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Component Reliability R&D

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Project ID: SCS001

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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.

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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

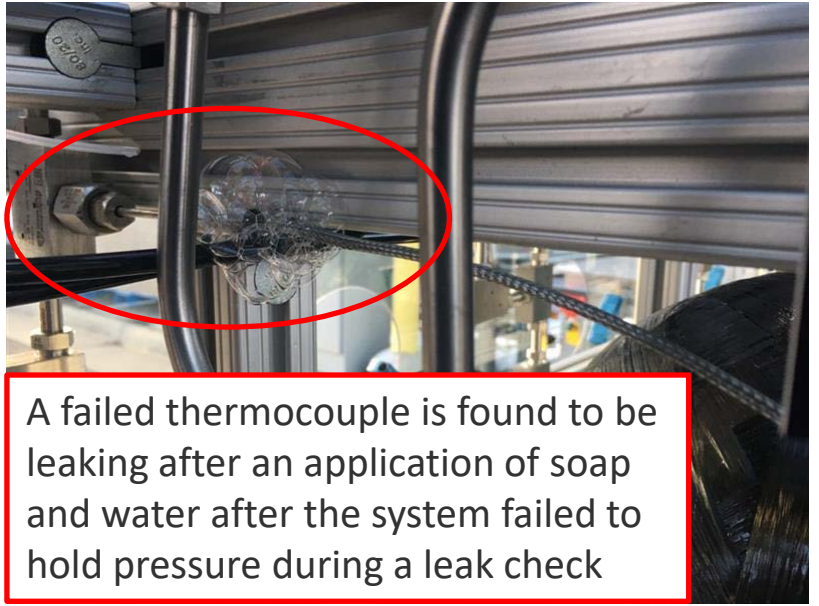
- Project Lead: Kevin Hartmann, NREL
- Co-PI(s) William Buttner, NREL and Katrina Groth, UMD

- University of Maryland Center For Risk and Reliability
  - Subcontract SUB-2020-10093: Development of Reliability Capabilities for Hydrogen Fueling Facilities with Onsite LH_2 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



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

Characterizing leaks from failed components to provide flow rate data to risk reduction models

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

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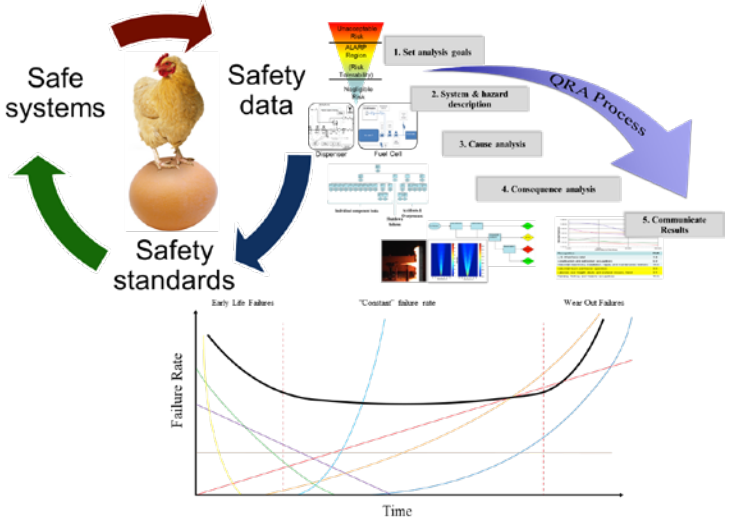
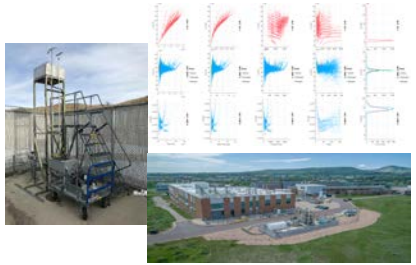
- UMD explores advanced models (QRA, PHM) to overcome lack of operational safety information and data.
  - Used to make data-driven decisions
  - Can improve safety, reduce downtime, and enable better standards
  - Needs sufficient technical data to be implemented effectively
- We are working with multiple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



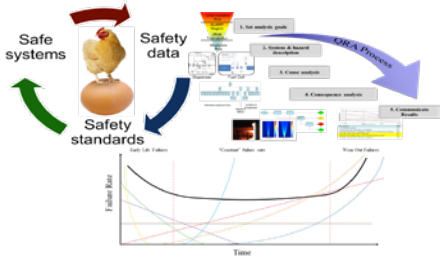
Providing a *rigorous scientific basis to* overcome lack of direct safety data by using new algorithms and multiple partially-relevant types of data

