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Component Failure R&D

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2023 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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Approach: Component Reliability Strategy

Inputs

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

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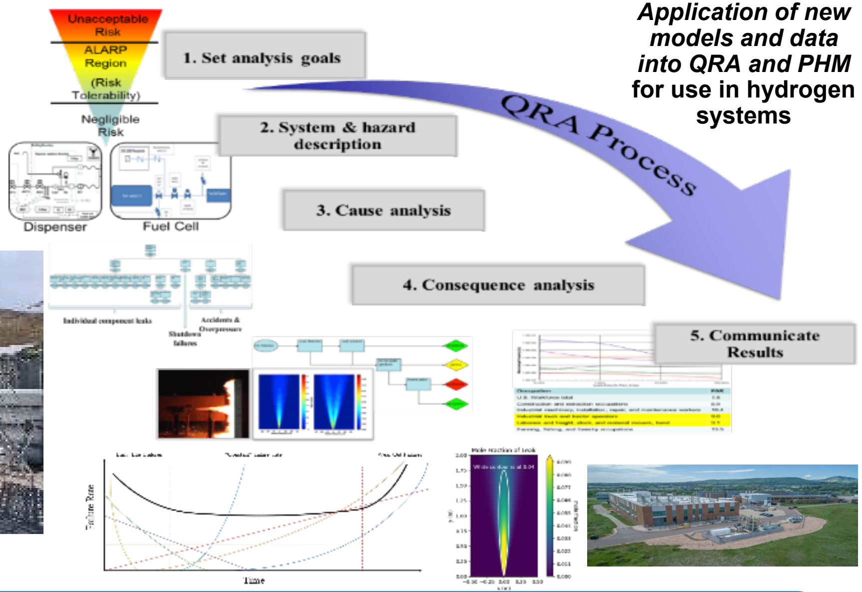
Component testing and industry engagement **to obtain usable quantitative data for rigorous QRA**

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



Outcome: Robust methodologies for risk reduction in hydrogen systems

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

Outputs

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

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 LH_2 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

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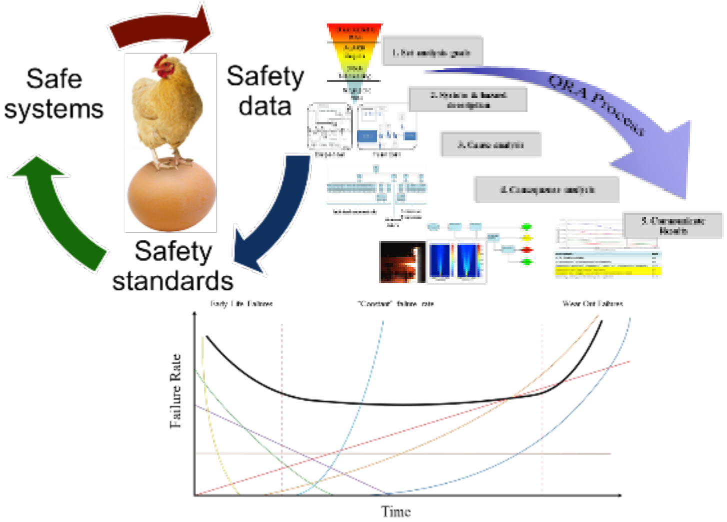
- UMD explores advanced models (QRA, PHM) to overcome lack of operational safety information and data.
  - Used to make data-driven decisions
  - Can improve safety, reduce downtime, and enable better standards
  - Needs sufficient technical data to be implemented effectively
- We are working with multiple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

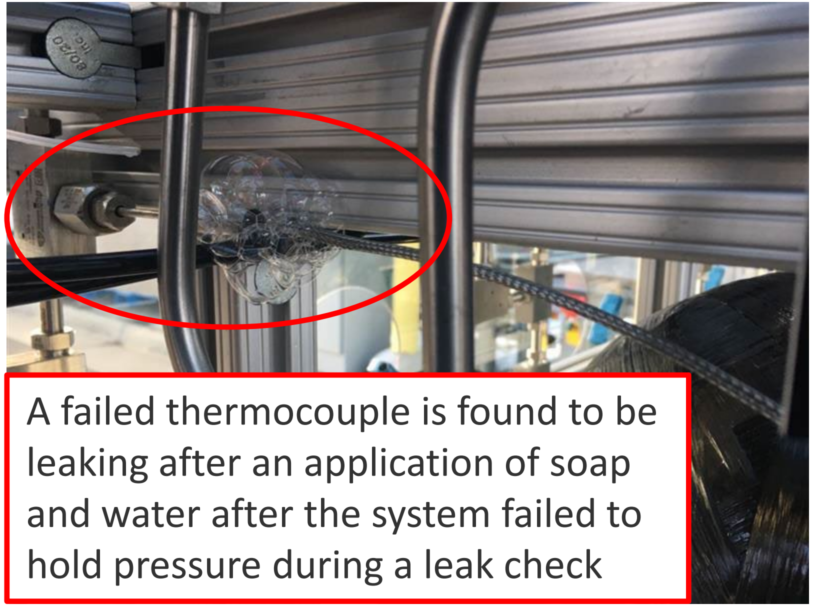


Providing a *rigorous scientific basis to* overcome lack of direct safety data by using new algorithms and multiple partially-relevant types of data

