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Component Failure R&D

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DOE WBS # 6.2.0.502
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DOE Hydrogen Program
2024 Annual Merit Review and Peer Evaluation Meeting

Project ID: SCS001

Project Goal

- Establish a scientific basis for risk and reliability analysis through integrated work with data collection, model development, and stakeholder engagement.
  - Deploy a Hydrogen Component Reliability Database (HyCReD) to track hydrogen specific component failure rates and failure modes
  - Develop a better understanding of leak behavior and leak size for a variety of components and failure modes
    - Quantify hydrogen releases and compare to component leak rates
  - Introduce new models and data into quantitative risk assessment (QRA) including PHM (Prognostics and Health Management) for use for hydrogen systems.
    - Utilize HyCReD for data input
    - Analyze and leverage existing hydrogen data sources for integration into QRA.

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Overview

Timeline and Budget

Project Start Date: 10/01/2018
FY23 DOE Funding: $325,000
FY24 Planned DOE Funding: $225.7k
Total DOE Funds Received to Date**: $1.85M

** Since the project started

Partners

- University of Maryland Center for Risk and Reliability
- A.V. Tchouvelev & Associates Inc. (AVT)
- Industry NDAs signed for further collaborations

Barriers

- Safety Data and Information: Limited Access and Availability
- Safety is Not Always Treated as a Continuous Process
- Insufficient Technical Data to Revise Standards

Targets

- Establish risk assessment protocol to identify failure modes and mitigate risks to enhance RCS development process.
- Conduct risk assessment and compile key data.
- Identify and evaluate failure modes to establish critical research and validation needs.

Potential Impact: Data Collection, Modelling, and Leak Detection

Holistic approach combines data, modelling, and experimental results to improve impact of each individually

➢ HyCReD & data collection (Component reliability data for failure rate analysis)

- Platform to develop a **common database for hydrogen component** failures and failure rates
- Supports activities in QRA, PHM, and reliability engineering that **improve safety and availability**
- Identify high risk components and common failure modes for **supply chain development**
- Data enables proactive risk monitoring and reliability-centered maintenance (RCM) analysis

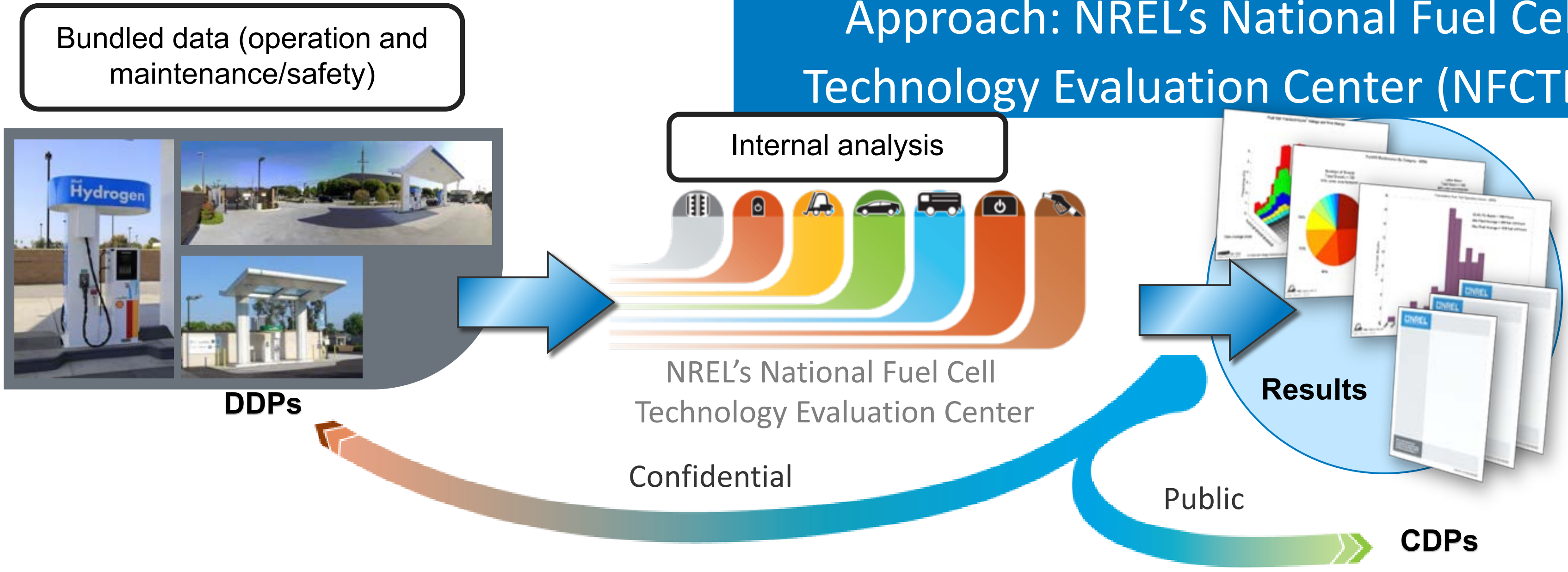
➢ Modelling of hydrogen releases and risk assessment (Mitigation of consequences)

