Component Failure R&D

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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.
Approach: Component Reliability Strategy

**Inputs**

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

**Outputs**

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

Component testing and industry engagement to obtain usable quantitative data for rigorous QRA

Outcome: Robust methodologies for risk reduction in hydrogen systems

1. Reduced downtime and cost due to maintenance and failures
2. Understanding of hazards associated with different size leaks
3. Improved reliability
Overview

Timeline and Budget
Project start date: 10/01/2018
FY22: $325,000
FY23 planned DOE funding: $325,000
Total DOE funds received to date*: $1,525,000
* Since the project started

Partners
• Project Lead: Kevin Hartmann, NREL
• Co-PI(s) William Buttner, NREL and Katrina Groth, UMD
• University of Maryland (UMD) Center For Risk and Reliability
  – Subcontract SUB-2020-10093: Development of Reliability Capabilities for Hydrogen Fueling Facilities with Onsite LH₂ Storage

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

- 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: Leak Rate Quantification Provides an Understanding of Leak Behavior and Hazard

- Quantifying the leak rates of failed hydrogen components with the Leak Rate Quantification Apparatus (LRQA) to provide flow rate data to risk reduction models
  - Determine severity of different leak scenarios
    - Use modeling to apply leak scenarios to hydrogen equipment enclosures
  - Use HyRAM to quantify hazards as measured by the LRQA
  - Test different leak sizes as defined by codes (e.g., NFPA 2 and IEC)

Characterizing leaks from failed components to quantify flow rates to support risk reduction models

A failed thermocouple is found to be leaking after an application of soap and water after the system failed to hold pressure during a leak check.
Developed a system to quantify the hydrogen mass flow rate from components that failed in operation

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 \( (dm/dt) \)
Motivation: QRA Data Types for H2 Systems – Work Addresses Key Gaps

Most critical needs at this project stage:

- **System design info**: operating conditions, process & instrumentation diagrams, functional block diagrams, reliability block diagrams, flow charts
- **Reliability & maintenance info**: FMEA, FRACAS maintenance records, field data, monitors, sensor logs
- **Operational monitoring logs**

Accomplishment: Defining a **Hydrogen Component Reliability Database (HyCReD)**

Using existing databases, we were able to extract and code failure information into the proposed database structure.

<table>
<thead>
<tr>
<th>Event Number</th>
<th>Plant Identification</th>
<th>Facility Type</th>
<th>Service/Usage</th>
<th>Facility Nominal Working Pressure (bar)</th>
<th>Equipment Description</th>
<th>Subsystem</th>
<th>Functional Group</th>
<th>Component</th>
<th>Component Nominal Working Pressure (bar)</th>
<th>Component Population</th>
<th>Installation Date</th>
<th>P&amp;ID Part Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>HyCFEd #1</td>
<td>Emergyle (Upgrade)</td>
<td>Pre-commercial, limited-access</td>
<td>Both heavy- and light-duty</td>
<td>700 bar</td>
<td>Pressure relief valve on the high-pressure storage tank</td>
<td>Bulk_Storage</td>
<td>Containment</td>
<td>Pressure relief valve</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>HyCFEd #2</td>
<td>Uno VKjarto</td>
<td>Commercial public</td>
<td>Light-duty</td>
<td>Unknown</td>
<td>Plugs on a high-pressure hydrogen storage tank</td>
<td>Bulk_Storage</td>
<td>Containment</td>
<td>Double-walled tank</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>HyCFEd #3</td>
<td>Unidentified (U.S.)</td>
<td>Unknown</td>
<td>Unknown</td>
<td>Unknown</td>
<td>Seal seal on hydrogen compressor</td>
<td>Compression_Process</td>
<td>Compression</td>
<td>Compressor</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>HyCFEd #4</td>
<td>Unidentified</td>
<td>Commercial limited access</td>
<td>Heavy-duty</td>
<td>700 bar</td>
<td>Solenoid valves were not operating correctly</td>
<td>Dispensing_Process</td>
<td>Sensing and control</td>
<td>Flow control valve</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>HyCFEd #5</td>
<td>MTRF</td>
<td>Research, limited-access</td>
<td>Both heavy- and light-duty</td>
<td>This is a 700-bar dispenser for light-duty use supplied by permanent on-site gaseous storage of approx. 600 kg</td>
<td>Medium-pressure manual isolation ball valve (normally open) on a high-pressure, light-duty H2 dispenser</td>
<td>Dispensing_Process</td>
<td>Sensing and control</td>
<td>Manual valve</td>
<td>410-860 bar</td>
<td>5</td>
<td>Jan-19</td>
<td>H2-20A'</td>
</tr>
</tbody>
</table>
Using existing databases, we were able to extract and code failure information into the proposed database structure.

