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Quantitative risk assessment of LH_2 systems: data and model needs

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In the U.S., authorities look to NFPA 2 for standards on how to site hydrogen fueling stations

- Different distances for different exposures
- Some distances able to be reduced with mitigations (barrier wall, insulation, etc.)
- Gaseous separation distances related to diameter and pressure
- Liquid separation distances related to storage volume
- Justification for gaseous separation distances provided in annex
  - Separation distance reductions in NFPA 2 2011 (previously based on OSHA tables) and 2020 (under review) enabled by Sandia-led scientific analyses

2–42 HYDROGEN TECHNOLOGIES CODE

Table 7.3.2.3.1.1(a) Minimum Distance (D) from Outdoor [GH_2] Systems to Exposures — Typical Maximum Pipe Size

Pressure	>15 to ≤250 psig		>250 to ≤3000 psig		>3000 to ≤7500 psig		>7500 to ≤15000 psig	
Internal Pipe Diameter (ID) d_{mm}	>103.4 to ≤1724 kPa $d=52.5_{mm}$		>1724 to ≤20,684 kPa $d=18.97_{mm}$		>20,684 to ≤51,711 kPa $d=7.31_{mm}$		>51,711 to ≤103,421 kPa $d=7.16_{mm}$	
Group 1 Exposures	m	ft	m	ft	m	ft	m	ft
(a) Lot lines (b) Air intakes (HVAC, compressors, other) (c) Operable openings in buildings and structures (d) Ignition sources such as open flames and welding	12	40	14	46	9	29	10	34
Group 2 Exposures	m	ft	m	ft	m	ft	m	ft
(a) Exposed persons other than those servicing the system (b) Parked cars	6	20	7	24	4	13	5	16
Group 3 Exposures	m	ft	m	ft	m	ft	m	ft
(a) Buildings of noncombustible non-fire-rated construction	5	17	6	19	4	12	4	14
(b) Buildings of combustible construction								

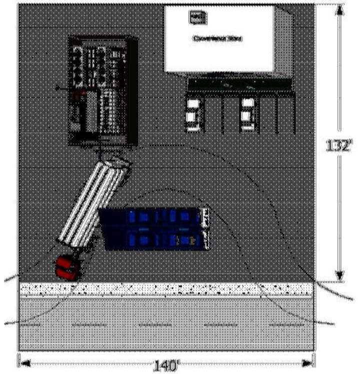
2–58 HYDROGEN TECHNOLOGIES CODE

Table 8.3.2.3.1.6(A) Minimum Distance from Bulk Liquefied Hydrogen [LH_2] Systems to Exposures

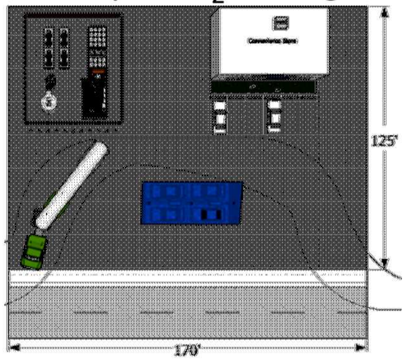
	Total Bulk Liquefied Hydrogen [LH_2] Storage					
	39.7 gal to 3500 gal	150 L to 13,250 L	3501 gal to 15,000 gal	13,251 L to 56,781 L	15,001 gal to 75,000 gal	56,782 L to 283,906 L
Type of Exposure	ft	m	ft	m	ft	m
Group 1						
1. Lot lines	25	7.6	50	15	75	23
2. Air intakes [heating, ventilating, or air conditioning equipment (HVAC, compressors, other]	75	23	75	23	75	23
3. Wall openings						
Operable openings in buildings and structures	75	23	75	23	75	23
4. Ignition sources such as open flames and welding	50	15	50	15	50	15
Group 2						
5. Places of public assembly	75	23	75	23	75	23
6. Parked cars (distance shall be measured from the container fill connection)	25	7.6	25	7.6	25	7.6
Group 3						
7. Building or structure						
(a) Buildings constructed of noncombustible or limited-combustible materials						
(1) Sprinklered building or structure or unsprinklered building or structure having	5[a]	1.5	5[a]	1.5	5[a]	1.5

Separation distances for liquid hydrogen are onerous and lack detailed scientific justification

gaseous H_2 storage

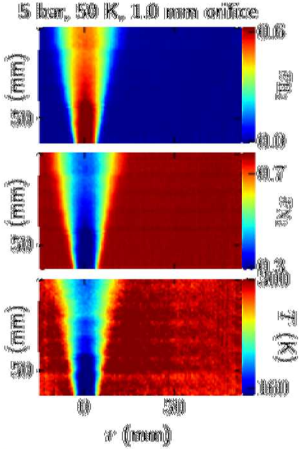


vs. liquid H_2 storage

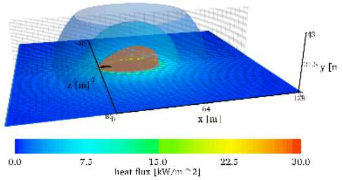


Sandia H_2 Safety Codes and Standards research includes coordinated activities that facilitate deployment of hydrogen technologies