- Data enables risk assessment and models that help **establish codes and standards**
- Enable improved selection of **risk mitigation strategies** and guidance
- Quantify impact of hydrogen detection and **sensor placement**
- Quantify **impact of ventilation** on hydrogen equipment enclosures
- Potential to reduce station footprint through **risk reduction credits**

➢ Leak detection and experimental support (Detection of releases to quantify emissions)

- **Leak rate quantification testing i**mproves understanding of component failures and failures modes
- Answer questions around **impact of unintentional hydrogen releases** from infrastructure

Approach: NREL's National Fuel Cell Technology Evaluation Center (NFCTEC)



- NFCTEC – data collection, analysis, and security
  - Drawing upon reputation and security doctrines established during 19 years of field evaluation work
  - Utilizing existing relationships and establishing new ones to enable high quality data collection
  - Developing online platform for continuous real-time data collection, hycred.nrel.gov (in development)

NFCTEC is supporting HyCReD with experience, procedures, and platform development

Approach: Hydrogen Component Reliability Database (HyCReD)

Inputs

- O&M Data
- Failed Components
- Industry Engagement
- Component Life
- Failure Modes
- System Description

HyCReD will address limitations of previous station data collection activities and expand analysis

New Approach

- ✓ New more comprehensive system taxonomy (v1 complete)
- ✓ Contextual data entry (in progress - target Summer 2024)
- ✓ Online data reporting (in progress – target Sept 2024)
- ✓ Deployment to initial industry stakeholders – imminent
- ✓ Coding guide to facilitate training (in progress - target Summer 2024)

Goals

- ❖ Robust taxonomy for cataloging maintenance and failure events to allow advanced analysis
- ❖ More continuous data collection to address quality issues
- ❖ Platform that is easy to use and secure
- ❖ Emphasize the dialog with industry

Outputs

- Hazard Classification
- Failed Component Taxonomy
- Leak Rates
- Component Reliability
- QRA
- PHM

Approach: PHM and QRA Provide a Basis for Scientifically Reducing Risk

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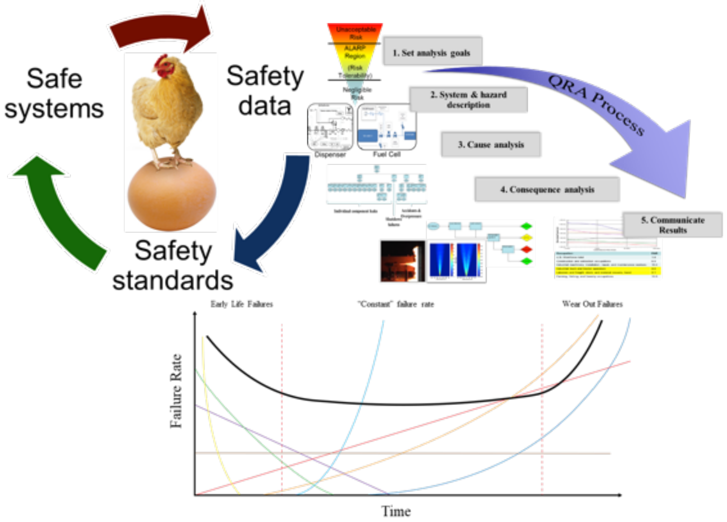
- UMD explores advanced models (QRA, PHM) to overcome lack of operational safety information and data.
  - Used to make data-driven decisions
  - Can improve safety, reduce downtime, and enable better standards
  - Needs sufficient technical data to be implemented effectively
- We are working with multiple industry, government, and academic partners to begin closing this gap in data.
- Connects to broader DOE Safety Codes and Standards (SCS) program activities to use QRA to enable changes to NFPA 2 and ISO 19880-1,
  - E.g., safety distances, alternative means and measures, and performance-based regulations codes and standards (RCS).

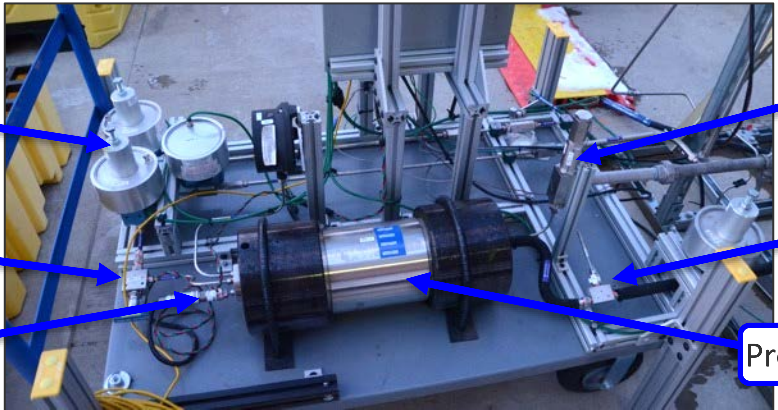


Providing a *rigorous scientific basis to* overcome lack of direct safety data by using new algorithms and multiple partially-relevant types of data

