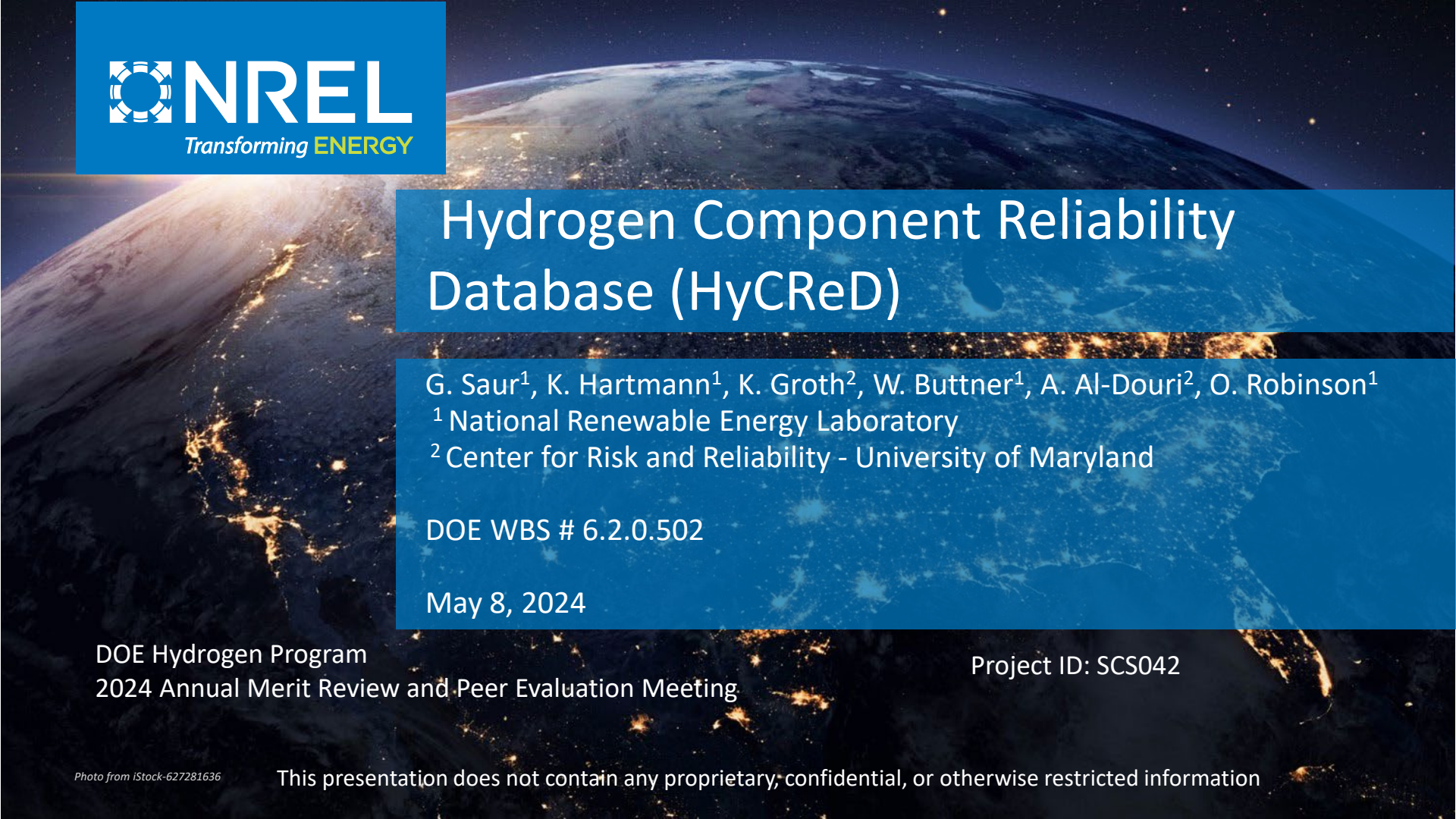

Hydrogen Component Reliability Database (HyCReD)

G. Saur[1], K. Hartmann[1], K. Groth[2], W. Buttner[1], A. Al-Douri[2], O. Robinson[1]
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[2] Center for Risk and Reliability - University of Maryland

DOE WBS # 6.2.0.502

May 8, 2024

DOE Hydrogen Program
2024 Annual Merit Review and Peer Evaluation Meeting

Project ID: SCS042

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Project Goal

The **Hy**drogen **C**omponent **Re**liability **D**atabase (HyCReD) is a collaborative project between the National Renewable Energy Laboratory, the University of Maryland, and hydrogen stakeholders to improve safety reliability for hydrogen facilities by integrating risk reduction methodologies and component reliability data taxonomies that support hydrogen infrastructure failure rate analysis.