- Hydrogen Behavior
  - **Develop and validate scientific models** to accurately predict hazards and harm from liquid releases, flames, etc.
- Quantitative Risk Assessment, tools R&D
  - **Develop integrated methods and algorithms** enabling consistent, traceable, and rigorous QRA (Quantitative Risk Assessment) for H_2 facilities and vehicles
- Enable Hydrogen Infrastructure through Science-based Codes and Standards
  - **Apply QRA and behavior models to real problems** in hydrogen infrastructure and emerging technology
  - **Facilitate updates to NFPA 2** through deep technical analyses



HyRAM
HYDROGEN RISK ASSESSMENT MODELS



Quantitative risk assessment (QRA) provides a basis for gaseous hydrogen separation distances

- Conservative: assess worst possible accident scenario(s) (e.g., full line shear, tank rupture)
  - Low frequency
  - Prohibitive distance
  - Separation distance does not *(and should not*)* protect against this scenario

** Author's opinion*

- Risk informed
  - Factor in leak frequency
  - Potential methods:
    - Perform QRA on each system of interest
    - Use QRA results from typical system to relate deterministic distance(s) to acceptable risk
    - Determine probable maximum leak size and assess accident scenario(s) (cover 95%, 99%, etc. of probable leaks)

Selected text from annex (I - NFPA 2, H – NFPA 55)

Size. The development of separation distances for hydrogen facilities can be determined in several ways. A conservative approach is to use the worst possible accidents in terms of consequences. Such accidents can be of very low frequency such that they likely would never occur. Although this approach bounds separation distances, the resulting distances are generally prohibitive. The current separation distances do not reflect this approach.

Component leak frequencies as a function of leak size were generated for several hydrogen components. The hydrogen-specific leakage rates were used to estimate the leakage frequency for four example systems used as the basis for the risk evaluation used in the study. The cumulative probability for different leak sizes was then calculated to determine what range of leaks represents the most likely leak sizes. The results of this analysis indicated that leaks less than 0.1 percent of the component flow areas represent 95 percent of the leakage frequency for the example systems. Leak areas less than 10 percent of the flow area are estimated to result in 99 percent of the leaks that could occur based on the results of the analysis.

Risk informed approach: acceptable risk must be decided along with a typical system

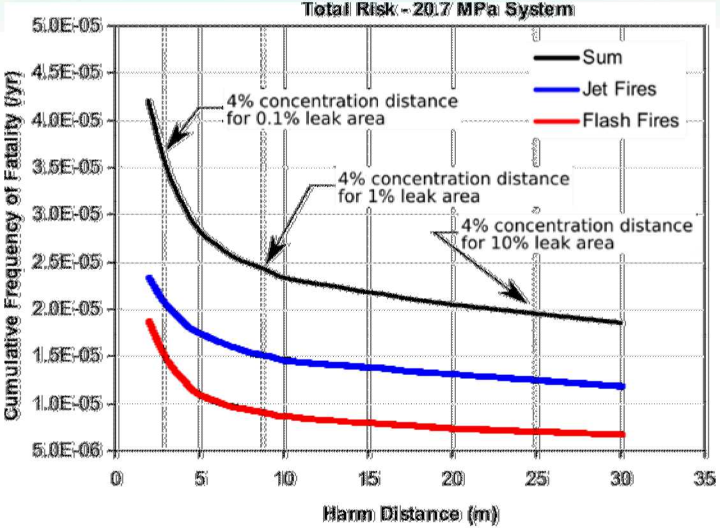
Selected text from annex (I - NFPA 2, H – NFPA 55)

The risks resulting from different size leaks were also evaluated for four standard gas storage configurations. The risk evaluations indicate that the use of 0.1 percent of the component flow area as the basis for determining separation distances results in risk estimates that significantly exceed the 2×10^{-5}/yr risk guideline selected by the NFPA separation distance working group, particularly for the 7500 psig and 15,000 psig systems. On the other hand, use of a leak size equal to between 1 percent and 10 percent of the component flow area results in risk estimates that are reasonably close to the risk guideline. The fact that the risk estimates are a factor of

Based on the results of both the system leakage frequency evaluation and the associated risk assessment, a diameter of 3 percent of the flow area corresponding to the largest internal pipe downstream of the highest pressure source in the

system is used in the model. The use of a 3 percent leak area results in capturing an estimated 98 percent of the leaks that have been determined to be probable based on detailed analysis of the typical systems employed. Typical systems to include