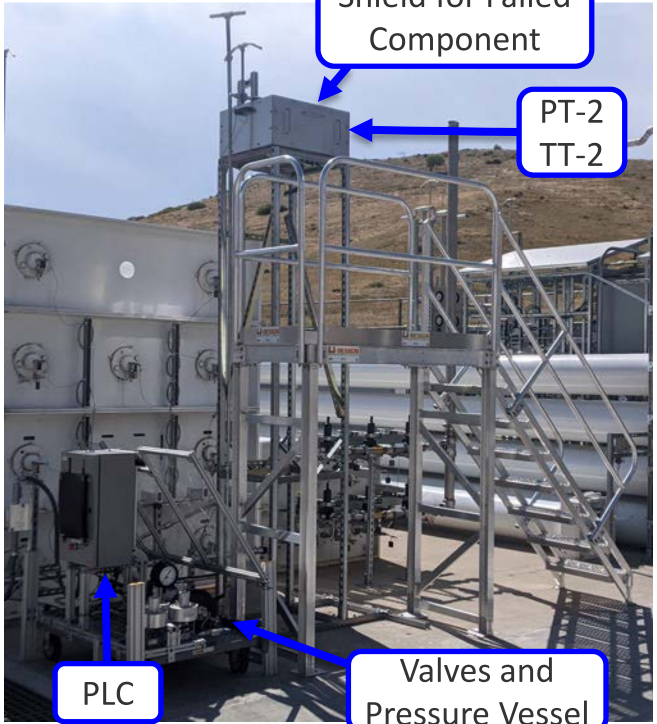
Approach: Lab Leak Rate Quantification Apparatus and Test Methodology

- Characterizing leaks from failed components to quantify flow rates to support risk reduction models
- NREL's lab LRQA will be joined by in-situ LRQA (in progress)

1. Pressurize the failed component on the Leak Rate Quantification Apparatus (LRQA) with a known volume with gas
2. Measure P&T to calculate mass at each timestep
3. Determine mass flow rate *(dm/dt)*
4. Relate *dm/dt* to an equivalent orifice diameter using standard equations (ISO 9300: *Measurement of Gas Flow by Means of Critical Flow Venturi Nozzles*)



NREL/Jake Thorson



NREL/Kevin Hartmann

Approach: Safety Planning and Culture

- Design of the Leak Rate Quantification Apparatus (LRQA) underwent an extensive safety review process prior to assembly and commissioning
  - Completed an extensive Process Hazard Analysis (PHA) with relevant NREL subject matter experts (SMEs)
    - Multiple PHA reviews were completed to support deployment in a new locations, experimentation with different gases, and to enable testing of components with larger leaks
    - NREL "Authorities Having Jurisdiction" (AHJs) for fire and pressure safety participated in the PHAs

- As part of this project the research team has been learning from and documenting component failures (e.g., HyCReD) with the goal to inform industry and improve safety and hydrogen system reliability.

- The best design, construction, and safety practices learned from a decade of experience building and operating hydrogen systems at NREL were implemented in this project.
- Training and requirements for build, operation, and maintenance of the hydrogen systems emphasize:
  - Reviewing the safety hazards of every task, every time
  - Everyone has "Stop Work" authority and the expectation to use it proactively
  - Immediate reporting of safety issues for review by SMEs and dedicated safety professionals
  - Prioritizing personnel safety above all else
- The established safety processes required per NREL's prime contract with the DOE exempted this project from Hydrogen Safety Panel review

Accomplishment: HyCReD Online Platform Development and Implementation

- **Metadata development team**
  - Taxonomy: All fields and their potential pick lists are defined for refueling stations in Groth et al. (2024) IJHE paper and the data coding guide (Draft).
  - Completing v1 data coding guide
  - Continue coding events from public/accessible data
  - Data coding by spreadsheet being distributed to industry and internally to work on streamlining process
- **Architecture development team**
  - NFCTEC data capabilities integrating a prototype system of common web services, designed at NREL, called Hybrid Environment Resources and Operations (HERO)
  - Core services include 1) authentication and authorization, 2) data repository, 3) task engine, 4) search capabilities
  - Developing v1 of JSON schema, in progress
  - Documenting work flow process requirements to accommodate data collection, analysis, results distribution

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Author(s): Olivia Robinson and Ahmad Aldouri

Coding Handbook for HyCReD Data Entry

Purpose:

This document will help maintenance and operation personnel of hydrogen fueling stations understand and execute inputting fueling station component failures including hydrogen leaks into the HyCReD database to continue the work of hydrogen fueling station component reliability. Reliability of hydrogen fueling stations needs to be understood to help hydrogen technologies be implemented and play a role in a decarbonized future.