Approach: 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

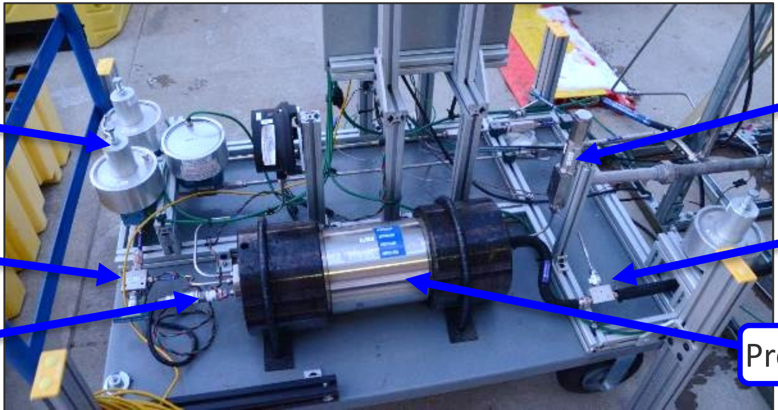


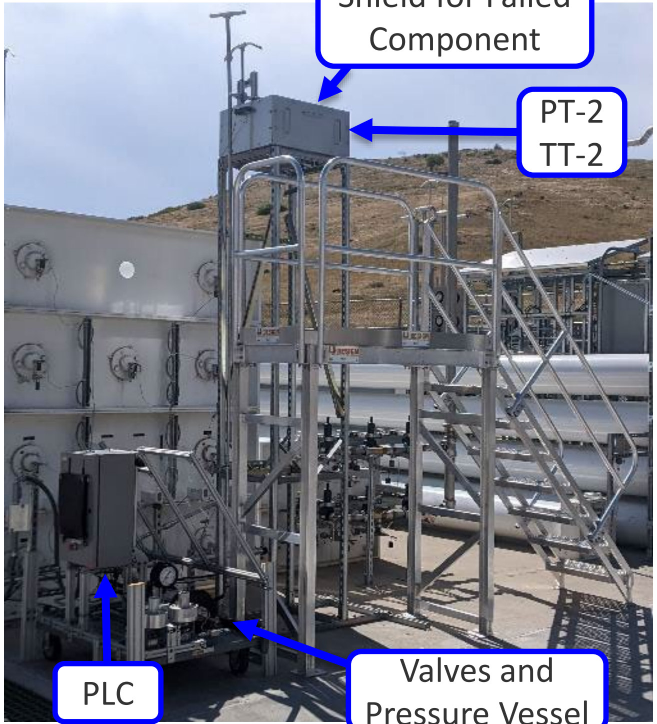
A failed thermocouple is found to be leaking after an application of soap and water after the system failed to hold pressure during a leak check