The project aims to quantify failure rates of hydrogen components through high quality data collection and analysis. Supports:

- Quantitative risk assessment (safety codes and standards, site design)
- Prognostic health maintenance (O&M protocols and cost, station availability)
- Identify hydrogen component R&D needs (supply chain development)

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NREL's National Fuel Cell Technology Evaluation Center

Overview

Timeline and Budget

Project Start Date: 06/2023
FY23 DOE Funding: $250k
FY24 Planned DOE Funding: $0
Total DOE Funds Received to Date**: $250k

** Since the project started

Partners

- University of Maryland Center for Risk and Reliability
- Industry NDAs signed for further collaborations
- Cross-cuts with SCS001

Barriers

- Hydrogen component failure data is limited in quality and quantity

Targets

- Quantify hydrogen component failure rates and modes
- Establish risk assessments on hydrogen components for codes and standards development
- Establish prognostic health maintenance protocols for increasing infrastructure reliability
- Identify and evaluate failure modes to establish critical research and validation needs.

Potential Impact

➢ 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

➢ Enabler for:

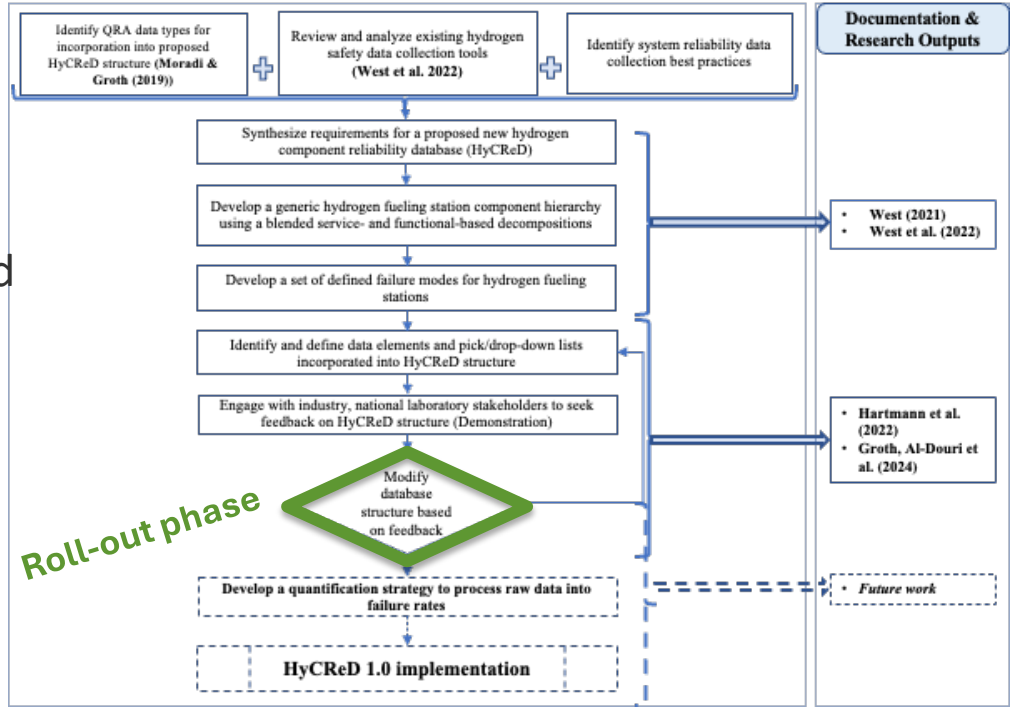
- Design and safety of projects (codes and standards development)
- Infrastructure reliability and O&M cost (component failure rates, maintenance protocols)
- Component R&D needs (robust supply chain)

Approach: Development and refinement of HyCReD

The **Hy**drogen **C**omponent **Re**liability **D**atabase is a collaborative project between NREL's Hydrogen Safety R&D team and National Fuel Cell Technology Evaluation Center (NFCTEC), University of Maryland and hydrogen stakeholders.

