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The #H2IQ Hour

Today's Topic:

Update on Changes to the National Fire Protection Association Hydrogen Technologies Code (NFPA 2)

This presentation is part of the monthly H2IQ hour to highlight hydrogen and fuel cell research, development, and demonstration (RD&D) activities including projects funded by U.S. Department of Energy's Hydrogen and Fuel Cell Technologies Office (HFTO) within the Office of Energy Efficiency and Renewable Energy (EERE).

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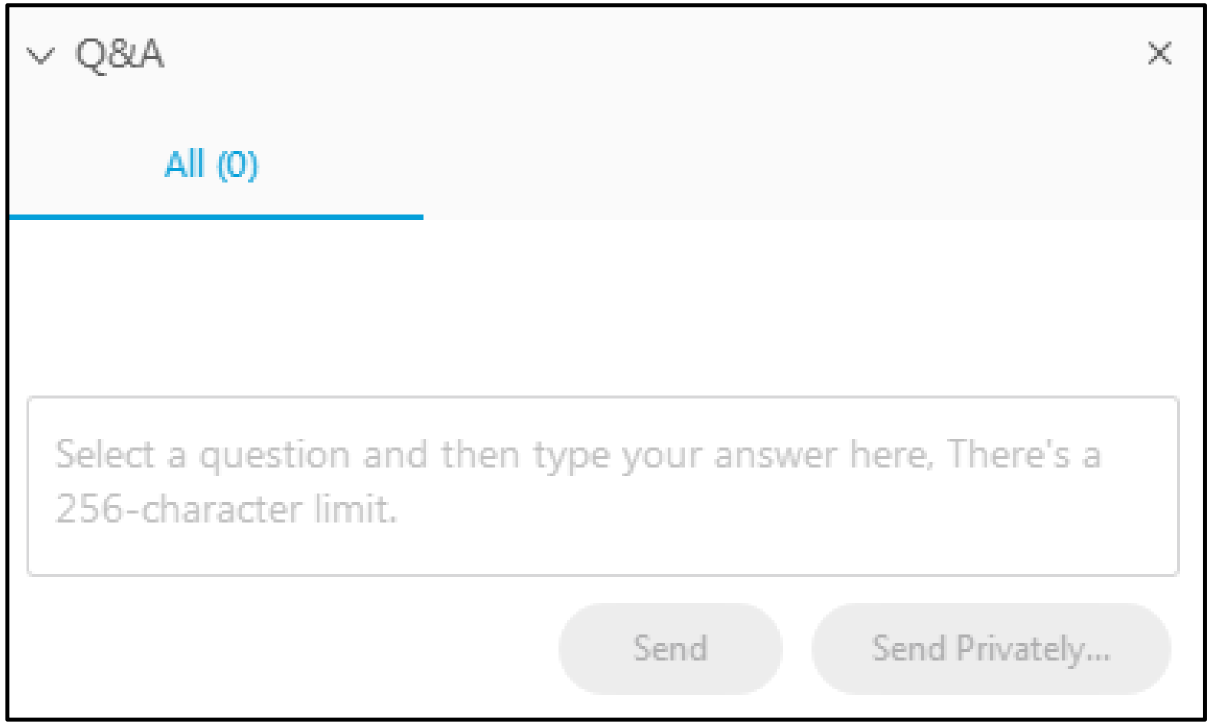
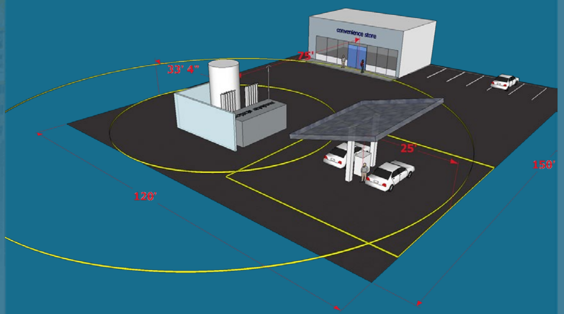
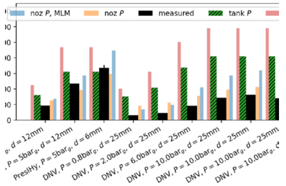
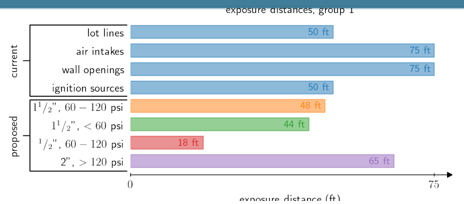
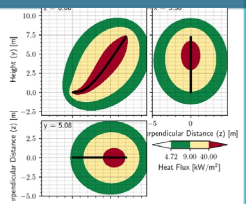


Setback Distances for Bulk Liquefied Hydrogen Storage









Brian D. Ehrhart, Ethan S. Hecht,
Benjamin B. Schroeder

April H2IQ Hour Webinar

April 26, 2023

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SAND2023-02542PE

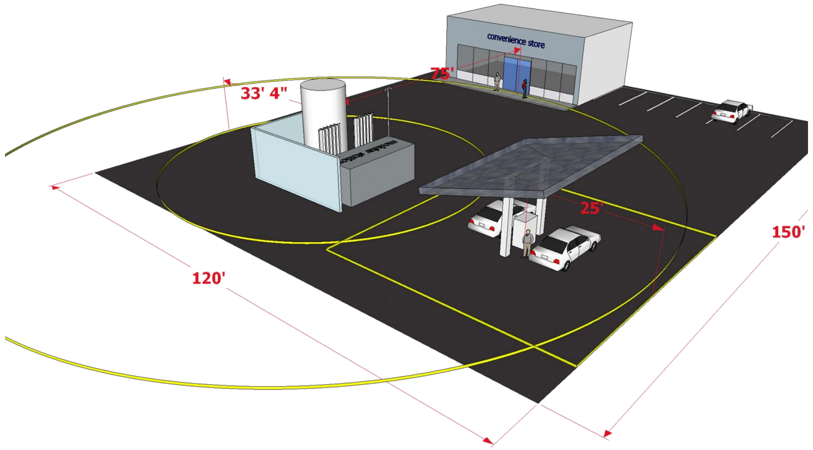
Introduction to Hydrogen Technologies Code (NFPA 2)

- Established in 2006 as an all-encompassing document to prescribe the necessary requirements for the storage, use, and handling of hydrogen
- **Scope**: This code shall apply to the production, storage, transfer and use of hydrogen.
  - Except:
    - Hydrogen components (including storage) onboard a vehicle
    - Mixtures of <95% hydrogen by volume
    - Storage, handling, use, and processing of metal hydrides (except metal hydride storage)
- 2023 Edition of NFPA 2 just released in December 2022
- Commonly used, but legal adoption can vary by state/local jurisdiction

Image: https://en.wikipedia.org/wiki/National_Fire_Protection_Association

Purpose and Impact of Setback Distances

- Setback distances define a **prescribed distance** from a potentially hazardous system
  - To people, buildings, or other hazardous materials
  - Can also work in reverse: protect the system from damage
- Setback distances do not completely eliminate risk
  - Meant to limit the risk to an acceptable level
  - Distances alone may not fully protect against unlikely worst-case scenarios
  - Distances are **in addition** to many of the other safety design features
- Setback distances impact system siting
  - Including the location within a larger facility
  - Often defines where a hydrogen system could be located
- Setback distances need a solid technical justification
  - Promote safety without being unnecessarily onerous

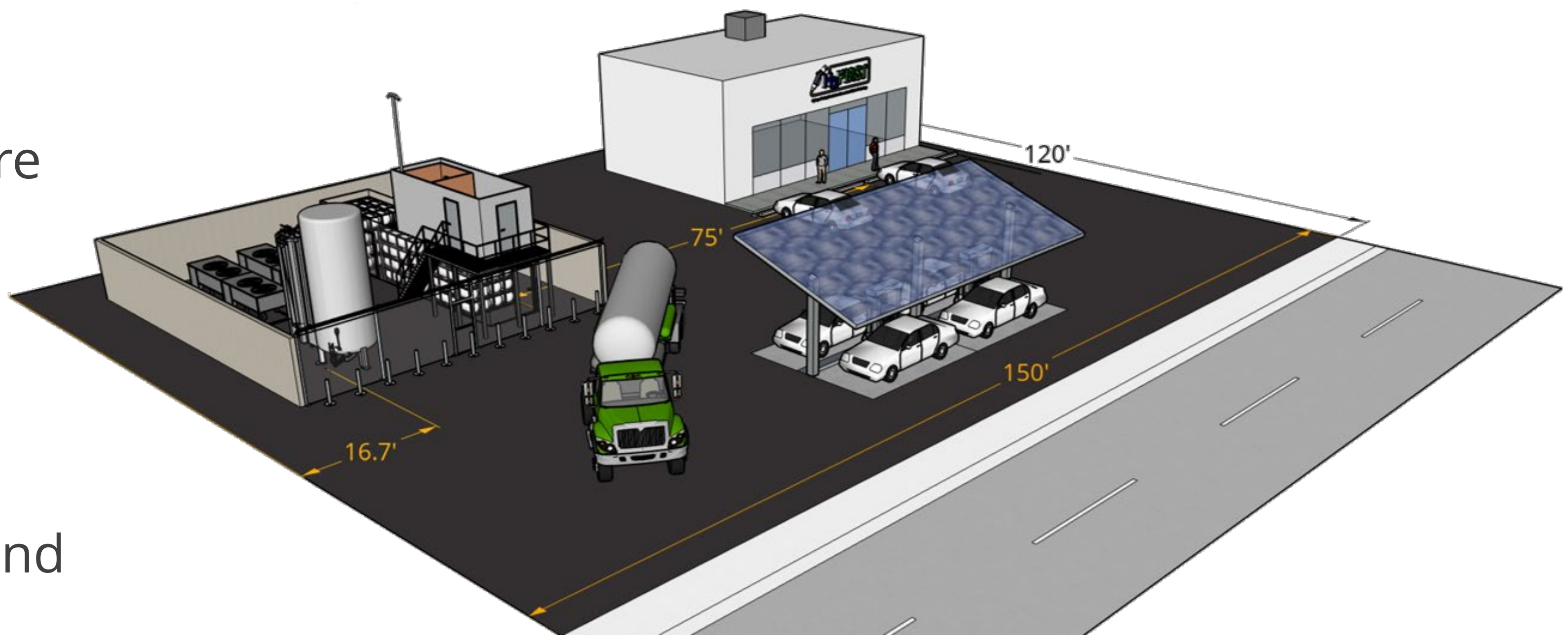


Previous distances in NFPA 2 for bulk liquid hydrogen storage were large, unique for each exposure, and lack documentation of basis

