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HYDROGEN EQUIPMENT ENCLOSURE RISK REDUCTION THROUGH EARLIER DETECTION OF COMPONENT FAILURES

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Project Goal

- Develop a quantified relationship between leak size, ventilation, and the location of gaseous hydrogen detectors on the flammable mass in a hydrogen equipment enclosure upon a component failure
  - CFD modeling of leaks in a hydrogen equipment enclosure (HEE)
  - Analyze the possible time to reach gaseous detector alarm levels
  - Evaluate the impact of leak size and ventilation on the flammable mass in the enclosure
  - Develop a better understanding of leak behavior and leak size for a variety of components and failure modes
- Deploy QRA to evaluate and mitigate risk associated with failures in the hydrogen equipment enclosure

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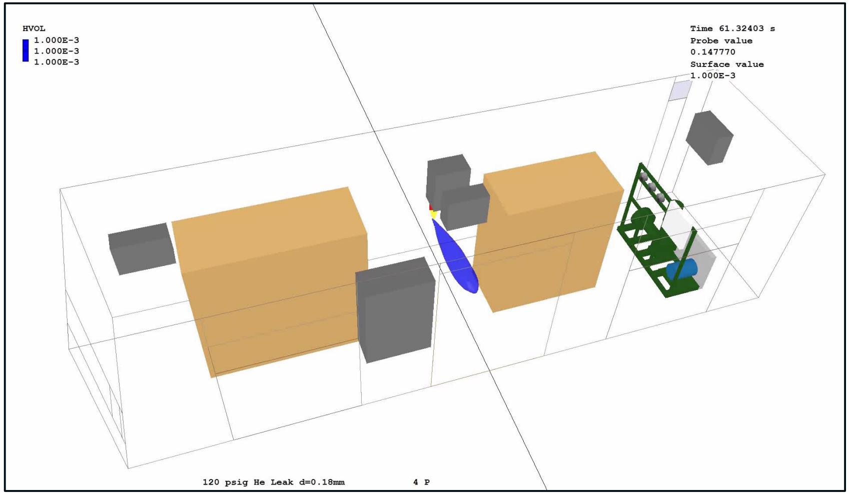
Collaboration and Coordination

- National Renewable Energy Laboratory (NREL)
  - Leak rate quantification and leak size selection
  - NREL sensor laboratory
- A.V. Tchouvelev & Associates Inc. (AVT) in partnership with Université Du Québec à Trois-Rivières
  - Industry and university collaboration
  - CFD modeling of quantified leaks in enclosures.
- University of Maryland Center for Risk and Reliability
  - Risk and reliability experts beginning to apply QRA to the modeled hydrogen equipment enclosure
  - Collaboration to obtain hydrogen component failure data (e.g., HyCReD) and apply data through QRA to reduce system risk