Addresses:

- **Design and safety of projects (codes and standards development)**
- **Infrastructure reliability and O&M cost (component failure rates, maintenance)**
- **Component R&D needs (robust supply chain)**



Please see SCS042 for more information

Hydrogen Safety R&D Team

NREL's National Fuel Cell Technology Evaluation Center

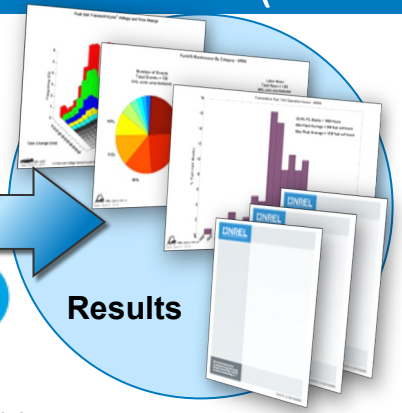
Approach: NREL's National Fuel Cell Technology Evaluation Center (NFCTEC)

Bundled data (operation and maintenance/safety)

DDPs

Internal analysis

NREL's National Fuel Cell Technology Evaluation Center



Confidential

Public

CDPs

- 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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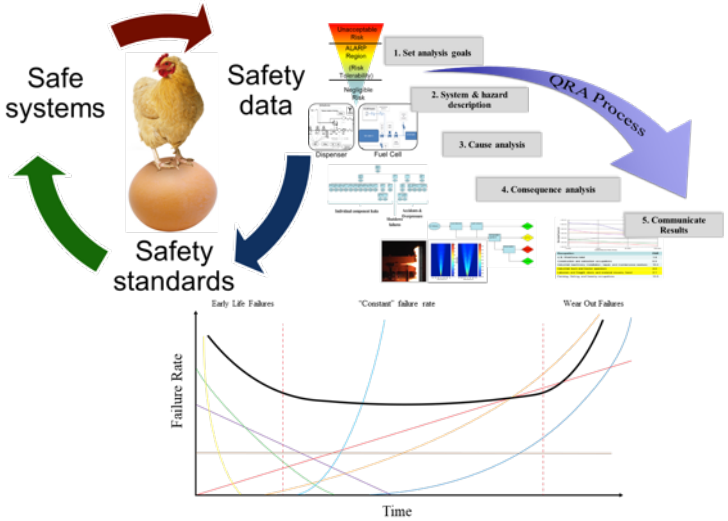
- UMD explores advanced models (QRA, PHM) to overcome lack of operational safety information and data.
  - Used to make data-driven decisions
  - Can improve safety, reduce downtime, and enable better standards
  - Needs sufficient technical data to be implemented effectively
- We are working with multiple 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

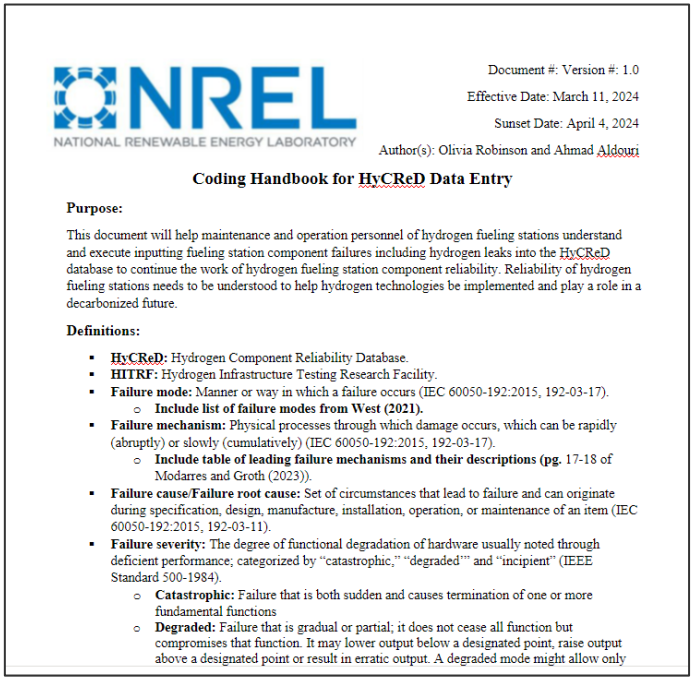
Approach: Safety Planning and Culture

- This project is more analysis, software development, and data collection focused.
- Output (failure rates and QRA) from this project will inform safety practices for hydrogen infrastructure.