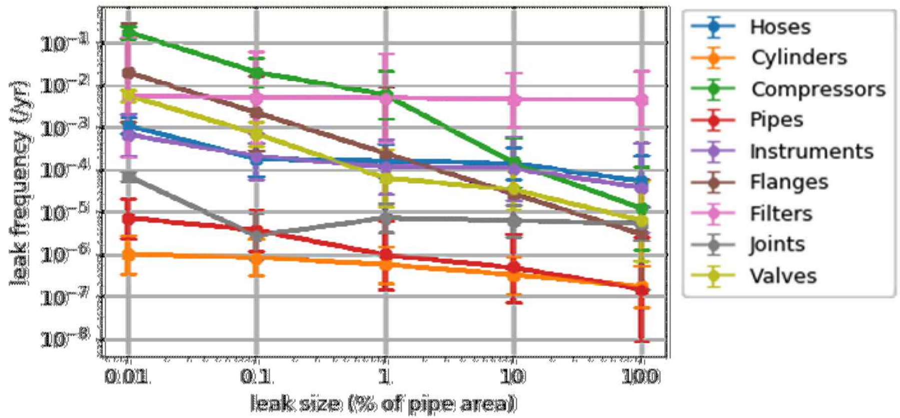
3% leak area reduced to 1% in proposed NFPA 2 update – gaseous hydrogen setback distances further reduced

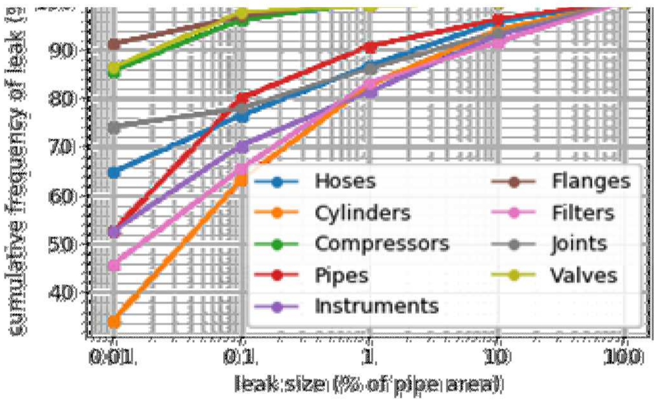


Gaseous distance reduction method:

- QRA performed on typical system
- Overall risk compared to deterministic hazard distances (jet flame radiation, unignited flammable concentration)

Key component of QRA is leak frequency – lacking for LH_2





- More 'leaky' components -> more risk
- Hazard/harm distance related to pressure (and temperature for LH_2) and flow area
  - Separation distances for gas also related to pressure and flow area
  - Separation distance for liquid related to capacity – analysis may show this to be poor criteria
- More specificity could improve accuracy – compression joint not going to have the same leak frequency as threaded as weld, etc.
- Lack of leak frequency data for liquid hydrogen components
- SNL currently gathering leak frequency data

The NFPA 2 liquid hydrogen setback distance task group has a path for separation distance reduction, but there are gaps for LH_2

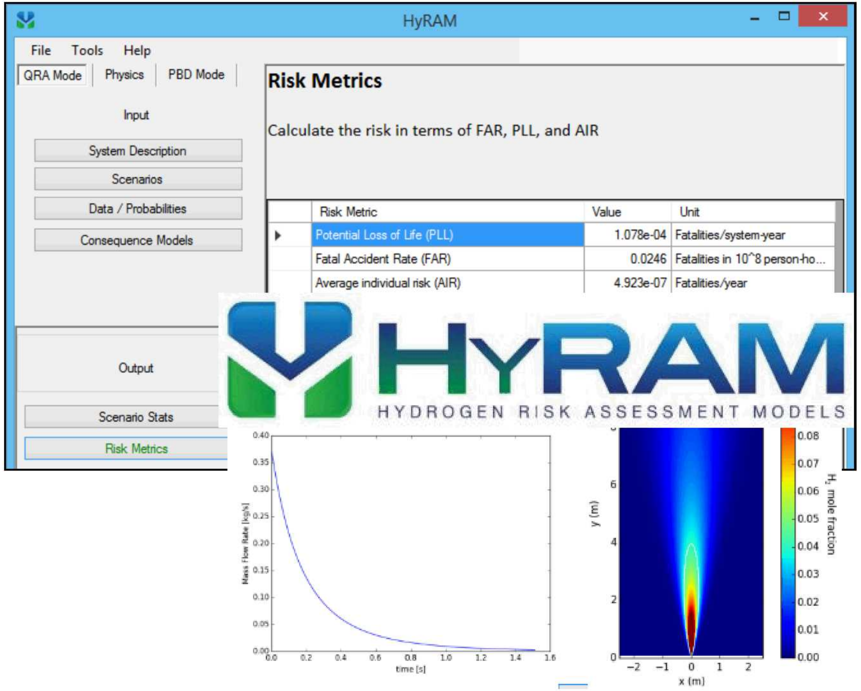
Gaseous

- ✓ Determine list of exposures
- ✓ Conduct hazard analysis
- ✓ Create representative system
- ✓ Acquire leak data
- ✓ Calculate leak frequency (using representative system and leak data)
- ✓ Calculate consequence distances using physics models and representative leak parameters
  - Unignited concentration of 8%
  - Heat flux of 4.7 kW/m^2
- ✓ Determine separation distance using frequency calculations and consequence calculations
  - Function of size and pressure