Previous Collaboration Strategies for Optimal Sensor Placement in Enclosures

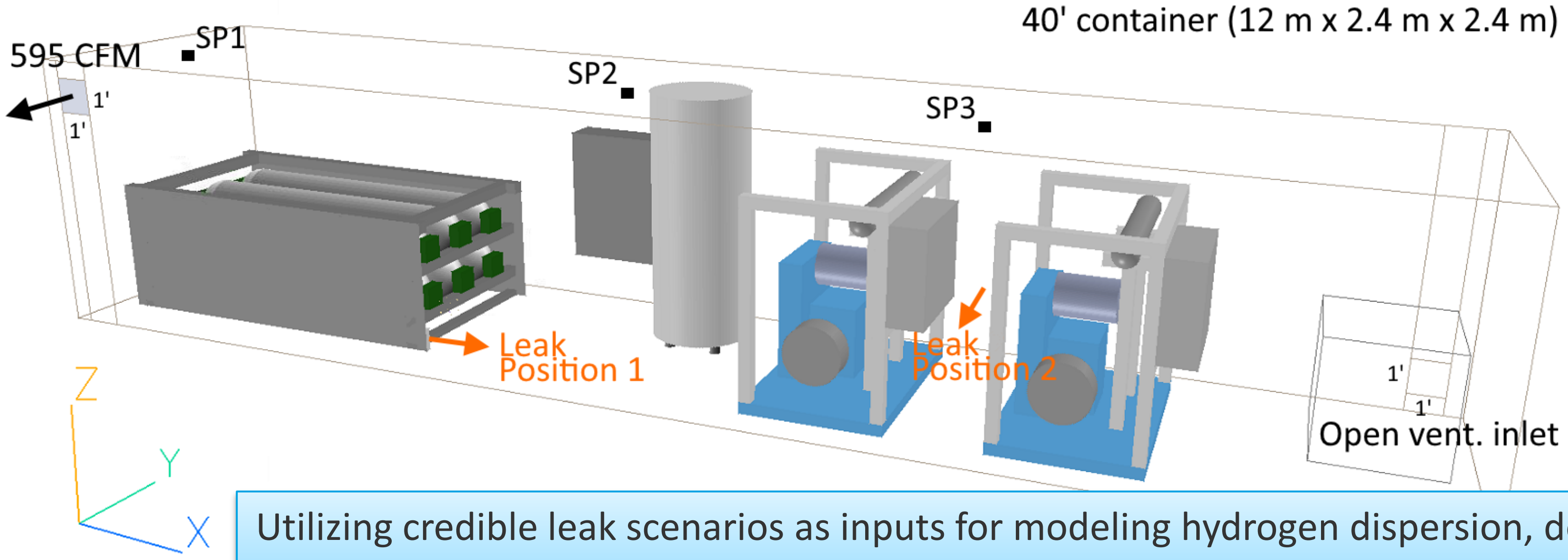
- AVT and NREL completed CFD Modeling and hardware validation of hydrogen releases in indoor facilities (including enclosures)
- “Predictable” dispersion guiding sensor placement for early detection
  - *Development of Risk Mitigation Guidance for Sensor Placement Indoors and Outdoors*, Tchouvelev, Buttner et al., IJHE 46 (2020) 12439-12454
  - CFD Modelling validated by NREL’s Hydrogen Wide Area Monitoring (HyWAM) system

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



- Developed a recommendation to use a lower detection limit of ~0.1 vol% hydrogen
- Developed recommendations for sensor placement in enclosures based on modeling and hardware experimentation

Applying Credible Leak Scenarios to Indoor Enclosures: Setup and Leak Parameters



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

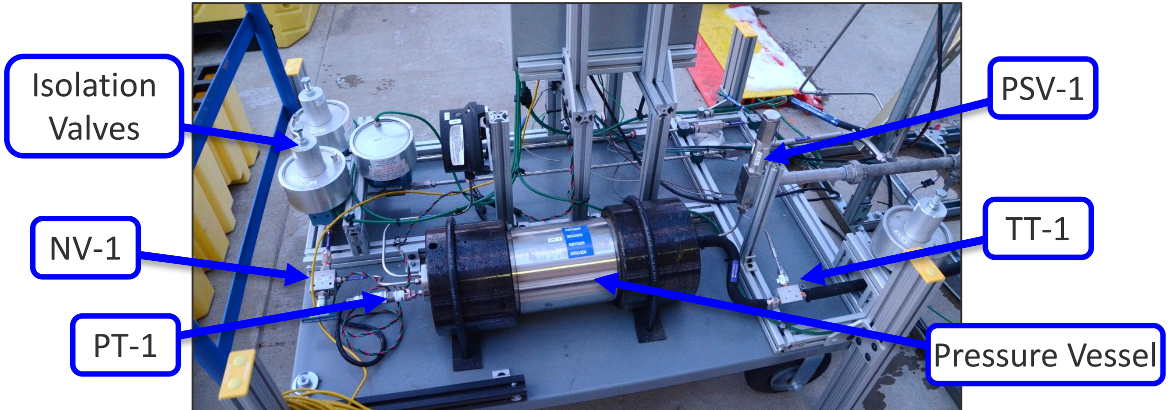
- 550 barg leak parameters using ideal gas equation of state for Leak 1 and Leak 2 positions