- 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.
- This project aligns with safety and sensor research in being done in SCS001, SCS021, SCS032
- 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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Document #: Version #: 1.0
Effective Date: March 11, 2024
Sunset Date: April 4, 2024
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)

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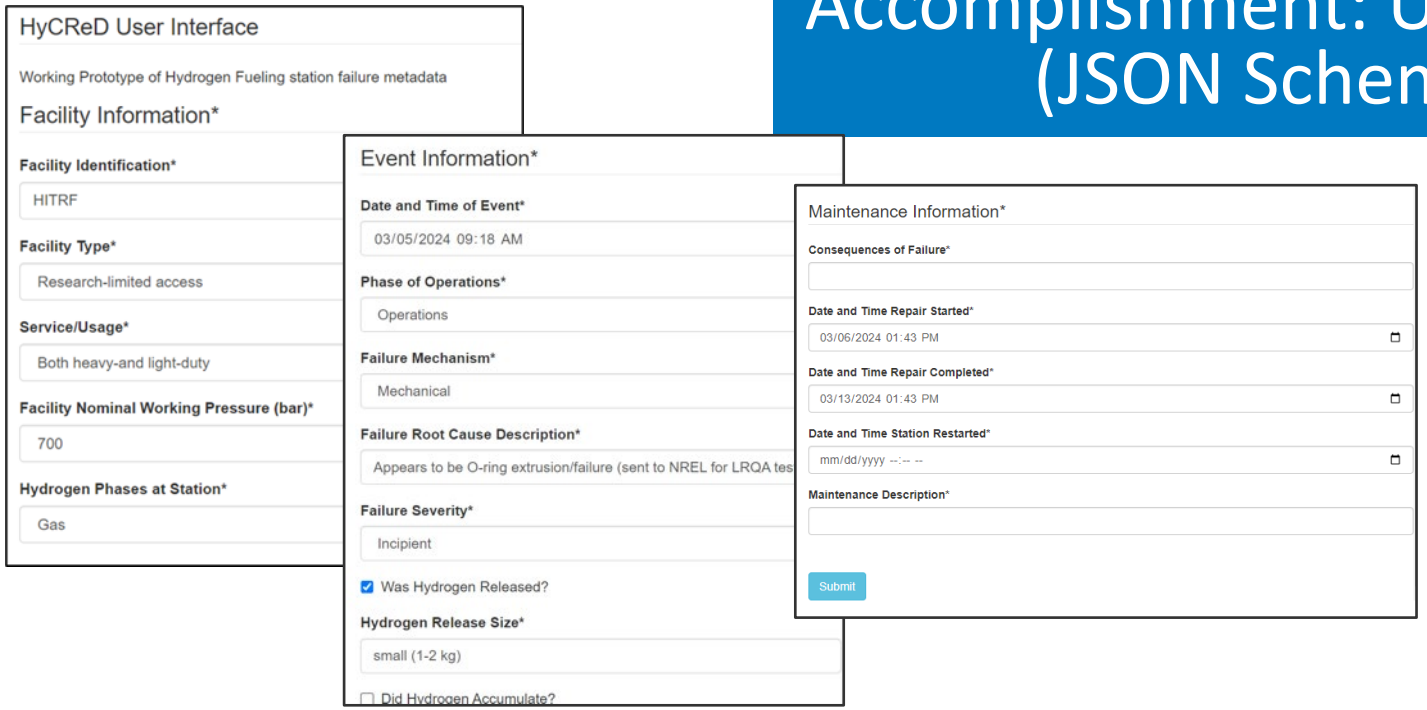
Groth, Katrina M., Ahmad Al-Douri, Madison West, Kevin Hartmann, Genevieve Saur, and William Buttner. "Design and requirements of a hydrogen component reliability database (HyCReD)." *International Journal of Hydrogen Energy* 51 (2024): 1023-1037.

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.