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

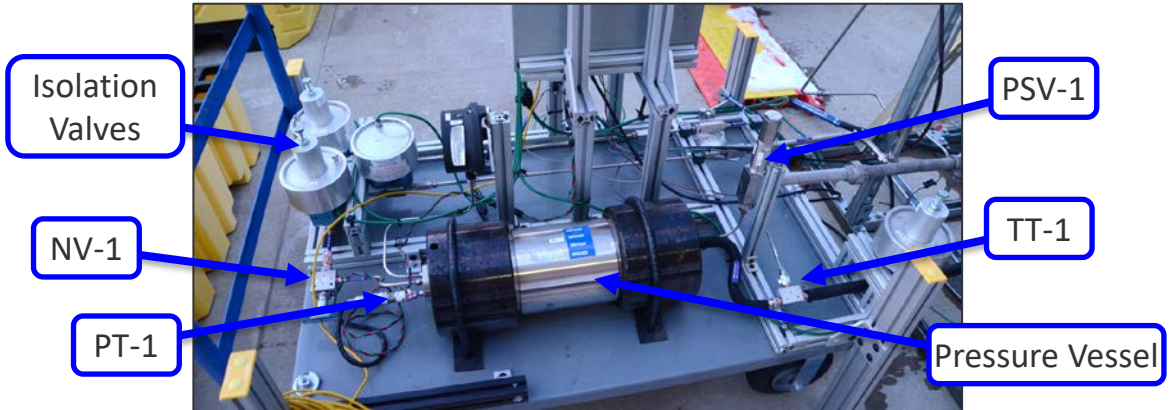
Enabling methods and data

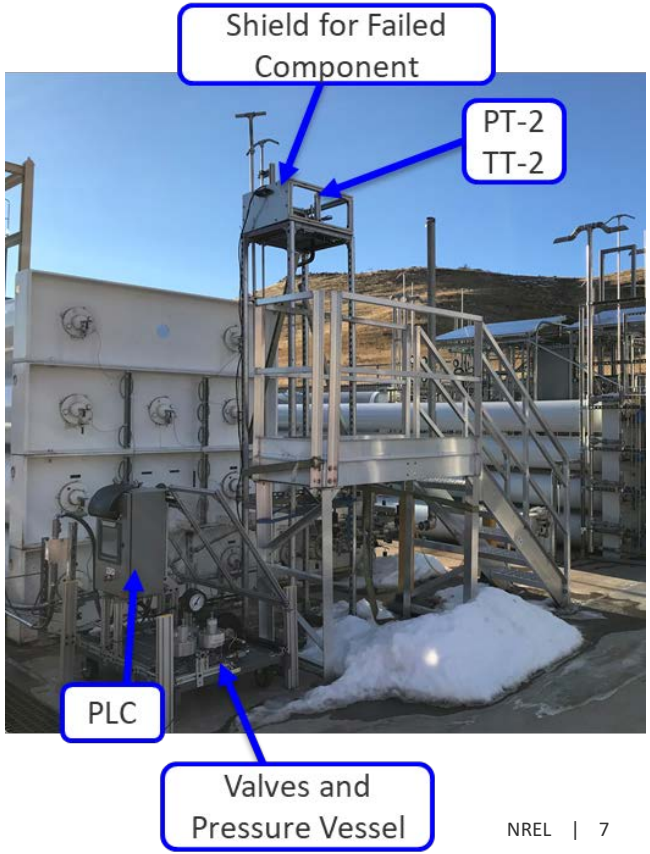
Outcome: Robust methodologies for risk reduction in hydrogen systems

Approach: Leak Rate Quantification Apparatus and Test Methodology

Developed a system to quantify the hydrogen mass flow rate from components that failed in operation