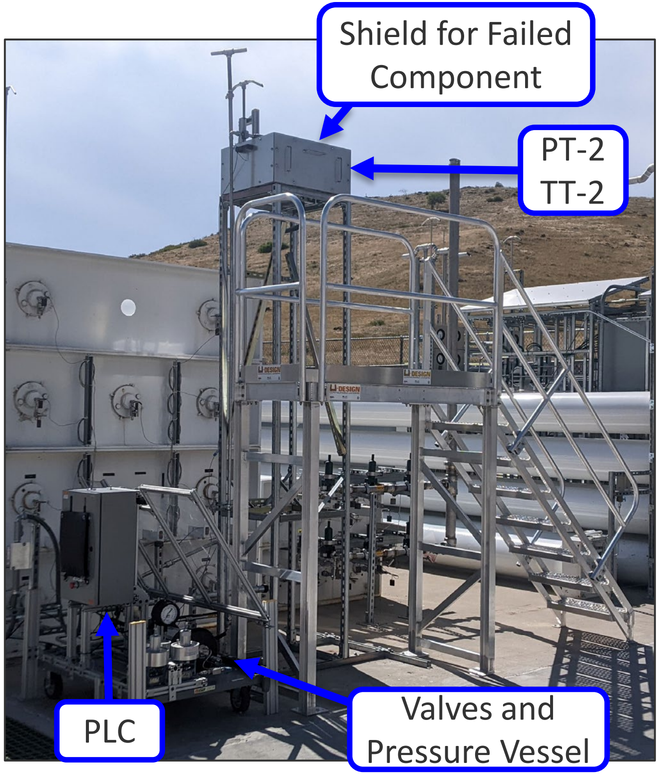
	Leak A	Leak B	Leak C
Pressure (barg)	550	550	550
Leak diameter (m)	**0.00018**	**0.00025**	**0.000358**
Equivalent diameter (m) (Birch 1984)	0.00319	0.00443	0.00635
Equivalent area (m^2)	7.9994×10^{-6}	1.5431×10^{-5}	3.1643×10^{-5}
Mass flow rate (g/s)	**0.875**	**1.688**	**3.462**
Turbulent Intensity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

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*)



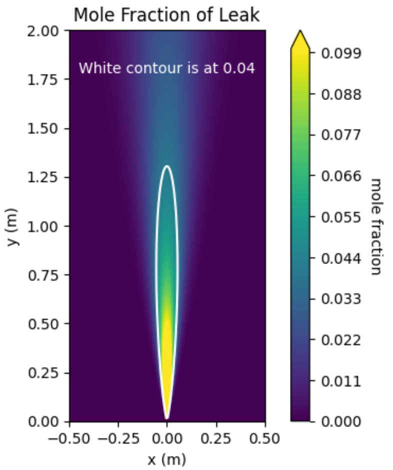


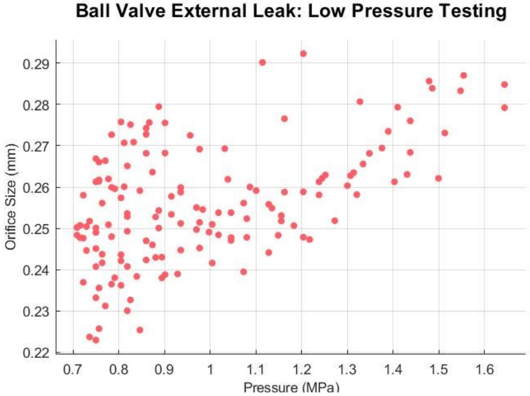
Component Leak Rate Quantification: Ball Valve with External Leakage