Accomplishments: Results: Coding of 5 public incidents

Event Number	Facility Identification	Facility Type	Service/Usage	Facility Nominal Working Pressure (bar)	H2 Phases on Site
10006	HITRF	Research-limited access	Both heavy- and light-duty	700	Gas
10022	White Plains, NY	Pre-commercial, limited-access	Light-duty	700	Unknown
10031	DS, Netherlands	Commercial, public	Heavy-duty	Unknown	Gas
10035	Aichi Prefecture, Japan	Commercial, public	Light-duty	700	Both
10036	United Kingdom	Unknown	Unknown	700	Gas

- Using existing databases, we were able to **extract and code system information into** the proposed database **structure**.
- HITRF incident was obtained through discussions, which shows information can be obtained readily.

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Accomplishments: Results: Equipment Description of 5 public incidents

Event Number	Equipment Description	Subsystem	Functional Group	Component	Component NWP (bar)	Component MAWP (bar)	Component Population	Install. Date	P&ID Part No.
10006	Medium-pressure manual isolation ball valve (normally open) on a high-pressure, light-duty H2 dispenser	Dispensing Process	Sensing and control	Manual valve	700	1378	5	Jan-19	HV-120A*
10022	Pressure switch	Cooling Process	Sensing and control	Pressure sensor	700	Unknown	-	-	-
10031	Hydrogen storage tank	Bulk Storage	Containment	Type IV tank	Unknown	Unknown	-	-	-
10035	Relief valve (back pressure valve) on a liquid hydrogen storage tank	Bulk Storage	Containment	Pressure relief device	700	Unknown	-	-	-
10036	Hydrogen fuel dispenser	Dispensing Process	Dispensing	Pressure relief device	700	Unknown	2	-	-

- **Using mostly narrative descriptions, we were able to extract and code failed component information into the proposed HyCReD structure.**

Accomplishments: Results: Failure event data for 5 dispensing-related incidents

Event Number	Date & Time of Event	Failure Mode	Failure Mechanism	Failure Root Cause Description	Failure Severity	H2 release?	H2 release size	Accumulation?	Detection?	Detect-ion notes	Ignition?
10006	12/20/2021; 11:45	External leak hydrogen	Mechanical failure	Appears to be O-ring extrusion/failure (sent to NREL for LRQA testing)	Incipient	Yes	Small (1-2 kg)	No	Yes	Audible	No
10022	8/21/2008	External leak hydrogen	Leakage	Hydrogen was released from a failed weld on a pressure switch causing the initial fire. This cascaded down to 3 stainless steel line failures, release of glycol coolant, and release/combustion of compressor oil. Non-metallic seals and hoses containing hydraulic fluid and coolant melted/burned and caused leakage of the fluid, which was mostly consumed by the fire. The compressor skid was consumed by the fire and was a total loss. Other equipment were also moderately damaged.	Critical	Yes	Unknown	Unknown	No	-	Yes
10031	07/21/2023; 2:39 PM	External leak hydrogen	-	-	Incipient	Yes	Unknown	No	Yes	Audible	No
10035	7/9/2021	Spurious operation	Leakage or Control failure	The pressure relief valve operated and ignited a fire at the outlet of the discharge pipe during an automatic discharge of hydrogen gas.	Incipient	Yes	Unknown	No	Yes	Visible	Yes
10036	7/19/2013	External leak hydrogen	Leakage	The event description only mentioned that the dispenser was shut down and fueling operations switched to the second dispenser. There is not enough detail on the mechanism and root cause of this event.	Incipient	Yes	Unknown	No	Yes	Pressure drop	No

- Availability of **HyCReD** as a reporting structure **would enhance data quality**, leading to more accurate failure rate estimates.

Accomplishments: HyCReD fields: Maintenance event data for 5 dispensing incidents

Event Number	Date & Time Repair Started	Date & Time Repair Completed	Date & Time Station Restarted	Maintenance Description
10006	-	-	-	-
10022	-	-	-	The fire department responded and shut off the power supply to the station as well as water spray the surrounding equipment which caught on fire. **The compressor skid had to be replaced as it was a total loss. The pressure switch component was replaced with a better design.** Additional lessons considered by the team include shutoff valve location and/or redundant shutoff valves at storage vessels to prevent escalation.
10031	-	-	-	-
10035	-	-	-	Immediately after the event, the site safety supervisor closed the relief valve and confirmed the fire was extinguished. Later, maintenance personnel installed additional fire extinguishing equipment.
10036	25/07/2013	25/07/2013	-	The leaking valve caused Dispenser A to be down until a replacement was ordered. The replacement valve was scheduled to be installed on 25/07/2013. The station continued operating as normal using Dispenser B.