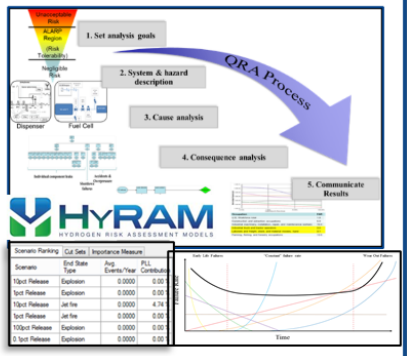
1. Pressurize the failed component on the Leak Rate Quantification Apparatus (LRQA) with a known volume with gas
2. Measure P&T to calculate mass at each timestep
3. Determine mass flow rate (*dm/dt)*
4. Relate *dm/dt* to an equivalent orifice diameter using standard equations (ISO 9300: *Measurement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





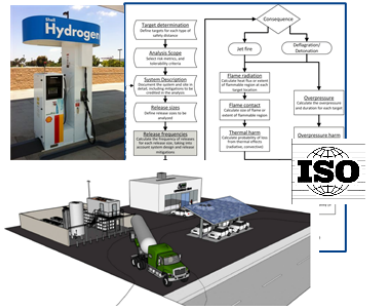
UMD Approach: *Integrated Research, Education, and Industry Engagement* Enable Rigorous Safety, Risk, and Reliability Analysis for H2 Systems

Risk & reliability methods R&D



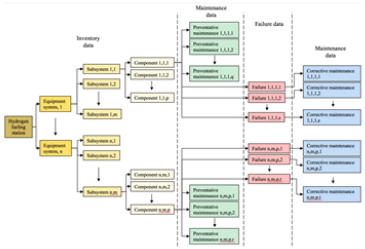
Develop advanced methods & algorithms (QRA, PHM)

Application in H2 problems



Apply methods & data to solve to H2 system problems to support safe, reliable deployment

