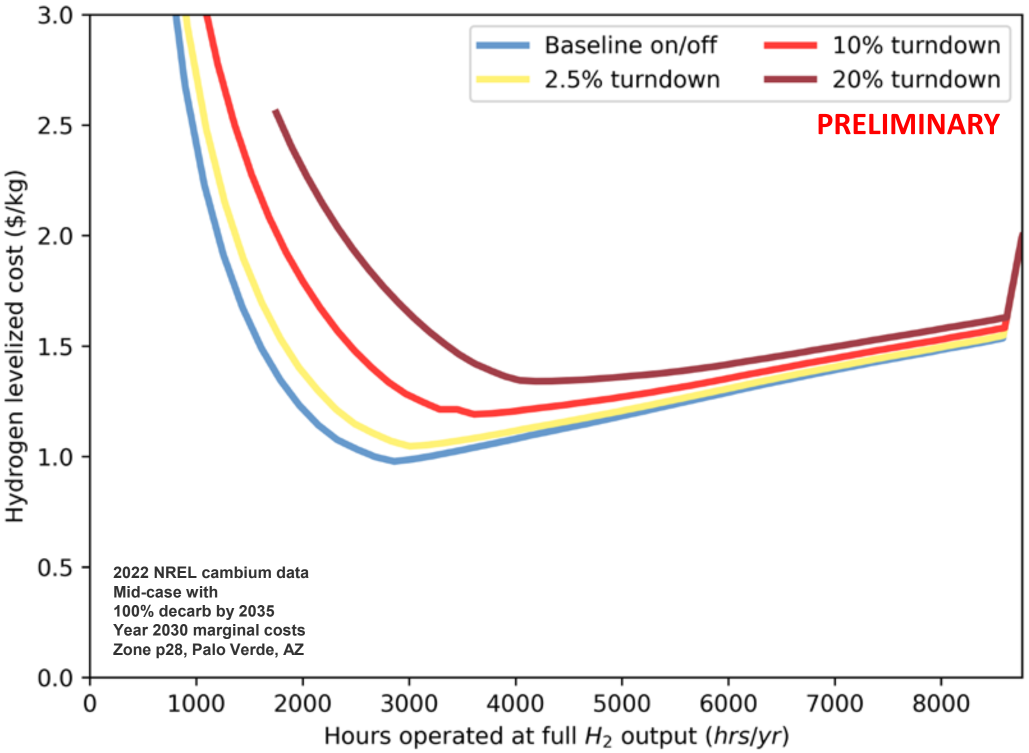
Amarillo, TX



Badgett A, Saha P, Brauch J, Pivovar B. SUBMITTED: Decarbonization of the electric power sector and implications for low-cost hydrogen production from water electrolysis 2023;Advanced Sustainable Systems.

Accomplishment: Impact of turndown (ratio) to idle state to avoid start-up/shutdown cycles

- Full impact of start-up/shutdown on durability is unknown, avoiding shutdown events is possible by staying on and going to lower operating level.
- Lowest operating level achievable to rated power is termed idle state.
- Idle state is ratio of minimum operating power density to rated power density, set by safety/operating limitations.
- Optimum HLC is strong function of turndown and minimum HLC achieved for systems capable of achieving smallest turndown.



Badgett A, Saha P, Brauch J, Pivovar B. SUBMITTED: Decarbonization of the electric power sector and implications for low-cost hydrogen production from water electrolysis 2023;Advanced Sustainable Systems.

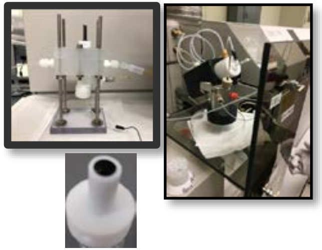
Low Temperature Electrolysis (LTE)

Task 1: Durability (more content in AMR Poster P196a)

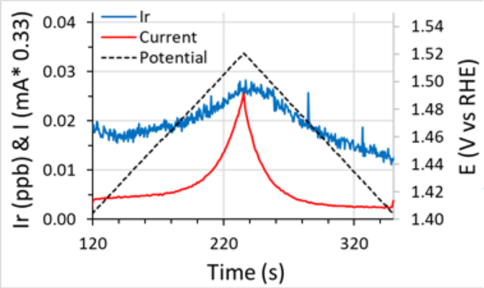
Accomplishment: Time resolved Ir dissolution – Effect of lower potential limit

1.523 V Upper Potential Limit (equivalent to 2V iR-corrected in FuGeMEA); 1 mV/s

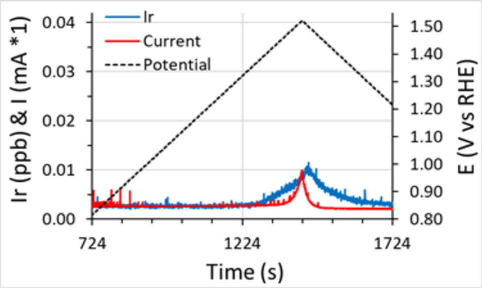
Electrochemical flow cell coupled with ICP-MS. 0.1 M $HClO_4$ electrolyte.



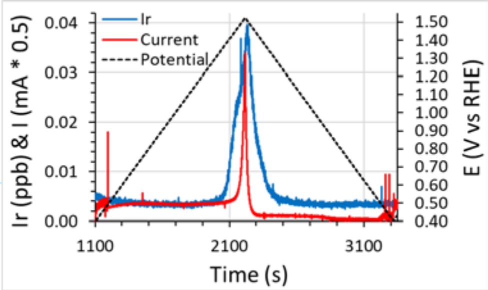
Lower Limit: 1.4 V

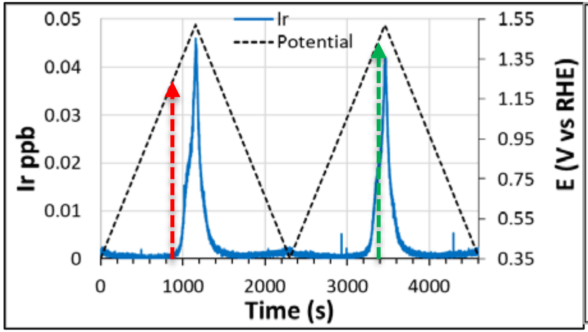


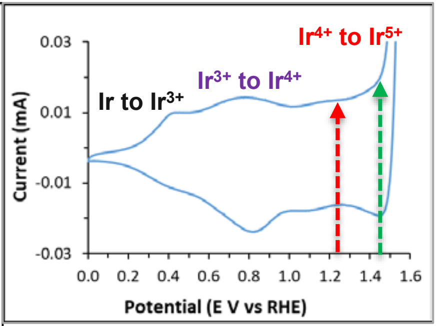
0.8 V



0.4 V

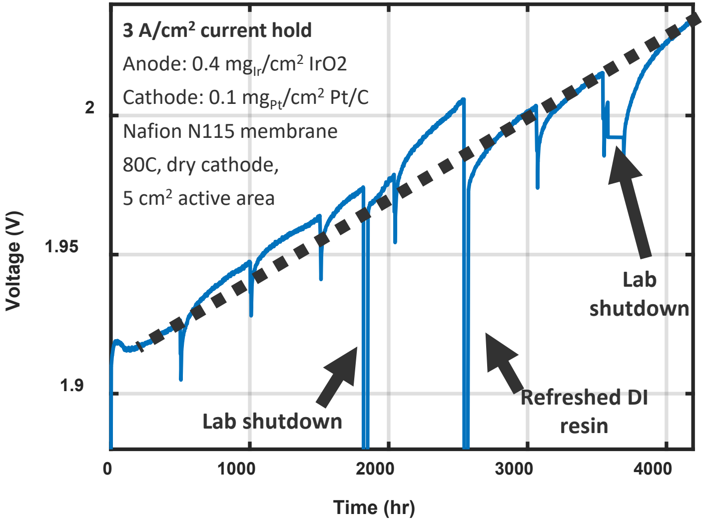


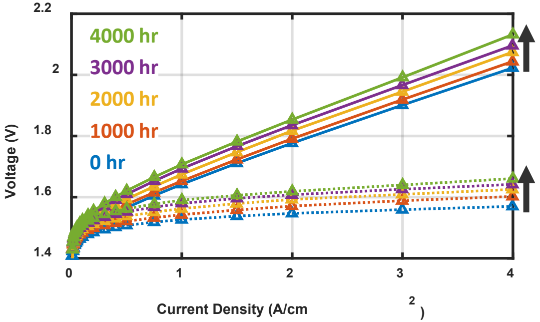




- Alfa Aesar IrO_x is stable at potentials between 0.35 V and ~1.25 V
- Onset of Ir dissolution is at 1.25 V, coinciding with oxidation of Ir^{4+} to Ir^{5+} (determined using in situ X-ray absorption spectroscopy)
- Sharp increase in dissolution at >1.45 V coinciding with onset of OER
- Ir dissolution **during positive potential sweep** decreases with decreasing lower limit of sweep to 0.8 V and increases when lower limit is 0.4 V
- Indicates that increased degradation of Ir during start up-shut down cycling is not caused by dissolution of Ir metal, but by increased dissolution during Ir oxidation

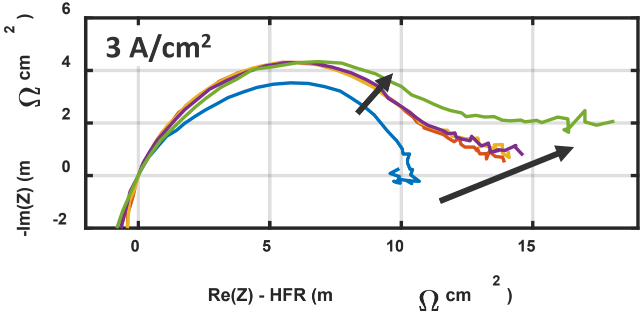
Accomplishment: Establishing Relevant Durability Baselines (4000 hour test)

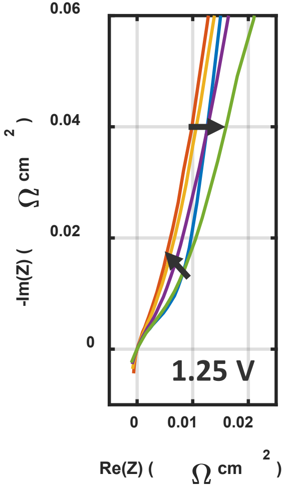




Completed 4,000 hr durability test of FuGeMEA cell:

- Benchmarking decay rates:
  - ~28 µV / hr at 3 A/cm^2
    - ~ 7 µV / hr ohmic, 21 $\mu V_{HFR\text{-}free}$ / hr
    - Slower decay of ~ 11 $\mu V_{HFR\text{-}free}$ / hr at 0.1 A/cm^2
- Understanding mechanisms of steady-state degradation:
  - Catalyst activity or surface area loss
  - Increasing catalyst layer resistance
  - Possible cation contamination

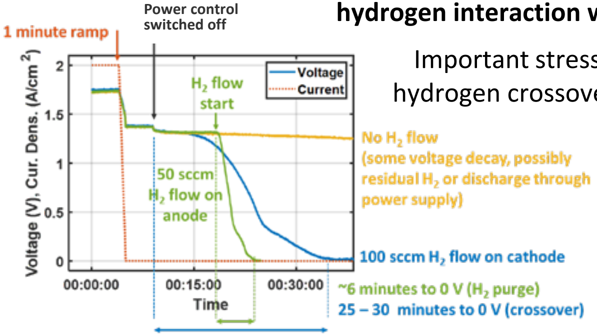




Post-mortem characterization underway to inform mechanistic understanding.

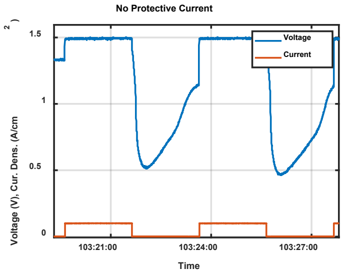
Accomplishment: Cell Depolarization Mechanisms and Reference Electrodes for Start/Stop Durability

Different Depolarization Behavior Depending on Shutdown Conditions



Slow depolarization (minutes) caused by hydrogen interaction with the anode

Important stressor to anode from hydrogen crossover during shutdown

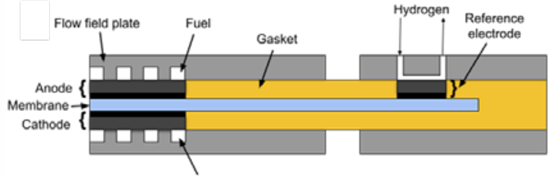


Fast depolarization (seconds) caused by rapid current stepping (possible capacitive effect)

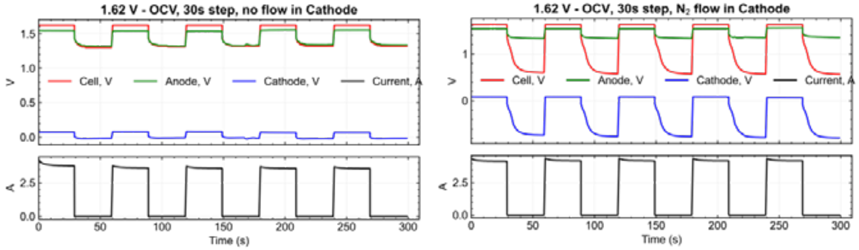
Mechanisms must be understood and controlled to design ASTs and mitigation strategies.

Reference Electrode for Understanding Stressors on Each Electrode

Reference electrode is an essential tool for monitoring anode and cathode states



On/Off current cycling without hydrogen on cathode causes cathode potential to change.



[1] Abdelrahman, M. E. et al. Electrochimica Acta 416 (2022): 140262.

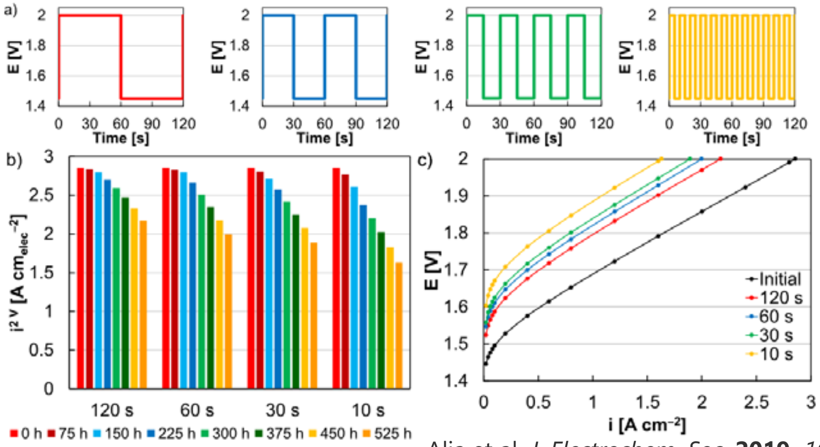
Potential on both electrodes can change during shutdown, creating different stressors depending on conditions.

Understanding and controlling different shutdown stressors is key focus for ongoing work to create targeted, reproducible durability tests

Accomplishment: AST Development – Cycle Frequency, Cell Potential Control

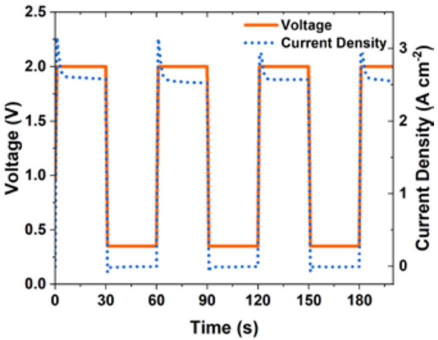
- Higher cycling frequency
  - Relevant to increasing loss rate, consistency in mechanism; Concerns at cycle time below 10 s with load stabilization, reproducibility
- Set of options evaluated for catalyst layer ASTs:
  - HFR-free potential is optimal, capabilities limit implementation
  - Potential based cycling less severe, requires setting other components (more suitable component level AST for comparing catalysts)
  - Current based may be more field test relevant, heavily affected by manufacturing and catalyst layer properties (More suitable for MEA level ASTs)
- Forcing anode potential to below Ir redox increases degradation rate

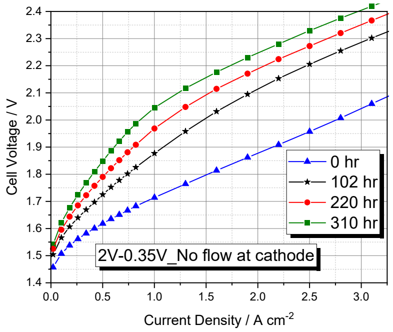
Increasing Cycling Frequency



Alia et al. *J. Electrochem. Soc.* **2019**, *166* (15), F1164.