Goal: Develop science-based, defensible bulk liquid hydrogen setback distances (can identify where distances could be reduced)

Steps:

1. Verify and validate necessary models
2. Characterize exposure groups and acceptable hazard levels
3. Use quantitative risk assessment to determine characteristic leak size
4. Calculate consequence based distances using leak size and validated models



Previous distances were:

- Based on storage volume
- 75 ft from air intakes
- Various distances to exposures within a group

Sandia previously had a large role in updating compressed gaseous storage setbacks in NFPA 2 (2011 and 2020)

Quantitative risk assessment on representative refueling station

- No direct link to setback distances, but did indicate that overall risk was acceptable

Changed criteria to pipe diameter and pressure, rather than stored quantity

- Quantity can affect leak duration, but hazard distances set by steady-state leak

Leak frequencies suggested that high percentage of leaks were small

- This led to 3% of flow area, then revised down to 1% of flow area

Table of setback distances calculated for 3 groups of exposures

- 4 pressure "bins" and tables varied by inner diameter of connecting pipe
- Safety factor of 1.5 used on calculated consequence-based distances

Distance reduction for some exposures allowed for fire-rated walls

- Distance reduced to half

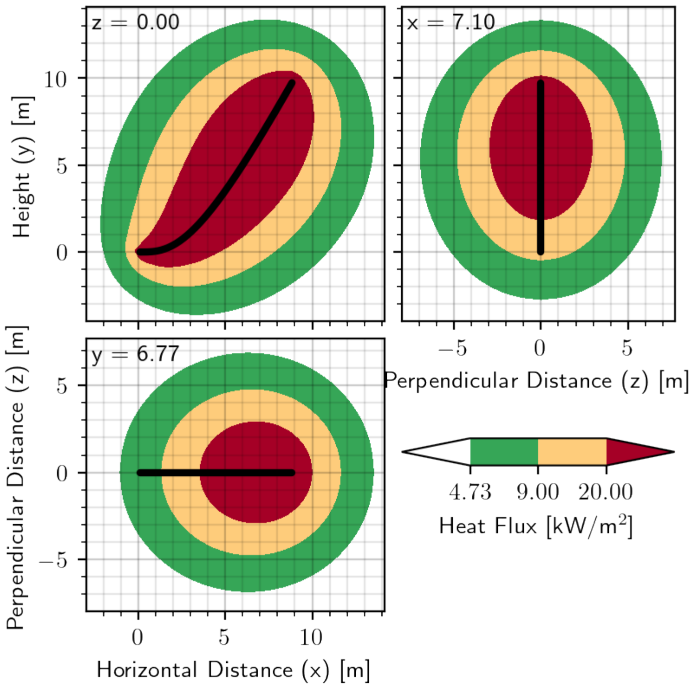
Similar approach used as a starting point for liquid hydrogen

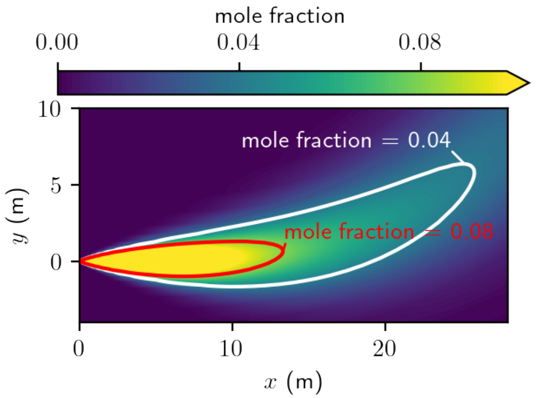
LaChance et al. "Analyses to Support Development of Risk-Informed Separation Distances for Hydrogen Codes and Standards" SAND2009-0874, March 2009.
NFPA 2 "Hydrogen Technologies Code" National Fire Protection Association, 2020 Edition.

The Sandia developed HyRAM+ toolkit was used for calculations

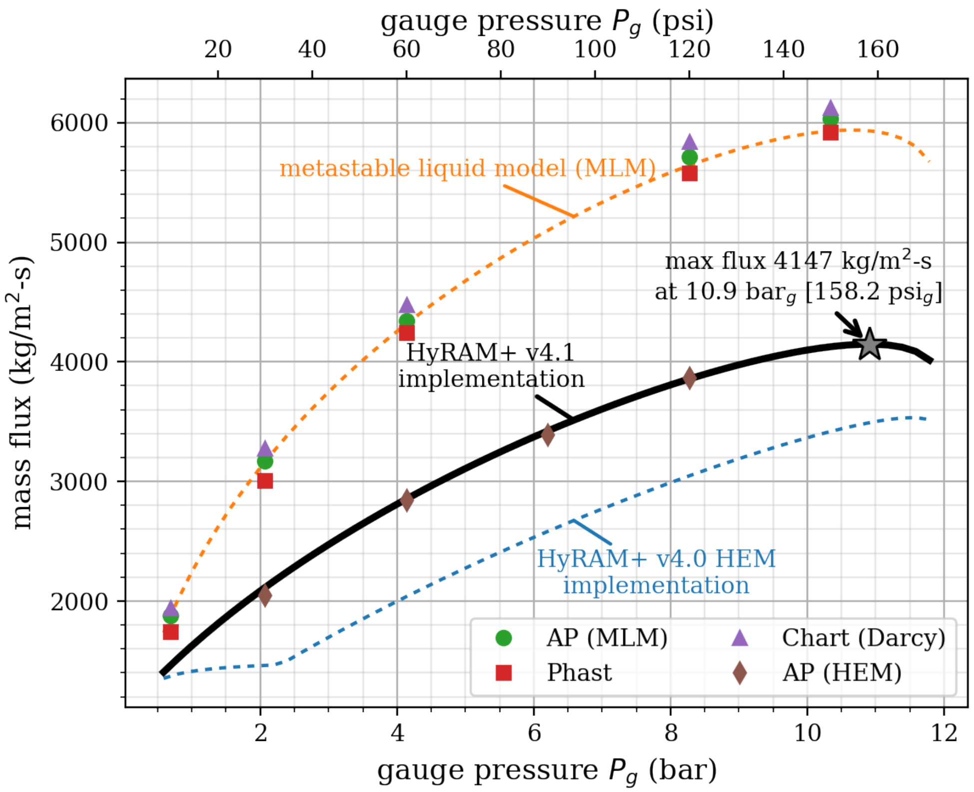
Available at hyram.sandia.gov, from PyPI and conda-forge

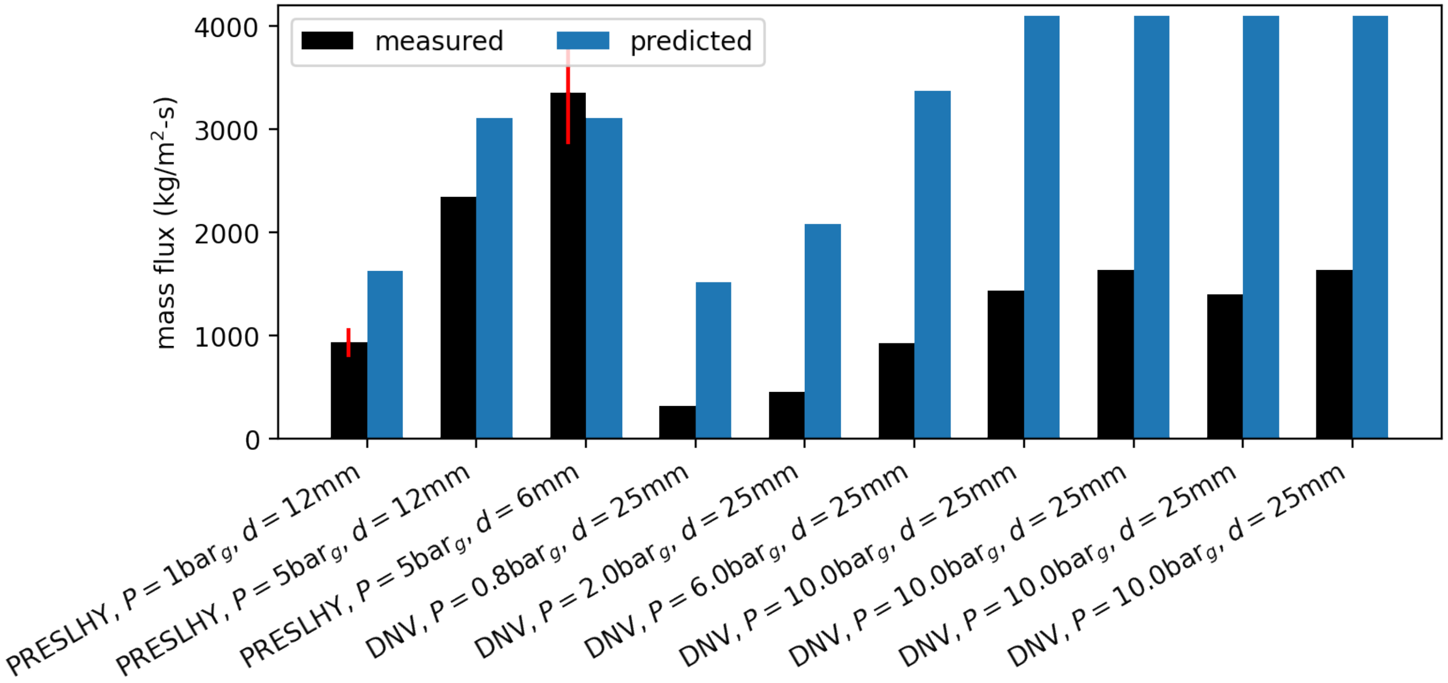
- Fast running, reduced order models
  - Unignited dispersion
  - Flames - trajectory and heat flux
  - Unconfined overpressure
- Behavior models used standalone or for quantitative risk assessment
- Python backend enables flexibility of modeling
- Version 4.1 used for these calculations