Definitions:

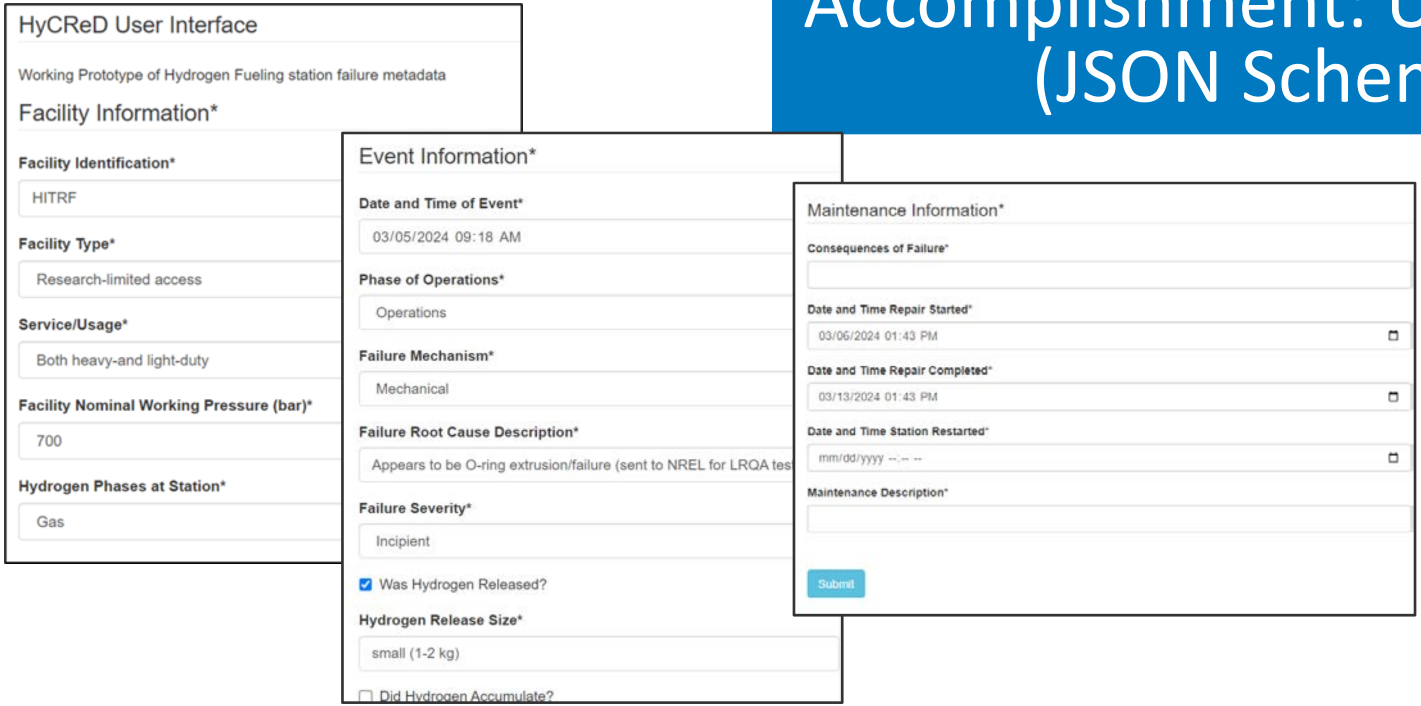
- **HyCReD:** Hydrogen Component Reliability Database.
- **HITRF:** Hydrogen Infrastructure Testing Research Facility.
- **Failure mode:** Manner or way in which a failure occurs (IEC 60050-192:2015, 192-03-17).
  - **Include list of failure modes from West (2021).**
- **Failure mechanism:** Physical processes through which damage occurs, which can be rapidly (abruptly) or slowly (cumulatively) (IEC 60050-192:2015, 192-03-17).
  - **Include table of leading failure mechanisms and their descriptions (pg.** 17-18 of Modarres and Groth (2023)).
- **Failure cause/Failure root cause:** Set of circumstances that lead to failure and can originate during specification, design, manufacture, installation, operation, or maintenance of an item (IEC 60050-192:2015, 192-03-11).
- **Failure severity:** The degree of functional degradation of hardware usually noted through deficient performance; categorized by "catastrophic," "degraded"" and "incipient" (IEEE Standard 500-1984).
  - **Catastrophic:** Failure that is both sudden and causes termination of one or more fundamental functions
  - **Degraded:** Failure that is gradual or partial; it does not cease all function but compromises that function. It may lower output below a designated point, raise output above a designated point or result in erratic output. A degraded mode might allow only

Data Coding Guide Draft (publication forthcoming)

NREL's National Fuel Cell Technology Evaluation Center

Groth, Katrina M., Ahmad Al-Douri, Madison West, Kevin Hartmann, Genevieve Saur, and William Buttner. "Design and requirements of a hydrogen component reliability database (HyCReD)." *International Journal of Hydrogen Energy* 51 (2024): 1023-1037.