Leak Rate Quantification Apparatus and Test Methodology

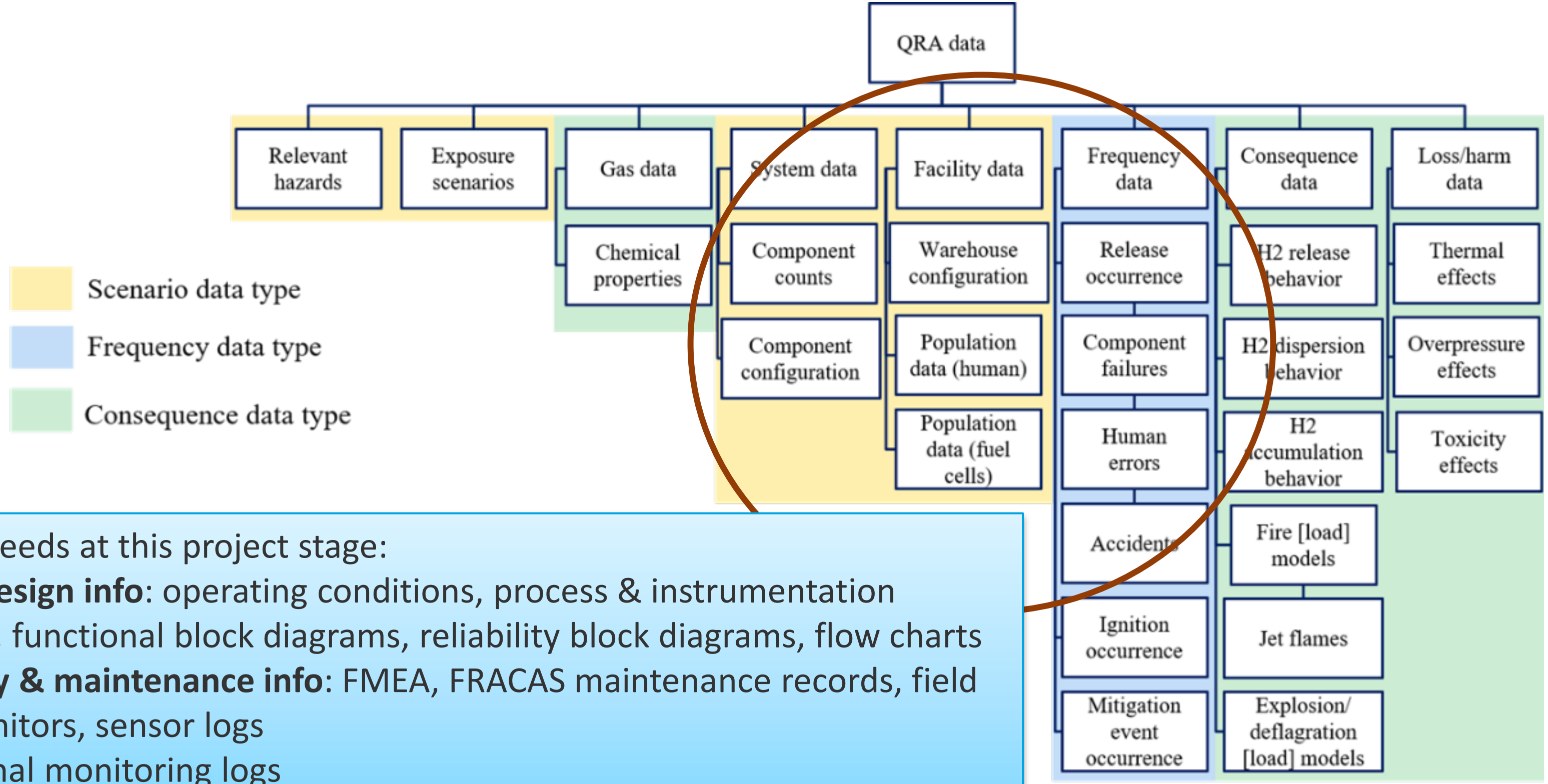
Developed a system to quantify the hydrogen mass flow rate from components that failed in operation

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*)





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

Adapted from Correa-Jullian & Groth (2022) Data Requirements for Improving the Quantitative Risk Assessment of Liquid Hydrogen Storage Systems, *International Journal of Hydrogen Energy*, 47.

Accomplishment: Defining a **Hy**drogen **C**omponent **Re**liability **D**atabase (HyCReD)

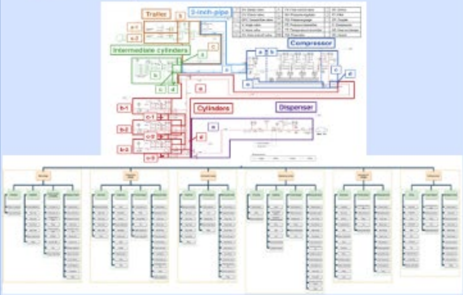
Evaluated existing H2 safety data collection tools

	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	×

Defined a set of 23 requirements for HyCReD

Characteristics	Static data	Failure event data	Maintenance event data
• Design for usability • Publicly available • Regular reporting • Anonymity • Quality assurance • Regular updating • Process documentation	• Component location • Operating condition • Component life • Number of like components	• Narrative event description • Failure mode • Failure mechanism • Root cause • Release location & size • Hydrogen accumulation • Detection • Isolation • Consequence • Severity	• Type of maintenance • Maintenance action performed • Active repair time • Manhours

Developed H2 fueling station system decomposition taxonomy



Defined 44 H2-specific component failure modes

Failure Mode	Definition
Abnormal output-high	Above normal output indicates potential failure(s)
Abnormal output-low	Below normal output indicates potential failure(s)
Bent/warped/damaged	Visible damage
Contamination	Component allows foreign material to contaminate product
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

Developing & validating HyCReD structure

- **Static data fields**

Event Number	Station/Facility Identification	Facility Type	Service/Usage	Nominal Working Pressure	H2 phases on site
25	A	Commercial, public	Heavy-duty	700 bar	Gas
26	B	Research, limited-access	Both heavy- and light-duty	350 bar	Gas

Event Number	Equipment Description	Subsystem	Functional Group	Component	Component Nominal Working Pressure	Component Population	P&ID Part Number
25		Bulk storage	Containment	Type III tank	250-300 bar	18	TK-103
26		Compression process	Compression	Compressor	400-680 bar	2	CO-E-49A

- **Failure event data fields**

Event Number	Time & Date of Failure	Failure Mode	Failure Severity	Failure Mechanism	Failure Root Cause Description	Hydrogen Release (Yes/No)	Release Size (Small/ Medium/Large)	Ignition (Yes/No)
25	07/17/2021 08:32	External leakage-Process medium	Critical	Leakage		Yes	Medium	No
26	10/17/2021 15:33	Parameter deviation	Degraded	Overheating		No	Small	No

- **Maintenance event data fields**

Date & Time Repair Started	Date & Time Repair Completed	Date & Time Station Restarted	Action Performed	Maintenance Description
07/18/2021 09:55	07/28/2021 10:00	07/29/2021 09:30	Replacement	
10/17/2021 17:30	10/20/2021 13:30	10/20/2021 15:30	Repair	

- Al-Douri, A.; West, M. A. & Groth, K. M. "A Foundational Framework for Reliability Data Collection for Hydrogen Systems." AIChE 2022 Spring Meeting and the 18th Global Congress on Process Safety, 2022
- Katrina M. Groth, Ahmad Al-Douri, Madison West, Kevin Hartmann, Genevieve Saur, William Buttner. "Design and Requirements of a Hydrogen Component Reliability Database (HyCReD)," Submitted to IJHE in March 2023.