The mass flow rate model was updated and compared to data

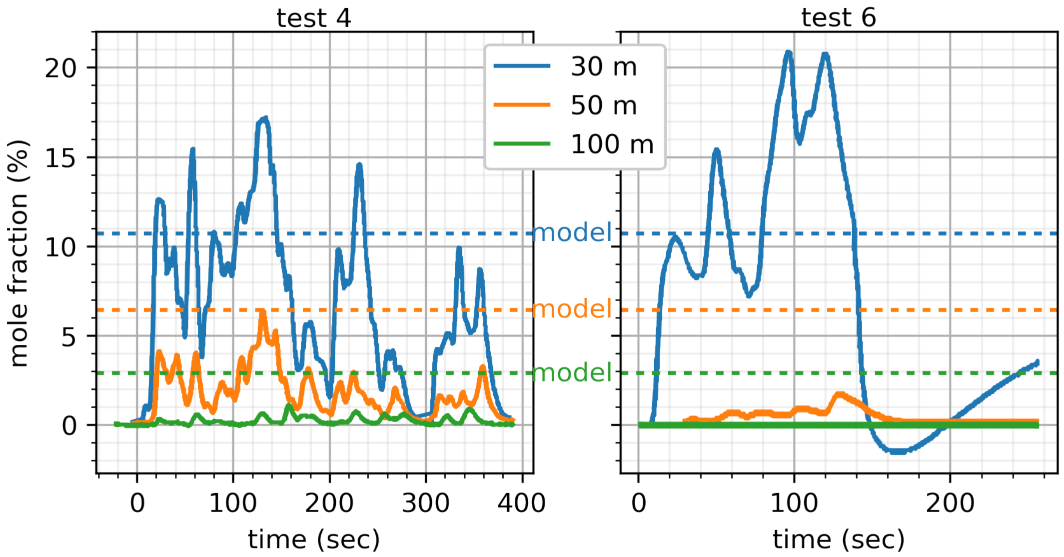


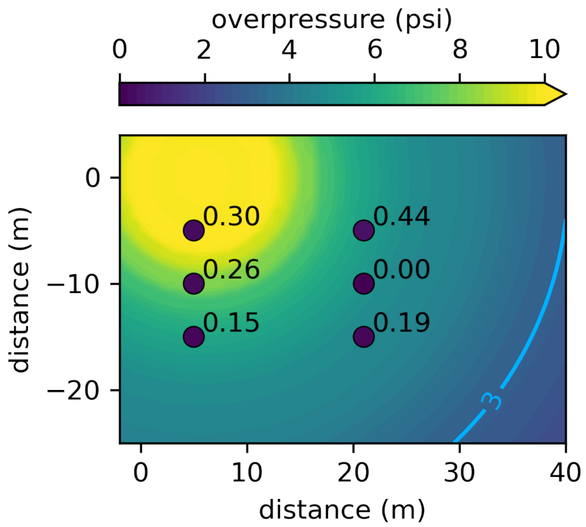


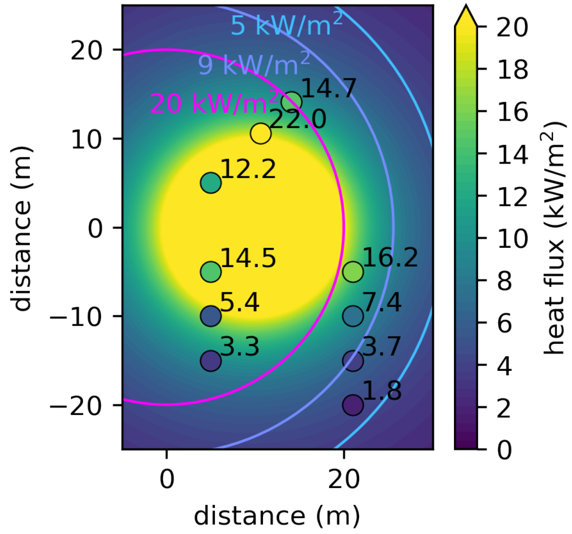
- Calculations updated – resulted in increased mass flow for liquid hydrogen
  - No longer relies on uncertain calculation of speed of sound for two-phase fluids
  - Verified by comparing to other models
  - Metastable liquid model considered too conservative
- Updated model compares well to data from two experimental campaigns attempting to maximize liquid H_2 flows

Data from (PRESLHy): Lyons et al., 2020 and (DNV): Huescar-Medina et al. 2020, report #853182, rev 2

Dispersion, heat flux and overpressure models were compared to data







- Very limited number of experimental campaigns
- Mole fractions overpredicted on average, especially in far-field where mole fractions are lower
- Unconfined overpressure greatly overpredicted
- Heat flux creteria distances encompass measurements

Data from Huescar-Medina et al. 2020, report #853182, rev 2

Regrouped liquid hydrogen exposure groups

Group 1	1. Lot lines 2. Air Intakes 3. Operable openings in buildings 4. Ignition sources such as open flames/welding	**Should avoid:** • Harm to the general public • Damage from heat flux • Damage from overpressure • Flammable concentration
Group 2	5. Exposed persons other than those servicing the system 6. Parked cars 7. Buildings of combustible construction 8. Hazardous materials storage systems above ground or fill/vent openings for below ground storage systems 9. Ordinary combustibles, including fast-burning solids such as ordinary lumber, excelsior, paper, or combustible waste and vegetation other than that found in maintained landscaped areas	**Should avoid:** • Harm to people aware of risk (people at the fueling station) • Significant damage to buildings • Fire spread to ordinary combustibles
Group 3	10. Buildings of non-combustible non-fire-rated construction 11. Flammable gas storage systems above or below ground 12. Heavy timber, coal, or other slow-burning combustible solids 13. Unopenable openings in buildings and structures 14. Encroachment by overhead utilities (horizontal distance from the vertical plane below the nearest overhead electrical wire of building service 15. Piping containing other hazardous materials 16. Flammable gas metering and regulating stations such as natural gas or propane	**Should avoid:** • Escalation of event (fire spread)

Criteria for unignited concentration based on ability to form a jet flame

Exposures to consider:

- Air intakes
- Sewer inlets
- People (fireball)

NFPA 2 GH2 uses 8% by volume

- Based on ability to sustain ignition
- Rather than 4% by volume lower flammability limit

NFPA 59A uses lower flammability limit (LFL), or 50% of LFL depending on model used

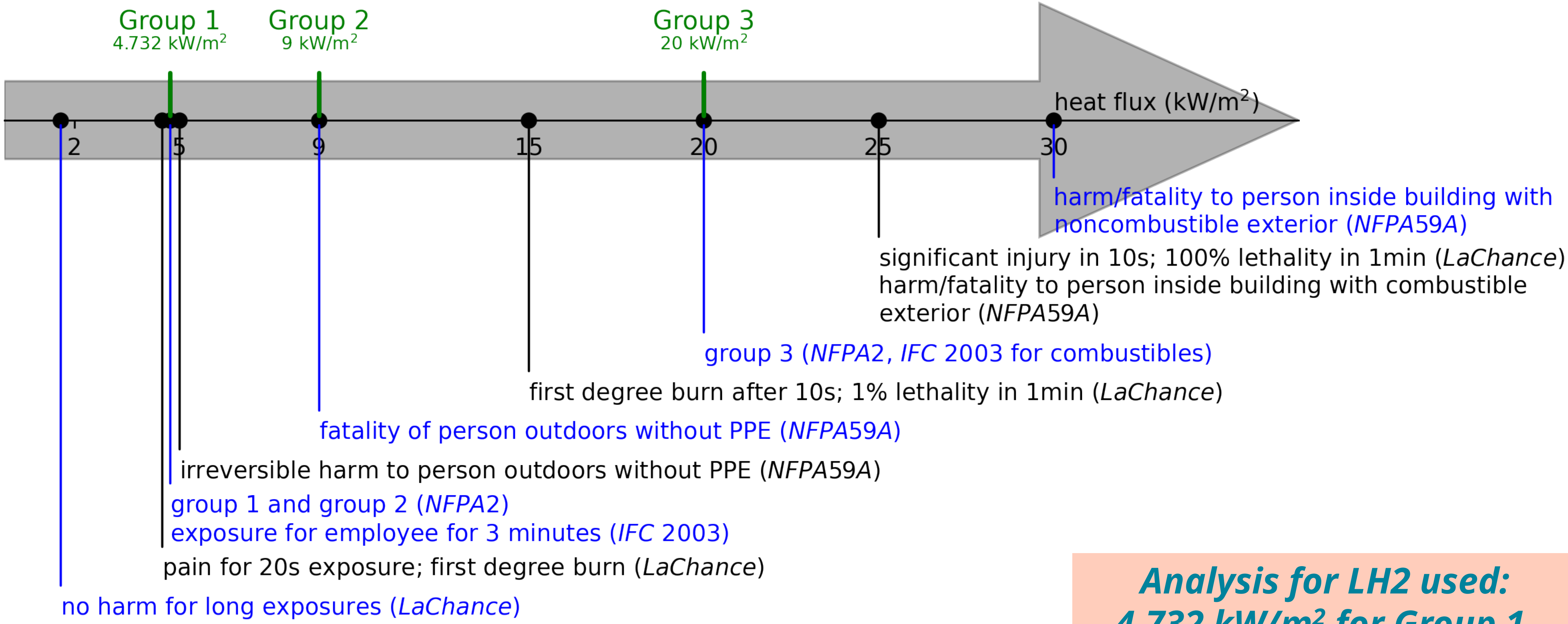
- Also considers higher concentrations for oxygen displacement