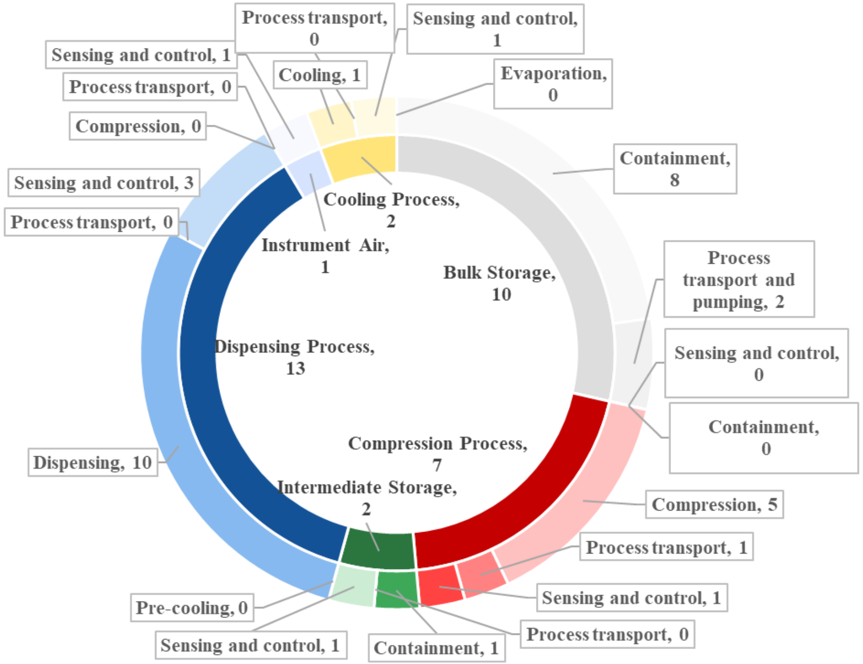
Accomplishment: User Interface (JSON Schema v1)



- Easy to use with formatted cells and dependent drop downs for indicating the failed component.
- Remember past inputs for facility information to remove duplicate work and a potential for QR codes on parts of the station to allow for quick failed component identification.

Accomplishment: HyCReD Results

Based on 35 incidents as of March 2024.



Initial data from 4 public sources

- **NREL's Hydrogen Infrastructure Testing and Research Facility (HITRF)**
  - Research station(s)
- **KHK Database (Japan)**
  - High Pressure Gas Safety Institute of Japan
  - Incidents involving high pressure gases, including hydrogen
- **HIAD**
  - European Joint Research Commission
  - Public H2 incident reporting and lessons learned
- **H2Tools Lessons Learned**
  - Pacific Northwest National Lab
  - Public H2 incident reporting and lessons learned

- Initial results identify *dispensing process* subsystem as the source of most failures in a hydrogen fueling station.
- The dispensing functional group is the leading contributor to dispensing process failures.

Accomplishments: HyCReD Virtual Technical Seminar held on March 13, 2024

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EDT (MDT)	Day 1 (Monday Dec 11, 2023)	
Start Time	**Topic**	**Presenter**
11:00 AM (9:00 AM)	Introduction	William Buttner, NREL Christine Watson, DOE/HFTO
11:05 AM	What is the hydrogen component reliability database (HyCReD)?	Genevieve Saur, NREL
11:20 AM	Analysis to support reliability and safety at hydrogen refueling stations	Katrina Groth, University of Maryland
11:35 AM	Using the database and evolution	Ahmad Al-Douri, University of Maryland Olivia Robinson, NREL
11:50 AM	Ways to collaborate; support the project, support the industry	Genevieve Saur, NREL
11:55 AM	Open Discussion: ☐ Feasibility of implementation ☐ Industry needs ☐ Feedback	All
12:15 PM	End (Presenters available for continued discussion)	

Seminar materials available at:

- https://www.youtube.com/watch?v=jA2fh4kcGbE
- https://www.nrel.gov/docs/fy24osti/89353.pdf

Questions: HyCReD@nrel.gov

Photo: Wikipedia

- By-invitation to >200 people
  - 72 registrations
  - 53 attendees
  - 18 unique organizations (9 industry, 9 research oriented)
  - 5 countries(poll of attendees, partial response)
  - Australian interest, but time zone constraint

Accomplishments: HyCReD Virtual Technical Seminar – Take-aways

NREL's National Fuel Cell Technology Evaluation Center

Key themes from discussion:

- High interest in expansion to other H2 equipment, mentioned: electrolyzers, on-board
- Emphasis on conversations with manufacturers and owner/operators, closing data loop
- Engage with regulatory committees explicitly
- Definition of S/M/L leaks
- **WHEN will it be available**

Current status and outreach:

- 2 NDAs signed, 4 in progress
- Initial vetting of taxonomy started
- Good contact list developed from invitations and response

Have you evaluated who in the field is operating systems and whether they are capable of completing a data collection form?

Any thoughts on extending this database to on-vehicle hydrogen components?

Seems to me industry needs to be aware of failures at stations and address these in component manufacturing. How is this data collection being circulated with manufacturers?