Forcing cell potential to 0.35V





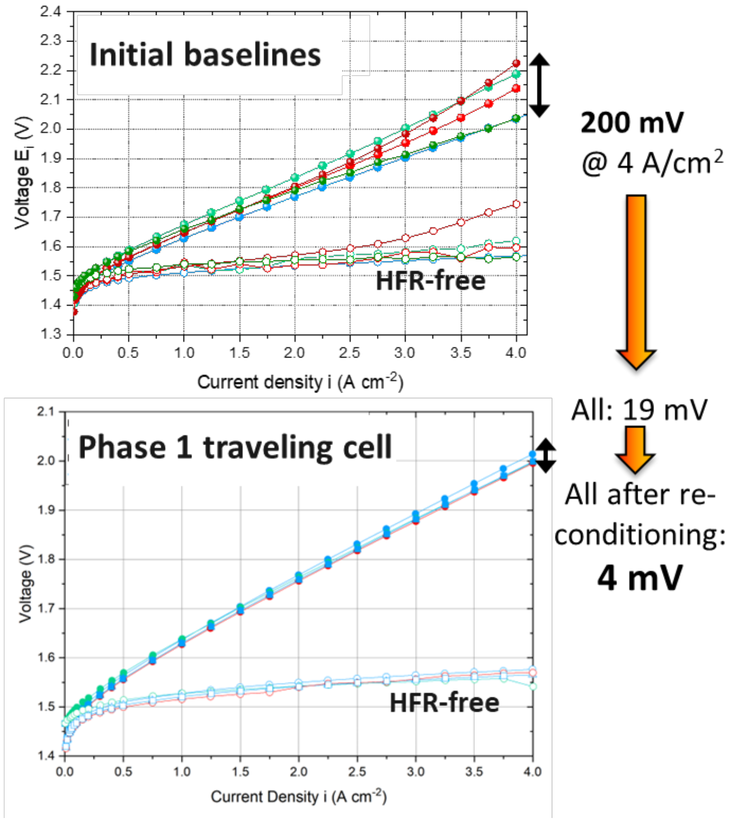
Enhanced degradation rates

Low Temperature Electrolysis (LTE)

Task 2: Performance and Benchmarking (more content in AMR Poster P196b)

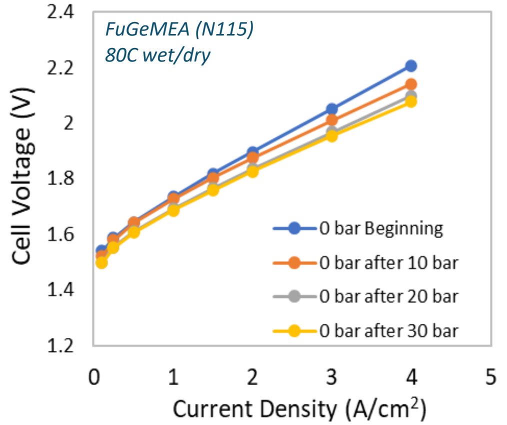
Accomplishments – Established Methodology for Reproducible Cross-lab Benchmark Performance

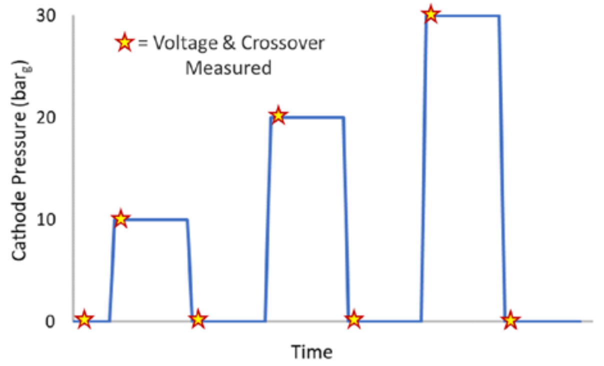
- Evaluating progress in cell performance and durability toward Hydrogen Shot targets requires reproducible polarization curves across the LTE labs
- Several test iterations dramatically improved comparability across consortium labs using traveling cell hardware
- Improvement from 200 mV variation down to 4 mV
  - ✓ Removal of water quality issues
  - ✓ Protocol expansion to include reconditioning between separate experiments
- In-situ experimental results are fully reproducible across labs
- Successful benchmarking activities with the international community (IEA) achieved ~20 mV variations with cell assembled at each location



Accomplishment: Elucidated Effects of Pressure Cycling

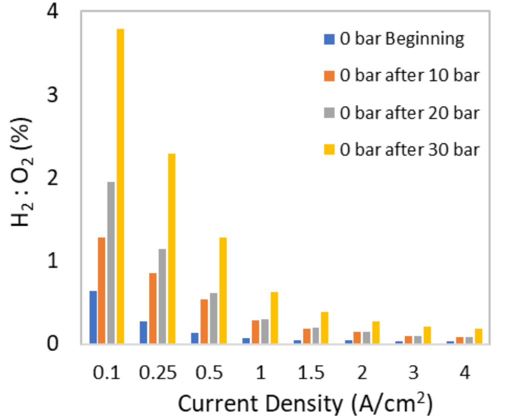
- **Studied impact of differential pressure cycling on ambient pressure VI performance and H_2 crossover**
- **Cell voltage decreased after cell exposure to increasing Δp**
  - ➢ **In contrast to expectations from Nernst equation**
  - ➢ **A second process is occurring**
  - ➢ **We are suspecting a decrease in membrane thickness as cathode pressures force CCM intrusion into the PTL**





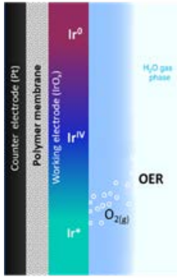
Pressure cycle test plan

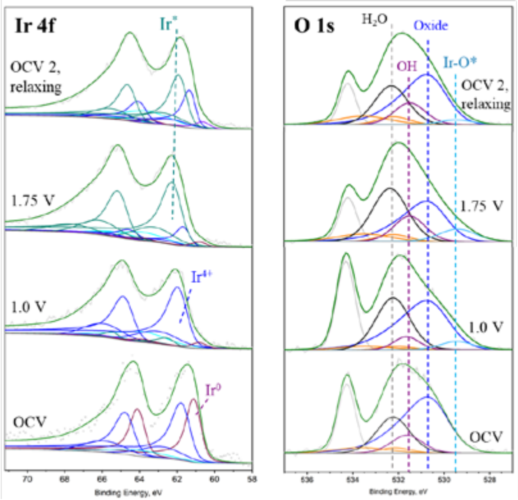
- **H_2 crossover increases dramatically after exposure to elevated pressures**
  - ➢ **This supports the membrane thinning theory**
- **Future work will include EIS to enable a full voltage breakdown analysis**



Accomplishments: Developed Operando Characterization

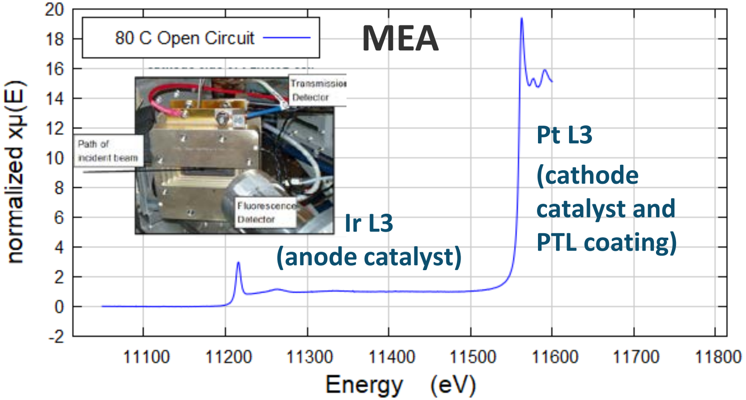
X-ray Photoelectron Spectroscopy (XPS)



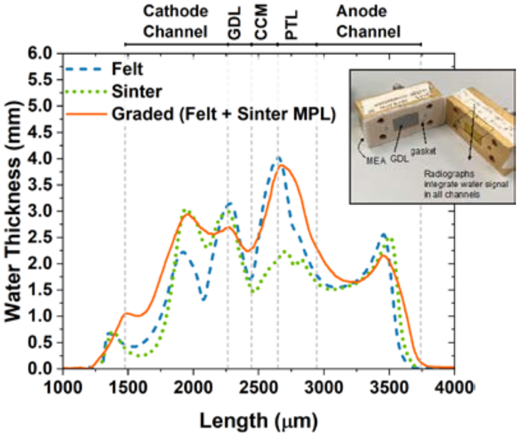


- Operando characterization provides insight into:
  - ✓ Oxidation state of anode catalyst impacting OER activity and degradation processes (XPS, XAFS)
  - ✓ Through plane water distribution impacting cell resistances and transport (Neutron imaging)
- Advanced characterization techniques enable observations of processes within operating electrolyzers and inform model development

X-ray Absorption Spectroscopy (XAFS)



Neutron Imaging (MIT/NIST)



Accomplishments – Developed Models for Hydrogen and Oxygen Crossover and Contaminants

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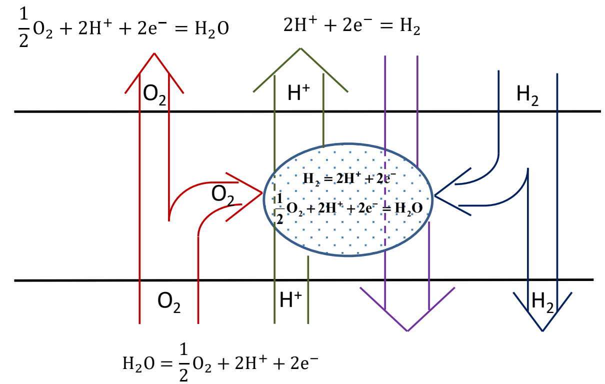
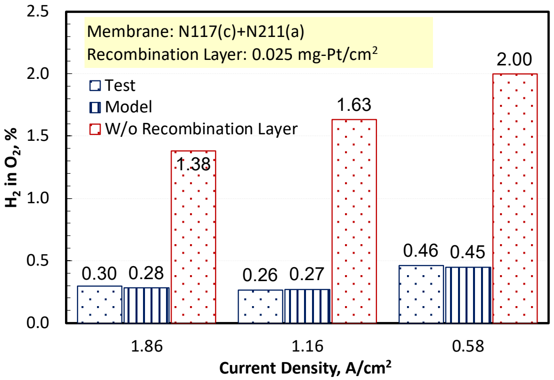
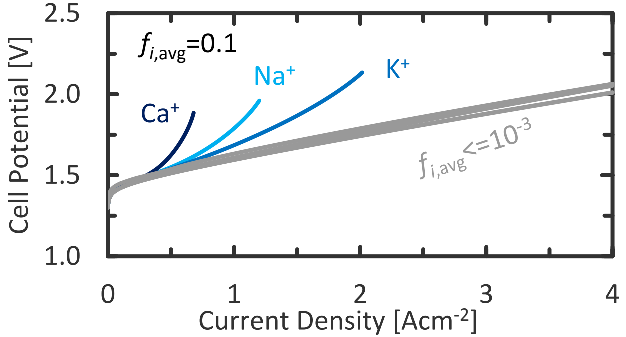
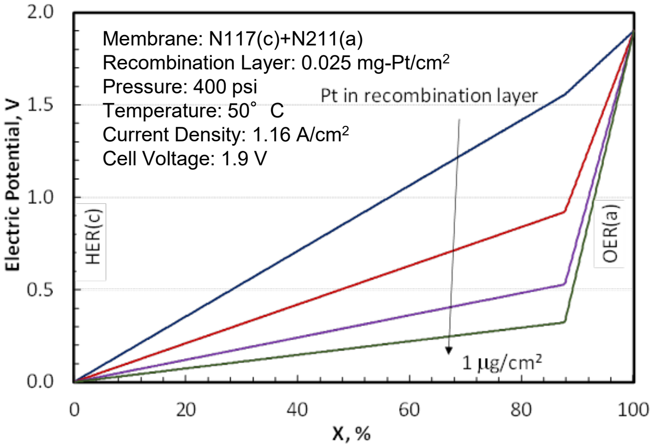


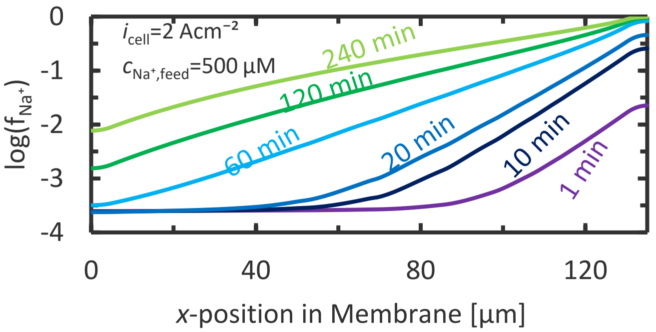




Steady-state polarization curves. f_i is the fraction of cation-exchanged sulfonic acid sites. Three cations were simulated Na^+, K^+, and Ca^{2+}.

- Modeling to inform the recombination layer experimental efforts
- Pt interlayer lowers the electric potential and promotes electrochemical reaction between crossover H_2 from cathode and O_2 from anode.
- Locating the interlayer closer to the anode mitigates H_2 crossover to anode with only a small increase in H_2 crossover from cathode. However, interlayer location may affect Pt stability.





Cation content as a function of position in the membrane with elapsed exposure time to 500 μM Na^+ feed as a parameter at 2 Acm^{-2}.

Low Temperature Electrolysis (LTE)

Task 3: Manufacturing, Scale-up and Integration (more content in AMR Poster P196c)

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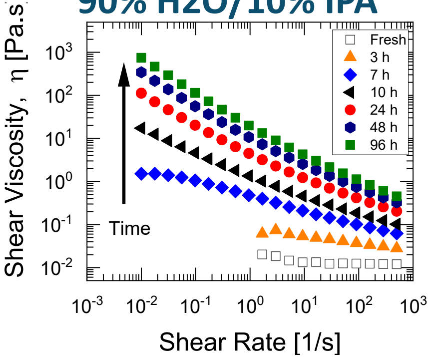
Accomplishment: Shelf-stability of Catalyst Inks

Studies performed to characterize properties of catalyst inks and electrodes as ink ages

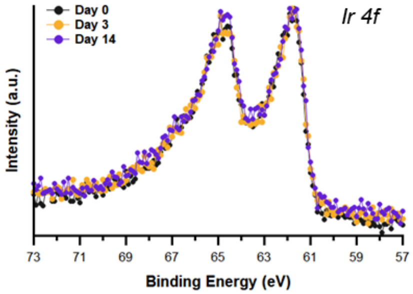
Inks:

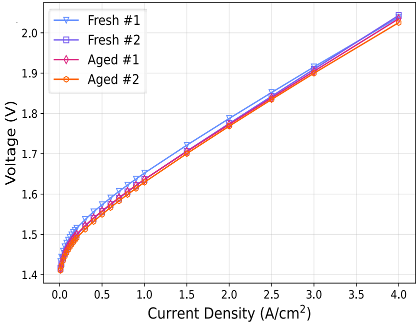
90% H_2O/10% IPA

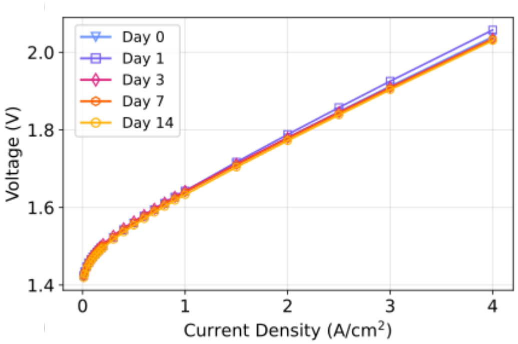


Electrodes from:

50% H_2O/50% NPA





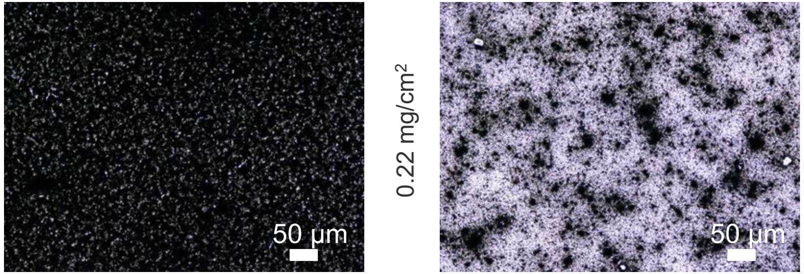


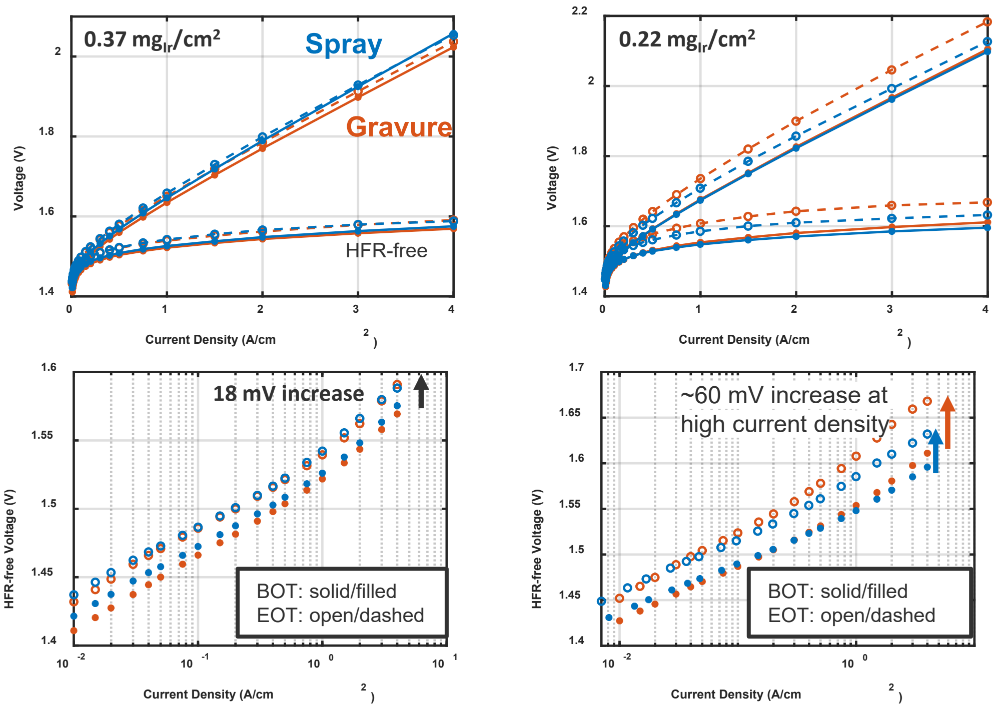
- Water-rich ink (90wt% water) shows dramatic thickening with aging
- XPS shows no change in iridium bonding
- **Most significantly, aged inks perform the same as fresh inks demonstrating shelf-stability**

Accomplishment: Impact of Coating Method on Durability

- DOE 2030 Goal – 0.125 mg_{PGM}/cm^2
- Conducted testing to understand impacts of coating methods on performance and durability
- Compared spray and R2R gravure at two loadings

Gravure-coated electrodes





- **CL coating method and homogeneity do not impact initial IV performance**
- **Higher CL heterogeneity not coating method accelerates degradation**

Low Temperature Electrolysis (LTE)

PTLs (Porous Transport Layers)

Cross-task effort (additional information found in Posters 196a, b and c)

Accomplishment: Development of PTL/MPL fabrication routes with tunable properties

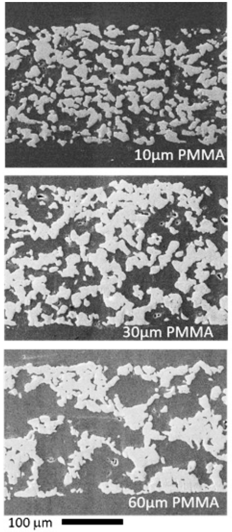
Objectives:

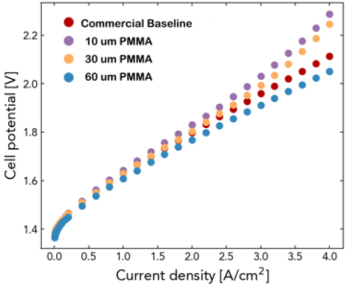
- Develop PTLs with optimized structure using scalable processing methods
- Improve understanding of critical structural parameters (pore size, pore shape, pore volume, graded porosity)
- PTL/MPL structures

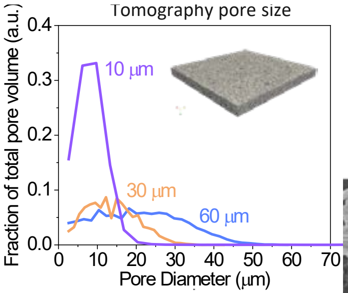
Accomplishments

- Demonstrated good control of structure via tape casting
- Surpassed performance of baseline commercial PTL

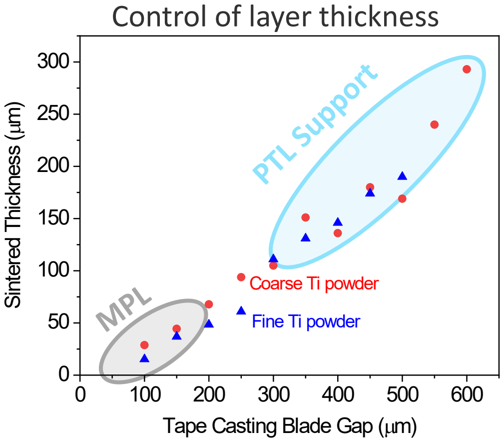
Control of Pore Size with PMMA Porogen



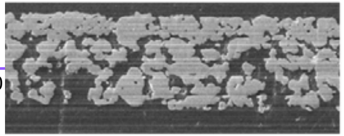




Support/MPL Bilayers



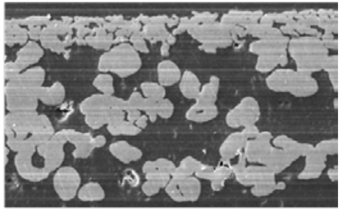
Fine MPL



Fine support

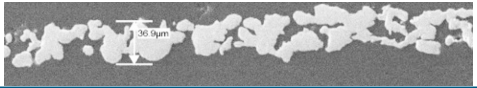
100μm

Fine MPL

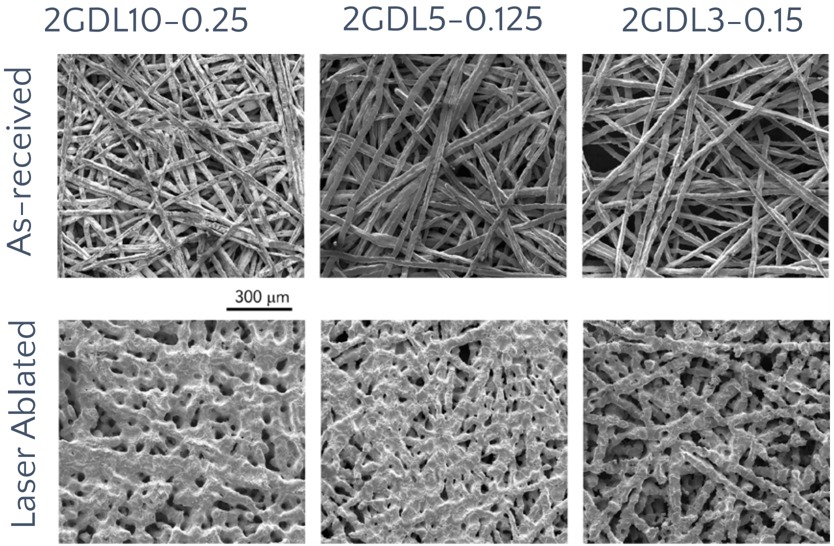


Coarse support

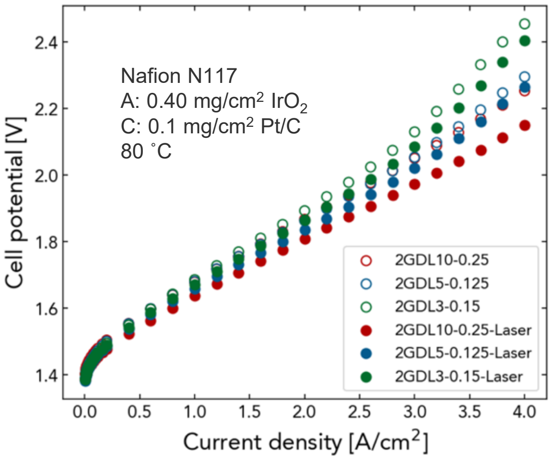
Free-standing MPL



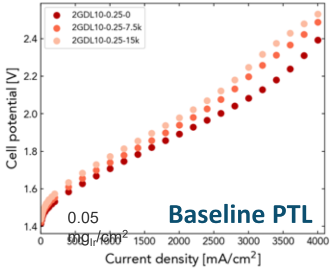
Accomplishment: Improving CL/PTL Interface via PTL Surface Modification; Example: Laser Ablation

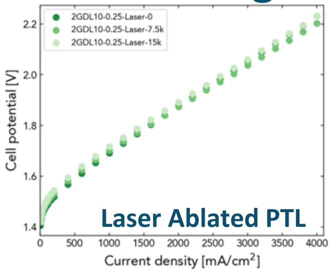


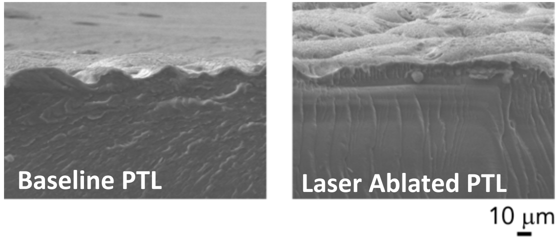
IV Performance



Accelerated Stress Testing







- Investigated use of laser ablation to improve CL/PTL interface and impacts on performance and durability
- Laser ablated PTLs show increase in the measured double layer capacitance, indicating larger ECSA.
- Observed less indentation to the CL/Membrane seed with laser ablated PTLs after AST
- **Demonstrated that:**
  - **Laser ablation improves Vi performance and durability**
  - **PTL surface abrasions can improve Vi performance**

Accomplishment: Characterized the Effects of PTL Morphology

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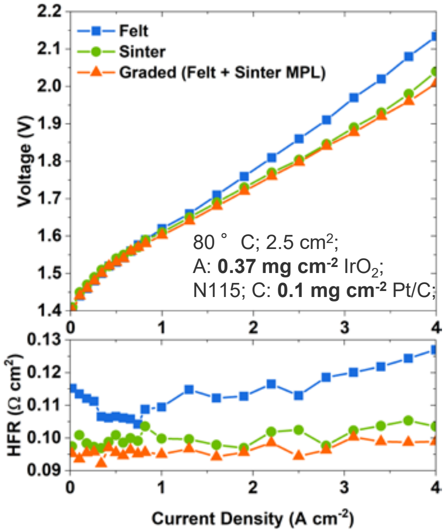
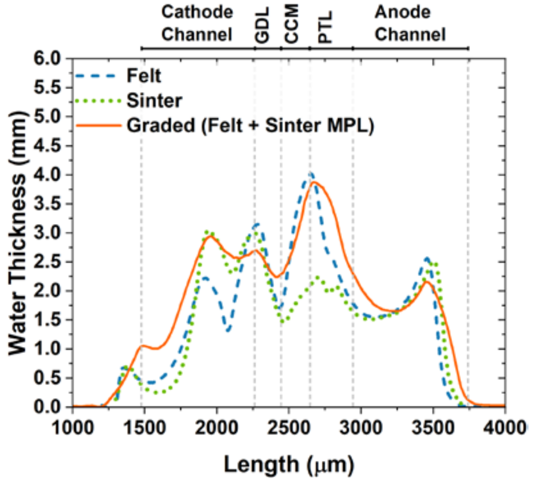
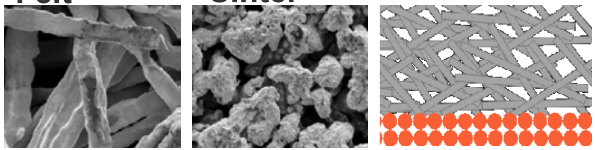


- **Performance of cell with microporous layer (MPL) on PTL is higher due to better contact with anode catalyst layer**
- **Hierarchical structure of PTL with MPL provides better water management**
- **Able to compare same PTL with neutrons and X-ray imaging**

Water thickness from neutron Imaging at 2 A cm^{-2}

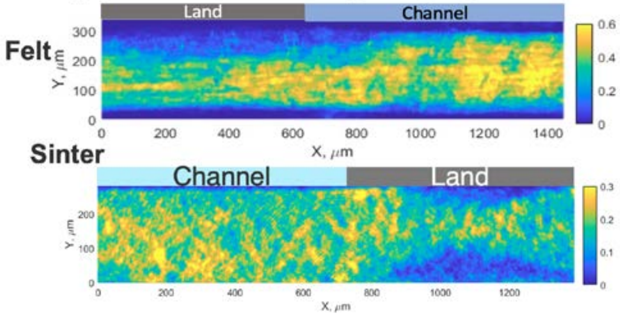


Felt **Sinter** **Graded**



PTL	Thickness (μm)	Porosity	Average Pore Size (μm)
Felt	~240	0.67	15.40
Sinter	280	0.37	4.90
Graded	240+60	0.67+0.40	15.40 + 3.97

O_2 saturation from X-Ray Imaging at 2 A cm^{-2}



- **Combination of operando Neutron and X-Ray imaging to study O_2 bubble in PTL and water distribution across the MEA.**
- **Future Work: Ex-situ and operando characterization of new PTLs (laser modified, PTLs with MPL, PTLs graded porosity) being studied in H2NEW**

H2NEW Activities: Low Temperature Electrolysis (LTE)

Liquid Alkaline (more content in AMR Poster P196h)

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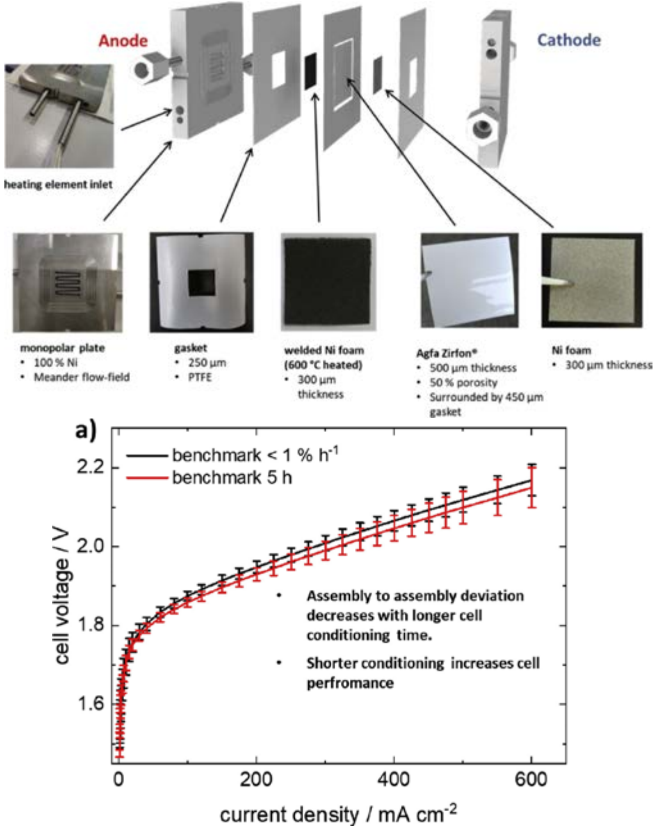
Liquid Alkaline Water Electrolysis

- Mature Technology? Yes, but …
  - Designed for 24/7 steady-state operation
  - Dynamic operation challenges significant (needed for low-cost electrons/energy systems integration)
  - Power density low (turndown capability limited)
  - Degradation not understood, particularly under dynamic operation
- Research needs
  - Reproducibility / Benchmarking
  - Explore optimized operating strategies, quantify durability impacts
    - ✓ Maximum/minimum operating conditions (turndown capability limit key concern for economics)
    - ✓ Impact/ability to tolerate start-up/shut-down
  - Achieve higher operating current density (lower cell resistance, engineered separator)
  - Reduce minimum turndown (gas crossover reduction, engineered separator)
  - Improve efficiency (improved catalysis, engineered separator)
  - Improve durability (mitigation strategies)
  - Increased pressure operation (cell operating strategy, engineered separator)
  - Systems and Techno-economic Analysis (system design, operating strategy, hydrogen levelized costs)



C. Karacan et al., Intern. J. of Hydrogen Energy 47 (2022) 4294

Accomplishments : Reference Liquid Alkaline Water Electrolysis (LAWE) System

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- ➢ Develop reference system configurations for performance, durability and cost studies
- ➢ Develop quantitative understanding of mechanisms that determine system dynamic response to load changes, turndown, efficiency at rated power and partial loads, and durability.