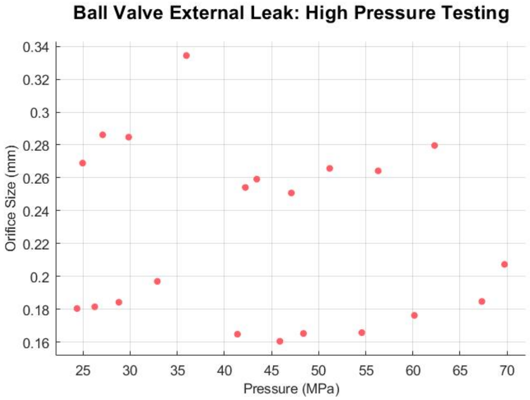
- The LRQA was used to quantify leak rates of failed hydrogen components
  - Data below is for a leaking ball valve with an average orifice size of 0.25 mm
    - The ball valve originally had failed in service with an audible ASME B31.12 Grade 1 Leak
    - During LRQA testing the o-ring significantly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

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.

NFPA 2 and IEC Recommended Leak Sizes

- NFPA 2 references 1% of the flow area of the largest tubing in a system as a leak area estimate.
  - Using the method for leak estimating outlined in NFPA 2 for 3/8-inch (9.525 mm) outer diameter and 0.203 inch inner diameter medium pressure tubing
    - Leak orifice diameter of 0.52 mm or less for most components

- IEC 60079-10-1 table B.1 provides potential leak sizes for different times of components and fittings.
  - Sealing elements on fixed parts, small-bore connection
  - For conditions where the release opening will not expand to be between 0.18 mm to 0.36 mm
  - For conditions where the release opening may expand to be between 0.36 mm and 0.56 mm

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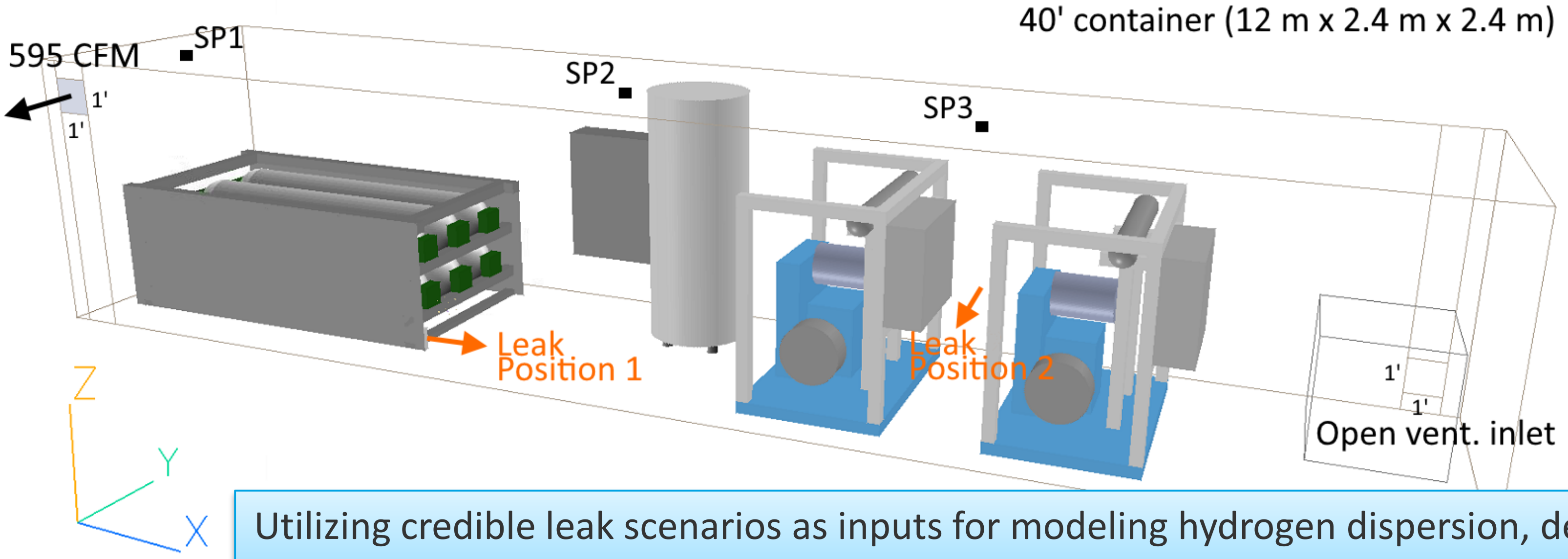