Sample Database Entries: HIAD & H2Tools Incidents

Hydrogen Incident and Accident Database (HIAD)

	System Information											
Event Number	Plant Identification	Facility Type	Service/Usage	Facility Nominal Working Pressure (bar)	Equipment Description	Subsystem	Functional Group	Component	Component Nominal Working Pressure (bar)	Component Population	Installation Date	P&ID Part Number
HyCReD #1	Emeryville (Upgrade)	Pre-commercial, limited-access	Both heavy- and light-duty	700 bar	Pressure relief valve on the high-pressure storage tubes	Bulk_Storage	Containment	Pressure relief valve	-	-	-	-
HyCReD #2	Uno-X Kjørbo	Commercial, public	Light-duty	Unknown	Plugs on a high-pressure hydrogen storage tank	Bulk_Storage	Containment	Double-walled tank	-	-	-	-
HyCReD #3	Unidentified (U.S.)	Unknown	Unknown	Unknown	Shaft seal on hydrogen compressor	Compression_Process	Compression	Compressor	-	-	-	-
HyCReD #4	Unidentified	Commercial, limited access	Heavy-duty	700 bar	Solenoid valves were not operating correctly	Dispensing_Process	Sensing and control	Flow control va	-	-	-	-
HyCReD #5	HITRF	Research, limited-access	Both heavy- and light-duty	This is a 700-bar dispenser for light-duty use supplied by permanent, on-site gaseous storage of approx. 600 kg	Medium-pressure manual isolation ball valve (normally open) on a high-pressure, light-duty H2 dispenser	Dispensing_Process	Sensing and control	Manual valve	480-860 bar	5	Jan-19	HV-120A*

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

SYRRA

Sample Database Entries: HIAD & H2Tools Incidents

Failure Information												
Date & Time of Event	Phase of Operations	Failure Mode	Failure Mechanism	Failure Root Cause Description	Failure Severity	H2 release (yes/no)	H2 release size (small/medium/ large)	Accumulation?	Detection?	Detection notes	Ignition? (yes/no)
5/4/2012; 07:45	Operations	External leak hydrogen; Failure to close on demand	Hydrogen embrittlement	Improper materials selection	Critical	Yes	Large (300 kg)	Yes	No	-	Yes
6/10/2019; 17:30	Operations	External leak hydrogen	Human error	-	Critical	Yes	Large	Yes	No	-	Yes
10/06/09	Operations	External leak hydrogen	Mechanical failure	-	Critical	Yes	Unknown	No	Yes	-	No
07/23/13	Operations	Fail to operate	Binding/jamming	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.	Minor	No	Unknown	No	Yes	-	No
12/20/2021; 11:45	Operations	External leak hydrogen	Mechanical failure	Appears to be O-ring extrusion/failure (sent to NREL for LRQA testing)	Minor	Yes	Small (1-2 kg)	No	Yes	Audible	No

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

SYRRA

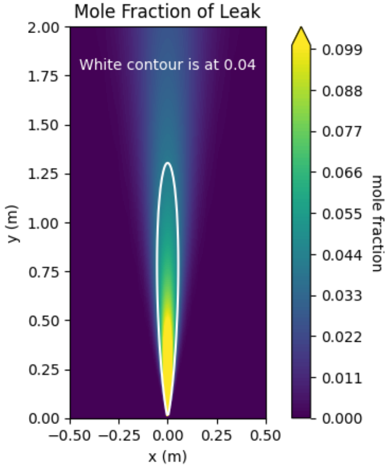
Component Leak Rate Quantification: Ball Valve with External Leakage

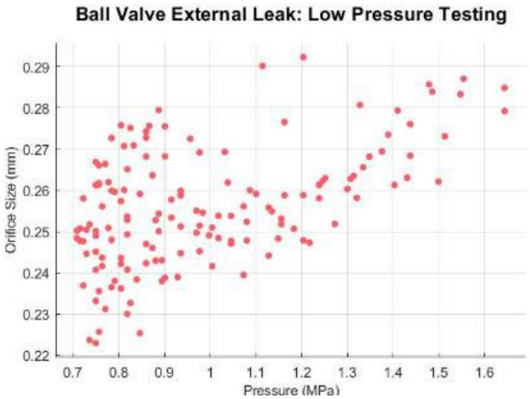
- The LRQA was used to quantify leak rates of failed hydrogen components
  - Data below is for a leaking ball valve with an average orifice size of 0.25 mm
    - The ball valve originally had failed in service with an audible ASME B31.12 Grade 1 Leak
    - During LRQA testing the o-ring significantly 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