- **Maintenance event data is sparse**, with only narrative descriptions being available.
- Begun roll-out of data collection at NREL's research station, working with researchers doing the maintenance

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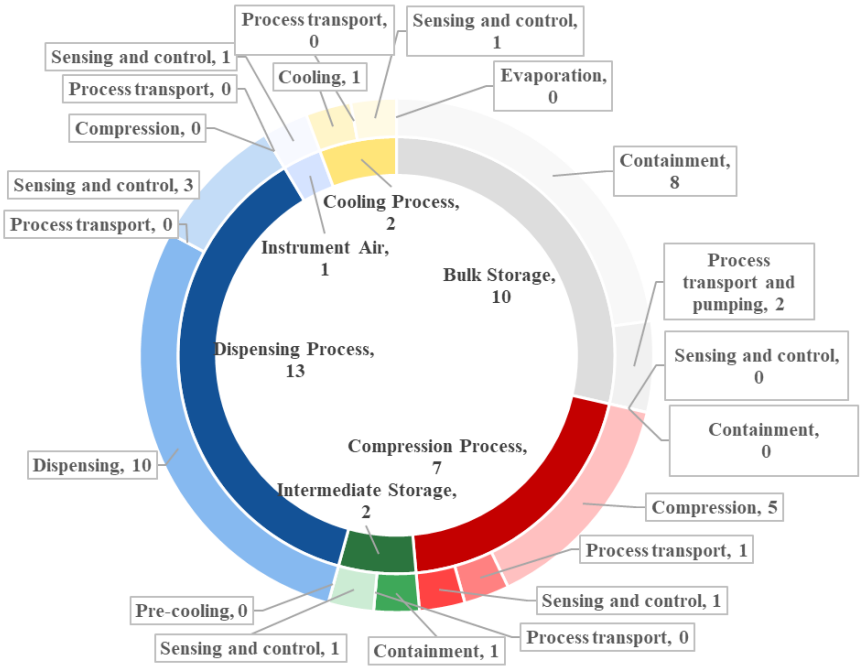
Accomplishment: HyCReD Results

Based on 35 incidents as of March 2024.



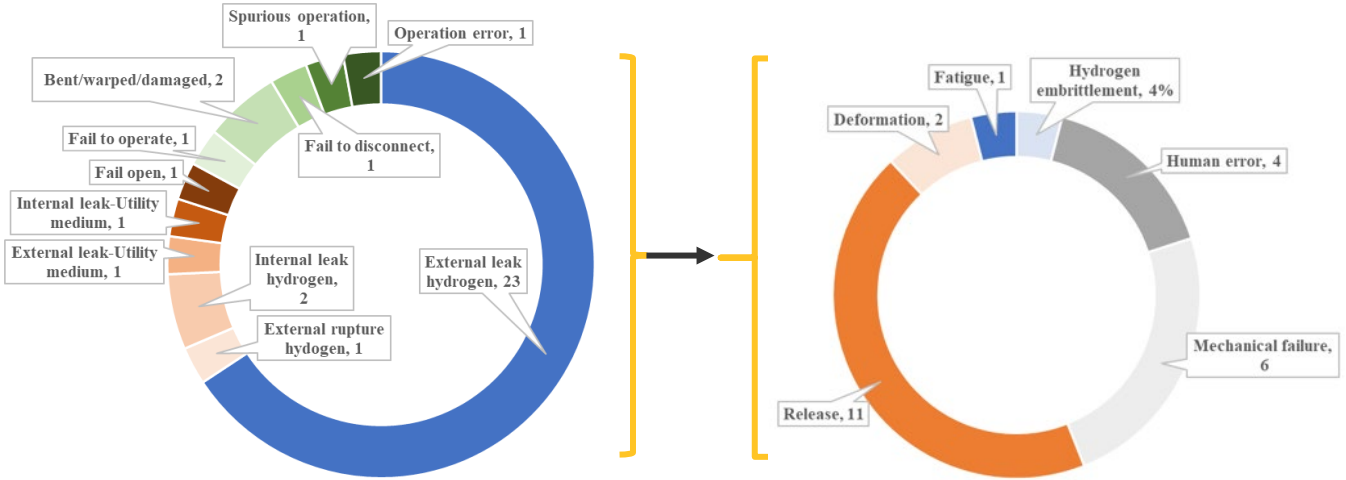
Initial data from 4 public sources

- **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.