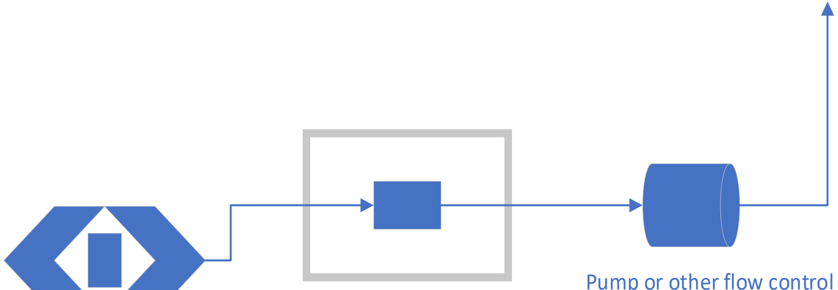
Have you engaged with fueling system designers?

Thanks for the presentation! Are you engaging with any regulatory committees for this work?

Really interesting early results, thank you.

Accomplishments: In-situ Leak Detection

Goal: Develop a portable system capable of measuring the in-situ leak rate of failed hydrogen components.
Impact: Quantify leaks from components in the field without needing to recreate operating conditions.



Accomplishments:

1) Developed design of a semi-sealed enclosure that work for a variety of valves or components that could leak.
2) Determined calculations for calibration of in-situ device and the gas flows and pressures needed to enable leak rate quantification of different size leaks.
3) Developed a test plan to validate the systems results.
4) Identified the hardware components needed. Pumps, MFC, MFM, gases, sensors/instrumentation and controls for controlled repeatable results.
5) Started building out the device and waiting for parts needed to finish build.

Moving Forward:

1) Finish building out device, and use calculations to calibrate the device to helium.
2) Make any alterations to in-situ device to be used for Hydrogen. Start using the in-situ device in laboratory on leaking parts to understand variations in orifice sizes.
3) Alter the device as necessary for field deployment testing. Test on leaking components in the field.

NREL/Jeffrey Mohr

Example of a valve that this in-situ leak rate quantification system could work with

Accomplishments and Progress:
Response to Previous Year Reviewers' Comments

- "However, the gaps seem to be lack of failure data." ;" The project could engage more with industry and other organizations (CSA Group, HSP, etc.) to support HyCReD. "; " The project's major weakness is the lack of industry involvement. "
  - *Populating the database has been a major focus of this year. We have signed 2 NDAs with companies, with 4 more in progress that potentially represent hundreds of stations. We have also supported outreach activities such at attendance at 3 DOE workshops in which component reliability was a major theme, a virtual technical seminar to provide tool introduction and solicit feedback, a new e-mail address, HyCReD@nrel.gov which will allow us to better monitor the topic.*
- "The team successfully compiled a database with existing information. To get more input, the user-facing interface should continue to be enhanced to allow the inputting operation to be more simple. Also, the tool should allow periodic uploads of large datasets from users. "
  - *The HyCReD team agrees that ease of use is a major feature that must be realized. We are working on contextualized user–interface that is envisioned to auto-populate in places and provide dependent drop-downs based on contextual information about the component to limit lists as much as possible to valid choices. We are vetting the current system taxonomy, ease of use with our research technicians and working to do that with industry stations. The vetting process will allow refinement of the system taxonomy and work processes. We expect functionality to enter individual events as well as periodic uploads of collections of events for a station.*
- The project proponents are strongly urged to explore expanding the project scope to include mobile applications (tube trailers and mobile fuelers) and onboard vehicle systems (heavy trucks, trains, ships, and aircraft) in which QRA forms an integral part of the hazard and risk assessment of the fuel cell electric vehicle system.
  - *We have not expanded to the vehicle itself, but we have begun development for expanding the taxonomy to electrolyzer systems which has also been a prominent request by industry and DOE/HFTO.*
- The project could evaluate how the Offshore and Onshore Reliability Data (OREDA) databank was structured to gather operational information.
  - *In development we have referred to a number of similar reliability data systems, including OREDA. Please see the following article for fuller discussion:*
  - *Groth, K. M., Al-Douri, A., West, M., Hartmann, K., Saur, G., and Buttner, W. Design and Requirements of a Hydrogen Component Reliability Database (HyCReD). International Journal of Hydrogen Energy, August 2023.*