Liquid

- ✓ Determine list of exposures
- ✓ Conduct hazard analysis
- ✓ Create representative system – additional parameters for LH_2
  - Temperature
  - Phase (liquid or gas)
- ☐ Acquire leak/vent data
  - ☐ Unanticipated leaks
  - ☐ Vent rates
- ☐ Calculate leak/vent frequency
- ☐ Calculate consequence distances using physics models and representative leak/vent parameters
- ☐ Determine separation distance using frequency calculations and consequence calculations
  - Function of LH_2 volume or something else?

Sandia developed software – HyRAM – enables QRA of gaseous hydrogen systems

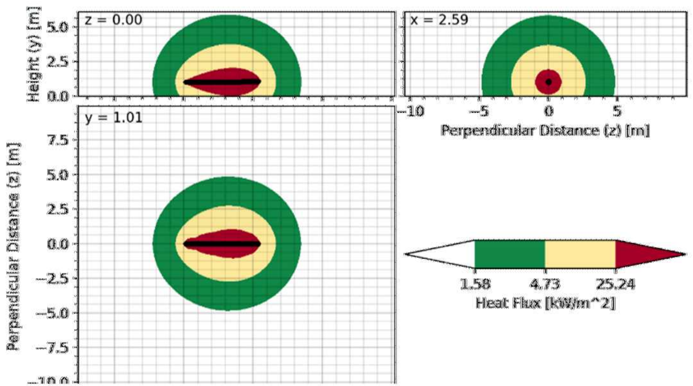


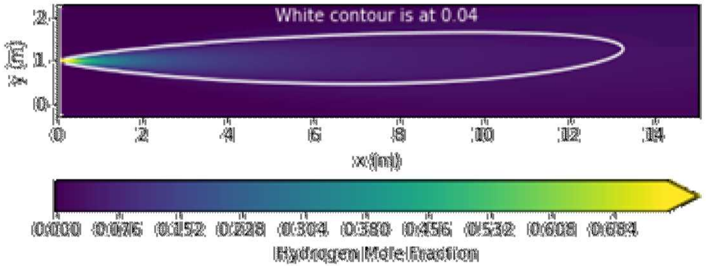
- Documented, repeatable QRA methodology
- Frequency & probability data for compressed hydrogen component failures
- Fast-running models of hydrogen gas and flame behaviors
- Model for cryogenic hydrogen dispersion available in next release
- Moving to open source

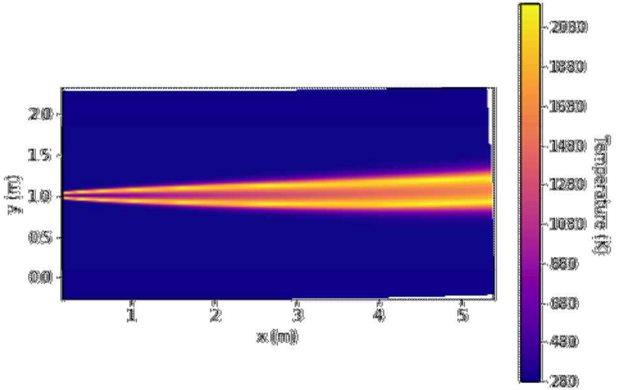
Free download at http://hyram.sandia.gov

A variety of validated physical models are used in HyRAM – valid models for LH_2 are needed

- Unignited dispersion
  - Distance to certain concentration
- Flame model
  - Temperature field
  - Heat flux field
- Overpressure for delayed ignition of indoor releases