H2 Reliability Data R&D

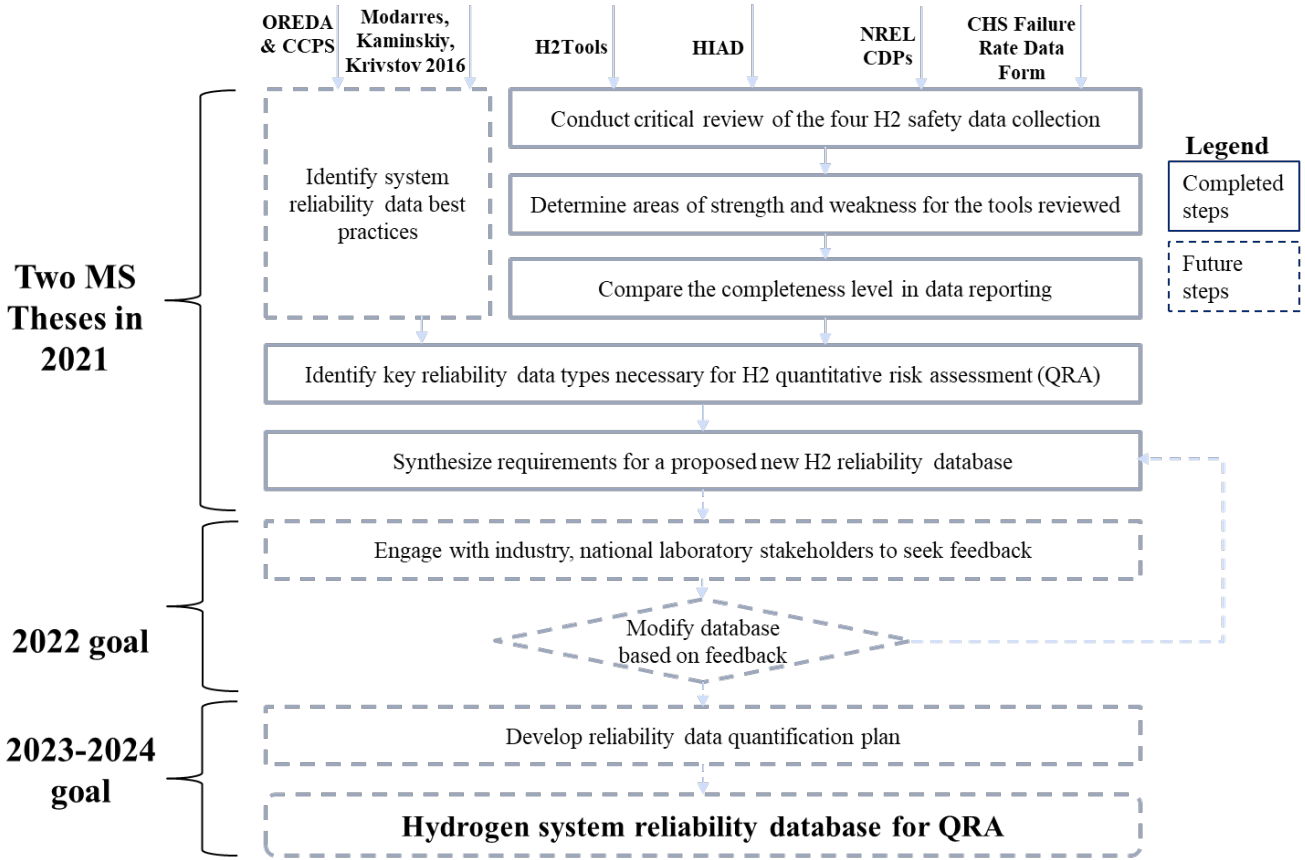


Develop data structures to integrate multiple data types to support QRA, PHM

Research, education, and industry engagement

Robust engineering basis for risk reduction in hydrogen systems & talent pipeline for expanding H2 industry

Approach: UMD Tasks and Timeline



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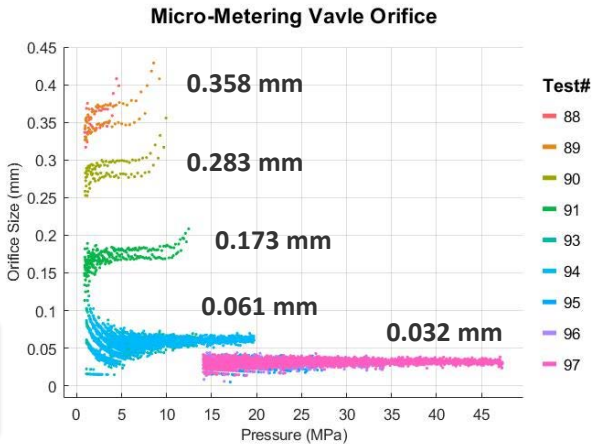
Accomplishments: Characterization Leaks with Defined Orifice Size

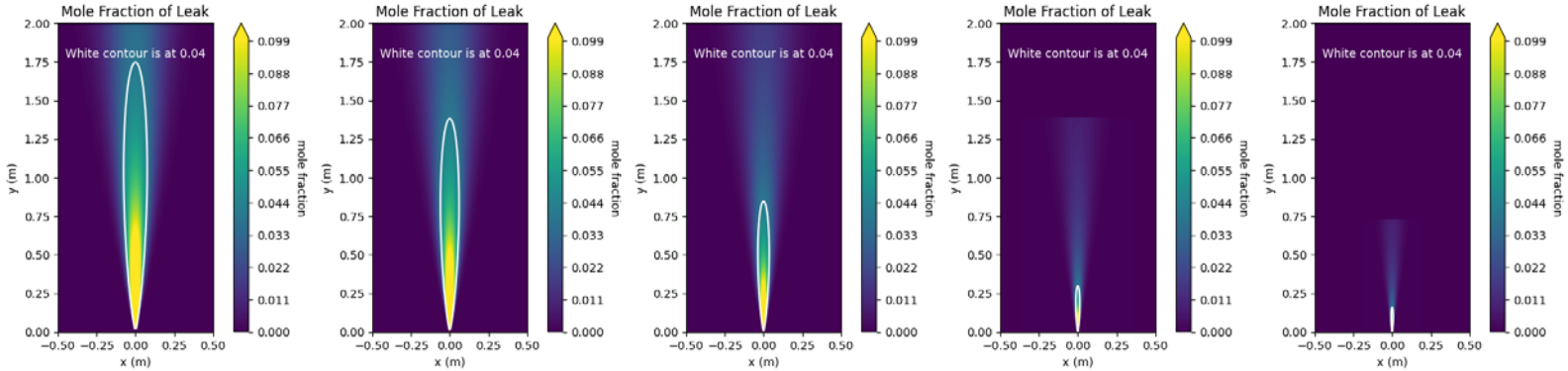
- Used the LRQA to characterize leaks of varying orifice size
  - Micro-metering valve used to control the leak office size
  - Determined the mass flow rate and equivalent orifice size of leaks
  - Used HyRAM to model the leak plume dispersion for the various orifice sizes at a nominal upstream pressure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