Collaboration and Coordination

- University of Maryland Center For Risk and Reliability
  - Subcontract SUB-2020-10093: Development of Reliability Capabilities for Hydrogen Fueling Facilities with Onsite LH2 Storage
  - Collaboration to obtain hydrogen component failure data (e.g., HyCReD) and apply data through QRA to reduce system risk.
- A.V. Tchouvelev & Associates Inc. (AVT)
  - Subcontract SUB-2022-10421: Ventilation Study of Confined Hydrogen Releases of Failed Components (under NREL sensor lab AOP, see presentation SCS021)
  - In partnership with Université Du Québec à Trois-Rivières
  - Industry and university collaboration
  - Collaboration on risk and hazard analysis through modeling of quantified of leaks in enclosures.
- National Fuel Cell and Technology Evaluation Center (Internal NREL collaboration with the Technology Acceleration Group)
  - Working to develop at web application for hydrogen component failure tracking utilizing the robust HyCReD framework
- Industry collaboration through NDAs
  - 2 signed, 4 in progress as of March 2024
- Other Outreach (Significant component reliability aspect to hydrogen infrastructure)
  - Supported 3 DOE workshops (Medium- and Heavy-Duty Vehicle Decarbonization Action Plan Stakeholder Workshop, HFTO Hydrogen Infrastructure Strategies to Enable Deployment in High-Impact Sectors Workshop, HFTO Hydrogen Infrastructure Priorities to Enable Deployment in High-Impact Sectors Workshop
  - Working groups: IEA TCP Task 43: Subtask E: Hydrogen System Safety, DOE Zero-Emission Freight Working Group
  - Two conference presentations at International Conference on Hydrogen Safety (ICHS 2023), Quebec (Sep. 19-21, 2023)
  - Two presentations at CHS conference in May 2024
  - Multiple support activities for ASME HyRRAC Hydrogen Risk and Reliability Analysis Conference, Glendale, CA (Feb 3-5, 2025)
  - Collaborations with Australia's Hume H2 Highway Initiative, CSIRO, Kyushu University, NEDO, Japan Rubber Manufacturing Company, BAM, KHK

DEIA/Community Benefits Plans and Activities

Commitment to Diversity and Economic/Environmental Justice

- Working with NREL's Faculty-Applied Clean Energy Sciences (FACES) Program aimed at course material development for minority supporting universities
  - One professor identified whose research interests overlap - hydrogen infrastructure impacts to surrounding communities and hydrogen leakage in pipelines
- Working on hosting 2 women graduate researchers (in-person)
  - Educating next generation of researchers and engineers in hydrogen
- Support of John Hopkin's SARE program for under-privileged youth (coordinated by Olivia Robinson).
- Supporting the development of safety and monitoring plans for several pending large-scale hydrogen projects that include outreach to support hydrogen as a clean and safe fuel to community stakeholders.

FACES
Faculty-Applied Clean Energy Sciences

https://orise.orau.gov/faces/

Identification of opportunities an on-going activity

Remaining Challenges and Barriers

- Experimental – Lab LRQA
  - Challenge recreating leaks in the LRQA following removal from the system due to a failure.
  - The LRQA does not accommodate all components or leak scenarios (e.g., cold gas)

- HyCReD
  - High quality data of sufficient quantity needed for statistically significant analysis
  - Industry support for data sharing through NDAs help, but not entire challenge; express interest but lack resources to properly documents failure events (internal focus is on maintaining operation)
  - Phased roll-out of HyCReD to industry collaborators in progress, need to show solid, incremental value through new platform to increase involvement

Proposed Future Work

HyCReD

- Outreach: Kick-off meetings with NDA partners (FY24) and continued industry outreach for data (NDAs) and feedback on approach
- Platform Development: Contextual data entry and online data reporting (in progress – target Sept 2024)
- FY25
  - Continuing development of partnerships and feedback
  - Development of analysis
  - Public and private facing reporting on data from HyCReD website

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

Experimental

- LRQA – Identify failed components that can be tested
- In-situ LRQA – Build-out and validate apparatus (FY25)
- (FY25) Develop plan for what support NREL can provide to component testing facilities and testing protocol development (identified supply chain need from FY2024 outreach activities)

Modelling

- Continue ventilation study of leaks in hydrogen equipment enclosures
  - Model step change leak expansion under the transient conditions of one simulation - Represents a likely scenario in the field
  - Investigate effects of ventilation set up (e.g. impact of air intake configuration)
- Use QRA to model total system risk
  - Develop the risk scenario models and equipment failure logic models (e.g., event tree, fault tree) of QRA for the equipment inside the enclosure
    - Connect the risk scenario models with the consequences identified in the CFD HEE simulations.
  - Develop QRA models for the system to identify probability of failures, probability of undesired outcomes, and calculate total risk to the populations and facilities of interest in the NFPA 2
    - Compare that risk to similar systems and/or established risk tolerability metrics

Summary

- Project taking a holistic approach to component reliability R&D that combines:
  - Data
  - Modelling
  - Experimental
- **HyCReD** (**Hy**drogen **C**omponent **Re**liability **D**atabase)
  - Fills a gap in the hydrogen community for high quality data on hydrogen components
  - Will support QRA, PHM, and reliability engineering that improve safety and availability and inform supply chain R&D needs
- **Modelling** work continues and new results will be available
  - Focus on modelling likely scenarios in enclosures
  - Work on QRA, connecting risk models to consequence simulations
- **Experimental**
  - Continuing to identify failed components and test in Lab LRQA
  - Develop in-situ LRQA so that we can quantify leaks from components in the field without needing to recreate operating conditions, an identified challenge from Lab LRQA
  - Quantification of leaks support risk reduction modelling

Thank You

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Technical Backup and Additional Information

Technology Transfer Activities

- ROI for HyCReD was declined by NREL; a software record is being developed.