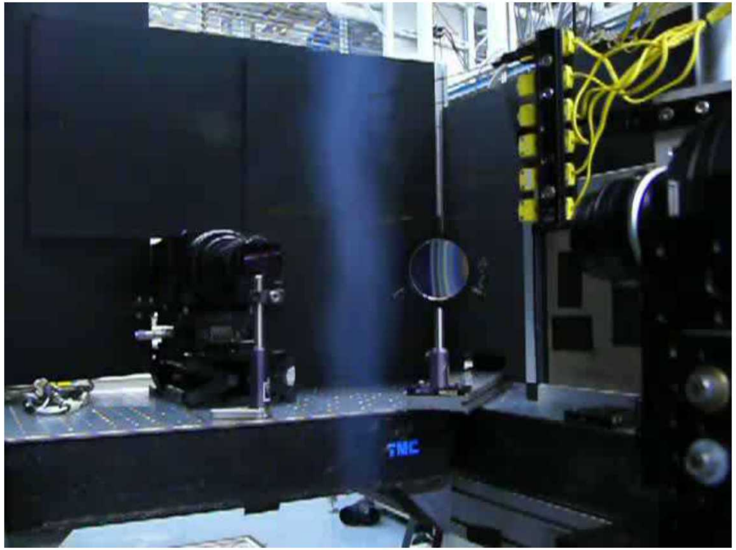


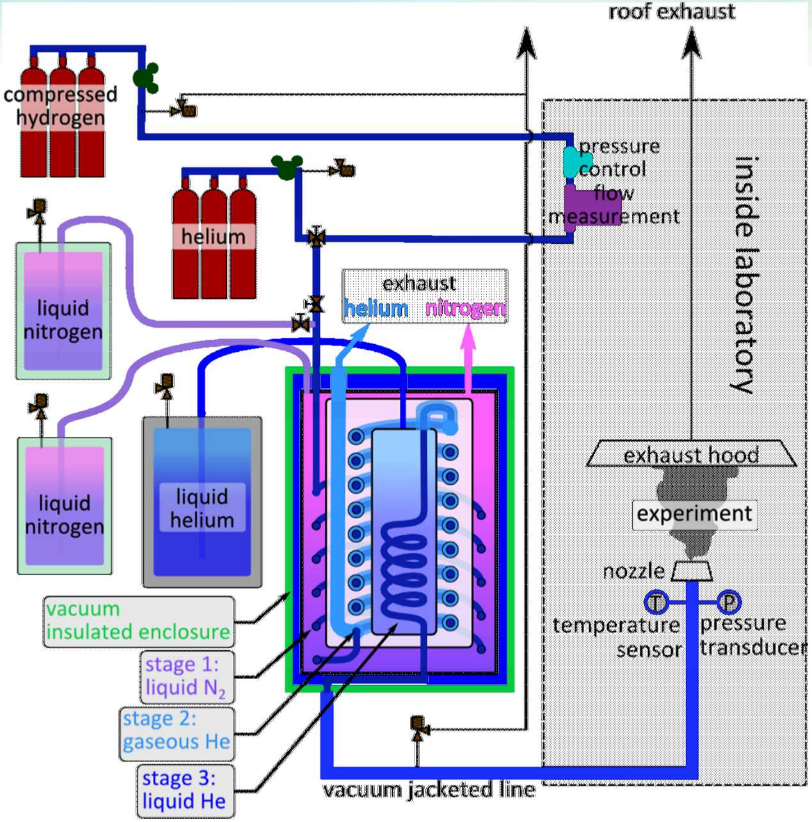
We are working to validate and develop new models (as needed)

A unique experimental platform has been developed at Sandia to release cryogenic hydrogen through approximately 1 mm orifices at up to 10 bar

- Research and validation for models of ignition, flames and dispersion

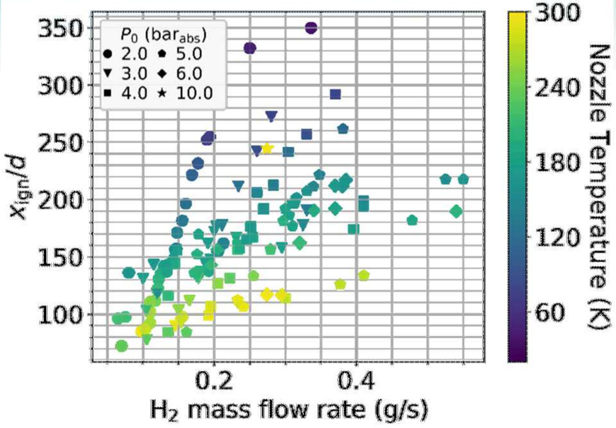
P = 1 bar, T = 37 K, ignition distance = 325 mm

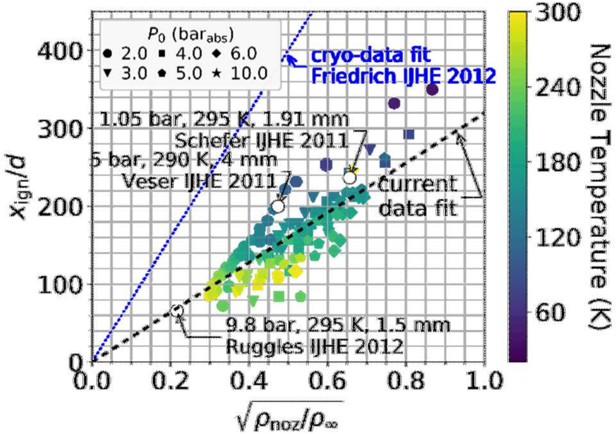




We have measured and can calculate the maximum ignition distance for cryogenic hydrogen