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

Orifice Size: 0.358 mm | 0.283 mm | 0.173 mm | 0.061 mm | 0.032 mm

Nominal upstream pressure of 55 MPa used



Accomplishments: New Deployment Location

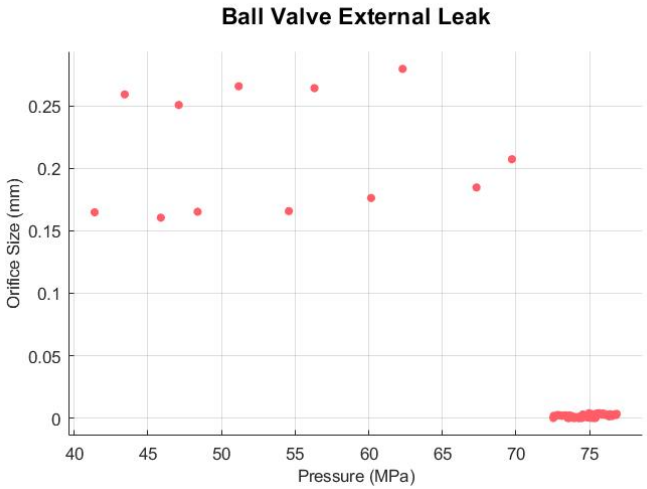
LRQA returned to the NREL Hydrogen Infrastructure Testing and Research Facility (HITRF) following capability upgrades

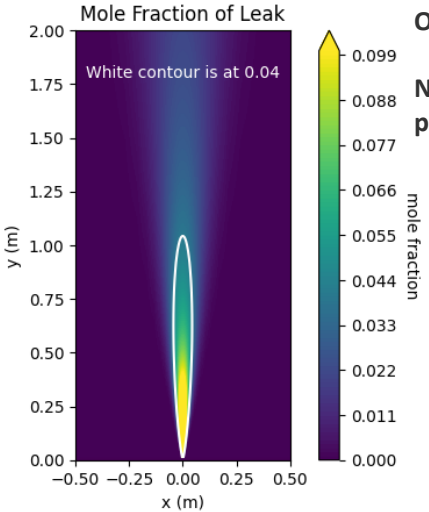
LRQA Capabilities

- Component testing up ~87 MPa with H_2
- Component testing up to bottle pressure with He, N_2, and H_2/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





Orifice Size: 0.2 mm

Nominal upstream pressure of 55 MPa

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 LH_2 risk scenarios

Definition of bulk LH_2 storage system

Result: FMEA & Risk Screening

Task II:

Objective: Determine QRA data requirements

Development of QRA tools for LH_2 risks (ESD & FTA)

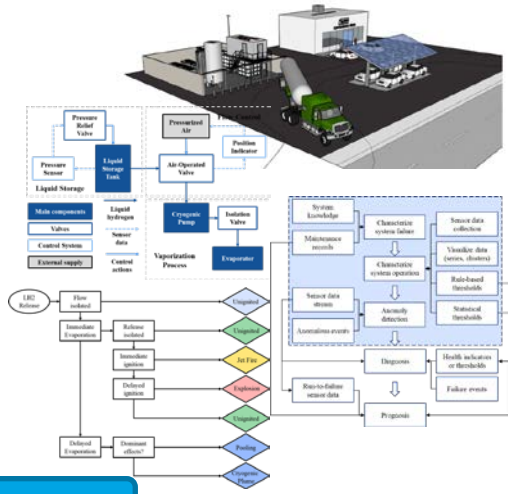
Result: Data requirements for credible QRA

Task III:

Objective: Design concept of LH_2 PHM tools

Identification of PHM data sources in LH_2

Result: Conceptual design of PHM framework



-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. Data Requirements for Improving the Quantitative Risk Assessment of Liquid Hydrogen Storage Systems. *International Journal of Hydrogen Energy*, **2022**, *47*, 4222-4235.

Key Results

1. Employed FMEA and **QRA modeling tools** to identify, model LH_2 risk scenarios,
2. Identified reliability data needs to **add LH_2 components to QRA**,
3. Developed PHM concept for **future applications in LH_2 systems**.

Recommended Actions

1. Design **QRA-oriented data collection** tool for H2 systems,
2. Update leak frequencies and release models in **LH_2 context**,
3. Pilot **PHM approach** development for diagnostic methods,
4. Explore connection between **PHM, reliability & safety**.