### Sample Database Entries: HIAD & H2Tools Incidents

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>5/4/2012; 07:45</td>
<td>Operations</td>
<td>External leak hydrogen; Failure to close on demand</td>
<td>Hydrogen embrittlement</td>
<td>Improper materials selection</td>
<td>Critical</td>
<td>Yes</td>
<td>Large (300 kg)</td>
<td>Yes</td>
<td>No</td>
<td>-</td>
<td>Yes</td>
</tr>
<tr>
<td>6/10/2019; 17:30</td>
<td>Operations</td>
<td>External leak hydrogen</td>
<td>Human error</td>
<td>-</td>
<td>Critical</td>
<td>Yes</td>
<td>Large</td>
<td>Yes</td>
<td>No</td>
<td>-</td>
<td>Yes</td>
</tr>
<tr>
<td>10/06/09</td>
<td>Operations</td>
<td>External leak hydrogen</td>
<td>Mechanical failure</td>
<td>-</td>
<td>Critical</td>
<td>Yes</td>
<td>Unknown</td>
<td>Yes</td>
<td>No</td>
<td>-</td>
<td>No</td>
</tr>
<tr>
<td>7/23/13</td>
<td>Operations</td>
<td>Fail to operate</td>
<td>Binding/jamming</td>
<td>It was found that solenoid valves were not operating properly because a strap connector on an air line in the FC workshop came apart overnight.</td>
<td>Minor</td>
<td>No</td>
<td>Unknown</td>
<td>No</td>
<td>Yes</td>
<td>-</td>
<td>No</td>
</tr>
<tr>
<td>12/20/2021; 11:45</td>
<td>Operations</td>
<td>External leak hydrogen</td>
<td>Mechanical failure</td>
<td>Appears to be O-ring extrusion/failure (sent to NREL for LRQA testing)</td>
<td>Minor</td>
<td>Yes</td>
<td>Small (1-2 kg)</td>
<td>Yes</td>
<td>Yes</td>
<td>Audible</td>
<td>No</td>
</tr>
</tbody>
</table>
Component Leak Rate Quantification: Ball Valve with External Leakage

- The LRQA was used to quantify leak rates of failed hydrogen components
  - Data below is for a leaking ball valve with an average orifice size of 0.25 mm
- The ball valve originally had failed in service with an audible ASME B31.12 Grade 1 Leak
- During LRQA testing the o-ring significantly extruded
- HyRAM was used to simulate the plume dispersion
  - A 0.25 mm leak at 55 MPa is shown below to help understand risk and visualize the theoretical flammable region

Leak rates for failed components were quantified by the LRQA
- This work is ongoing as we acquire a larger inventory of failed components

Previously AVT and NREL did CFD Modeling and hardware validation of hydrogen releases in indoor facilities (including enclosures)
• Well-defined 3-dimensional footprint
• “Predictable” dispersion guiding sensor placement for early detection [Development of Risk Mitigation Guidance for Sensor Placement Indoors and Outdoors, Tchouvelev, Buttner et al., IJHE 46 (2020) 12439-12454]
  – CFD Modelling validated by HyWAM
• Sensor mandated by code for many applications
• Delayed ignition of unmitigated leak can be disastrous
  – Generally, point sensors have been effective

AVT and NREL are working together using Outputs of the Component Reliability AOP Task 3 work, quantifying leaks, as inputs for hydrogen behavior models, detection strategies, and hazard mitigation studies

Indoor Releases—Predictable H2 Behavior
(for optimal sensor placement)
Applying Credible Leak Scenarios to Indoor Enclosures: Setup and Leak Parameters

Utilizing credible leak scenarios as inputs for modeling hydrogen dispersion, detection response time, and hazards

- 550 barg leak parameters using Ideal gas equation of state for Leak 1 and Leak 2 positions

<table>
<thead>
<tr>
<th></th>
<th>Leak A</th>
<th>Leak B</th>
<th>Leak C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure (barg)</td>
<td>550</td>
<td>550</td>
<td>550</td>
</tr>
<tr>
<td>Leak diameter (m)</td>
<td>0.00018</td>
<td>0.00025</td>
<td>0.000358</td>
</tr>
<tr>
<td>Equivalent diameter (m) (Birch 1984)</td>
<td>0.00319</td>
<td>0.00443</td>
<td>0.00635</td>
</tr>
<tr>
<td>Equivalent area (m²)</td>
<td>7.9994x10⁻⁶</td>
<td>1.5431x10⁻⁵</td>
<td>3.1643x10⁻⁵</td>
</tr>
<tr>
<td>Mass flow rate (g/s)</td>
<td>0.875</td>
<td>1.688</td>
<td>3.462</td>
</tr>
<tr>
<td>Turbulent Intensity</td>
<td>6.0973</td>
<td>5.8520</td>
<td>5.5951</td>
</tr>
</tbody>
</table>
Applying Credible Leak Scenarios to Indoor Enclosures: Leak B (0.25 mm)

Impact of leak size and ventilation on detection response time and hazard mitigation: faster detection time and reduced (by x 2) hazardous flammable mass