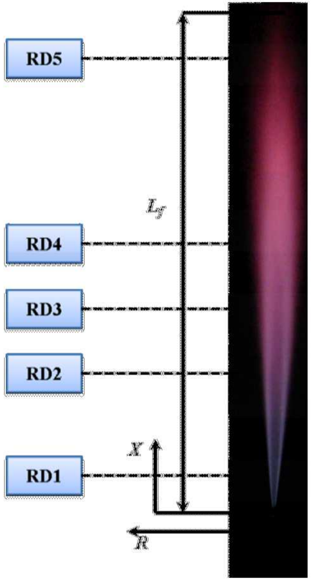
- for a given mass flow, ignition of cold H_2 occurs much further from the release point
- a larger ignition distance is observed at a lower mass flow rate of hydrogen for the colder jets
- Ignition distance linearly varies as a function of effective diameter (same as literature reported room temperature releases)

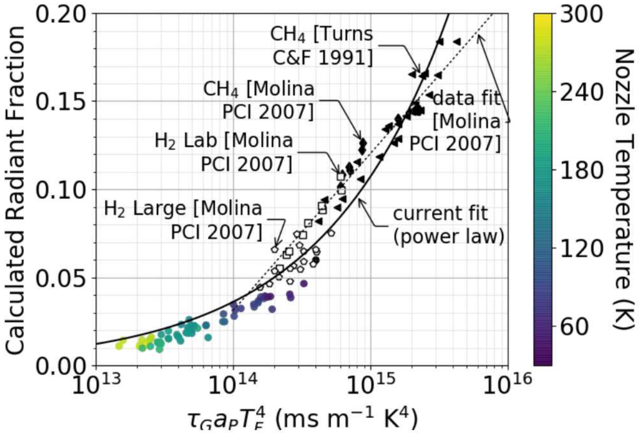


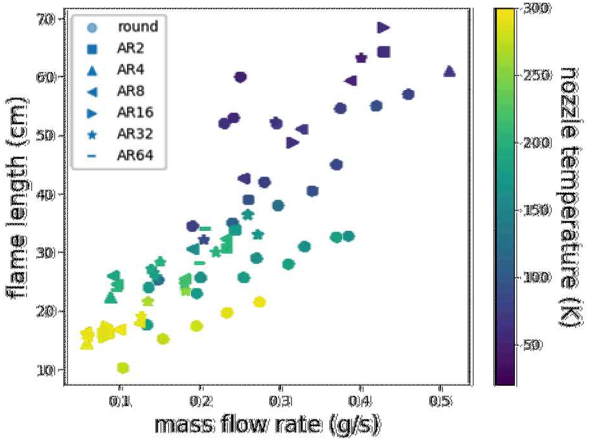


We have measured and can calculate the flame length and radiant heat flux for cryogenic hydrogen jet flames

- Hydrogen flames have lower radiant heat flux compared to methane or syngas flames
- An increase in radiant fraction is observed for colder H_2 jets (for a given nozzle size and pressure) due to longer flame residence time (more mass flux)
- Aspect ratio does not significantly affect flame length



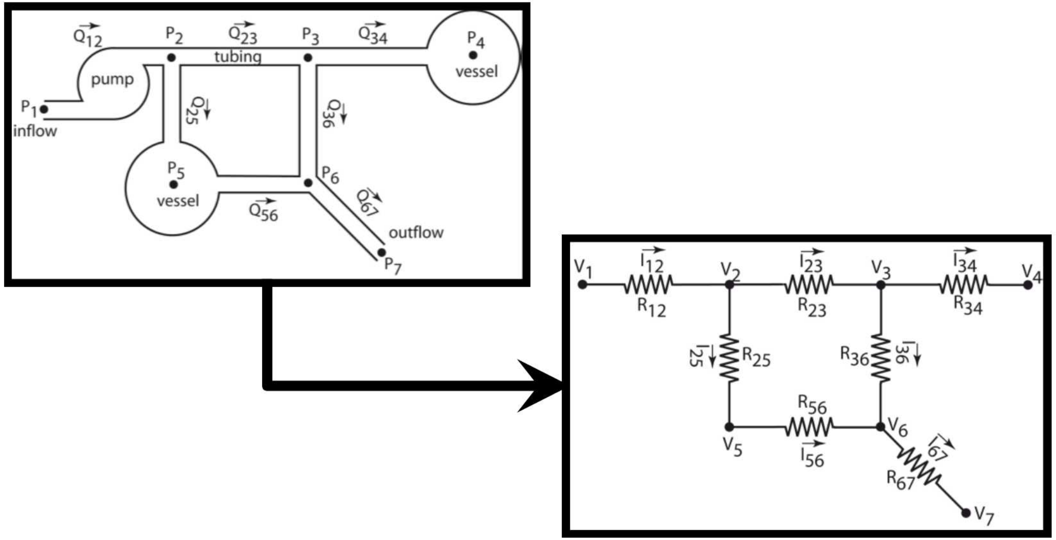




$$radiant\ heat\ flux \propto (radiant\ fraction)(mass\ flow)(heat\ of\ combustion)(transmissivity)$$