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

Major Gaps
- Failure mode
- Failure mechanism
- System response
- H2 accumulation
- H2 detection
- Component life

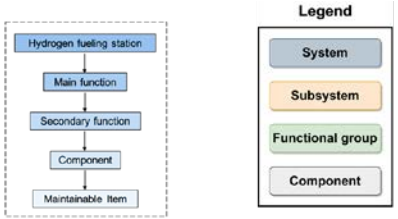
	Data Type	H2Tools	NREL CDPs	HIAD	CHS Failure Rate Data
Event and failure characterization	Initiating event (description)	✓	✓	✓	×
	Location within system	×	✓	O	×
	Failure mode	×	×	×	×
	Failure mechanism	×	×	×	×
	Failure root cause	✓	✓	✓	×
	Release size	×	O	✓	✓
	Incident severity	✓	✓	✓	✓
	Consequences	O	✓	✓	O
	System response (Mitigation)	×	×	×	O
	H2 accumulation	×	×	×	×
	H2 detection	×	×	×	O
Life/usage	Component life	×	×	×	×
	Operations	×	✓	×	O
	Maintenance	×	✓	×	O
	Site inventory	×	✓	×	O
Data scope	Public access to data	✓	×	✓	?
	Scope includes any H2 incident	✓	×	✓	✓
	Regular reporting	×	✓	×	✓
	Anonymous data presentation	✓	✓	✓	✓
	Data quality checks	×	✓	×	?
	Process documentation	×	×	O	×

Framework Characteristics	Static Data	Maintenance Event Data	Failure Event Data
Design for usability	Component location	Type of maintenance	Narrative event description
Publicly available	Operating conditions	What was performed	Failure mode
Regular reporting	Component life	Active repair time	Failure mechanism
Anonymity	Number of like components	Manhours	Root cause
Quality assurance			Release location and size
Regular updating			Hydrogen accumulation
Process documentation			Detection
			Isolation
			Consequence
			Severity

Published in:
- Madison West "Development of a reliability data collection framework for hydrogen fueling station QRA" Masters Thesis University of Maryland, Dec. 2021
- 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



Drift	Erroneous reading due to lack of calibration
Erratic output	Inconsistent output
External leak hydrogen	Hydrogen leak from within system to environment
External leak utility medium	Utility medium leak from the system to the environment
External rupture hydrogen	Complete loss of containment, hydrogen exhausts to the environment
External rupture utility medium	Complete loss of utility medium to the environment
Fail closed	Component stops working in the closed position
Fail open	Component stops working in the open position
Fail to close	Component does not close on demand
Fail to disconnect	Components meant to disconnect does not do so on demand
Fail to evaporate	Hydrogen remains in liquid form after passing through evaporator
Fail to operate	Component does not function on demand
Fail to stop	Component does not stop on demand
Freezing	Component is frozen and becomes inoperable/requires maintenance
Insufficient heat transfer	Target parameters for temperature are not met in a heat exchanger
Internal leak hydrogen	Hydrogen leak within system boundary (e.g. across a closed valve)
Internal leak utility medium	Utility medium leak within system boundary (e.g. across a closed valve)
Internal rupture hydrogen	Complete loss of containment, hydrogen stays within the system boundary
Internal rupture utility medium	Complete loss of containment, utility medium stays within the system boundary
Open circuit	Electrical circuit that is not complete
Overheating	Component is exposed to temperatures above design specifications
Overspeed	Component operates above desired/specified speed
Plugging	Buildup of material restricting flow
Restrict flow	Component is restricting flow when not intended to do so
Short circuit	Diversion of current
Spurious operation	Activation without specified demand (components normally idle)
Spurious stop	Stop without specified demand (components normally active)
Stuck connection	Component is stuck at point of contact (nozzle)
Underspeed	Component operates below desired/specified speed