Utilizing credible leak scenarios as inputs for modeling hydrogen dispersion, detection response time, and hazards

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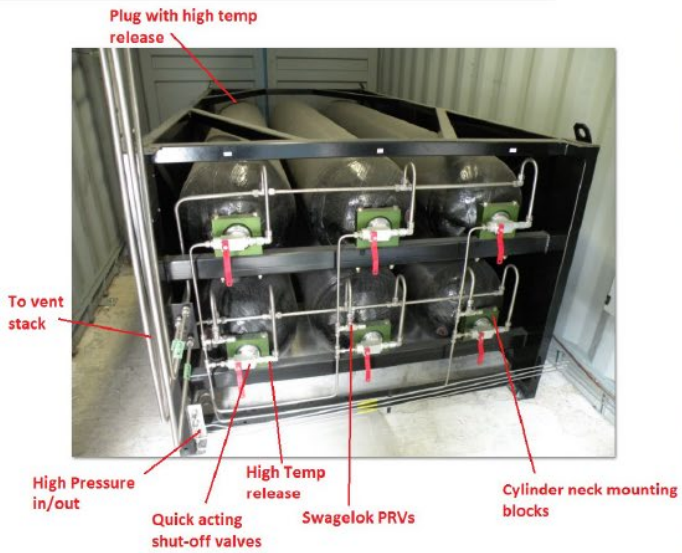
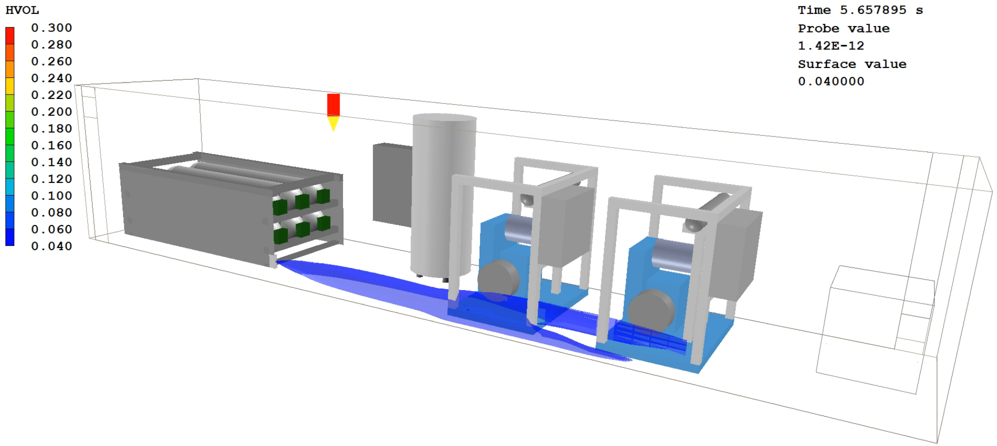
Physical Enclosure Hardware

- Key components of selected large enclosure (typical 40-ft container): HP H2 storage skid. Photo Credit: Andrei V. Tchouvelev (ref. Canadian Tire Pilot Project)