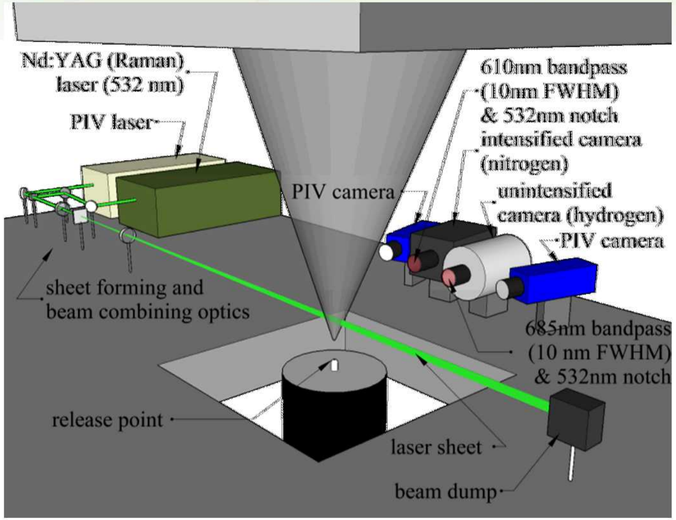
A model for internal, phase-changing flow is necessary to calculate plume/flame boundary conditions

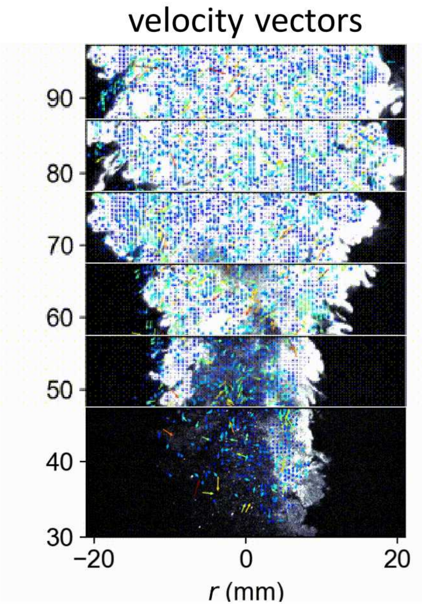
- Flow out a vent stack is no longer at LH_2 temperature
- Valves, piping, and other components represented as an electrical network in Sandia's MassTran model
- Need details (heat transfer rate, component orifice sizes, etc.) to accurately calculate conditions at release point

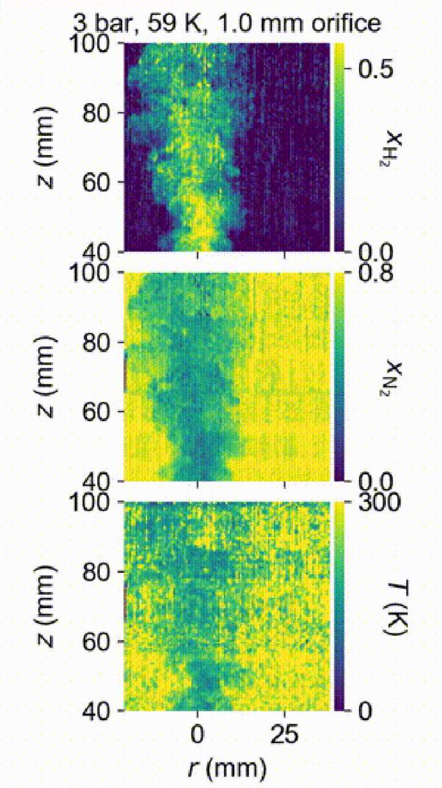


Liquid hydrogen storage tank

H_2-N_2 Raman imaging and particle imaging velocimetry are used to measure concentration, temperature, and velocity of cryogenic H_2