Distributed LAWE System

1. Electrolyzer Stack
- MEA
  Separator: ZrO_2 Diaphragm (Zirfon)
  OER Anode Catalyst: Raney Ni (Ni-Al)
  HER Cathode Catalyst: Mo-doped Raney Ni (Ni-Al-Mo)
  Electrode Substrate: Ni-coated Expanded SS Sheet
- Anode O_2 PTL: Sintered Porous Ni
- Cathode H_2 PTL: Sintered Porous Ni
- Bipolar Plates: Ni Coated SS
- Current Collectors: Ni Coated Expanded SS
- End Plates: SS

2. Electrical BOP System
- Transformer
- Rectifier

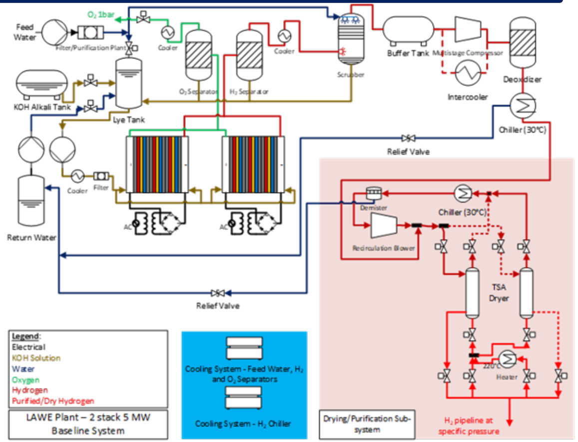
3. Feed Water System
- Feed Pumps
- Water Purification Plant
- Water Reservoir

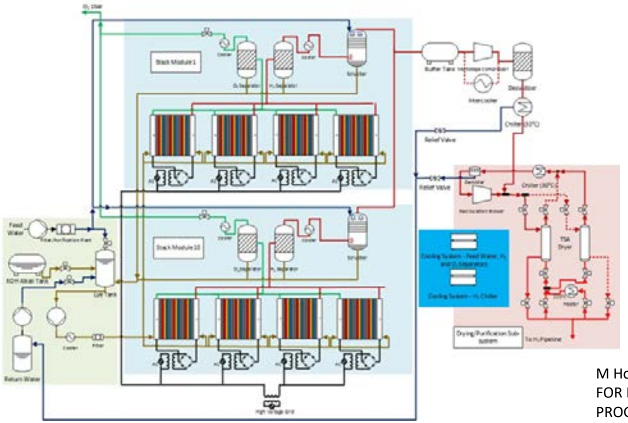
4. KOH System
- KOH Recirculation Pump
- KOH Cooler

5. Gas Treatment System
- Anode H2-Water Separator
- H2 Cooler
- H2 Scrubber
- Cathode O2-Water Separator
- O2 Cooler

6. H_2 Purification System
- H_2 Buffer
- H_2 Compression Unit
- Deoxidizer
- Condenser
- H_2 TSA Dryer

7. Cooling Water System
- Compression Chiller
- Dry Cooler





Centralized LAWE System

1. Stack Modules
- 1.1 4 X 2.5 MW stacks
- 1.2 Electrical BOP Subsystem
- 1.3 KOH Subsystem
- 1.4 Gas Treatment Subsystem

2. High Voltage Transformer

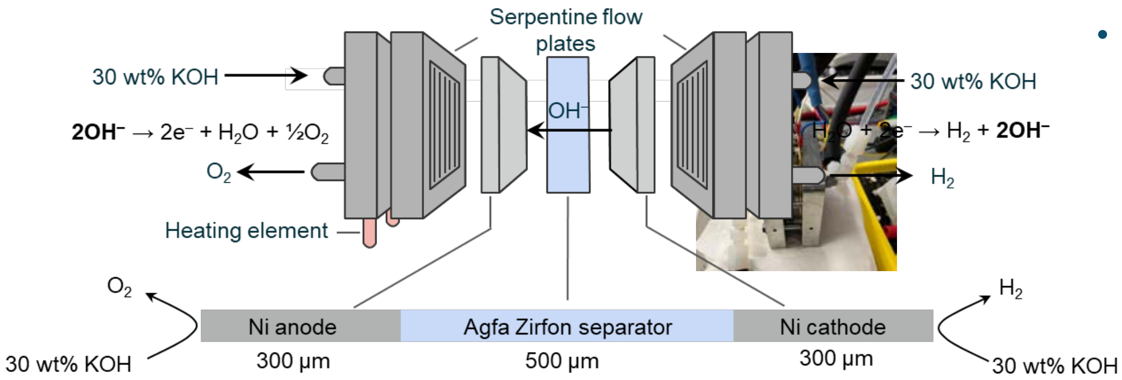
3. Feed Water System

4. H_2 Purification System

5. Cooling Water System

M Holst, S Aschbrenner, T Smolinka, C Voglstätter, G Grimm, COST FORECAST FOR LOW TEMPERATURE ELECTROLYSIS – TECHNOLOGY DRIVEN BOTTOM-UP PROGNOSIS FOR PEM AND ALKALINE WATER ELECTROLYSIS SYSTEMS, Fraunhofer Institute for Solar Energy Systems ISE, Oct 2021

Accomplishment: Cell level model development



$$\nabla \cdot n_i = \varepsilon_l \sum_i R_{k,i}$$

$$n_i = -D_i^{\text{eff}} \nabla c_i + z_i \frac{F}{RT} D_i^{\text{eff}} c_i \nabla \phi_l$$

$$\sum_i z_i c_i = 0$$

$$\nabla \cdot \mathrm{i}_s = -\nabla \cdot (\sigma_{\text{eff}} \phi_s)$$

Bubble coverage

$$a_v = a_v^0 (1 - \theta)$$

$$\theta = 0.023 i_{total}^{0.3}$$

$$R_{B,i} = M_i \sum_i s_{i,n} \Big(k_n \prod_{s_{i,n}<0} c_i^{-s_{i,n}} - \frac{k_n}{K_n} \prod_{s_{i,n}>0} c_i^{s_{i,n}}\Big)$$

$$R_{CT,i} = -M_i \frac{a_v s_{i,k} i_k}{n_k F}$$

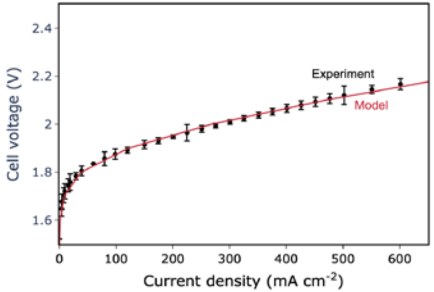
$$i_{\text{HER,base}} = -i_{0,\text{HER,base}} \; exp\left(-\frac{\alpha_{c,\text{HER}} F}{RT} \eta_{\text{HER}}\right)$$

$$i_{\text{OER,base}} = i_{0,\text{OER,base}} \left(\frac{c_{\text{OH}^-} \gamma_{\text{OH}^-}}{1\,[\text{M}]}\right) exp\left(\frac{\alpha_{a,\text{OER}} F}{RT} \eta_{\text{OER}}\right)$$

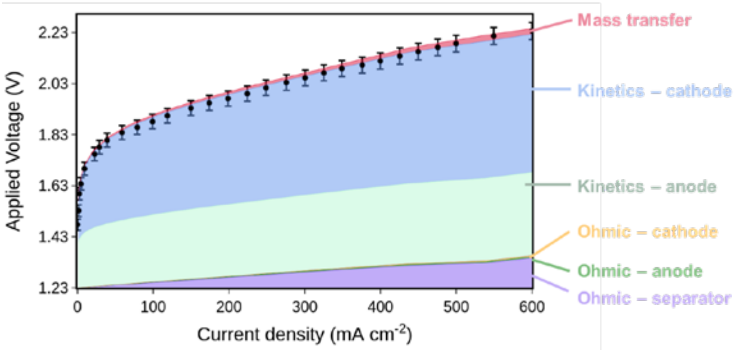
$$\eta_k = \phi_s - \phi_l - \left(U_k^0 - \frac{2.303RT}{F} \text{pH}\right)$$

$$\text{pH} = -\log K_W - \log \frac{a_W}{\gamma_{\text{OH}^-} m}$$

- **Utilize physics-based cell modeling to understanding limiting phenomena and be able to conduct sensitivity studies**

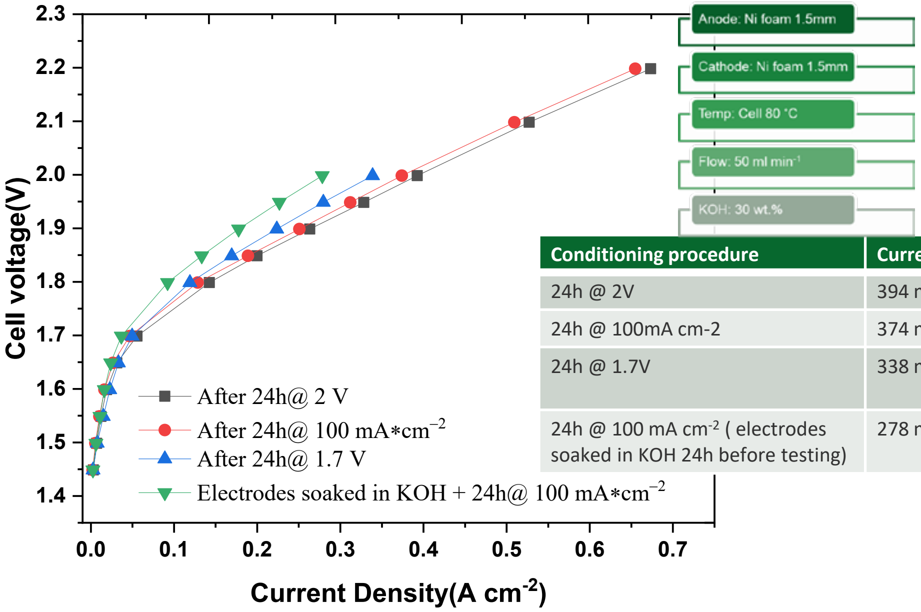


Applied Voltage Breakdown

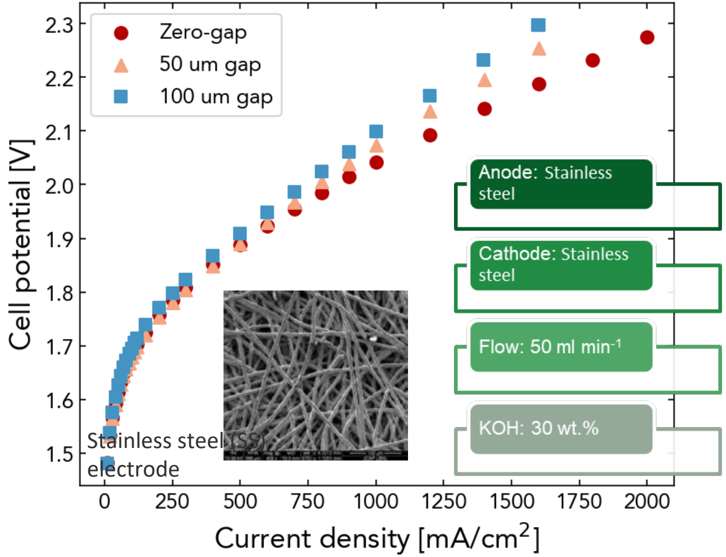


Karacan et al., **2022** *Int. J. Hydrog. Energy*, 47, 7, 4294-4303

Accomplishment: Initial studies - Activation Procedure, Zero-gap vs Finite-gap



Conditioning procedure	Current @ 2 V
24h @ 2V	394 mA cm^{-2}
24h @ 100mA cm-2	374 mA cm^{-2}
24h @ 1.7V	338 mA cm^{-2}
24h @ 100 mA cm^{-2} (electrodes soaked in KOH 24h before testing)	278 mA cm^{-2}



- It is of utmost importance that a stable cell condition is established prior to performance testing.
- The effects of the conditioning process are essential to understanding the electrodes, separator, and cell performance.
- Finite-gap underperform even with very small gap due to increased HFR especially at high currents
- **Regulating bubble transport pathway will be a potential method to improve finite-gap performance**

H2NEW Activities: High Temperature Electrolysis (HTE)

Richard Boardman, H2NEW Deputy Director, and HTE Lead

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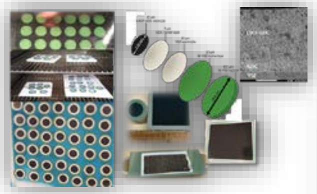
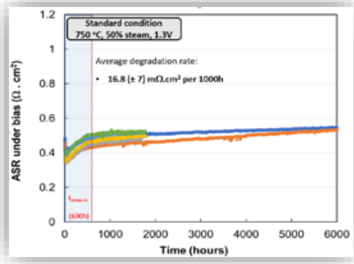
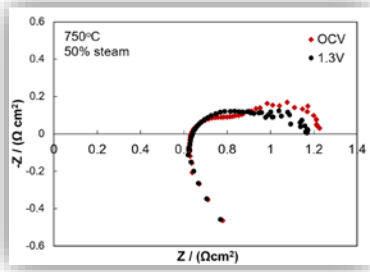
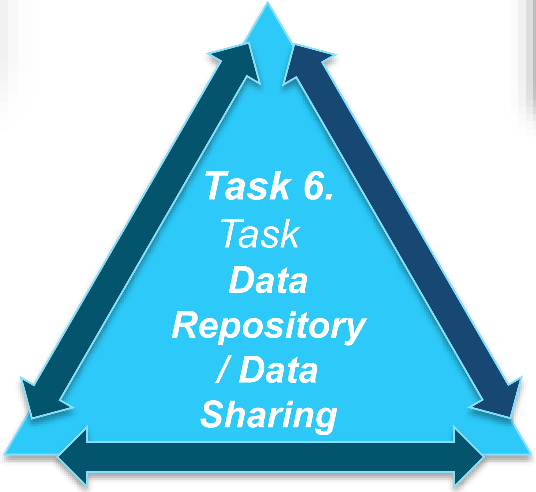
Approach: High Temperature [Steam] Electrolysis: o-SOEC

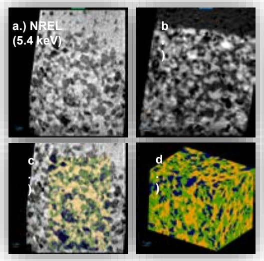


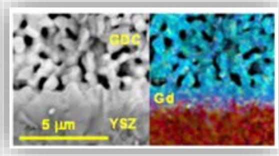
Task 5. Cell Accelerated Stress Testing and Measurements



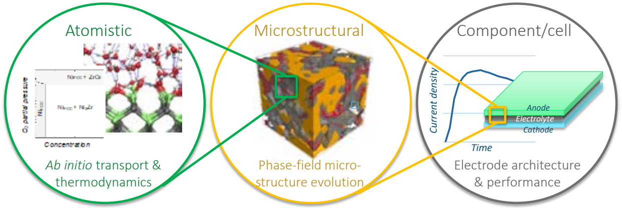








Multiscale physics-based modeling of mechanisms

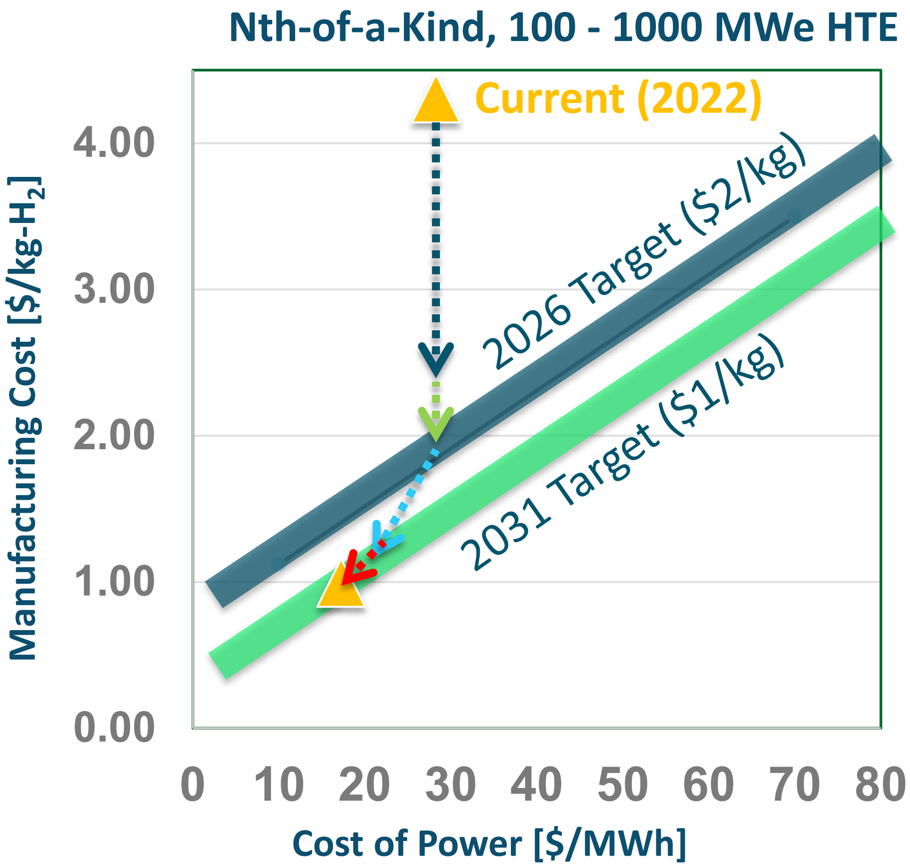


Task 7. Characterization: Cell and Materials Analysis

Task 8. Multi-Scale Degradation Modeling

Relevance: HTE Path to DOE hydrogen cost goals.