Analysis for LH2 used: 8% by volume unignited concentration for Group 1 exposures

Ignition kernel forms but does not form jet flame

Jet flame is sustained after ignition

Criteria for heat flux were carefully chosen

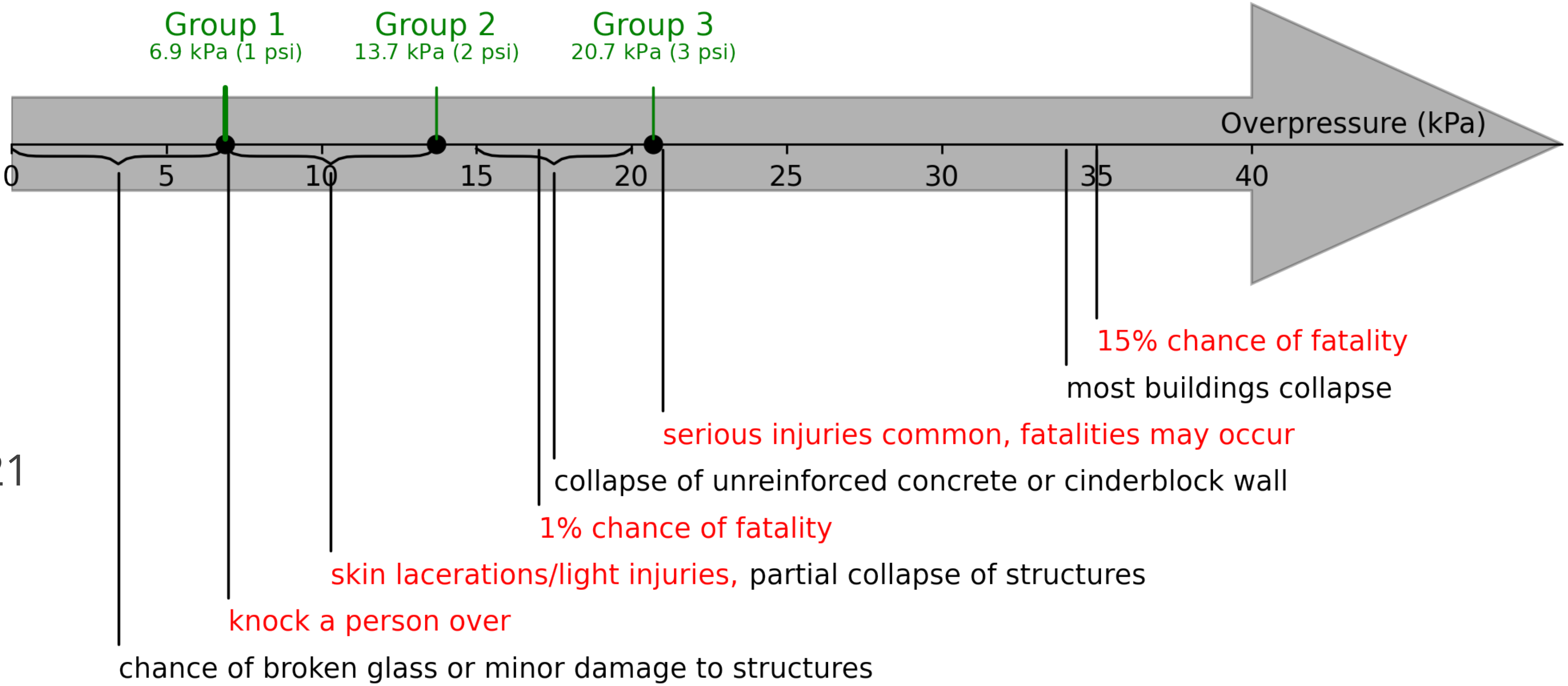


Analysis for LH2 used: 4.732 kW/m² for Group 1, 9 kW/m² for Group 2, and 20 kW/m² for Group 3

From:
LaChance et al. (2011)
NFPA 59A Table 19.8.4.2.1
NFPA 2 (2020)

Criteria for peak overpressure were determined

Data from:
Lobato, Afinidad, 2009
Huang, IJHE 2018
Quest Consultants Inc.
LaChance, IJHE 2011
Jallais, PSP 2018
Argo, FPRF 2014
HSE, 2014



Exposures to consider:

- People
- Cars
- Buildings

Hecht and Ehrhart, ICHS 2021

- Group 1: 0.7 psi
- Group 2: 2.3 psi
- Group 3: 10.2 psi

NFPA 59A Table 19.8.4.3.1

- 3 psi fatality to person outdoors
- 1 psi irreversible harm to person outdoors
- 1 psi limit for buildings

Analysis for LH2 used:
1 psi (7 kPa) for Group 1 exposures,
2 psi (14 kPa) for Group 2 exposures,
3 psi (21 kPa) for Group 3 exposures

Fractional Hole Size to Estimate Steady-State Leaks

Fractional instead of absolute hole size

- NFPA 2 GH2 tables use 1% of flow area

Gives "credit" for using smaller pipe diameters

- Smaller pipes lower risk by limiting the consequences

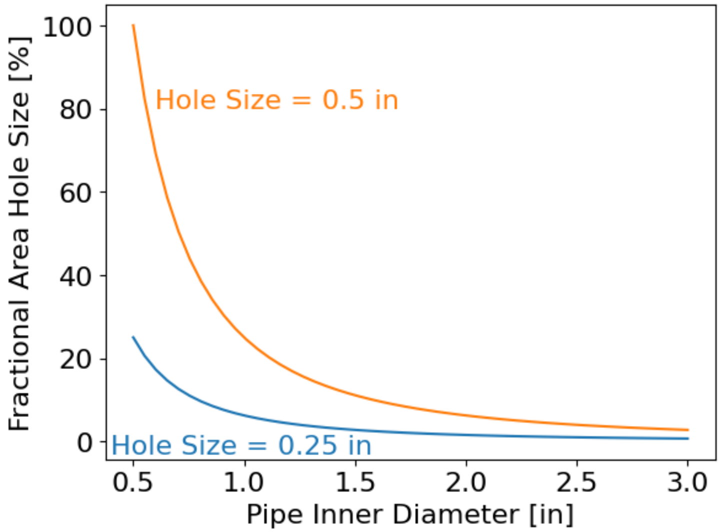
Allows setbacks to grow for larger pipe diameters

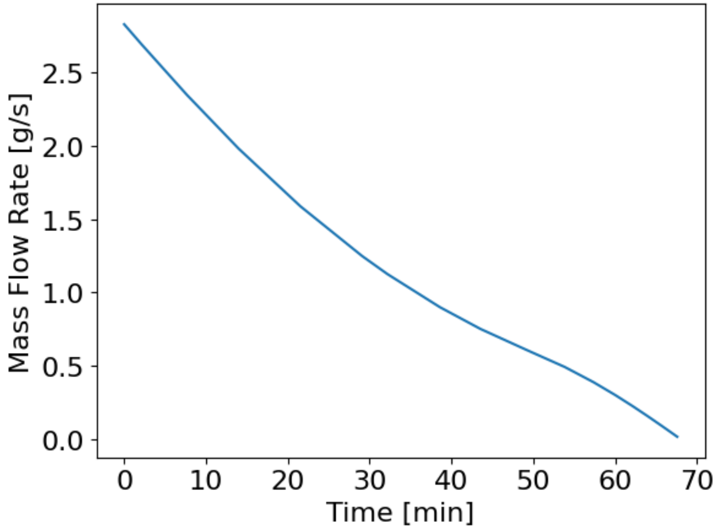
Fractional area leak size based on pipe inner flow area

- $Fraction = \frac{A_{leak}}{A_{pipeID}} = \frac{\frac{\pi}{4}d_{leak}^2}{\frac{\pi}{4}d_{pipeID}^2} = \left(\frac{d_{leak}}{d_{pipeID}}\right)^2$

Steady-state leaks mean volume affects leak duration, not extent

- In reality, leak flow rate diminishes over time





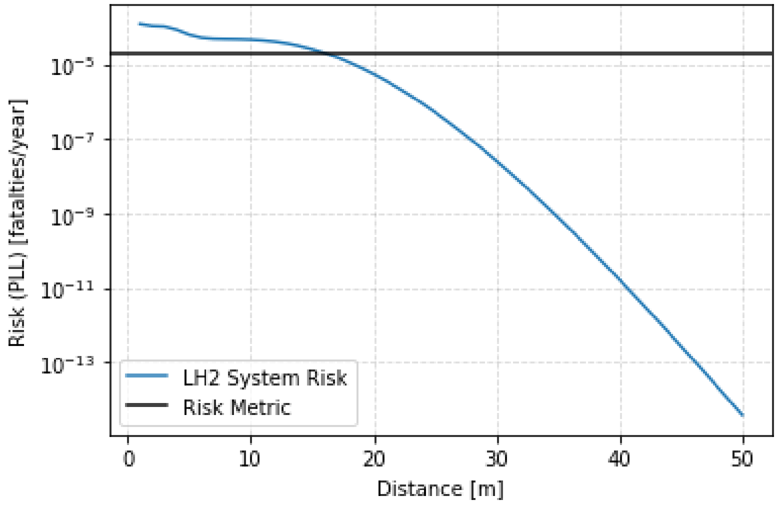
Setback Distance Basis Hole Size Justification: Risk Assessment

HyRAM+ quantitative risk assessment (QRA) methodology uses leak frequency, ignition probability, and fatality probability to estimate risk