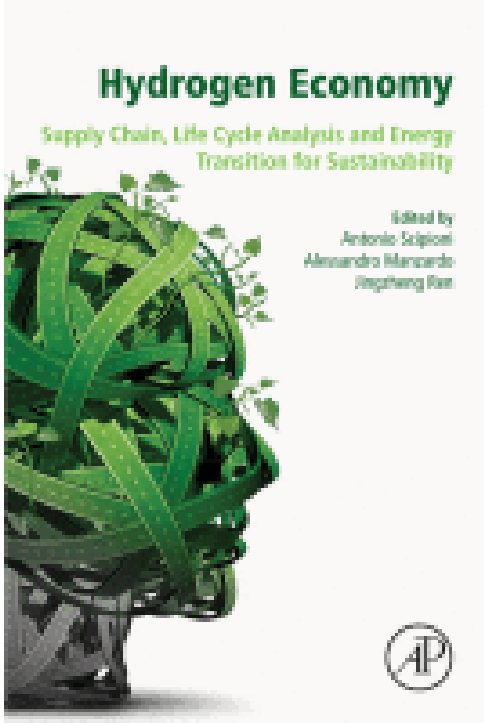
Standardized H2 reliability data collection supports:
- Verifiable, reproducible, comparable QRA
- Scientific basis for SCS requirements

Full details in: Madison West "Development of a reliability data collection framework for hydrogen fueling station QRA" Masters Thesis University of Maryland, Dec. 2021

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**
  - Moradi & Groth (2019) IJHE article, West (2021) thesis
- **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

- Invited contribution. Groth and Al-Douri chapter, to be published in: Scipioni, Antonio, Alessandro Manzardo, and Jingzheng Ren, eds. Hydrogen economy: supply chain, life cycle analysis and energy transition for sustainability. 2nd Edition. ~June 2022
- 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).
- Katrina Groth invited participant of U.S. Frontiers of Engineering Symposium, National Academy of Engineering, September 22-24, 2021.
- 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

- Camila Correa Jullian. “Data Requirements to Enable Prognostics and Health Management for Liquid Hydrogen Storage Systems from a Risk Assessment Perspective.” Master’s Thesis, University of Maryland, May 2021. Doi: 10.13016/9v8j-cyzu.
- Madison West. “Development of a reliability data collection framework for hydrogen fueling station QRA” Master’s Thesis, University of Maryland, Dec 2021. Doi: 10.13016/gfzf-e0ff.
- Kevin Hartmann, Camila Correa-Jullian, Jacob Thorson, William Buttner, and Katrina Groth. “Hydrogen Component Leak Rate Quantification for System Risk and Reliability Assessment through QRA and PHM Frameworks.” Proceedings of the International Conference on Hydrogen Safety (ICHS 2021), Sept 2021.
- Camila A. Correa-Jullian, Katrina M. Groth. “Data Requirements for Improving the Quantitative Risk Assessment of Liquid Hydrogen Storage Systems.” International Journal of Hydrogen Energy. 47(6), p 4222-4235, Jan 2022. Doi: https://doi.org/10.1016/j.ijhydene.2021.10.266.
- Madison West, Ahmad Al-Douri, Kevin Hartmann, William Buttner, and Katrina Groth. “Critical review and analysis of hydrogen safety data collection tools.” *International Journal of Hydrogen Energy,* March 2022. Doi: https://doi.org/10.1016/j.ijhydene.2022.03.244.
- Kevin Hartmann, Jacob Thorson, William Buttner, Katrina Groth, and Ahmad Al-Douri. “Component Failure R&D.” Presented to the Codes and Standards Tech Team (CSTT), March 2022.
- William Buttner, Kevin Hartmann, Matt Post, Jacob Thorson, David Pearman, and Ian Palin. “Hydrogen Release Quantification.” Presented at Clean Hydrogen JU Expert Workshop on Environmental Impacts of Hydrogen, April 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.
- Camila A. Correa-Jullian, and Katrina M. Groth. “Opportunities and Data Requirements for Data-Driven Prognostics and Health Management in Liquid Hydrogen Storage Systems” *International Journal of Hydrogen Energy*. **Accepted April 2022.**
- Katrina M. Groth and Ahmad Al-Douri. “Hydrogen Safety, Risk, and Reliability Analysis” *Hydrogen Economy, 2nd edition*. Eds: Antonio Scipioni, Alessandro Manzardo, Jingzheng Ren. **Accepted, to be published ~June 2022.**
- Ahmad Al-Douri, Madison A. West, and Katrina M. Groth. “A Foundational Framework for Reliability Data Collection for Hydrogen Systems.” Abstract submitted to the AIChE 2022 Spring Meeting and the 18th Global Congress on Process Safety. **To be presented in April 2022.**

NREL Key Orifice Equation

Unknown

$$q_m = \frac{m_2 - m_1}{t_2 - t_1} = \frac{\boxed{A_{nt} * C_d'} * C^* * p_0}{R_g * T_0}$$