- ❑ **Reduce systems/balance of plant costs**
  - Lower operating temperature
  - Reduce oxygen-sweep
  - Increase external heating source
  - Optimize systems design and operations
  - Maximize plant scale
- ❑ **Reduce stack manufacturing costs**
- ❑ **Increase stack efficiency**
  - Increase steam conversion efficiency
  - Reduce ohmic heating by reducing area-specific resistance
  - Increase area-specific Faradaic efficiency by increasing current density
- ❑ **Increase stack endurance (>60,000 hr)**
- ❑ **Couple with industrial process**
  - Heat source (e.g., ammonia or fuels synthesis
  - Replacement of air-separation unit for O_2



Approach: Select HTE Milestones*

Milestone Name/Description	Due Date	Type	Status
Stack test stand check (including power, hydrogen and steam supply, connection, etc), and test protocol finalization and get the concurrence from the Nexceris team. (INL, NETL)	12/31/ 2022	QPM	Complete
Complete inter lab button cell performance validation using benchmarking protocols: obtain I-V and EIS data and compare the degradation rate reproducibility equivalent to a standard deviation of 20%. (PNNL, LBNL)	12/31/ 2022	QPM	Complete
Identify priority samples for testing, analysis, and characterization in order to inform and validate modeling activities. (LLNL, NETL, LLNL, NREL, PNNL)	12/31/ 2022	QPM	Complete
Develop advanced electrical waveform technique for interrogation of button cells. (INL,NETL) Steam cycling frequency testing and power cycling testing (LBNL)	3/31/ 2023	QPM	Complete
Modify HydroGEN/H2NEW data hub to facilitate data sharing. Create a datahub file structure for storing and exchanging of model codes, synthetic microstructures, and simulation data. (NETL, LLNL, NREL, PNNL, INL, LBNL)	3/31/ 2023	Milestone	Complete
Complete button and planar cell testing as well as cells with symmetrical Ni-YSZ electrodes, under high, 90%+, steam operating conditions. Complete post-test characterization of the Ni-YSZ electrode. (PNNL,NETL)	6/30/ 2023	Milestone	On Track
Determine if elevated pressure is an effective stressor capable of accelerating degradation of Ni/YSZ and/or LSCF by > 20% and establish effect of steam utilization on the degradation rates. (PNNL) Demonstrate that the calibrated performance model can be used within NETL's performance degradation modeling framework.(NETL, NREL)	9/30/ 2023	Milestone	On Track

*Partial list, see associated 2023 AMR posters for additional details

Select HTE Highlights

- 2023 AMR Select Highlights
  - Task 5 – Testing & Measurements
    - Established Multiple Size Cell Production
    - Achieved excellent production quality control and consistent testing
    - Established Inter-Lab Standardized Testing Protocol and Operating Procedures
    - Inter-Laboratory cell testing is closing on consistent test outcomes
    - Identified Stressors to Accelerate Degradation Mechanisms
    - Larger cell test stand with realistic interconnects, coatings, and contacts now under testing
  - Task 6b – Data Hub
    - Created Data Hub for H2NEW
    - Roll-out and demonstration, March 2023
  - Task 7 – Advanced Characterization
    - Cell characterization using standard microscopy and state-of-the-art X-ray and electron transmission microscopy.
    - Validated X-ray attenuation predictions and demonstrated XRD can be used to resolve crystal structures and defects from individual layers of intact cells (XRD, right) with simultaneous compositional analysis (XRF, below)
  - Task 8 – Degradation Modeling
    - Assessed impact of Ni/YSZ ration, operating conditions, and microstructure on Ni redistribution
    - Demonstrated multiscale framework for predicting penetration into packed GDC
    - Ab initio calculation use to parameterize multiscale models

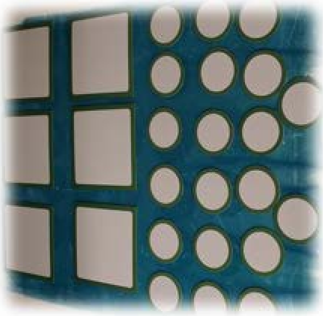
https://www.hydrogen.energy.gov/pdfs/review22/p196_pivovar_boardman_2022_o.pdf

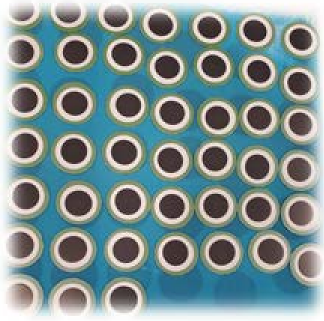
High Temperature Electrolysis (HTE)

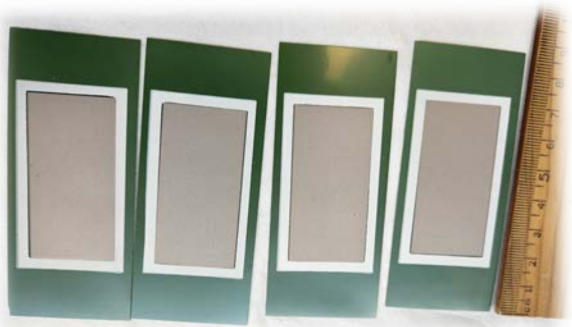
Task 5: Durability Testing and AST Development
(more content in AMR Poster P196E, Olga Marina, et al.)

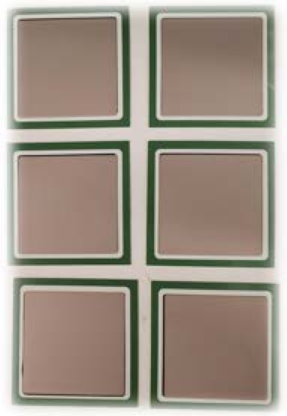
Technical Accomplishments:
Established Multiple Size Cell Production for H2NEW Partners

- Consortium labs use identical cells for testing, performance validation, and characterization
- Ni-YSZ electrode-supported cells in 4 different formats:
  - 2.5 cm diameter (1-5 cm^2 active area) cells
  - 1-5 cm^2 symmetric cells
  - 4 x 9 cm cells (13 cm^2 active area)
  - 5 x 5 cm cells (16 cm^2 active area)
- A batch fabrication process was developed to minimize the variance between separate cells





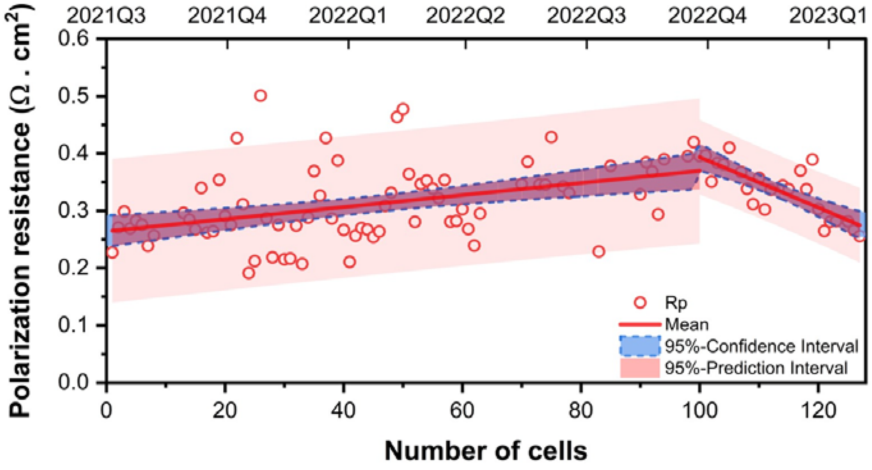


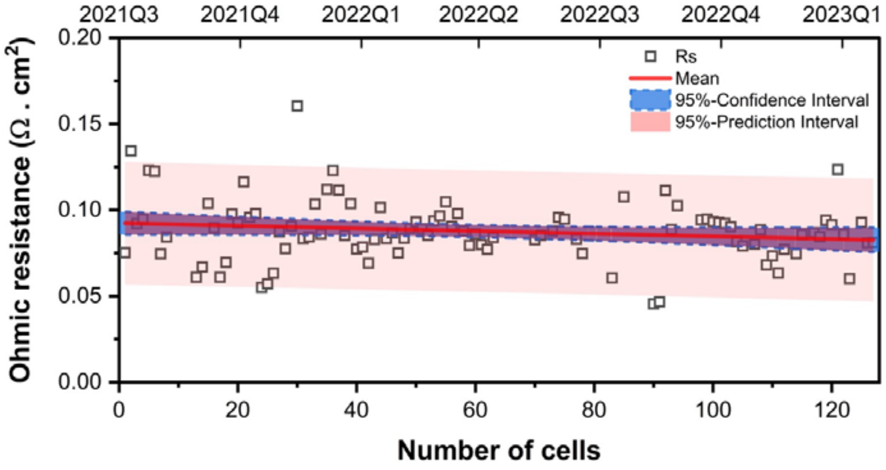


Technical Accomplishments:
Achieved Excellent Production Quality Control and Consistent Testing

Cell performance reproducibility at PNNL

130 different cells tested over period of 20 months using “standard” conditions: 750ºC, 1.3V, 50% H_2O





Automation of several fabrication steps and tighter test protocols improved polarization resistance

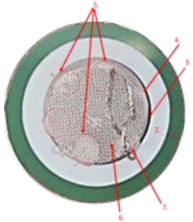
Ohmic resistance is consistently low

Technical Accomplishment:

Established Inter-Lab Standardized Testing Protocol and Operating Procedures

LSCF electrode paste used to mount platinum mesh current collectors on the oxygen electrode.

Steam/Hydrogen electrode uses nickel paste to mount nickel mesh.



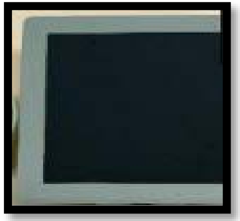
Cell preparation standardization

- Current collectors & attachment
- Precious metal reduction

Cell testing standardization:

- Heat-up
- Reduction
- Compositions

Button-Cell
2-4 cm^2 active area

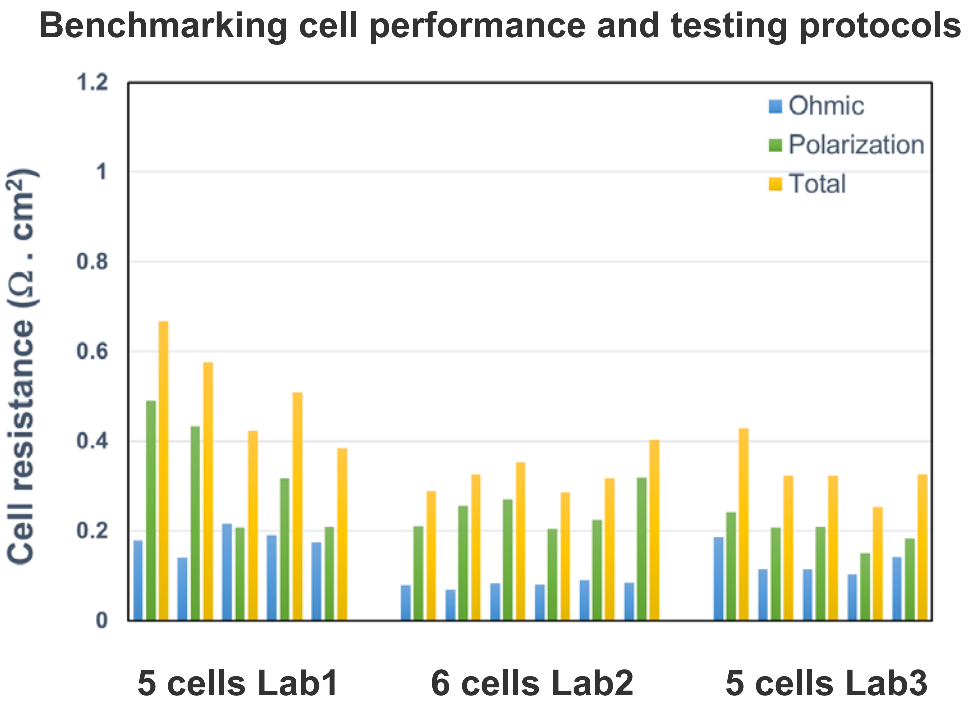


Enlarged Planar Cell
10-25 cm^2 active area

Text Parameters

- Temperature
- Voltage & Current Density
- Steam/H2 mixture flow and contact with cell

Technical Accomplishments: Significantly Improved Interlab Reproducibility by Developing SOP



	Ave. Ohmic R (Ω.cm²)	Std. Error (Ω.cm²)	Ave. Polarization R (Ω.cm²)	Std. Error (Ω.cm²)
Intra Lab Reproducibility				
LBNL	0.180	0.024 (13%)	0.331	0.115 (35%)
PNNL	0.081	0.007 (8%)	0.248	0.039 (16%)
INL	0.132	0.030 (23%)	0.198	0.031 (16%)
Inter Lab Reproducibility				
LBNL + PNNL + INL	0.128	0.046 (36%)	0.258	0.088 (34%)

- Observed substantial performance variances between the labs in early testing rounds
- Significantly improved interlab reproductivity by developing standard operating procedures