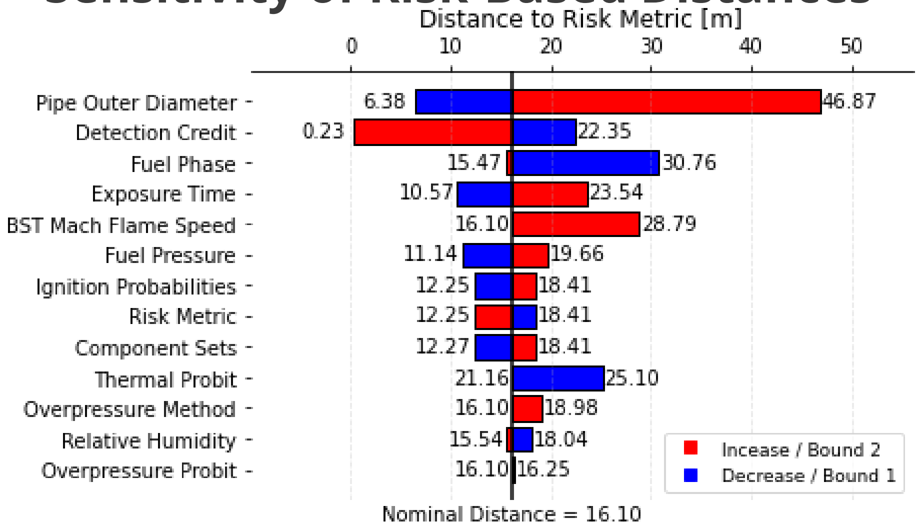
Risk acceptance metric can give a risk-based distance from a leak point based on a full QRA

- Varying QRA inputs can vary this distance significantly

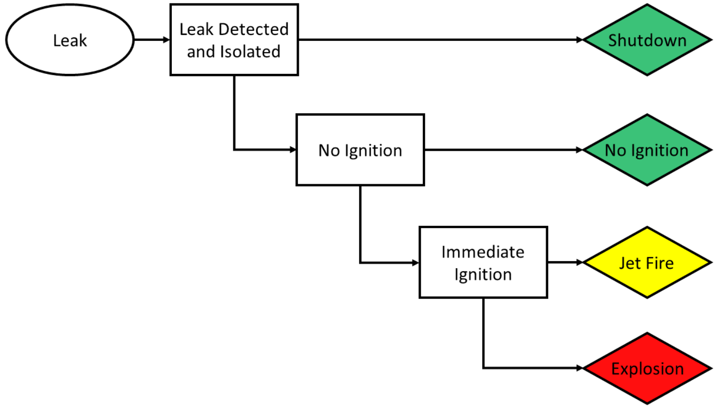
Potential Loss of Life (PLL) Risk Metric at Distances Away from Leak



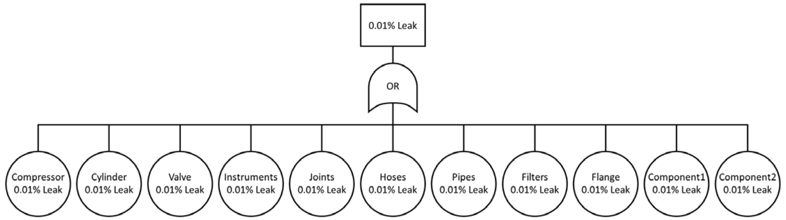
Sensitivity of Risk-Based Distances



Leak Outcome Event Tree



Component Leak Fault Tree



Risk Assessment Sensitivity Study Can Inform Fractional Hole Size

Sensitivity cases changed one given input value at a time

- Then calculated **equivalent hole size** for different system pipe diameter

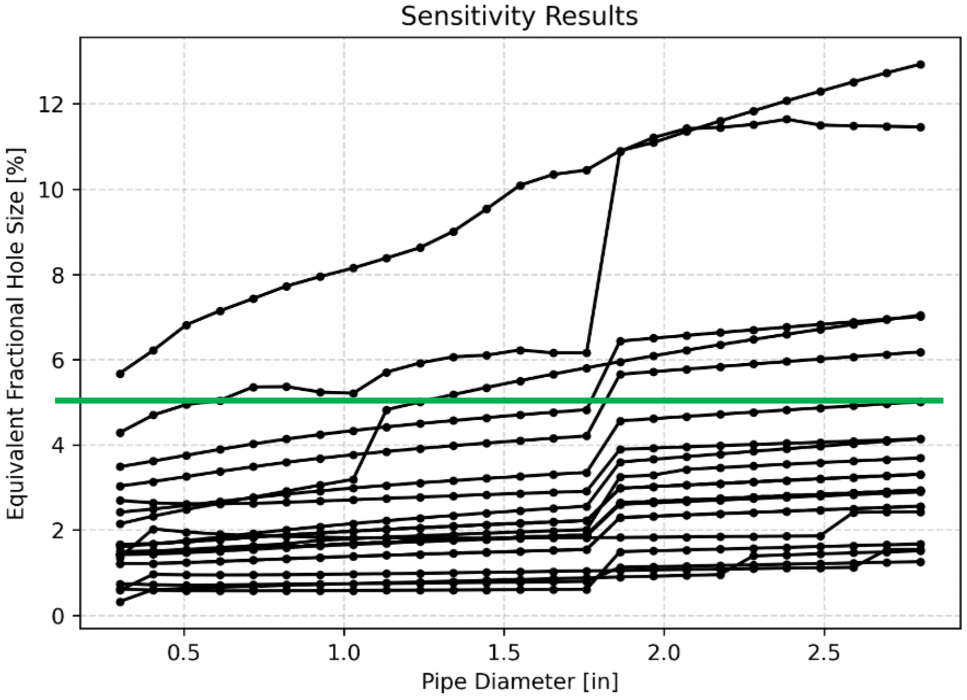
Sensitivity results are mostly well-below 10% fractional leak area

- **Only 2 of 26 cases exceed 10%** at largest pipe inner diameters:
  - Overpressure models with detonation (BST Mach 5.2 and Bauwens/Dorofeev)
- **Only 3 additional cases of 26 exceed 5%** at largest pipe inner diameters:
  - Sub-cooled liquid source, exposure time doubled (60s), Tsao and Perry thermal probit (includes infrared effects)
- **21 of 26 cases are below 5%**
  for all inputs and pipe diameters considered

Possibilities considered:

- 10% hole size (too conservative)
- **5% hole size (still conservative)**
- 3% hole size (mid-range, may not be sufficiently conservative)

5% of internal flow area selected as basis



Distances are calculated using chosen criteria and models

5% Fractional Leak Area

Group 1:

- Concentration: 8 mol% (streamline) – *dominates setback distance*
- Heat Flux: 4.732 kW/m^2 (1,500 $BTU/hr/ft^2$) (bird's eye)
- Peak Overpressure: 6.895 kPa (1 psi)

Group 2:

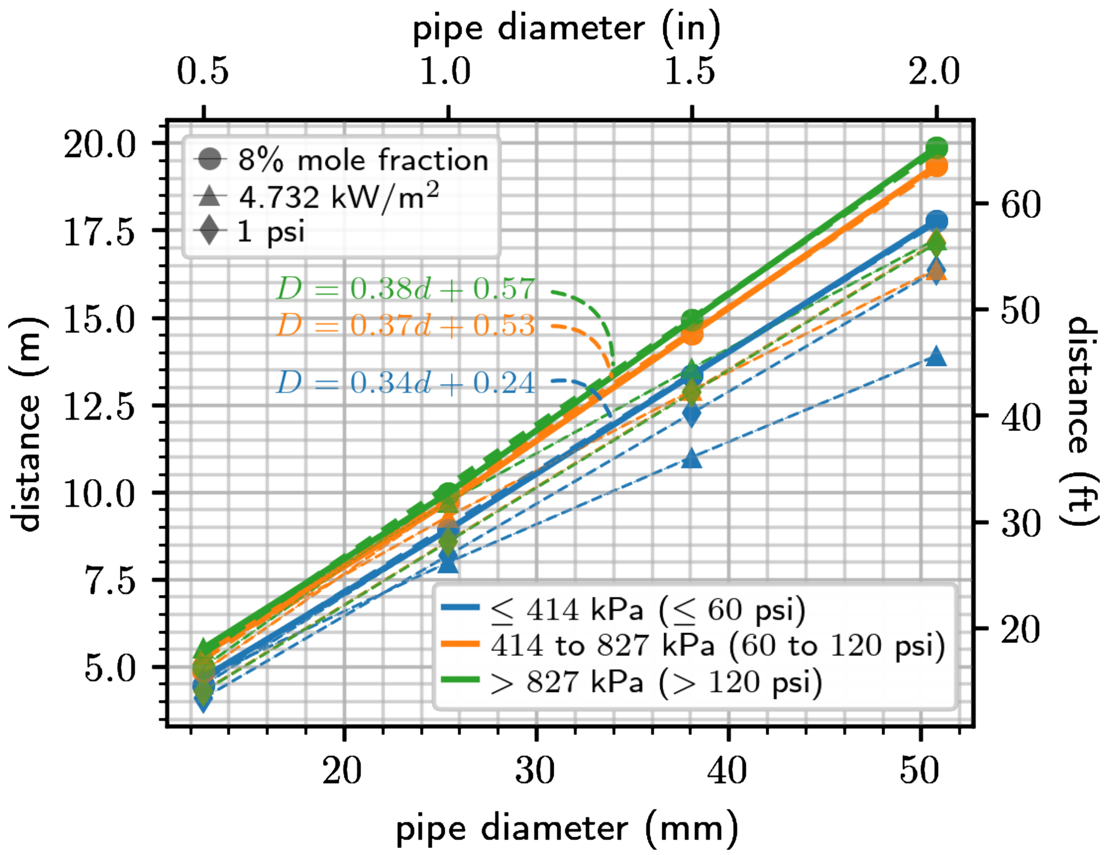
- Heat Flux: 9 kW/m^2 (2,853 $BTU/hr/ft^2$) (bird's eye) – *dominates setback distance*
- Peak Overpressure: 13.790 kPa (2 psi)

