Component Reliability R&D

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Project Goal

• Establishing a scientific basis for risk and reliability analysis through integrated work with data collection, model development, and stakeholder engagement.
  • Conducting leak rate quantification research to ultimately allow risk reduction credits through QRA (Quantitative Risk Assessment) in RCS.
  • Obtaining a better understanding of leak behavior and leak size for different components and failure modes
  • Introducing new models and data into QRA including PHM (Prognostics and Health Management) for use for hydrogen systems.
  • Analyzing existing hydrogen data sources for use in QRA.
Overview

Timeline and Budget

• Project start date: 10/01/2018
• FY21: $325,000
• FY22 planned DOE funding: $325,000
• Total DOE funds received to date*: $1,200,000
  * Since the project started

Partners

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

- 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 HyRAM to quantify hazards as measured by the LRQA
  - Test different leak sizes as defined by codes (e.g., NFPA 2 and IEC)

- Investigating how to “quantify leaks” in the field
  - Enable leak rate quantification for risk evaluation
    - Soap solution characteristics
    - Ultrasonic characteristics
    - Other detection methods

Characterizing leaks from failed components to provide flow rate data to 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.
Relevance: 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 (see collaborations).
- Connects to broader DOE 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 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: UMD & NREL Integration of QRA Elements

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

Application of new models and data into QRA and PHM for use in hydrogen systems

Outcome: Robust methodologies for risk reduction in hydrogen systems
Approach: Leak Rate Quantification Apparatus and Test Methodology

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 ($dm/dt$)

Isolation Valves

Pressure Vessel

Valves and Pressure Vessel

Shield for Failed Component

PT-2

TT-2

PSV-1

PLC

TT-1

NV-1

PT-1
UMD Approach: Integrated Research, Education, and Industry Engagement
Enable Rigorous Safety, Risk, and Reliability Analysis for H2 Systems

**Risk & reliability methods R&D**
- Develop advanced methods & algorithms (QRA, PHM)

**Application in H2 problems**
- Apply methods & data to solve to H2 system problems to support safe, reliable deployment

**H2 Reliability Data R&D**
- Develop data structures to integrate multiple data types to support QRA, PHM

Robust engineering basis for risk reduction in hydrogen systems & talent pipeline for expanding H2 industry
Approach: UMD Tasks and Timeline

Two MS Theses in 2021

- Identify system reliability data best practices
- Identify key reliability data types necessary for H2 quantitative risk assessment (QRA)
- Synthesize requirements for a proposed new H2 reliability database

2022 goal

- Conduct critical review of the four H2 safety data collection
- Determine areas of strength and weakness for the tools reviewed
- Compare the completeness level in data reporting

2023-2024 goal

- Engage with industry, national laboratory stakeholders to seek feedback
- Develop reliability data quantification plan
- Modify database based on feedback

Hydrogen system reliability database for QRA

Legend

- Completed steps
- Future steps
Accomplishments: Characterization Leaks with Defined Orifice Size

- Used the LRQA to characterize leaks of varying orifice size
  - Micro-metering valve used to control the leak office size
  - Determined the mass flow rate and equivalent orifice size of leaks
  - Used HyRAM to model the leak plume dispersion for the various orifice sizes at a nominal upstream pressure of 55 MPa

Developing an understanding of the potential hazards associated with different size leaks along with leak characteristics (e.g., noise)
Accomplishments: New Deployment Location

LRQA returned to the NREL Hydrogen Infrastructure Testing and Research Facility (HITRF) following capability upgrades

LRQA Capabilities
• Component testing up ~87 MPa with H₂
• Component testing up to bottle pressure with He, N₂, and H₂/NG blends
Accomplishments: Component Leak Rate
Ball Valve with External Leakage

- The LRQA was used to quantify leak rates of failed hydrogen components
  - Data below is for a Ball Valve where the leak orifice abruptly changed from ~0.003 mm to 0.2 mm in size
  - The ball valve originally had failed in service with an audible leak
  - The O-ring had significantly extruded on the valve leading to the leak
- HyRAM was used to simulate the plume dispersion
  - A 0.2 mm leak at 55 MPa is shown below to help understand risk and visualize the theoretical flammable region
- Additional components are ready for testing

Leak rates for failed components were quantified by the LRQA
- This work is ongoing as we acquire a larger inventory of failed components
Accomplishments and Progress: Identified Data Sources & Data Needs for QRA and PHM