Accomplishment: Identified Stressors to Accelerate Degradation Mechanisms

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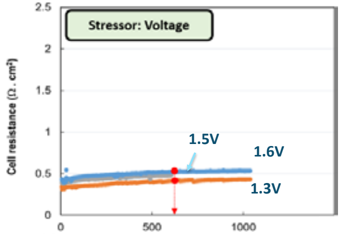
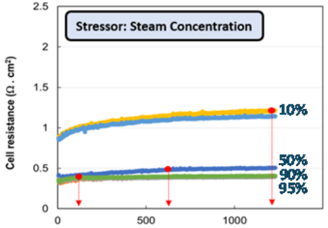
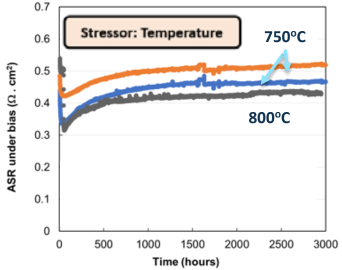
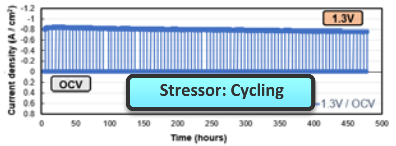
# of cells	Time (h)	H_2O (%)	V (V)	η (V)	T (°C)	Stressor
6	6,000	50	1.3	0.35	750	none
6	3,000	50	1.3	0.35	750	none
3	2,000	50	1.3	0.35	750	none
1	1,000	50	1.3	0.35	750	none
1	2,400	50	1.3	0.35	750	none
2	3,000	50	1.3 → 1.6	0.65	750	**V**
2	6,000	50	1.3 → 1.5	0.55	750	**V**
1	1,000	50	1.5	0.55	750	**V**
1	1,000	50	1.6	0.65	750	**V**
1	3,000	90	1.3	0.45	750	***p*** $\mathbf{H_2O}$
2	2,400	90	1.2	0.35	750	***p*** $\mathbf{H_2O}$
2	2,400	10	1.4	0.35	750	***p*** $\mathbf{H_2O}$
1	2,400	95	1.175	0.35	750	***p*** $\mathbf{H_2O}$
2	1,000	90	1.2	0.35	800	***p*** $\mathbf{H_2O}$
2	1,000	10	1.4	0.35	800	***p*** $\mathbf{H_2O+T}$
1	1,000	95	1.2	0.35	800	***p*** $\mathbf{H_2O+T}$
1	3,000	50	1.3 → 1.5	0.55	800	**T, V**
2	3,000	90	1.3	0.35	800	***p*** $\mathbf{H_2O+T}$
1	3,000	50	1.3 → 1.5	0.55	800	**T, V**
4	2,000	50	1.3 → OCV	0.35	750	**V cycling, different cycling frequency**
2	1000	50	1.3 → 0.8	0.35	750	**SOFC-SOEC cycling**

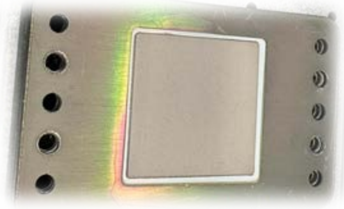


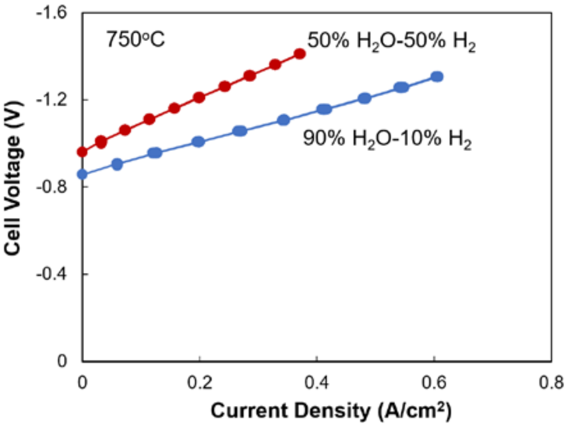


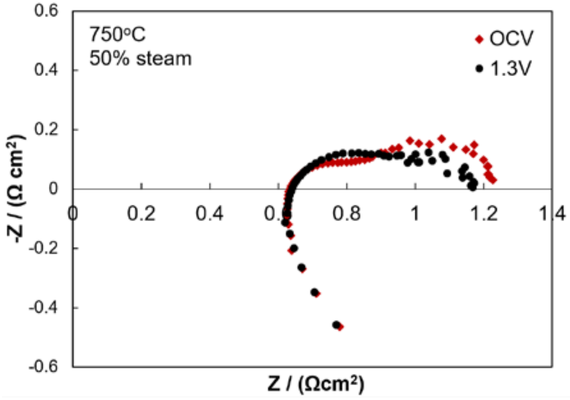




Technical Accomplishments: Evaluate Effect of Realistic Interconnect, Coatings, and Contacts on Cell Performance and Degradation Rate







- Validated seal quality
- Validated ability to produce and deliver 50-90% steam

- Separated ohmic and electrodic losses
- High ohmic losses attributed to poorer contacts compared to button cells

High Temperature Electrolysis (HTE)

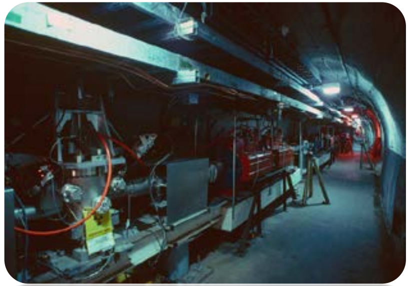
Task 7: Advanced Characterization
(more content in AMR Poster P196e and p196f)

Characterization

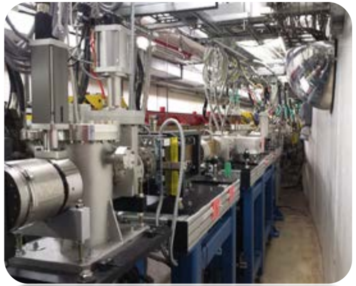
- ***Established multi-faceted characterization approach*** across multiple length scales (nm to micron) to elucidate failure mechanisms enabling next generation cell development.
  - Characterized cells aged for varying lengths of time and under varying conditions to ***discover trends in degradation*** and evaluate accelerated testing protocols to ensure kinetics, and not thermodynamics, of cell aging are altered.
  - ***Integrated characterization*** efforts with ***modeling*** efforts to understand the impact of observed cell degradation on performance.

PNNL Scanning Electron Microscope

NREL, PNNL, INL Advanced CT



Stanford Linear Particle Accelerator



ANL Advanced Photon Source

Characterization of oxygen electrode and barrier layer – Potential Impact

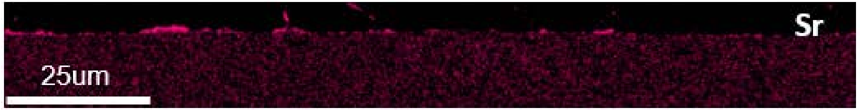
Highly integrated synchrotron XRD and electron microscopy approach.

STEM/EDX	Synchrotron XRD
Identifies frequently occurring cation correlations and locations at 1 nm-scale resolution. *XRD results inform TEM what phases are present	Identifies & quantifies all phases present at 1-μm resolution within minutes. *EDX results critical to differentiating between candidate phases w/ identical scattering patterns
Local phase concentrations	Bulk phase concentrations
Cation location within nm-resolution and migration pathways	Phase location with μm-resolution
Sub-nm resolution technique requiring significant sample prep	No sample prep/high throughput/μm-scale technique valuable for statistically relevant results & down selecting cells for further analysis

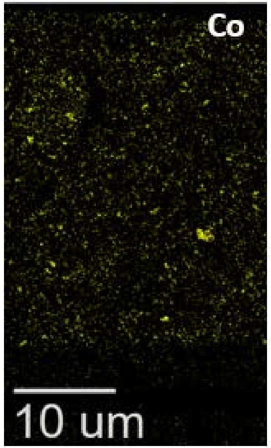
Results are integrated directly into the modeling effort.

Technical Accomplishments: Performed SEM/EDS Post-Test Cell Charterization to Elucidate Degradation Mechanisms

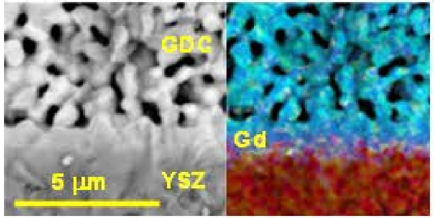
Oxygen Electrode Characterization



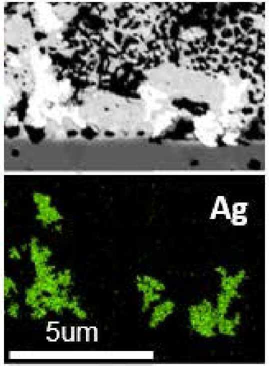
Sr surface segregation



Spinel formation increases during testing

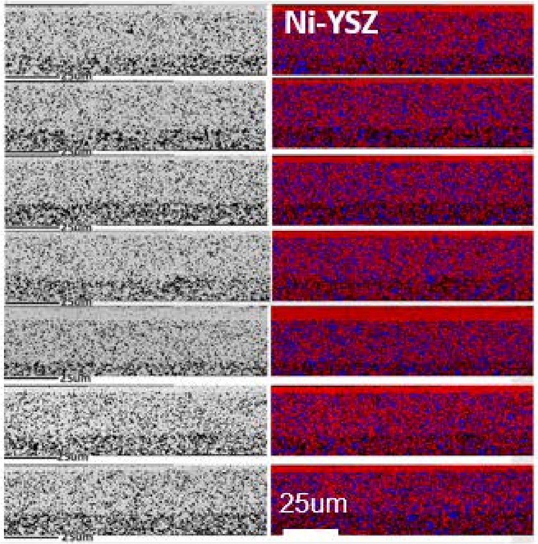


Dopant in barrier layer migrates into YSZ



Ag migration into barrier layer and YSZ

Elemental maps of Hydrogen Electrode



- No obvious Ni migration
- Ni coarsening and Ni – YSZ particle detachment observed in 90-100% steam at 750°C

Accomplishments and progress: Characterization of oxygen electrode and barrier layer

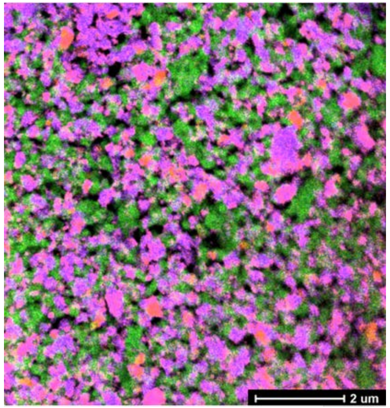
STEM-EDS – Pre Ni Reduction and Testing

- EDS of the oxygen electrode layer reveals initial cation exsolution (predominantly Sr) at the interface and in the barrier layer
- Formation of $CoFeO_x$, SrO, and other phases occur before testing

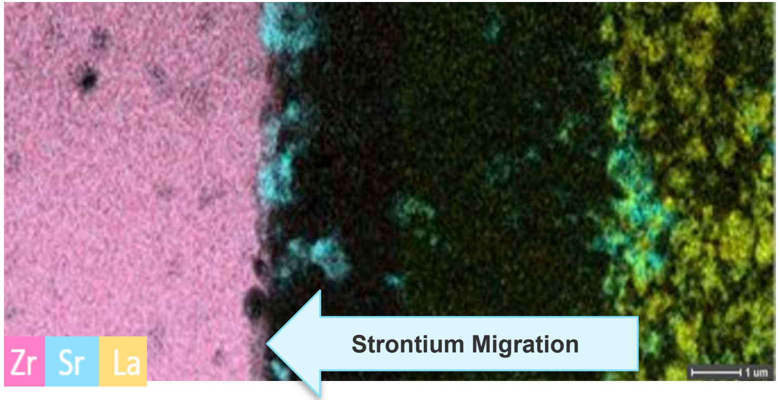
STEM-EDS – Tested for 1k hrs

- Sr migration through the GDC and accumulation at the YSZ interface occurs
- Increase in $CoFeO_x$ spinel concentration
- GDC breakdown resulation into $CeCoFeO_x$ spinelting in Gd accumulation at the YSZ interface

The oxygen electrode has undesired phases present prior to any ageing; cation migration and degradation increase in severity with cell ageing



EDS map of Co, Fe, and Ce in the oxygen electrode where $CoFeO_x$ spinel appears pink



Zr, Sr, and La EDS map of the electrolyte, barrier layer, and oxygen electrode illustrating the migration of Sr

Accomplishments and progress: Characterization of oxygen electrode and barrier layer

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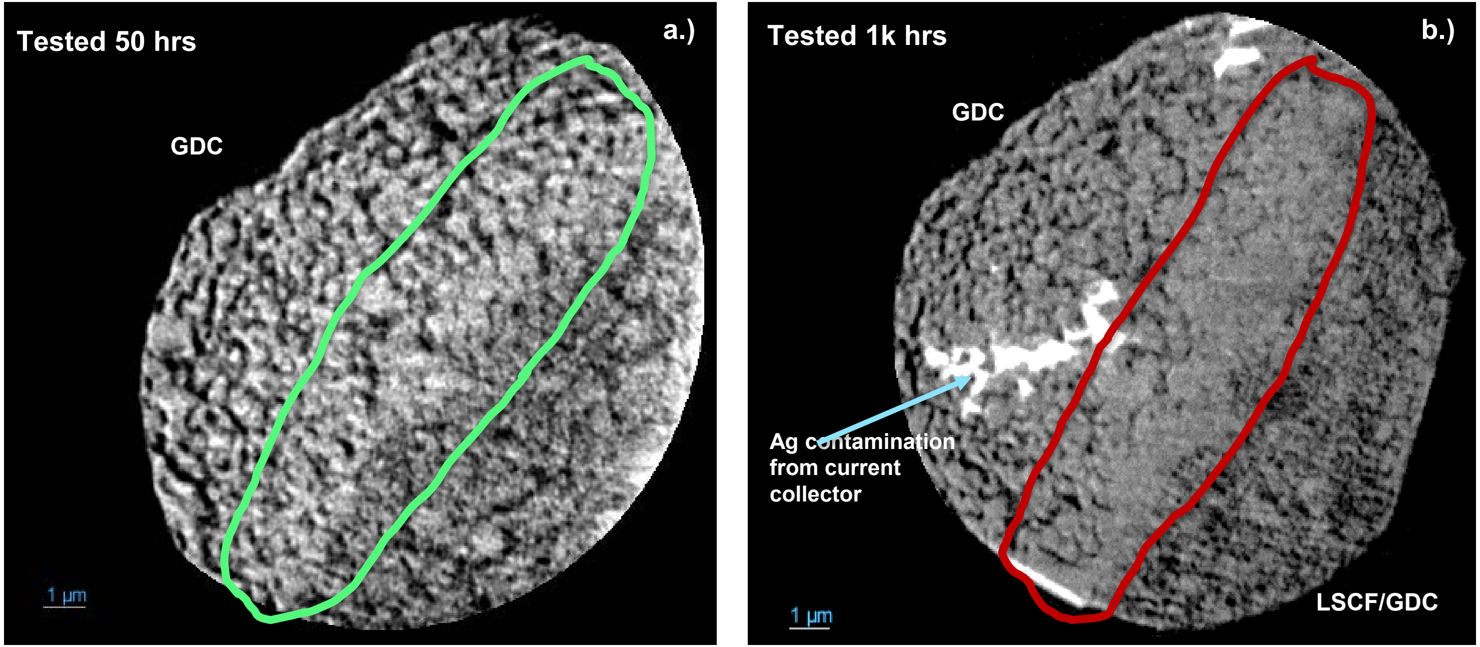


2D Nano-CT projections capturing the oxygen electrode and barrier layer interface in cells tested for a.) 50 and b.) 1k hours

Nano-CT images reveal interface densification occurring after extended cell operation, which may result in performance loss due to restricted mass and ionic transport

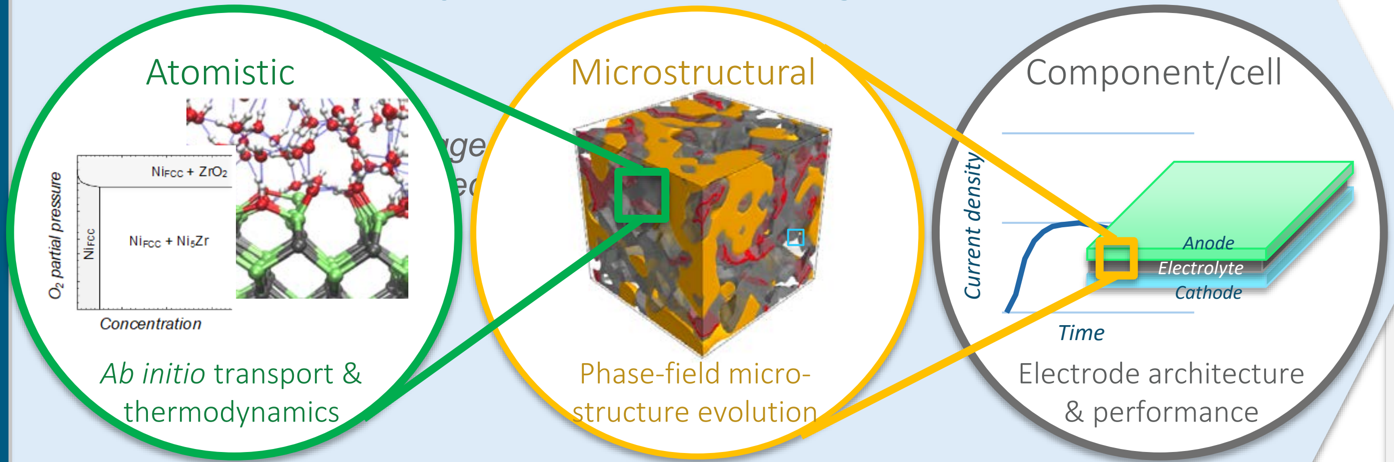
High Temperature Electrolysis (HTE)