Group 3:

- Heat Flux: 20 kW/m^2 (6,340 $BTU/hr/ft^2$) (bird's eye) – *dominates setback distance*
- Peak Overpressure: 20.7 kPa (3 psi)
- Visible Flame Length (bird's eye)

Safety factor = 1

Consequence-based calculations for Group 1

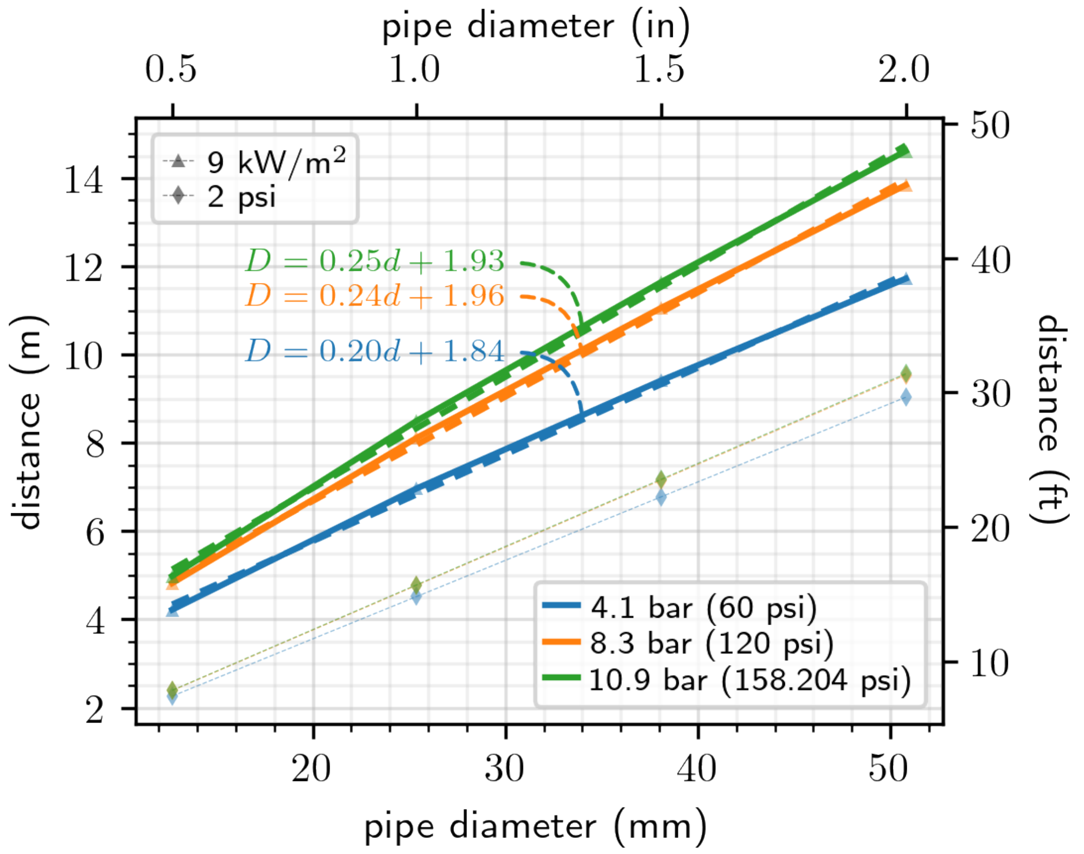


Exposures:
1. Lot lines
2. Air intakes
3. Operable openings in buildings
4. Ignition sources such as open flames/welding

Protects against:
- Flammable concentration
- Damage from heat flux
- Damage from overpressure
- General public

Distance to 8% concentration by volume drives setback distance

Consequence-based calculations for Group 2



Distance to 9 kW/m² heat flux drives setback distance

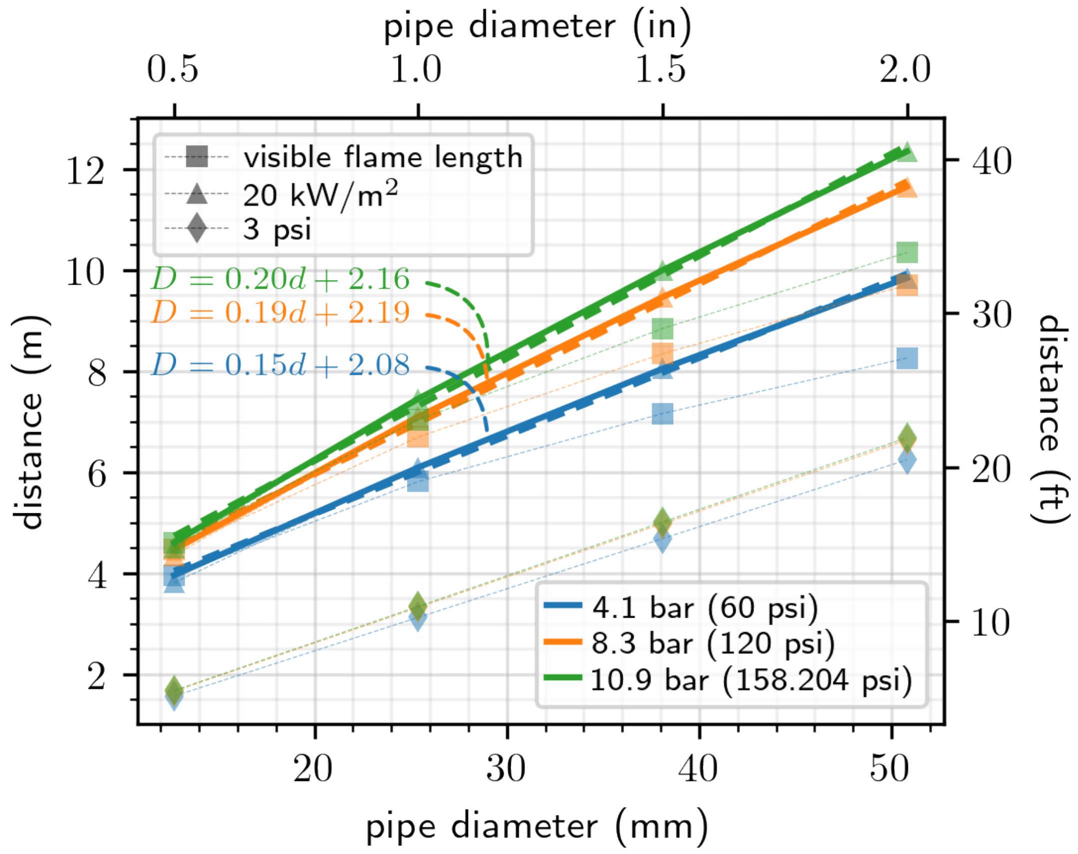
Exposures:

5. Exposed persons other than those servicing the system
6. Parked cars
7. Buildings of combustible construction
8. Hazardous materials storage systems above ground or fill/vent openings for below ground storage systems
9. Ordinary combustibles, including fast-burning solids such as ordinary lumber, excelsior, paper, or combustible waste and vegetation other than that found in maintained landscaped areas

Protects against:

- Fire spread to ordinary combustibles
- Significant damage to buildings
- Harm to people informed of risk (people at the fueling station)

Consequence based-calculations for Group 3



Distance to 20 kW/m² heat flux drives setback distance

Exposures:

10. Buildings of Non-combustible non-fire-rated construction
11. Flammable gas storage systems above or below ground
12. Heavy timber, coal, or other slow-burning combustible solids
13. Unopenable openings in buildings and structures
14. Encroachment by overhead utilities (horizontal distance from the vertical plane below the nearest overhead electrical wire of building service
15. Piping containing other hazardous materials
16. Flammable gas metering and regulating stations such as natural gas or propane

Protects against:

- Escalation of event (fire spread)

Distances were tabulated for a typical and range of pipe sizes

- Single distance for each exposure group and pressure
- Pressure ranges do not show large differences, but may be useful in some cases
- Pipe size can significantly affect distances

Table 8.3.2.3.1.6(a) Minimum Distance from Outdoor Bulk Liquefied Hydrogen (LH_2) Systems to Exposures, Up to 75,000 gal (280,000 L) — Typical Inner Diameter *(d)* 1.5 in. (38.1 mm)

Maximum Operating Pressure (MOP) (gauge)	<60 psi (<414 kPa)		60 to 120 psi (414 kPa to 827 kPa)		>120 psi (>827 kPa)	
Exposures Group 1	ft	m	ft	m	ft	m
1. Lot lines 2. Air intakes (e.g., HVAC, compressors) 3. Operable openings in buildings and structures 4. Ignition sources such as open flames and welding	44	13.3	48	14.5	49	14.9
Exposures Group 2	ft	m	ft	m	ft	m
5. Exposed persons other than those servicing the system 6. Parked cars 7. Buildings of combustible construction 8. Hazardous materials storage systems above ground or fill/vent openings for belowground storage systems 9. Ordinary combustibles, including fast-burning solids such as ordinary lumber, excelsior, paper, or combustible waste and vegetation other than that found in maintained landscaped areas	31	9.4	36	11.1	38	11.6
Exposures Group 3	ft	m	ft	m	ft	m
10. Buildings of noncombustible non-fire-rated construction 11. Flammable gas storage systems above or below ground 12. Heavy timber, coal, or other slow-burning combustible solids 13. Unopenable openings in buildings and structures 14. Encroachment by overhead utilities (horizontal distance from the vertical plane below the nearest overhead electrical wire of building service) 15. Piping containing other hazardous materials 16. Flammable gas metering and regulating stations such as natural gas or propane	26	8.0	31	9.5	33	10.0