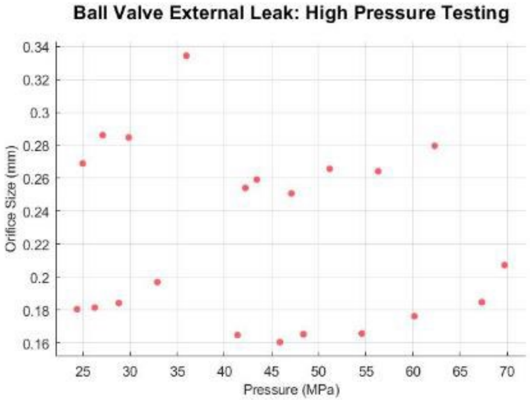
Leak rates for failed components were quantified by the LRQA
- This work is ongoing as we acquire a larger inventory of failed components

Orifice Size: 0.25 mm

Nominal upstream pressure of 55 MPa







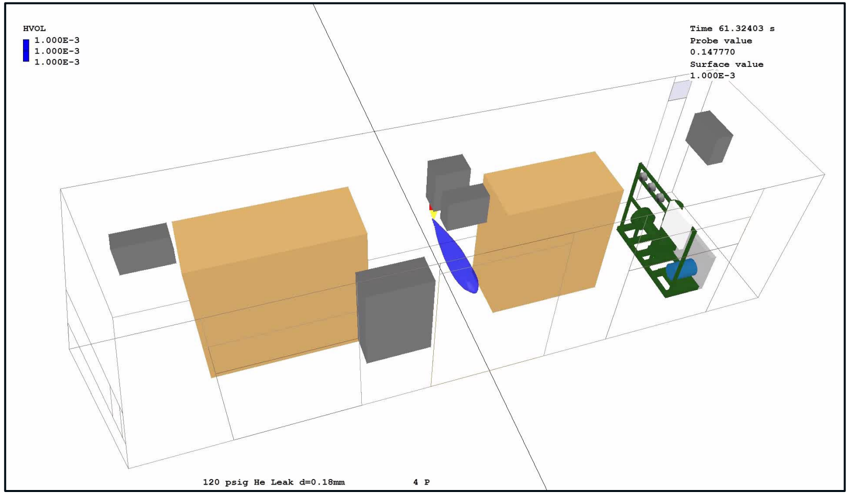
HyRAM Reference: Brian D. Ehrhart, Ethan S. Hecht, and Katrina M. Groth. Hydrogen Risk Assessment Models (HyRAM) Version 3.1 Technical Reference Manual. SAND2021-5812, May 2021.

AVT and NREL have Collaboration on Strategies for Optimal Sensor Placement in Enclosures

Previously AVT and NREL did CFD Modeling and hardware validation of hydrogen releases in indoor facilities (including enclosures)

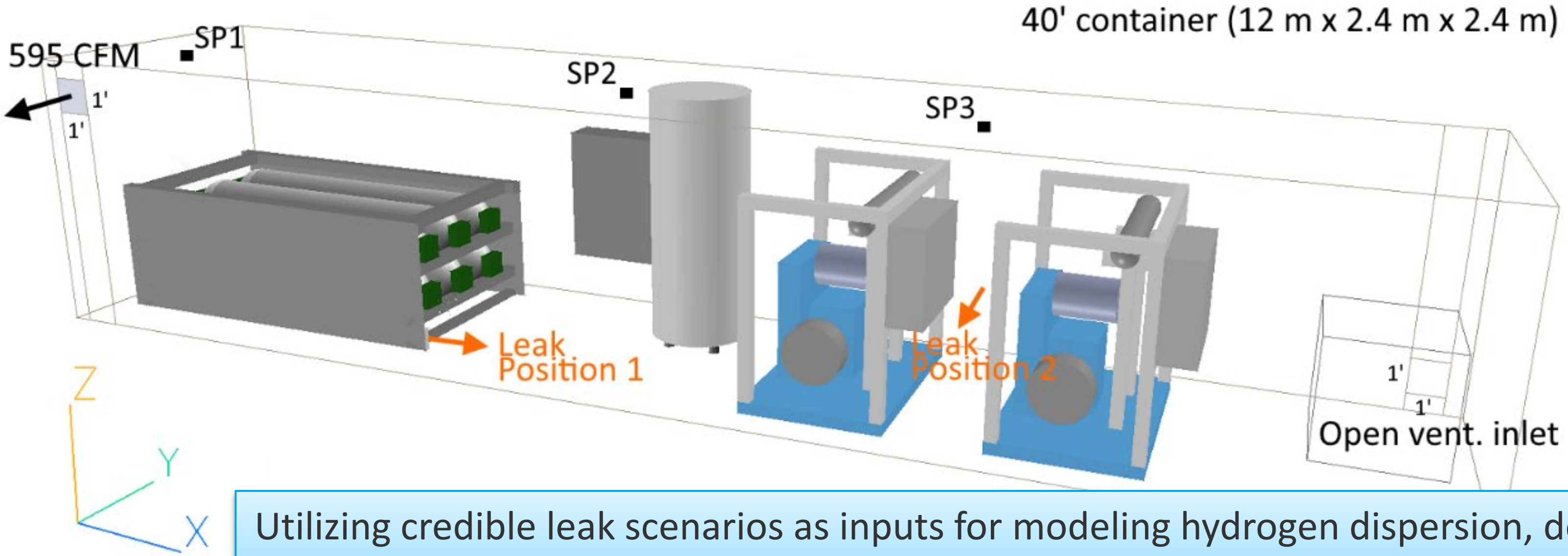
- Well-defined 3-dimensional footprint
- "Predictable" dispersion guiding sensor placement for early detection [*Development of Risk Mitigation Guidance for Sensor Placement Indoors and Outdoors*, Tchouvelev, Buttner et al., IJHE 46 (2020) 12439-12454]
  - CFD Modelling validated by HyWAM
- Sensor mandated by code for many applications
- Delayed ignition of unmitigated leak can be disastrous
  - Generally, point sensors have been effective