Acomplishments: HyCReD Results Breakdown

Based on 35 incidents as of March 2024.



Breakdown of current HyCReD events by failure mode

Breakdown of "external leak-hydrogen" events by failure mechanism

- Initial results, *external leak of hydrogen* is the dominant failure mode. For this mode, release and mechanical failure are primary failure mechanisms.
- These results indicate the importance of *leak prevention and mechanical integrity*

- **Early reporting allowing analyses and processes to be developed.**
- **Developing analysis to calculate failure rates and identify most impactful based on severity classes**

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

NREL's National Fuel Cell Technology Evaluation Center

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)	

Video recording and slides available (links forthcoming)
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

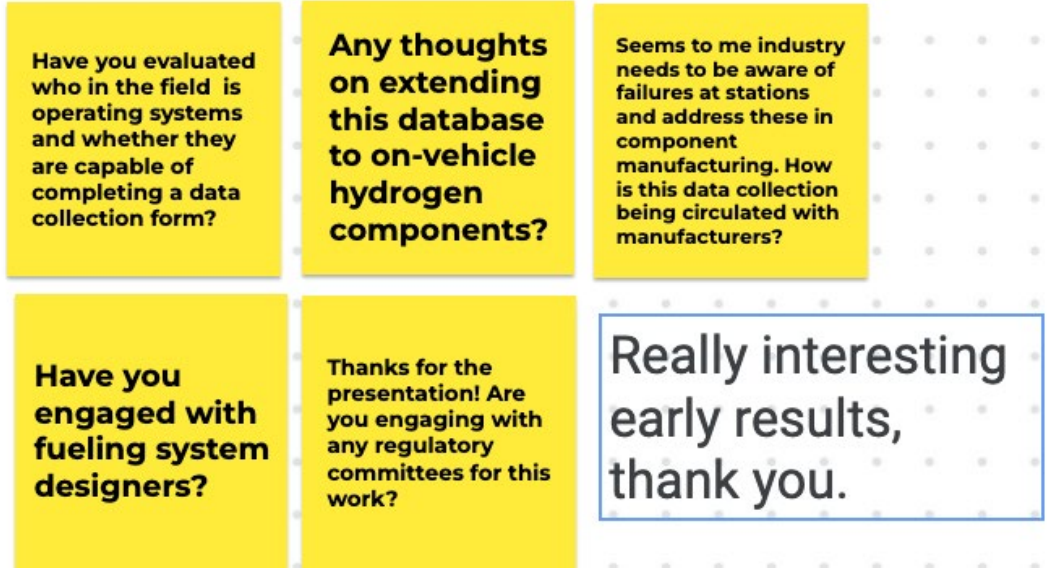
NREL's National Fuel Cell Technology Evaluation Center

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



Accomplishments and Progress:
Response to Previous Year Reviewers' Comments

Project reviewed as part of SCS001 last year. Comments and responses from that project.

- "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 refineiment 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.
- 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.

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

Identification of opportunities an on-going activity

Remaining Challenges and Barriers

- 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

- 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)
- Working on expanding system taxonomy to electrolyzer systems (FY24-25)
- FY25
  - Continuing development of partnerships and feedback
  - Continued development of analysis relevant to industry and research needs
  - Public and private facing reporting on data from HyCReD website

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

Summary

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
- Outreach and industry collaboration critical
- High quality data critical
- Initial vetting of system taxonomy for H2 refueling stations has begun
- V1 of platform for online tool that is secure and easy to use will be available end of FY24

Quantifying component reliability can accelerate deployment by addressing questions around:

- ❖ **Design and safety of projects (codes and standards development)**
- ❖ **Infrastructure reliability and O&M cost (component failure rates, maintenance)**
- ❖ **Component R&D needs (robust supply chain)**

Thank You

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