Special Recognitions and Awards

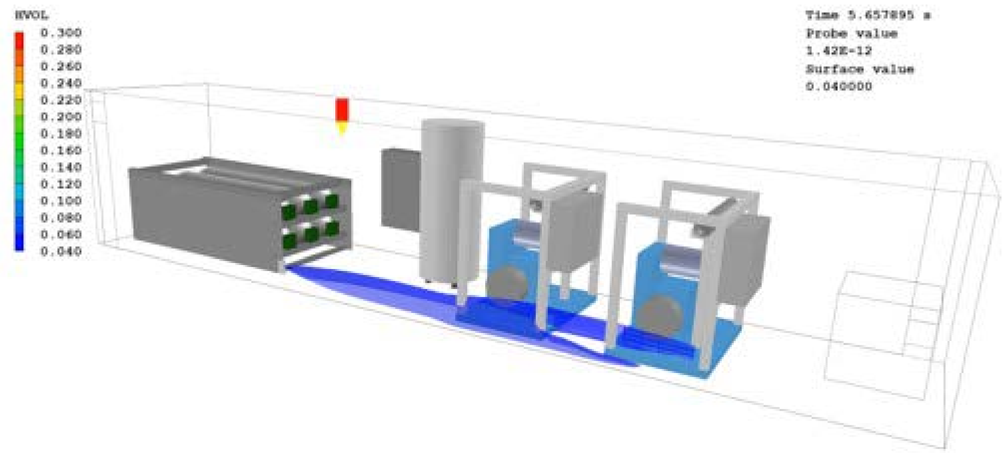
- List any special recognitions and awards this work (or the PI/team) received.

Publications and Presentations

- K. Gorth, "IEA Task 43 Subtask E: Hydrogen System Safety," *Presented at IEA Task 43 Meeting* (March 2023)
- **Book Chapter:** Groth, Katrina M. and Ahmad Al-Douri. “Hydrogen Safety, Risk, and Reliability Analysis.” *Hydrogen Economy: Supply, Chain, Life Cycle Analysis and Energy Transition for Sustainability* (February 2023).
- **Book**: M. Modarres & K.M. Groth, *What Every Engineer Should Know About Reliability and Risk Analysis, 2nd edition,* CRC Press (April 2023).
- Groth, K. M., Al-Douri, A., West, M., Hartmann, K., Saur, G., and Buttner, W. Design and Requirements of a Hydrogen Component Reliability Database (HyCReD). International Journal of Hydrogen Energy, August 2023.
- K. Groth et al, "Overview of International Activities in Hydrogen System Safety in IEA Hydrogen TCP Task 43,**"** *Proceedings of International Conference on Hydrogen Safety (ICHS 2023)*, Quebec (Sep. 19-21, 2023).
- A. Al-Douri et al, "Advancing the State of Hydrogen Systems Quantitative Risk Assessment: Design and Requirements of a Hydrogen Component Reliability Database (HyCReD)," *Presented at the 2023 AIChE Annual Meeting (Nov 2023)*
- K. Hartmann, A. Tchouvelev, B. Angers, W. Buttner, A. Al-Douri, K. Groth, “Risk Reduction Through Earlier Detection of Component Failures in Hydrogen Equipment Enclosures,” *Proceedings of International Conference on Hydrogen Safety (ICHS 2023)*, Quebec (Sep. 19-21, 2023).
- A. Al Douri, K. Groth, K. Hartmann, W. Buttner, G. Saur, “Design and Requirements of a Hydrogen Component Reliability Database (HyCReD)”, *Proceedings of International Conference on Hydrogen Safety (ICHS 2023)*, Quebec (Sep. 19-21, 2023).
- G. Saur, “Hydrogen Component Reliability Database (HyCReD)”, DOE’s Hydrogen Joint Tech Team Meeting, November 2023.
- W. Buttner, C. Watson, G. Saur, K. Groth, A. Al-Douri, O. Robinson, “Increasing Reliability and Safety of Hydrogen Components - Reliability Data Collection,” NREL-UMD Technical Seminar, Virtual (March 13, 2024)

0.358 mm Leak From Position 1, X+ direction, Passive Ventilation

- Color of the hydrogen plume is the hydrogen concentration at the detector
  - Detector location is shown by the yellow and red arrow at the top of the enclosure
- Activation of the emergency shutdown system and isolation of the hydrogen gas supply could reduce the hydrogen concentration in the HEE
  - Without mechanical ventilation the hydrogen concentrations can reach very hazardous 27% range, in the extended 18,000 second leak scenario



0.358 mm Leak From Position 1, X+ direction, 595 CFM Ventilation On

- Color of the hydrogen plume is the hydrogen concentration at the detector
  - Detector location is shown by the yellow and red arrow at the top of the enclosure
- Activation of the emergency shutdown system and isolation of the hydrogen gas supply could reduce the hydrogen concentration in the HEE
  - Even with ventilation the hydrogen concentration due to leaks from the largest expanded orifice can reach ~17% vol. at the monitor points in the extended 18,000 second leak scenario
- In the case of no mechanical ventilation the amount of flammable mass is ~50% higher than in the case with mechanical ventilation