Indoor Releases—Predictable H2 Behavior (for optimal sensor placement)



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

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

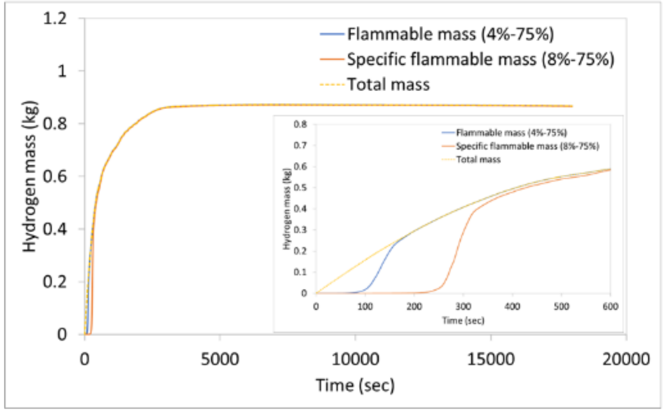
- 550 barg leak parameters using Ideal gas equation of state for Leak 1 and Leak 2 positions

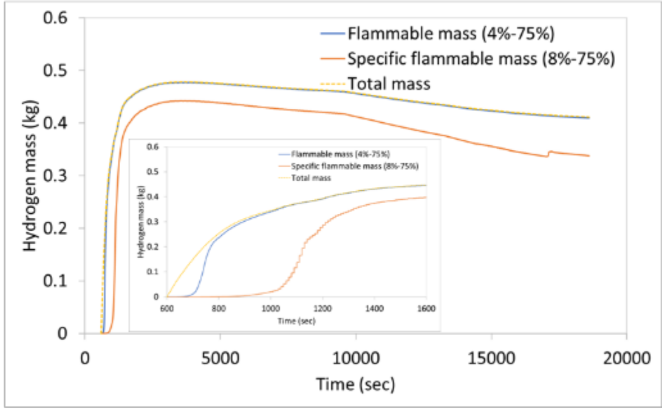
	Leak A	Leak B	Leak C
Pressure (barg)	550	550	550
Leak diameter (m)	**0.00018**	**0.00025**	**0.000358**
Equivalent diameter (m) (Birch 1984)	0.00319	0.00443	0.00635
Equivalent area (m^2)	7.9994×10^{-6}	1.5431×10^{-5}	3.1643×10^{-5}
Mass flow rate (g/s)	**0.875**	**1.688**	**3.462**
Turbulent Intensity	6.0973	5.8520	5.5951

Applying Credible Leak Scenarios to Indoor Enclosures: Leak B (0.25 mm)