Task 8: Multiscale Modeling
(more content in AMR Poster P196g)

Multi-Scale Degradation Modeling- Approach

“Bottom-up”

Multiscale physics-based modeling of mechanisms



Models are linked across scales, correlated to testing data, and accelerated with ML/AI

Relevant degradation modes

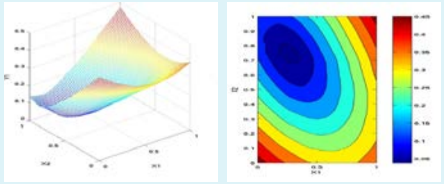
Materials/ components/ cells

Operating conditions

“Top-down”

Performance analysis

test matrix → correlations → inferences



Accomplishment: Computationally assessed impact of Ni/YSZ ratio, operating conditions, and microstructure on Ni redistribution

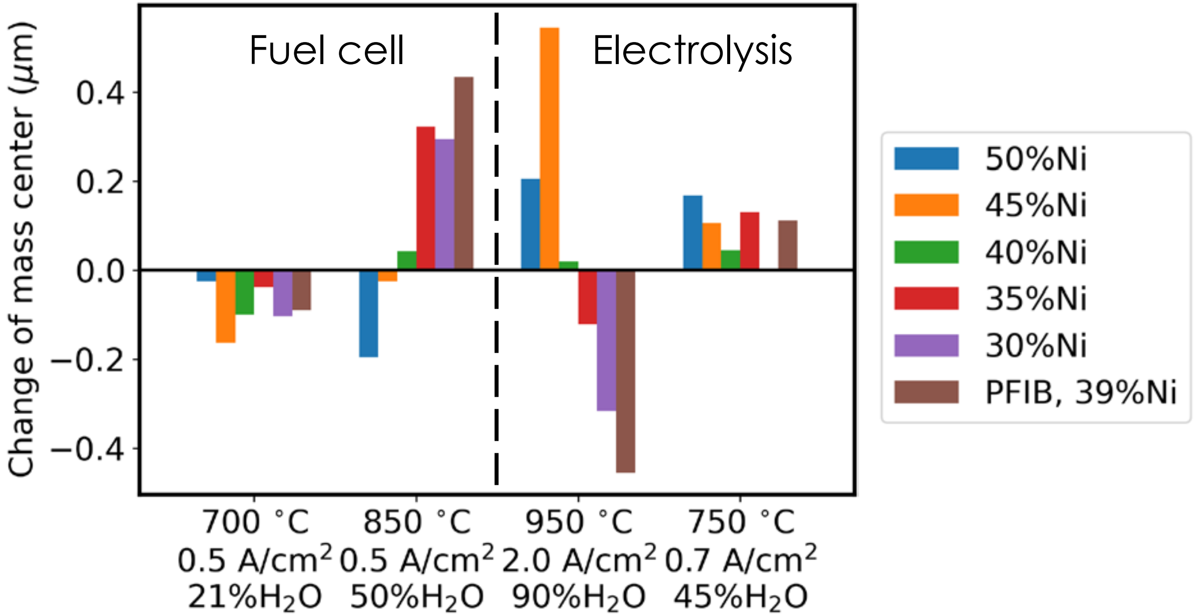
*Models suggest that not just **operating conditions**, but also **microstructural features** and **Ni loading** can impact the direction and magnitude of Ni redistribution*

Synthetic

Ni	YSZ	Pore
49.6%	30.0%	20.3%
44.5%	35.3%	20.2%
39.9%	40.0%	20.1%
34.5%	45.8%	19.7%
30.0%	50.1%	19.9%

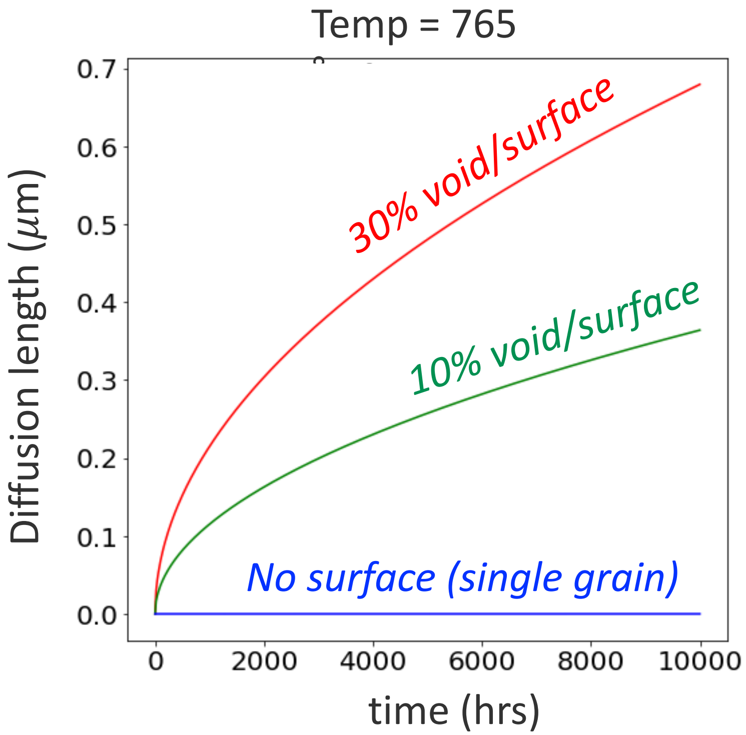
PFIB Reconstructed

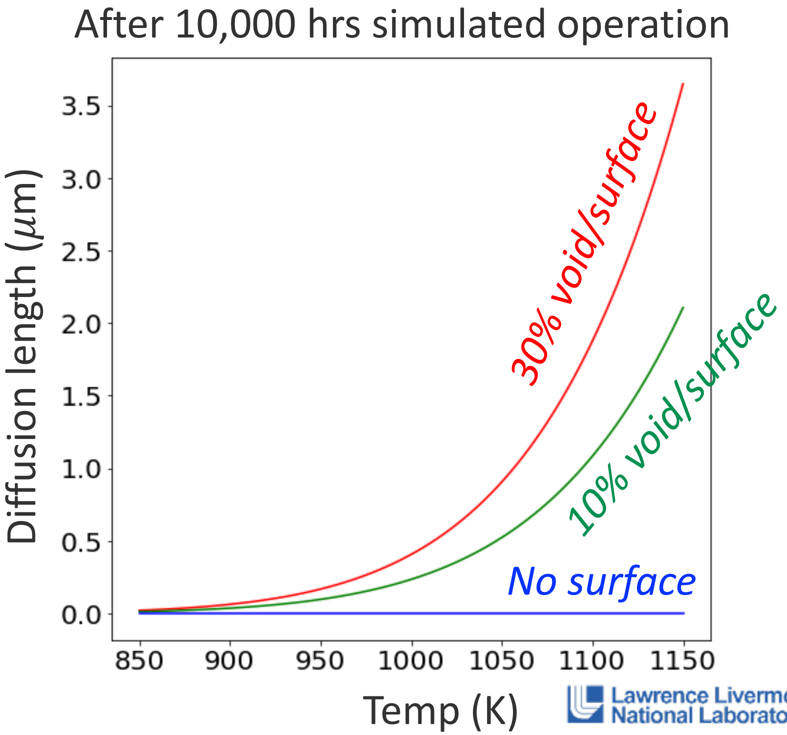
Ni	YSZ	Pore
39.4%	43.2%	17.4%



Accomplishment: Demonstrated multiscale framework for predicting Sr penetration into packed GDC as a possible failure mode

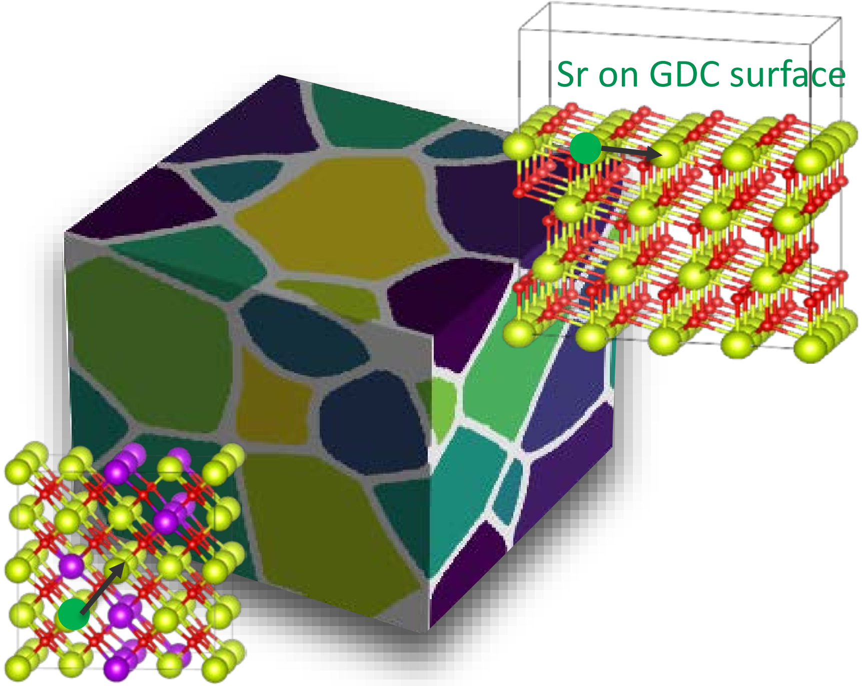
Porosity and loose particle packing create surface-dominated diffusion pathway for Sr and other cation impurities, with full permeation of GDC interlayer predicted as possible under operation

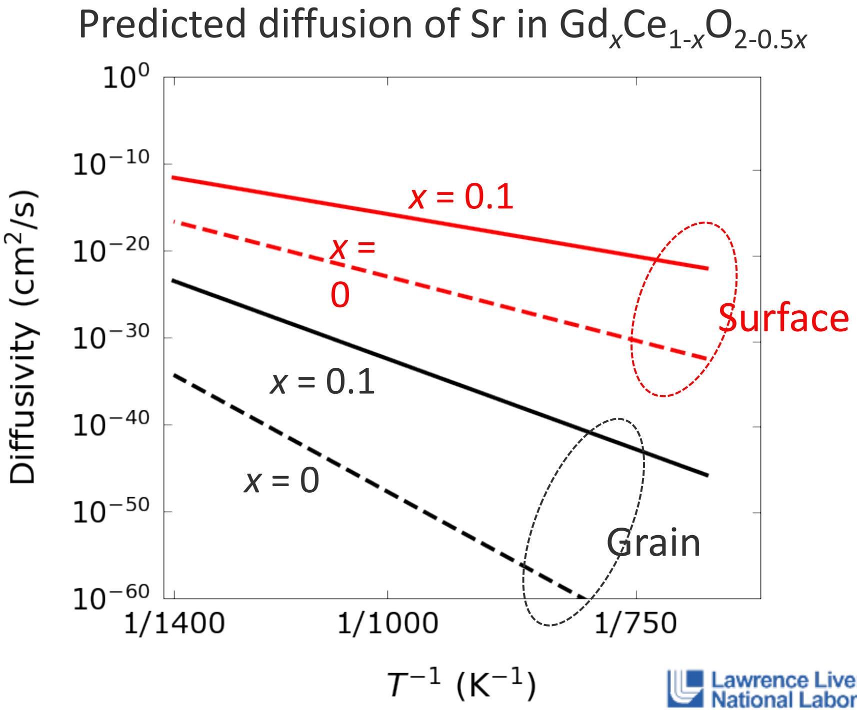




Accomplishment: Parameterization of models for cation impurity diffusion through GDC interlayer

Ab initio calculations parameterize multiscale model and show that Sr diffusion is enhanced by local O vacancy concentration and presence of surfaces





Responses to Previous Year Reviewers' Comments (Project wasn't reviewed in FY 22, but FY 21 comments below)

- Reviewer Comment: The project is performed solely by national laboratories, so industry participation is largely missing.
- Response: We have done what we can to incorporate this through our Advisory Board and other engagement with industrial partners, but this is in the process of changing with release of HFTO FOA 2922.

- Reviewer Comment: Alkaline electrolysis is not addressed in the project, yet there have been substantial technology advances in recent years, and it is likely to capture a large market share in 2030 and beyond.
- Response: As can be seen in this presentation, Alkaline is now part of H2NEW and discussed in detail.

- Reviewer Comment: There is no mention of other emerging technologies, such as HTE proton-conducting technology or LTE anion exchange membrane technology.
- Response: This was by design and is beyond the scope of H2NEW for now and is covered in HydroGEN (2.0).

- Reviewer Comment: The project is focused on standard technologies and material sets. It would be great to see some investigation into promising alternatives that have the potential to leapfrog over the existing state of the art.
- Response: This is also changing as HFTO FOA 2922 addresses this area and there is also a Lab Call out supporting novel materials development that will feed into H2NEW activities.

Remaining Challenges/Proposed Future Work (LTE) (Refer to P149a,b,c,d & h for more detail at Task Level)

Task 1 (Durability): Aging Studies; Mitigation Strategies; Ex-situ Characterization of MEAs/components/interfaces; Ex-situ Catalyst Durability; Ex-situ Membrane Durability; Accelerated Stress Test Development

Task 2 (Performance): Performance benchmarking, baselining, validation; Cell performance testing in support of electrode development; Ex-situ studies focused on performance factors; Cell level model development

Task 3 (Scale-up): MEA fabrication, Interface engineering (inks, electrodes, cell integration and interfaces); Components (porous transport layers, recombination layers)

Task 3c (Analysis): Performance, manufacturing, and system models; Durability factors; Energy system integration

Task 9 (Alkaline): Fundamental degradation mechanisms, AST development, Benchmarking, Baselines, Modeling, Scale-up

Any proposed future work is subject to change based on funding levels

Remaining Challenges and Barriers (HTE)

(Refer to P196e,f & g for more detail at Task Level)

Task 5: Durability Testing and AST Development

i. SOEC materials and component degradation mechanisms are the result of multiple, coupled phenomena derived from operating conditions and a comprehensive and accurate understanding of the interplay of these phenomena remains to be established
ii. Larger planar cell test stand capacity is needed to fully understand cell degradation phenomena

Task 6: Task Integration and Protocol Validation

i. H2NEW is generating large volumes of data that require review, validation, and interpretation

Task 7: Advanced Characterization

i. In-operando testing is needed to reduce the number of test samples and to expedite AST outcomes

Task 8: Multiscale Modeling

i. Defining and modeling the mechanisms requires the combined talents, experience and capabilities of each of the Lab Consortium
ii. Degradation processes at the YSZ|GDC|LSCF-SDC interface are probably coupled in a non-linear fashion

Any proposed future work is subject to change based on funding levels

Collaboration and Coordination

NREL Team Members: Shaun Alia, Carlos Baez-Cotto, Guido Bender, Sarah Blair, Ai-Lin Chan, Sunil Khandavalli, Chang Liu, Scott Mauger, Samantha Medina, Elliot Padgett, Makenzie Parimuha, Chance Parrish, Jason Pfeilsticker, Bryan Pivovar, Robin Rice, Meital Shviro, Abi Schmeiser, Michael Ulsh, Sam Ware, Jacob Wrubel, James Young, Jason Zack , David Ginley, Sarah Shulda

INL Team Members: Richard Boardman, Dong Ding, Micah Casteel, Lucun Wang, Wie Wu, Jeremy Hartwigsen, Josh Gomez, Daniel Wendt, Fred Steward, Nick Kane

LBNL Team Members: Grace Anderson, Claire Arthurs, Ashley Bird, Ethan Crumlin, Arthur Dizon, Elizabeth Greenberg, Rebecca Hamlyn, Ahmet Kusoglu, Grace Lau, Jason Keonhag Lee, Jiangjin Liu, Rangachary Mukundan, Xiong Peng, Michael Tucker, Adam Weber

PNNL Team Members: Olga Marina, Jamie Holladay, Chris Coyle, Kerry Meinhardt, Dan Edwards, Matt Olszta, Nathan Canfield, Lorraine Seymour, Nathanael Royer, Jie Bao, Brian Koeppel

ANL Team Members: Rajesh Ahluwalia, C. Firat Cetinbas, Luke Johnson, Nancy N. Kariuki, Samuel J. Kazmouz, A. Jeremy Kropf, Debbie Myers, Dennis Papadias, Jae Hyung Park, Jui-Kun (Michael) Peng, Xiaohua Wang, Di-Jia Liu

ORNL Team Members: David Arregui-Mena, Jefferey Baxter, Dave Cullen, Neus Domingo, Xiang Lyu, Harry Meyer, Shawn Reeves, Alexey Serov, Hanyu Wang, Haoran Yu, Michael Zachman

LANL Team Members: Tanvir Arman, Sergio Diaz-Abad, Kaustubh Khedekar, Siddharth Komini Babu, Kui Li, Jacob Spendelow, Mahlon Wilson, Abdurrahman Yilmaz

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ASTWG Collaborators: Kathy Ayers (Nel Hydrogen), Nemanja Danilovic (Electric Hydrogen), Corky Mittelsteadt (Plug Power), Andrew Park (Chemours), Udit Shrivastava (Cummins), Andrew Smeltz (De Nora)

Other Partnerships and Collaborations: MIT, B. Khaykovich; FZ Jülich, Germany; Fraunhofer ISE, Freiburg, Germany; Paul Scherrer Institute, Aargau, Switzerland, IEA Annex 30 Working Group; Gen-IV International Forum for Hydrogen Production (Canada, France, Japan, England, United States)

Summary

H2NEW
U.S. DEPARTMENT OF ENERGY

- Significant science advances within H2NEW since inception
  - Establishment of capabilities (staff/facilities)
  - Execution of R&D scope
- Significant expansion in 2023 tied to Bipartisan Infrastructure Law (BIL) funding
  - Expansion of PEM and O-SOEC scope
  - Addition of LAWE as a R&D area
- HFTO FOA 2922 and Lab Call DE-LC-0000022 to leverage H2NEW assets and expand scope of efforts to date – novel materials development and supply chain considerations in particular.