**Tasks & Approach**

**Task I:**
Objective: Identify LH₂ risk scenarios
- Definition of bulk LH₂ storage system

Result: FMEA & Risk Screening

**Task II:**
Objective: Determine QRA data requirements
- Development of QRA tools for LH₂ risks (ESD & FTA)

Result: Data requirements for credible QRA

**Task III:**
Objective: Design concept of LH₂ PHM tools
- Identification of PHM data sources in LH₂

Result: Conceptual design of PHM framework

**Key Results**
1. Employed FMEA and QRA modeling tools to identify, model LH₂ risk scenarios,
2. Identified reliability data needs to add LH₂ components to QRA,
3. Developed PHM concept for future applications in LH₂ systems.

**Recommended Actions**
1. Design QRA-oriented data collection tool for H₂ systems,
2. Update leak frequencies and release models in LH₂ context,
3. Pilot PHM approach development for diagnostic methods,
4. Explore connection between PHM, reliability & safety.

-Published:
- Correa Jullian, C.
Data requirements to enable PHM for liquid hydrogen storage systems from a risk assessment perspective. Master’s Thesis. University of Maryland, May, 2021
- Correa-Jullian & Groth.
Accomplishments and Progress: Critical Analysis of H2 Safety Data Sources

- Conducted critical analysis of current H2 safety data collection tools
- Defined 23 requirements for hydrogen fueling station reliability data collection
  - Closes gaps in current data collection efforts

Published in:
- West, Al-Douri, Hartmann, Buttner, & Groth. Critical review and analysis of hydrogen safety data collection tools. International Journal of Hydrogen Energy, Accepted April 2022
Accomplishments and Progress: Built Hydrogen Component Hierarchy and Defined Failure Modes

- Constructed hydrogen component hierarchy for fueling station systems using representative stations from H2FIRST and published literature
  - Backbone of data collection framework
  - Captures location and functional relationships between components
- Fully defined failure mode taxonomy
  - Generated hydrogen-specific failure modes
  - Defined failure modes for each component

Standardized H2 reliability data collection supports:
- Verifiable, reproducible, comparable QRA
- Scientific basis for SCS requirements

Accomplishment: Book Chapter, Groth and Al-Douri, Hydrogen Safety, Risk, and Reliability Analysis

- **Introduction**
- **Background on Hydrogen Safety & Hazards**
  - Safety-relevant physicochemical properties (flammability limits, auto-ignition temperature, deflagration index).
  - Hydrogen safety issues (leak/release, ignition, jet fire, explosions)
- **Quantitative Risk Assessment of Hydrogen Systems- HyRAM**
  - Motivation and requirements behind development of HyRAM toolkit.
  - Methodology and models (QRA mode, risk metrics supported, consequence models)
- **Safety/Reliability/Risk Data Collection**
- **Hydrogen risk analyses in different parts of the supply chain** *(production, transportation by truck and trail, transportation by pipeline, storage, refueling stations)*
- **Conclusions & Discussion**
  - Provide future directions for hydrogen QRA research

- Enables further education of safety activities into formal education of hydrogen engineers
Collaboration and Coordination:

- **Engagement With Industry**
  - Codes and Standards Tech Team
  - Center for Hydrogen Safety
    - Participant in the H2 Equipment and Component Failure Rates Working group
  - Presented at the CaFCP Station Developers and Operator Group Meeting
  - First Element
  - BAM Institute
  - Gas Technology Institute (GTI)
  - International Energy Agency (IEA): working with to define the subsequent task for task 31 hydrogen safety

- **Engagement with Data Providers and the Safety Community**
  - NREL’s Composite Data Products
  - Sandia National Laboratories and HyRAM
  - Conference paper and presentation at the International Conference on Hydrogen Safety 2021

Working to engage with industry, data providers, safety, and RCS experts to guide our research focus to meet the needs of the hydrogen community
Remaining Challenges and Barriers

- **Lack of operating experience and experimental data** (e.g., leak rate quantification studies) to generate QRA inputs for hydrogen system component failures, leak frequencies, detection effectiveness, etc.