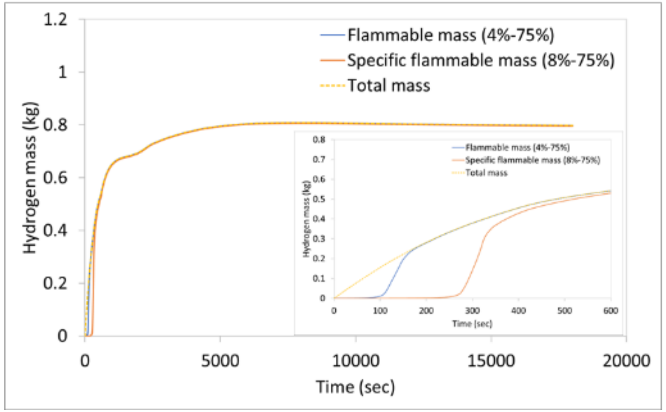
No Ventilation | 595 CFM

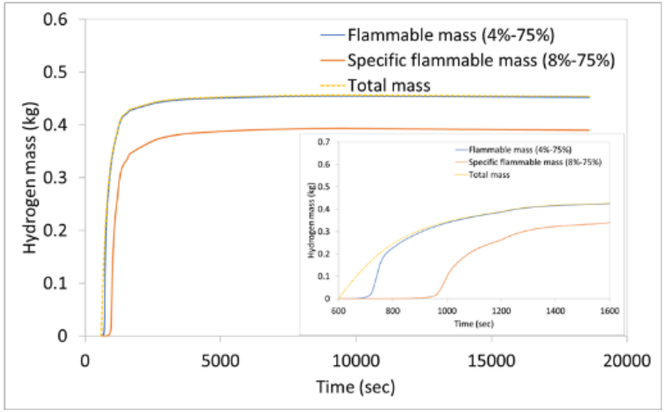
Leak Position 1
Horizontal X+





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

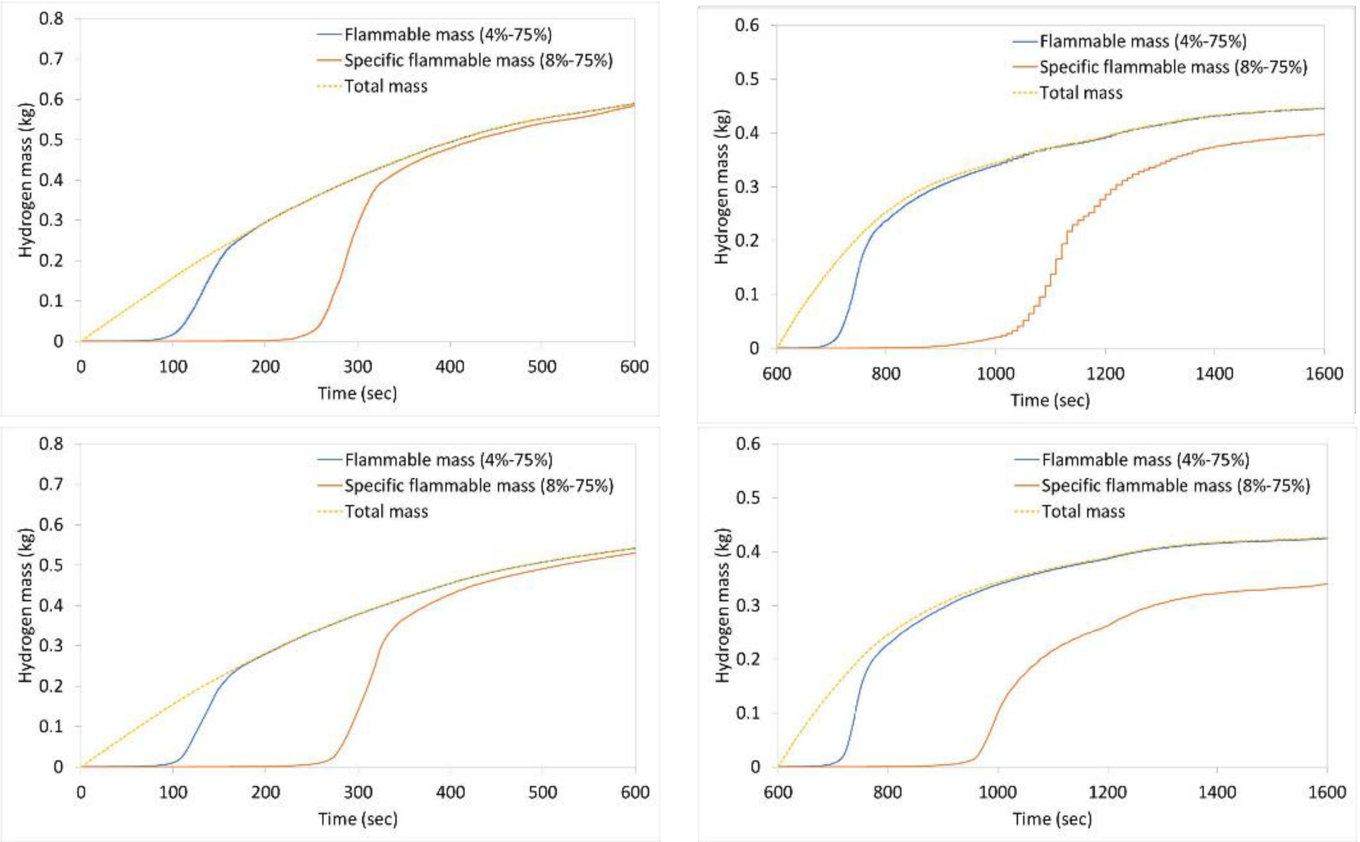
Leak Initiation Behavior: Leak B (0.25 mm)