Technical Backup and Additional Information Slides

Technology Transfer Activities

- All H2NEW laboratories are actively engaged with industry both within and outside of the consortium partners and seek to provide H2NEW developed technology and knowledge to help the electrolysis community
  - Including CRADAs, SPPs, TSAs, etc.
- Engagement through Stakeholder Advisory Boards seek to determine areas of most benefit and highest commercial interest
- H2IQ webinar highlighting H2NEW capabilities presented Jan 26, 2023
  - https://www.energy.gov/eere/fuelcells/january-h2iq-hour-h2new-consortium-overview-electrolyzer-development-capabilities-0
- H2NEW website
  - https://h2new.energy.gov/
- Preparing for HFTO FOA 2922 support of FOA awardees

Presentations (LTE)

International Conference on Electrolysis (ICE) 2021, Golden, Colorado, USA, June 19-22, 2022:

- J. Foster, "X-ray photoelectron spectroscopy characterization of polymer electrolyte membrane fuel cell and water electrolyzers, poster presentation, student poster award.
- S. Khandavalli, M. Ulsh, S. Mauger, "Tuning the Rheology of Anode Inks with Aging for Low-Temperature Polymer Electrolyte Membrane Water Electrolysers".
- E. Padgett, G. Bender, A. Haug, K. Lewinski, F. Sun, H. Yu, D. Cullen, A. Steinbach, S. Alia, "Catalyst Layer Resistance, Utilization, and Degradation in PEM Electrolysis".
- D. Myers, N. Kariuki, X. Wang, A. Star, and R. Ahluwalia, "Understanding the Potential Dependence of Ir Dissolution from IrO2 PEM Electrolyzer Anode Catalysts Through Modeling of Time-Resolved Measurements".
- J.K. Lee, A.W. Tricker, X. Peng, N. Danilovic, A.Z. Weber, "Porous-transport-layer interface design for PEM electrolyzers via laser ablation" (poster)
- J. Foster, S.F. Zaccarine, C. Baez-Cotto, S. Kim, M.J. Dzara, M. Batool, M. Shepherd, X. Lyu, A. Serov, J. Jankovic, S. Mauger, M. Ulsh, S. Pylypenko, "X-ray photoelectron spectroscopy characterization of polymer electrolyte membrane fuel cell and water electrolyzers"
- A. Serov, "Design of Catalyst Layers for Fuel Cell and Electrolyzer Application"
- S. A. Mauger, S. Lee, E. Padgett, S. Khandavalli, G. Stelmacovich, T. Schuler, S. M. Alia, S. Pylypenko, and M. Ulsh, "Fabrication, Performance, and Durability of Roll-to-Roll Coated Iridium-Based Anodes"

Presentations (LTE)

- D. Myers, B. Pivovar, R. Boardman, “H2NEW: Hydrogen (H2) from Next-generation Electrolyzers of Water Overview”, 23rd International Conference on Solid State Ionics, Boston, MA, July 18, 2022. (Invited)
- D. J. Myers, E. E. Alp, J. H. Park, A. J. Kropf, E. Wegener, J. Wright, R. Ahluwalia, X. Wang, and N. Kariuki, “Activity, Degradation and Integration of Oxygen Reduction and Evolution Electrocatalysts in Polymer Electrolyte Fuel Cells and Water Electrolyzers”, 23rd International Conference on Solid State Ionics, Boston, MA, July 18, 2022. (Invited)
- X. Peng, “Pathways to Terawatt Scale Electrolysis—— Importance of Interfaces and Underexplored Opportunities”, Fuel Cell Gordon Research Conference, Providence, RI, July 27, 2022.
- X. Peng, “The Cutting-edge in Clean Electrolysis for Green Hydrogen Production”, Invited talk, U.S. Frontiers of Engineering Symposium, Seattle, WA, Sept. 22, 2022.

242nd Electrochemical Society (ECS) Meeting, Atlanta, USA, Oct. 9-13, 2022:

- R. Mukundan, S. Komini Babu, D.J. Myers, D.A. Cullen, S.M. Alia, and R.L. Borup, “Comparing and Contrasting Fuel Cell and Electrolyzer Characterization Techniques”.
- S. Komini Babu, R. Mukundan, J.M. LaManna, A. Yilmaz, J.S. Spendelow, F. Suarez, S. Lee, T. Schuler, D. Kulkarni, J. Stansberry, D. Jacobson, D. Hussey, S.A. Mauger, G. Bender, I.V. Zenyuk, and B. Khaykovich, ”Characterizing Effect of Porous Transport Layers on Electrolyzer Performance Using Neutron Imaging”.
- S. Khandavalli, J. Park, R. Rice, G. Bender, D. J. Myers, M. Ulsh, and S. A. Mauger, “Tuning the Rheology of Anode Inks with Aging for Low-Temperature Polymer Electrolyte Membrane Water Electrolyzers”.
- S. A. Mauger, S. Lee, E. Padgett, S. Khandavalli, G. Stelmacovich, T. Schuler, S. M. Alia, S. Pylypenko, and M. Ulsh, “Fabrication, Performance, and Durability of Roll-to-Roll Coated Iridium-Based Anodes”.

Presentations (LTE)

242nd Electrochemical Society (ECS) Meeting, Atlanta, USA, Oct. 9-13, 2022:

- J.K. Lee, A.W. Tricker, X. Peng, N. Danilovic, A.Z. Weber, ”Advanced Porous-Transport-Layer Interface Design for PEM Electrolyzers”.
- J. Park, N.N. Kariuki, and D. Myers, “In-Situ X-Ray Scattering Study of Iridium Oxide Catalyst for Polymer Electrolyte Membrane Water Electrolyzer during Ink Sonication and Drying Process”.
- C. Liu, J. Wrubel, E. Padgett, G. Bender, ”The impacts of membrane pinholes on PEM water electrolysis”.
- S. Alia, K.S. Reeves, H. Yu, A.J. Kropf, N.N. Kariuki, J. Park, D.J. Myers, D.A. Cullen, “Anode Catalyst Durability and Accelerated Stress Tests in Proton Exchange Membrane-Based Low Temperature Electrolysis”.

Presentations (LTE)

- G. Stelmacovich, M. Walker, J. Foster, J. Cullen, A. Paxton, G. Bender, T. Schuler, S. Ware, S. Pylypenko, “Time of Flight Secondary Ion Mass Spectrometry (ToF-SIMS) as a Novel Approach to the Characterization of Coatings and Interfaces of Porous Transport Layers”, AVS 68th International Symposium & Exhibition, Pittsburgh, PA, November, 2022.
- S. Pylypenko, “Analysis of Surfaces and Interfaces in Polymer Electrolyte Membrane Fuel Cell and Electrolyzer Devices”, AVS 68th International Symposium & Exhibition, Pittsburgh, PA, November, 2022. (Invited)
- S. Pylypenko, “Characterization of surfaces and interfaces in polymer electrolyte membrane electrolyzers”, PacSurf 2022, Waikoloa Beach, Hawaii, December, 2022.
- S. Khandavalli, “Effect of dispersion media composition on the rheology of the short-sidechain perfluorosulfonic acid ionomer dispersions”, 93rd Society of Rheology Meeting, Chicago, IL, Oct., 2022.
- A. Serov “Catalyst Layers: From Materials to Roll-to-Roll Manufacturing”, Fuel Cell Seminar, Long Beach, CA, February, 2023.
- S. Pylypenko, “Catalyst/Ionomer Interactions: What We Learned from XPS Analysis”, Telluride Science Research Center (TSRC) Workshop 4 Platinum Group Metal and Platinum Group Metal-free Electrocatalysts: Catalyst/Ionomer Interactions, Telluride, CO, March, 2023.
- J. Brauch, A. Badgett, A. Thatte, R. Rubin, A. Star, X. Wang, and R. Ahluwalia, “Bottom-up PEM Electrolyzer Cost Modeling based on Manufacturing and Assembly Processes”, 2023 Hydrogen and Fuel Cell Seminar, Long Beach, CA.
- A. Badgett, “System Designs and Operational Strategies for Low-cost Hydrogen Production from Electrolyzers Operating in Wholesale Power Markets or Directly Coupled with Wind and Solar”, 2023 Hydrogen and Fuel Cell Seminar, Long Beach, CA.

Publications (LTE)

- S.M. Alia, K.S. Reeves, H. Yu, J. Park, N. Kariuki, A.J. Kropf, D.J. Myers, D.A. Cullen, "Electrolyzer Performance Loss from Accelerated Stress Tests and Corresponding Changes to Catalyst Layers and Interfaces," J. Electrochem. Soc., 169 (5) (2022) 054517.
- "Multi-Scale Multi-Technique Characterization Approach for Analysis of PEM Electrolyzer Catalyst Layer Degradation", S.F. Zaccarine, M. Shviro, J.N. Weker, J. Nelson, M.J. Dzara, J. Foster, M. Carmo, S. Pylypenko, J. Electrochem. Soc., 169 (2022) 064502.
- A. Badgett, M. Ruth, B. Pivovar, Chapter 10 - Economic Considerations for Hydrogen Production With a Focus on Polymer Electrolyte Membrane Electrolysis, *Electrochemical Power Sources: Fundamentals, Systems, and Applications* (2022).
- J.K. Lee, T. Schuler, G. Bender, M. Sabharwal, X. Peng, A.Z. Weber, N. Danilovic, "Interfacial Engineering via Laser Ablation for High-Performing PEM Water Electrolysis", Applied Energy, 336 (2023) 120853.
- J.K. Lee, G. Y. Lau, M. Sabharwal, A.Z. Weber, X. Peng, and M.C. Tucker, "Titanium porous-transport layers for PEM water electrolysis prepared by tape casting", J. Power Sources, 559 (2023) 232606.

Presentations (HTE)

- L. Le, C. Coyle, L. Seymour, J. Zaengle, J. Escobar, T. Liu, J. Bao, K. Meinhardt, O. A. Marina, *Ni-YSZ Electrode Stability in Solid Oxide Electrolysis Cells Operated in 90-98% Steam*, Presented at the 243 ECS meeting with SOFC-18, Boston, MA, May 30, 2023.
- D. Wang, J. Bao, B. Koeppel, K. D. Meinhardt, O. A. Marina, *Long-Term Degradation Models for the Solid Oxide Electrolysis Cell,* Presented at the 243 ECS meeting with SOFC-18, Boston, MA, May 30, 2023.
- T. Liu, D. J. Edwards, L. Le, C. Coyle, L. Seymour, M. Olszta, K. D. Meinhardt, O. A. Marina, *Phase Evolution in* $(La_{0.6}Sr_{0.4})_{0.95}Co_{0.2}Fe_{0.8}O_{3-\Delta}$ *Oxygen Electrodes after SOEC Operation*, Presented at the 243 ECS meeting with SOFC-18, Boston, MA, May 28, 2023.
- O.A. Marina, *High Temperature Electrolyzers for Hydrogen and Chemicals Production*, Lecture, *The 4th Hydrogen Economy Program* organized by University of Houston in collaboration with the American Institute of Chemical Engineers (AIChE), March 8, 2023
- O.A. Marina, *Perspectives of Hydrogen Production Using SOECs,* Invited Speaker at Colorado School of Mines, Mechanical Engineering Distinguished Seminar Series, October 28, 2022.
- O.A. Marina, *Hydrogen and Syngas Production Using High Temperature Electrolyzers,* APEP UCI Seminar on H2 production, Irvine, CA, August 8, 2022.
- O.A. Marina, *High Temperature Electrolyzers for Hydrogen and Chemicals Production*, *The 4th Hydrogen Economy Program* organized by University of Houston in collaboration with the American Institute of Chemical Engineers (AIChE), September 7, 2022
- O.A. Marina, L.Q. Le, C.A. Coyle, L.M. Seymour, K.D. Meinhardt, D.J. Edwards, and J. Bao, et al. *Effect of Operating Conditions on Durability of Solid Oxide Electrolysis Cells,* Presented at the 15th EFCE, Lucerne, Switzerland, Switzerland, July 4-8, 2022.
- J. Bao, N.K. Karri, B.J. Koeppel, O.A. Marina, *Solid Oxide Electrolysis Cell Reliability Analysis Using Modeling,* Presented at the 15th EFCE, Lucerne, Switzerland, Switzerland, July 4-8, 2022.
- M.C. Tucker, M.M. Welander, and F. Shen, "Metal-Supported Solid Oxide Electrolysis Cells", 3rd International Conference on Electrolysis, Golden, Colorado.
- O.A. Marina, K.D. Meinhardt, D.J. Edwards, and J. Bao, *Perspectives of Hydrogen and Syngas Production Using High Temperature Electrolyzers,* Presented at 23rd International Conference on Solid State Ionics (keynote invited), Boston, MA, July 17-21, 2022, Boston, MA.
- O.A. Marina, K.D. Meinhardt, C.A. Coyle, L.Q. Le, N. Royer, L.M. Seymour, and J.T. Zaengle, et al. 06/21/2022. *Understanding Performance and Durability of Solid Oxide Electrolyzers,* Presented at the 3rd International Conference on Electrolysis, Golden, Colorado.

Publications (HTE)

- J. Bao, N. Karri, K. Recknagle, C. Wang, B. Koeppel, O. A. Marina, *Modeling framework to analyze performance and structural reliability of solid oxide electrolysis cells*, *J. Electrochem. Soc.* 169 (2022) 054523
- Y.S. Chou, J.S. Hardy, O.A. Marina, *Leak Test for solid oxide fuel cells/solid oxide electrolysis cells*, *Frontiers in Energy Research*, 2022. doi: 10.3389/fenrg.2022.945788
- S. B. Karki, L. Seymour, L. Le, C. Coyle, R. Springer, J. Escobar, K. Meinhardt, O. A. Marina, *Strontium Free Cu-Doped* La_2NiO_4 *Oxides as Promising Oxygen Electrodes for Solid Oxide Electrolysis Cells*, *ECS Transactions*, 2023 (submitted)
- T. Knighton, R. Boardman, Analysis of Industrial Heat Source for Hydrogen Production via HTS April 2023, INL/RPT-23-72181