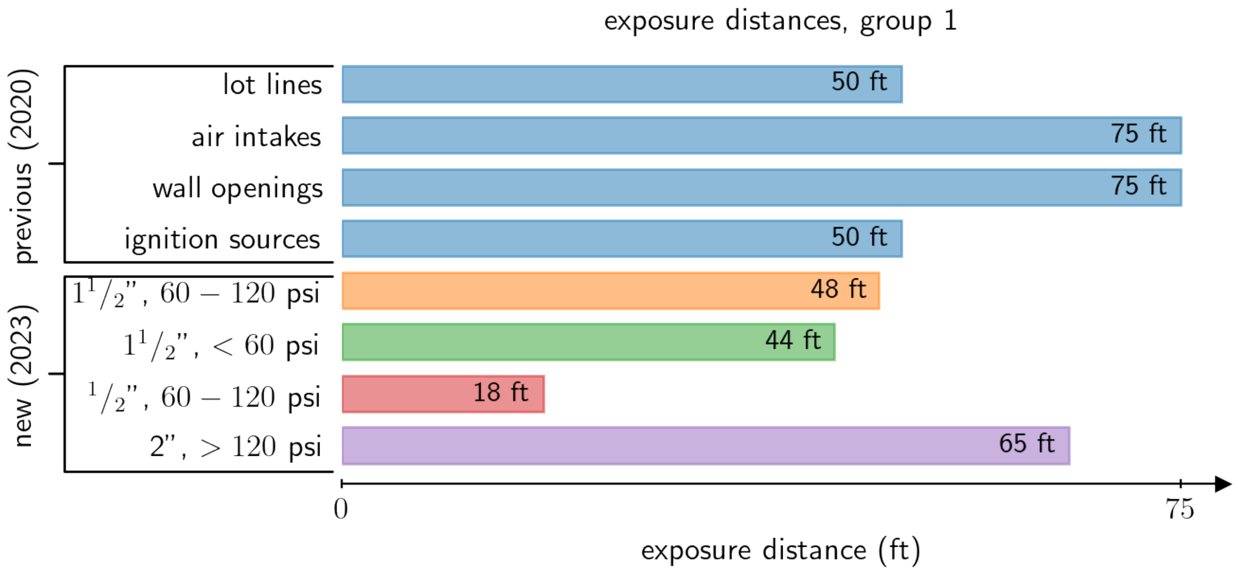
Table 8.3.2.3.1.6(b) Minimum Distance from Outdoor Bulk Liquefied Hydrogen (LH_2) Systems to Exposures by Inner Diameter *(d)*

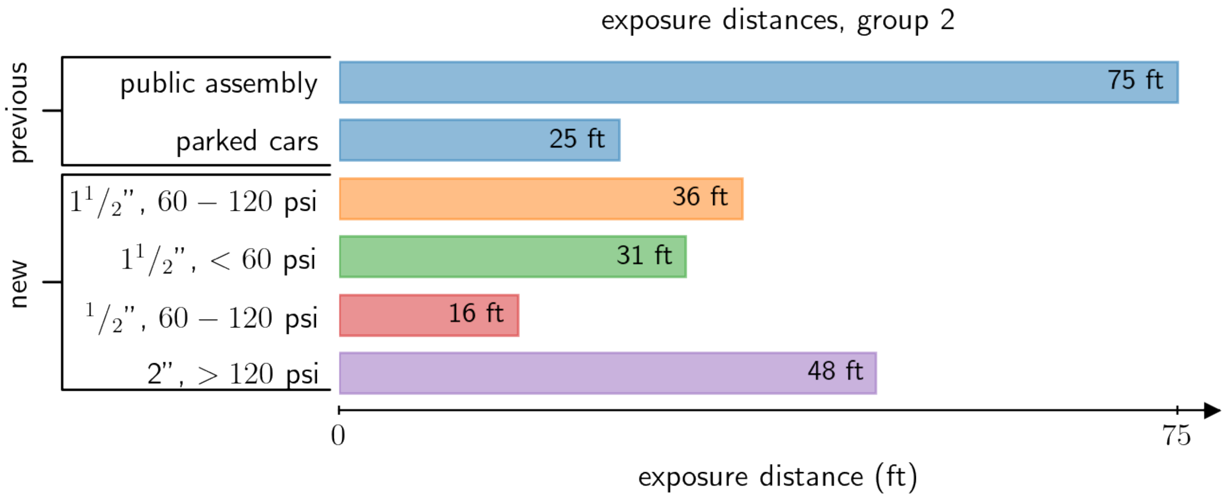
Maximum Operating Pressure (MOP) (gauge)		<60 psi (<414 kPa)						60 psi to 120 psi (414 kPa to 827 kPa)						>120 psi (>827 kPa)					
Inner Diameter *(d)*		Group 1		Group 2		Group 3		Group 1		Group 2		Group 3		Group 1		Group 2		Group 3	
		$0.34d + 0.24$		$0.20d + 1.84$		$0.15d + 2.08$		$0.37d + 0.53$		$0.24d + 1.96$		$0.19d + 2.19$		$0.38d + 0.57$		$0.25d + 1.93$		$0.20d + 2.16$	
in.	mm	ft	m	ft	m	ft	m	ft	m	ft	m	ft	m	ft	m	ft	m	ft	m
0.5	12.7	15	4.7	14	4.2	13	4.0	18	5.4	16	4.8	15	4.5	18	5.5	16	5.0	15	4.6
1.0	25.4	29	8.9	23	7.0	20	6.1	32	9.7	27	8.1	23	7.1	33	10.0	28	8.5	24	7.5
1.5	38.1	44	13.3	31	9.4	26	8.0	48	14.5	36	11.1	31	9.5	49	14.9	38	11.6	33	10.0
2.0	50.6	58	17.8	38	11.7	32	9.8	63	19.3	45	13.8	38	11.6	65	19.9	48	14.6	41	12.3

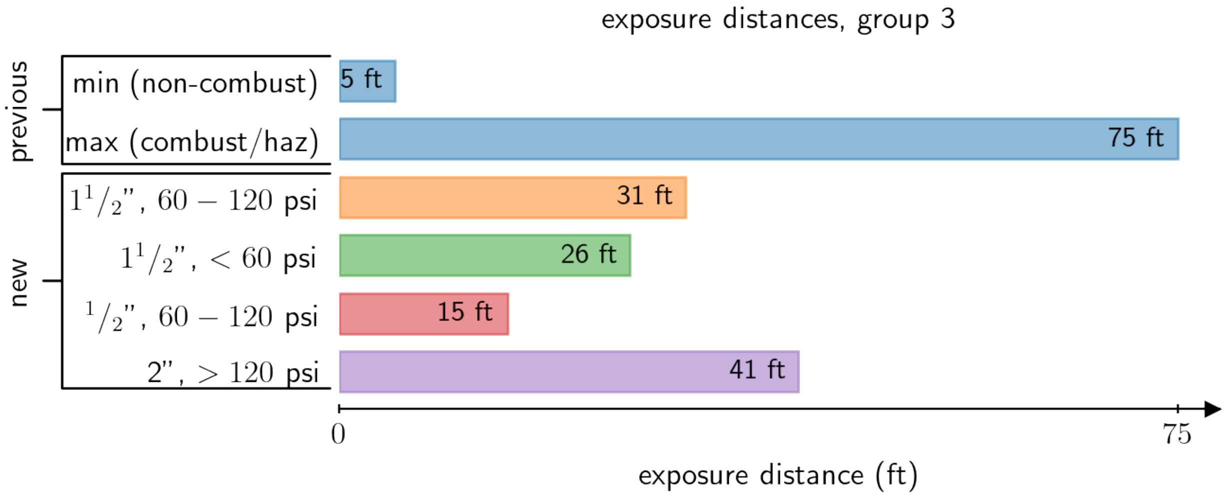
(1) Linear interpolation of internal pipe diameters and distances between table entries is allowed.
(2) For a list of exposures in each exposure group, see column 1 of Table 8.3.2.3.1.6(a).
(3) When calculating the minimum separation distance using the formulas indicated, based on the exposure group and pressure indicated, the inner diameter *(d)* is entered in millimeters (mm). The calculated distance is returned in units of measure in meters (m). To convert distance to units of measure in feet, multiply the value in meters by 3.2808 and round to the nearest whole foot.

New distances are smaller in some cases, but larger in others

- Distances are most often reduced for group 1 exposures
- Distances for group 3 exposures are increased in many cases