No Ventilation | 595 CFM

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

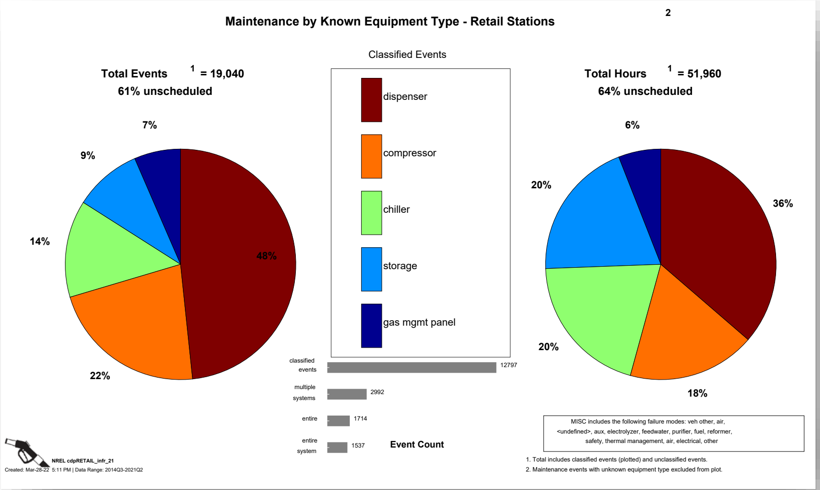
- Challenge recreating leaks in the LRQA following removal from the system due to a failure.
- The LRQA does not accommodate all components or leak scenarios (e.g., cold gas)
- Stakeholder buy in
  - Industrial stakeholders express interest but lack resources to properly documents failure events (internal 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



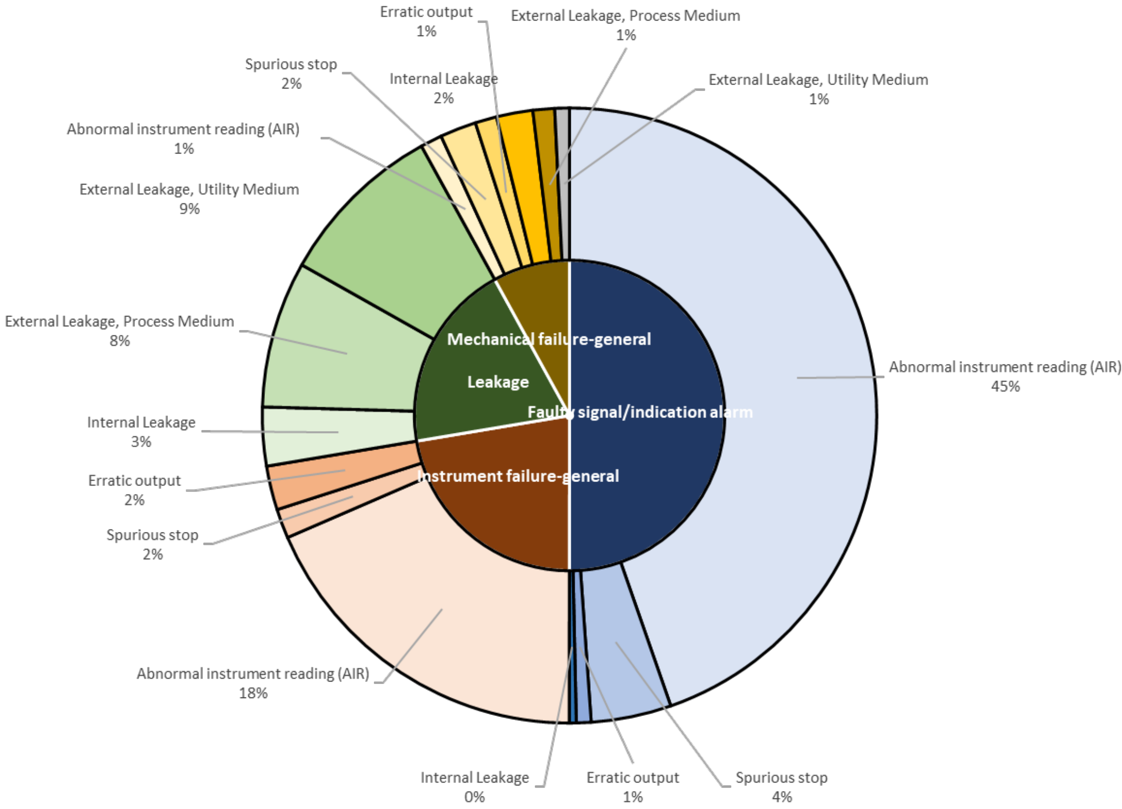
https://www.nrel.gov/hydrogen/infrastructure-cdps-retail.html

NFCTEC brings valuable experience working with similar data and anonymous data publication to support development of HyCReD

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

Expected Outcome: Statistical Representation of Failure Modes and Mechanisms

- From the **O**ffshore and Onshore **Re**liability **Da**ta (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

OREDA, 2015

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

Potential Impact

- 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 → higher number of fills → *greater economic returns*
  - Information for reliability-centered maintenance (RCM) analysis → Enables prioritizing replacement and/or maintenance activities → *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 **Hy**drogen **C**omponent **Re**liability **D**atabase (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

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Thank You

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