Leak Position 1
Horizontal X+

Leak Position 2
Horizontal Y-

*Detection time of 0.1% vol. target
Impact of leak size and ventilation on detection response time and hazard mitigation: faster detection time and reduced (by x 2) hazardous flammable mass.
Accomplishments and Progress: Response to Previous Year Reviewers’ Comments

• This project was not reviewed last year
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
Remaining Challenges and Barriers

• 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)
• Stakeholder buy in
  – Industrial stakeholders express interest but lack resources to properly document failure events (internal focus is on maintaining operation)
• Concerns
  – H2 component failure rates may be higher than similar components in non-H2 applications (postulated but not yet demonstrated by data)
  – Tendency of some stakeholders to oversimplify reported descriptions (check the box) rather than to provide details to gain real insights.
Addressing the Need for Validation Data

• Currently working to demonstration and validate HyCReD through industry engagement and partnerships. Obtaining real validation data has been a challenge
  – Obtain data from NREL hydrogen research infrastructure
  – Leverage NRELs experience in technology validation through NFCTEC
  – Lead a subtask within IEA TCP Task 43: Subtask E: Hydrogen System Safety
  – Contribute to CHS meetings & presentations
  – Communicate with stakeholders who are potential data providers
    • Direct outreach to industry
NFCTEC and HyCReD Collaboration and Future Work

• Why:
  – Currently maintenance data submitted in quarters, late, and in variety of conditions
  – High quality data would allow better analysis for:
    • 1) safety (risk assessment), 2) component reliability, 3) prognostic maintenance assessment

• What: HyCReD
  – Establishes a system decomposition taxonomy for H2 refueling stations (first application)
  – Allow (near) real-time data submission
  – Work more closely with station operators and maintenance personnel
  • A few high-quality data sources is better than a lot of bad data

• How:
  – Establish relationships and start populating database
  – Create a version 0.1 of HyCReD as a webapp that is easy to access and use
  – Vet and refine database structure and ease-of-use with motivated first-users
    • Regular monitoring of submissions, especially at first, provides a feedback loop for data collection

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


NFCTEC brings valuable experience working with similar data and anonymous data publication to support development of HyCReD
Expected Outcome: Statistical Representation of Failure Modes and Mechanisms

- From the Offshore and Onshore Reliability Data (OREDA)
- Relative contribution of each failure mechanism to total failure rate.
- Percentage of occurrence of each combination of failure mechanism and failure mode.

- Reliability information can be vital in reliability-centered maintenance (RCM) analysis.
- Useful in identifying candidate components for scheduled replacement and/or maintenance.

Any proposed future work is subject to change based on funding levels.
Proposed Future Work

- Expand and validate HyCReD
  - Direct interaction with the hydrogen community to vet HyCReD
- Expand the collection of realistic hydrogen leak rate quantification data
  - Develop methodology for in-situ leak quantification
- Evaluation of potential consequences under different scenarios
  - Integration of component failure data into QRA and PHM
  - Develop QRA models for a hydrogen equipment enclosure to identify probability of failures, probability of undesired outcomes, and calculate total risk to the populations and facilities of interest in the NFPA 2
- 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. air intake impact

Any proposed future work is subject to change based on funding levels
• HyCReD (near and long term impact)
  – Platform to develop a common database of component failures and failure rates – supports multiple activities in QRA, PHM, and reliability engineering
  – Data enables industry to move toward proactive risk monitoring
  – Improves the overall system safety via a common basis and language for data collection
  – Helps identify high risk components and common failure modes
• Enable improved selection of risk mitigation strategies and guidance through modeling and risk assessment
  – Impact of hydrogen detection and sensor placement
  – Impact of ventilation on hydrogen equipment enclosures
  – Potential to reduce station footprint through risk reduction credits
• Improved understanding of component failures and failures modes through leak rate quantification testing
Impact: Reliability Data Collection has Immediate and Long-term Benefits

• For industry partners supplying data:
  – Improved station uptime $\rightarrow$ higher number of fills $\rightarrow$ **greater economic returns**
  – Information for reliability-centered maintenance (RCM) analysis $\rightarrow$ Enables prioritizing replacement and/or maintenance activities $\rightarrow$ **greater economic returns**

• For broader impact on industry:
  – Data enables risk assessment and models that help establish codes and standards.
  – Enable wider adoption of hydrogen technology.
  – Improves station uptime and reliability.
  – *Avoid overregulation* through proactive treatment of safety and reliability.
Summary

– Developed the **Hydrogen Component Reliability Database (HyCReD)** to track hydrogen specific component failure rates and failure modes

– Quantified leak rates from failed hydrogen components to establish credible real-world leak scenarios

– Utilized the credible leak scenarios as inputs for modeling hydrogen dispersion, detection strategies, and hazard quantification in a hydrogen equipment enclosure

– Direct outreach to industry and the hydrogen community to understand challenges related to component reliability