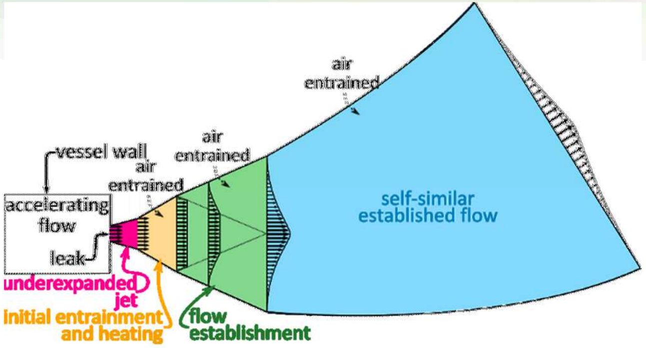


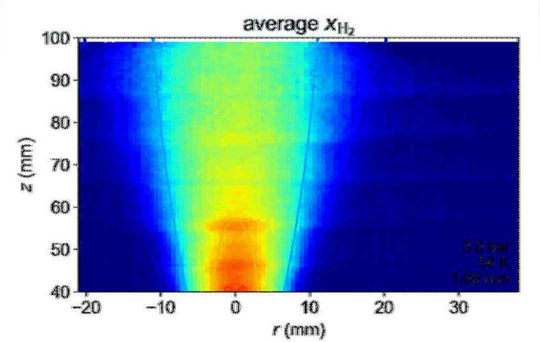


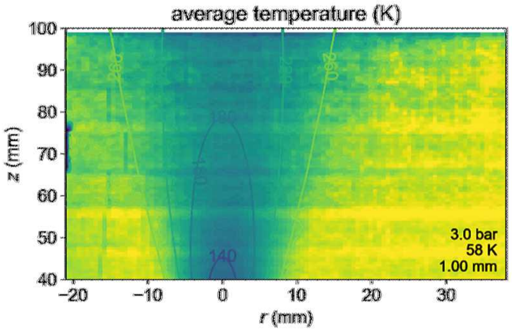
Independent model parameters:

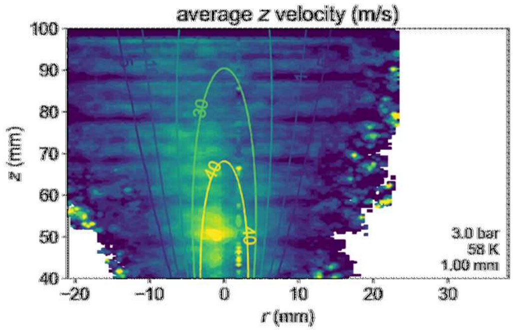
- ✓ T - temperature
- ✓ x - mole fraction
- ✓ v - velocity
- ✓ B - halfwidth (both velocity and concentration)

ColdPLUME model shows good agreement with the data







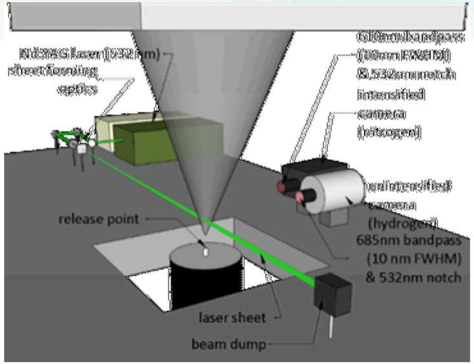


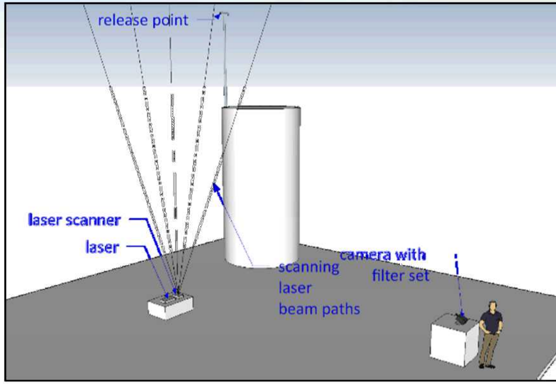
- Experimental results shown by shading and thick, dashed lines
- ColdPLUME model results are thin, solid lines

➢ Model accurately simulates mole fraction, temperature, and velocity -- can be used as a predictive tool

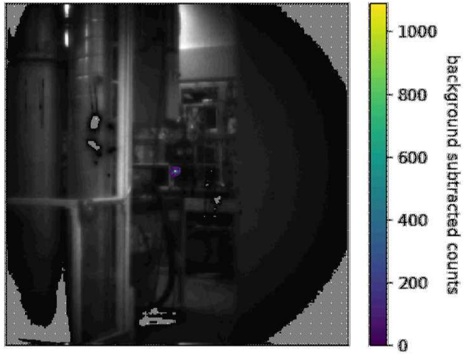
The diagnostic will be modified to study LH_2 vents and large-scale experiments

- Uniquely fast optics enable collection of small Raman signal from distance with wide field of view
- High-power laser scanning in space
- Concentrations measured along a series of lines
- Effective background light suppression is key (both sunlight and illumination source that reflects off of condensed water vapor)
  - Time gating
  - Spectral gating





Raman signal overlaid on laboratory scene



Summary of the QRA process for LH_2 systems, focusing on data and model needs

- Selection of a typical system
- Leak data for LH_2 systems
- Calculation of leak frequency (function of size)
- Models for physical behaviors and consequences:
  - Unignited dispersion
    - Pooling, vaporization
    - Interaction with the environment (e.g. wind)
  - Ignited behavior
    - Flame radiation
    - Overpressure
- Harm models (from consequence models)
- Determination of acceptable risk

- Planning experiments at well-controlled Sandia facilities
- Collaborations welcome (take diagnostics to other locations)

QUESTIONS?

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