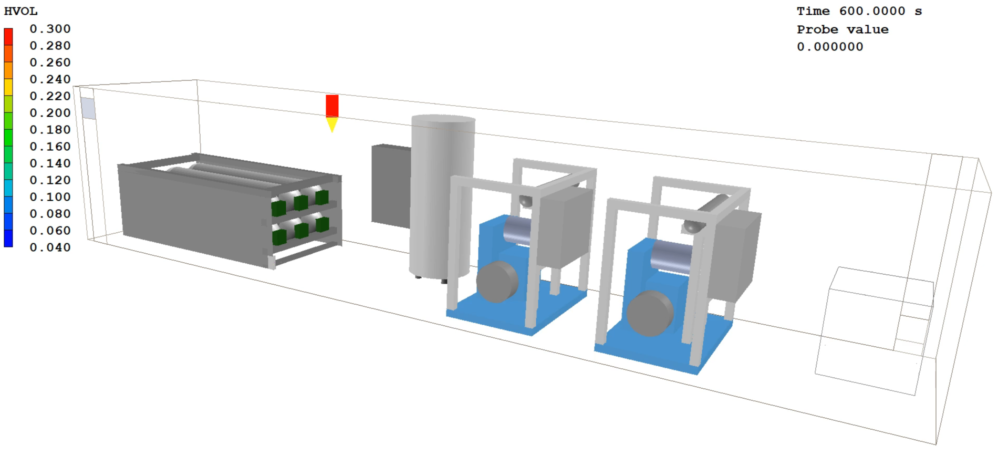
0.358 mm Leak From Position 1, X+ direction, Passive Ventilation

- Color of the hydrogen plume is the hydrogen concentration at the detector
  - Detector location is shown by the yellow and red arrow at the top of the enclosure
- Activation of the emergency shutdown system and isolation of the hydrogen gas supply could reduce the hydrogen concentration in the HEE
  - Without mechanical ventilation the hydrogen concentrations can reach very hazardous 27% range, in the extended 18,000 second leak scenario



0.358 mm Leak From Position 1, X+ direction, 595 CFM Ventilation On

- Color of the hydrogen plume is the hydrogen concentration at the detector
  - Detector location is shown by the yellow and red arrow at the top of the enclosure
- Activation of the emergency shutdown system and isolation of the hydrogen gas supply could reduce the hydrogen concentration in the HEE
  - Even with ventilation the hydrogen concentration due to leaks from the largest expanded orifice can reach ~17% vol. at the monitor points in the extended 18,000 second leak scenario
- In the case of no mechanical ventilation the amount of flammable mass is ~50% higher than in the case with mechanical ventilation

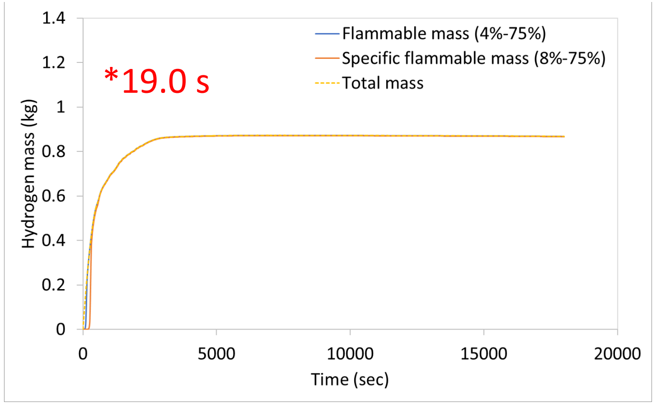


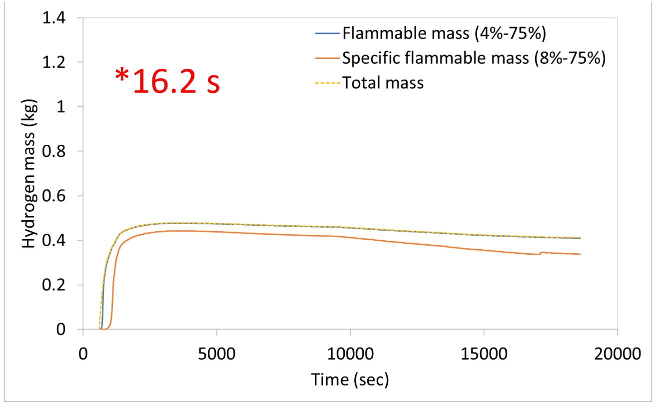
Applying Credible Leak Scenarios to Indoor Enclosures: Leak B (0.25 mm), Position 1