From ISO 9300

Key equation used to calculate the equivalent orifice from the mass flow rate

Where:

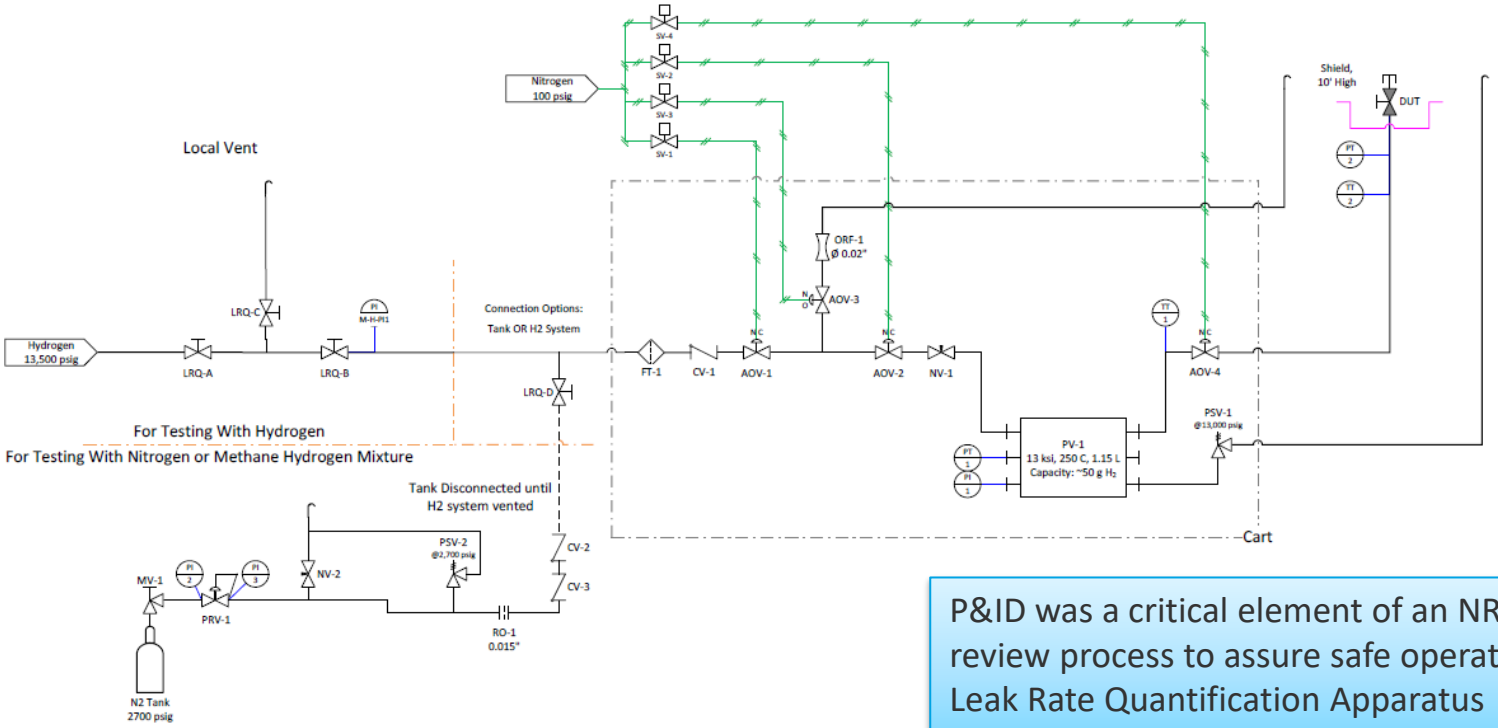
- $C_d' = 0.9$ For leaks of unknown geometry
- $A_{nt} = \frac{\pi}{4} * d_{nt}^2$ Where d_{nt} is the hydraulic diameter of the leak $\left(d_{nt} = \frac{4 * A_{nt}}{P_{nt}}\right)$
- $C^* = \rho^* * a^* * \frac{\sqrt{R * T_0}}{p_0 * \sqrt{M_g}}$ Real critical flow function from (John D. Wright, 2010)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

"ISO 9300 Measurement of gas flow by means of critical flow Venturi nozzles." International Organization for Standards (ISO), 2005, [Online]. Available: https://www.iso.org/standard/34272.html.

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