- **Lack of failed components** from industry for failure testing using LRQA

- **Lack of condition-monitoring data** for use in developing prototype PHM algorithm

- Actively seeking collaborators Please email Kevin.Hartmann2@nrel.gov
Proposed Future Work

• Test components with varied failure modes to ultimately allow risk reduction credits through QRA (Quantitative Risk Assessment) in RCS
  – Leaking through (e.g., valves that have been closed but do not seal)
  – Leaking out (e.g., leaks through valve packing to the environment)
• Develop a method to securely compile and communicate data and results with the RCS community
• UMD Near-term
  – Iterate on the core elements of reliability database with stakeholders
  – Modify the database to facilitate buy in from data providers
  – Apply elements of reliability database to NREL facility data
  – Simulated data from a digital twin
• UMD Long-term
  – Mature PHM, QRA, and reliability data collection framework(s) through engagement with partners to obtain data necessary to prototype and demonstrate algorithms for connecting data to QRA.

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

- Establishing a scientific basis for risk and reliability analysis through integrated work with data collection, model development, and stakeholder engagement
  - Leak rate quantification measurements to ultimately allow risk reduction credits through QRA (Quantitative Risk Assessment) in RCS
    - Quantifying risk associated with failed components
  - Obtaining a better understanding of leak behavior and leak size for different components and failure modes
  - PHM and QRA work with UMD is creating a robust framework for utilization of component failure data
  - Extending the state of the art in risk-mitigation measures to reduce barriers to deployment of LH2 storage technologies.
  - Introducing new models and data into QRA including PHM (Prognostics and Health Monitoring) for use for hydrogen systems
  - Analyzing existing hydrogen data sources for use in QRA
Thank You

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Technical Backup and Additional Information
Special Recognitions and Awards

• Katrina Groth, 2021 NSF CAREER award (Not funded by this project, but points to broader recognition of Dr. Groth and her technical work on risk and reliability).


• Camila Correa Jullian master’s degree in the Reliability Engineering from UMD’s Department of Mechanical Engineering (May, 2021) received “Second place winner of Dean’s Master’s Research Award 2021. (Among all M.S. degrees granted by UMD’s School of Engineering in academic year 2020-2021; UMD graduates 350 M.S. students per year)
Publications and Presentations


• Kevin Hartmann, Jacob Thorson, William Buttnr, Katrina Groth, and Ahmad Al-Douri. “Component Failure R&D.” Presented to the Codes and Standards Tech Team (CSTT), March 2022.

Publications and Presentations

- Kevin Hartmann, Jacob Thorson, and William Buttner. “Component Failure R&D.” Presented to CaFCP Station Developers and Operators Group Meeting. April 2022.


NREL Key Orifice Equation

\[ q_m = \frac{m_2 - m_1}{t_2 - t_1} = \frac{A_{nt} \cdot C'_d \cdot C^* \cdot p_0}{R_g \cdot T_0} \]

From ISO 9300

Where:

- \( C'_d = 0.9 \) For leaks of unknown geometry
- \( A_{nt} = \frac{\pi}{4} \cdot d_{nt}^2 \) Where \( d_{nt} \) is the hydraulic diameter of the leak \( \left( d_{nt} = \frac{4 \cdot A_{nt}}{P_{nt}} \right) \)
- \( C^* = \rho^* \cdot a^* \cdot \frac{\sqrt{R \cdot T_0}}{p_0 \cdot \sqrt{Mg}} \) Real critical flow function from (John D. Wright, 2010)
- \( m = \rho(p,T) \cdot V_{system} \) Density and other properties calculated in using equations of state
- \( p \gg p^* \) Ensures flow is choked

LRQA Failed Component Test Procedure

1. Identify a component with known leaks that does not show mechanical damage (e.g. from fire or corrosion)
2. Purge pressure vessel with the test gas
3. Pressurize the pressure vessel to the test pressure
4. Isolate the pressure vessel allowing the pressure and temperature to stabilize
5. Connect the pressure vessel to the device under test
6. Monitor and log the change in pressure and temperature at the vessel and device under test
7. Stop the test when the pressure has dropped to 100 psi or when 20 minutes have elapsed
8. Repeat test steps 3-7 increasing the test pressure until the maximum supply pressure is reached
LRQA P&ID

P&ID was a critical element of an NREL internal review process to assure safe operation of the Leak Rate Quantification Apparatus.
Accomplishments and Progress: Responses to Previous Year
Reviewers’ Comments

• Project was not reviewed last year
Technology Transfer Activities

• No technology transfer outcomes to date