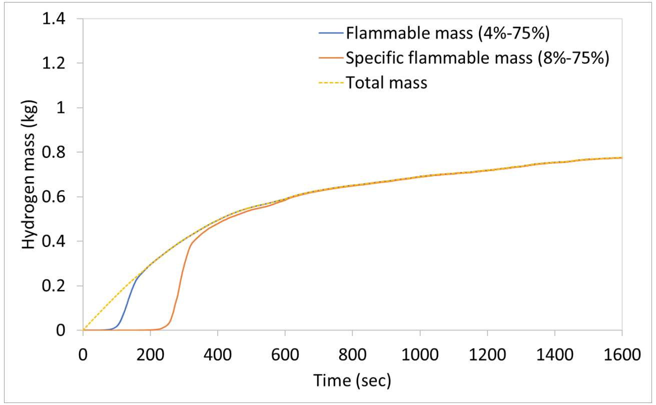
Leak Position 1

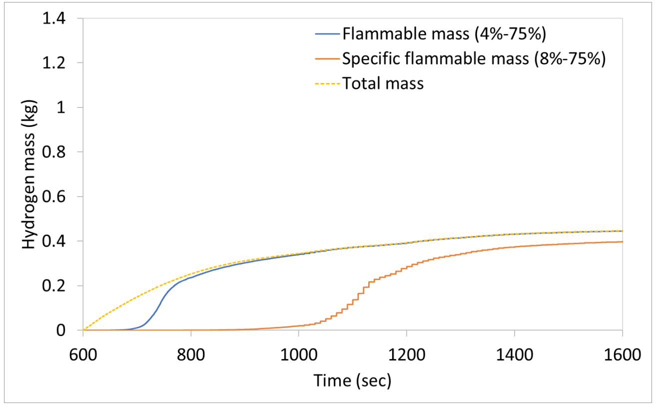
0.25 mm

Horizontal X+









*detection time of 0.1% vol. target

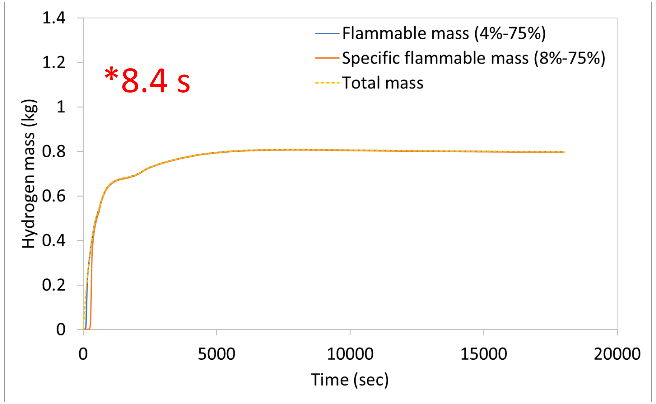
Impact of ventilation on detection response time and hazard mitigation: faster detection time and reduced (by x 2) hazardous flammable mass

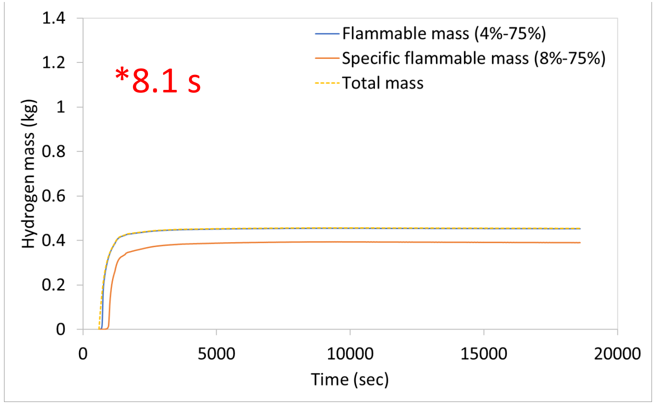
Applying Credible Leak Scenarios to Indoor Enclosures: Leak B (0.25 mm), Position 2

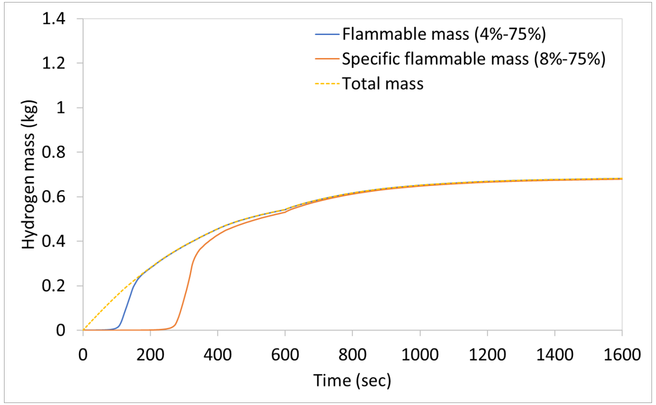
Leak Position 2

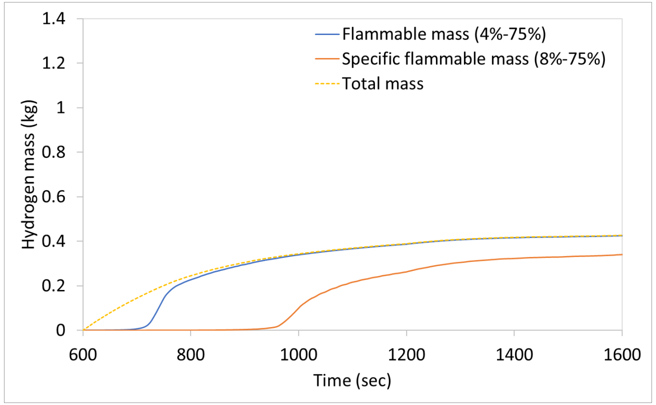
0.25 mm

Horizontal X+









*detection time of 0.1% vol. target

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

Conclusions

- Natural (passive) ventilation
  - Is insufficient to deal with any of the considered leak scenarios in the specified geometry and locations of air intake and exhaust
  - Most of the considered leak scenarios can be detected within 15 s under no mechanical ventilation condition
    - If the leak continues, the average hydrogen concentration can exceed 8% mole fraction within 150 s after the onset of the leak
- Mechanical ventilation
  - Ventilation was found to reduce the time needed for a leak to be detected at the considered detection locations
  - For this enclosure, the air flow rates are sufficient to prevent accumulation of hazardous flammable amount of hydrogen for the 0.18 mm leak size
    - Even for extended exaggerated leak duration
  - For this enclosure, the air flow rates are insufficient to prevent accumulation of hazardous flammable amounts of hydrogen for the expanded leaks of 0.25 mm and particularly 0.385 mm.

Proposed Future Work

- 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. impact of air intake configuration)

- Use QRA to model total system risk
  - Develop the risk scenario models and equipment failure logic models (e.g., event tree, fault tree) of QRA for the equipment inside the enclosure
    - Connect the risk scenario models with the consequences identified in the CFD HEE simulations.
  - Develop QRA models for the system to identify probability of failures, probability of undesired outcomes, and calculate total risk to the populations and facilities of interest in the NFPA 2
    - Compare that risk to similar systems and/or established risk tolerability metrics

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

Summary

- Utilized the credible leak scenarios as inputs for modeling hydrogen dispersion, detection, and hazard quantification in a hydrogen equipment enclosure
  - Mechanical ventilation, placement of sensors, and detection alarm level leading to shutdown can be critical in mitigating the hazards associated with the leaks from hydrogen piping and components

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Thank You

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Technical Backup and Additional Information

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.