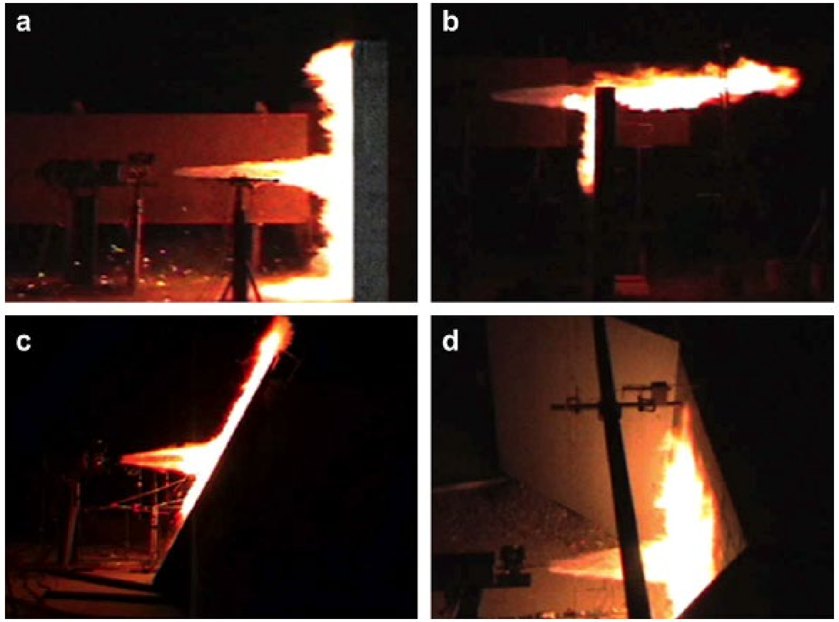






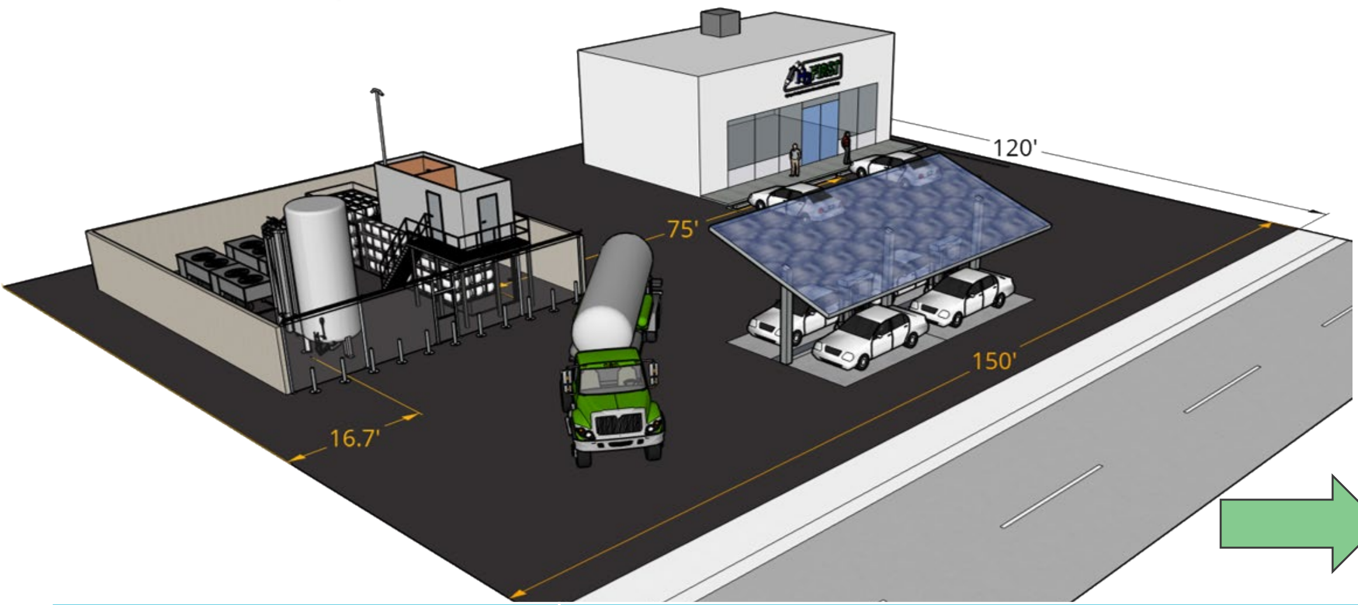
Credits for insulated piping and fire barrier walls remain

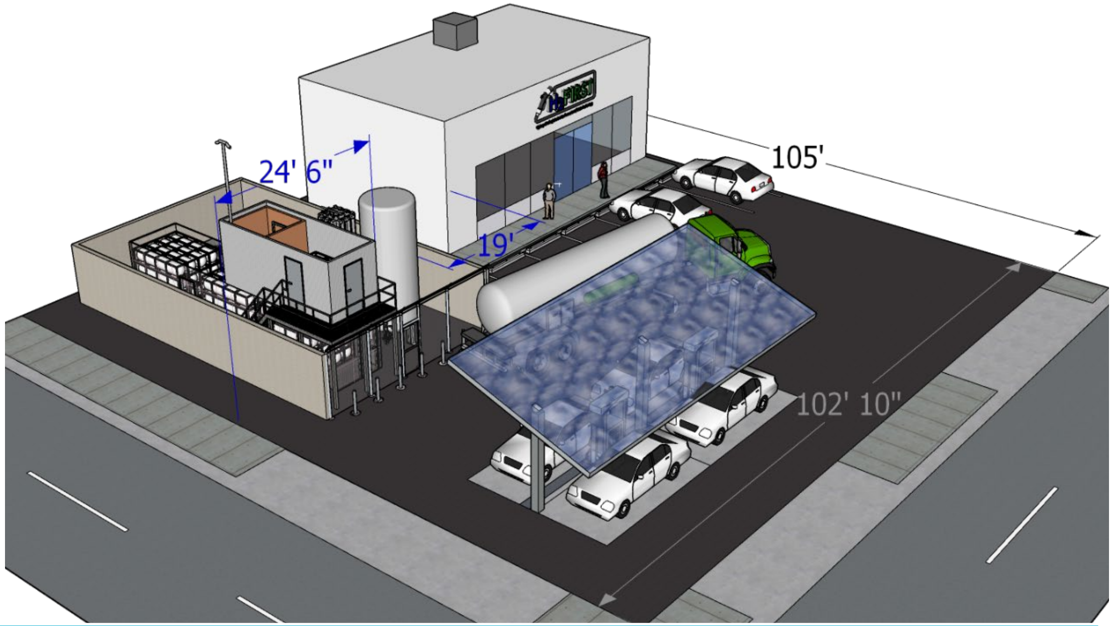
- Fire barrier walls reduce dispersion, heat flux, and overpressure
  - Fire barrier walls allow the reduction of distances in Groups 1 and 2 by 50% (including air intakes)
  - Fire barrier walls enable Group 3 distances to be reduced to 0 ft
- Vacuum insulated piping reduces propensity for leaks due to double walls and welded joints
  - Distances to exposures can be reduced by 2/3 for vacuum-insulated lines with no mechanical connections, joints, or leak sources
- An Emergency Shutdown System is required for all public refueling systems



Tests on mitigation from fire barrier walls for gaseous hydrogen flames. From Schefer et al. IJHE 2008.

Reduced footprint is enabled by updated tables and language in NFPA 2 (2023)





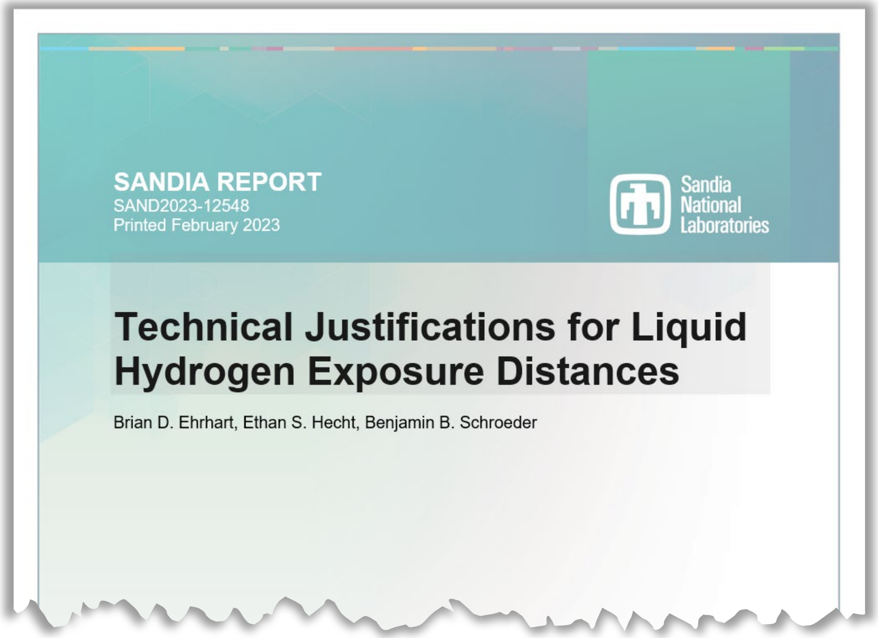
Characteristic	NFPA 2 (2020)	NFPA 2 (2023)
Assumed system	3,500-15,000 gal [950 - 4000 kg] tank	Same tank, 1.5” diameter piping, >120psi
Distance to air intakes	75 ft (unable to reduce with walls)	24’-6” (49 ft reduced by half due to barrier wall)
Lot lines	16.7’ (50 ft, reduced by 2/3 due to insulation)	24’-6” (49 ft reduced by half due to barrier wall)
Gaseous portion of system	Same setback distances as liquid system	Treated separately, divided by source valve (changed in 2020 version of NFPA 2)
Driver of setback distance to building	Air intakes	Distance to building /parking spaces (19 ft - group 2 exposure [38 ft reduced by half due to barrier wall])

Acknowledgements and Collaboration

- This work was part of the NFPA 2 Storage Task Group
  - Part of the Hydrogen Technologies Technical Committee
- This work was supported by the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE) Hydrogen and Fuel Cell Technologies Office (HFTO)
  - Part of the Safety Codes and Standards sub-program under the direction of Laura Hill
- Special thanks to task group members for input, direction, discussion, verification, and reviews:
  - David Farese (formerly Air Products, now Durham Consulting LLC)
  - Derek Miller (Air Products)
  - Thomas Drube (Chart Industries)
  - Mukesh Trivedi (Chart Industries)
  - John Anicello (Chart Industries)
  - Dusty Brooks (Sandia National Laboratories)
  - Jamal Mohmand (formerly at Sandia National Laboratories, now at Lockheed Martin)
  - Chris LaFleur (Sandia National Laboratories)

Summary and Future Work

- Updated distances are simplified, defensible, and well-documented
- Enables assumptions to be changed and incremental improvements to be made
- Framework could be applied to other setback distances in the future (gaseous setbacks could be revisited)
- Larger systems still need science-based codes and standards (currently limited to about 20 metric tons)
- Mitigations from fire barrier walls specific to liquid hydrogen dispersion and flames will be studied


SANDIA REPORT
SAND2023-12548
Printed February 2023

Sandia National Laboratories

Technical Justifications for Liquid Hydrogen Exposure Distances

Brian D. Ehrhart, Ethan S. Hecht, Benjamin B. Schroeder

Full report available: SAND2023-12548

Thank you!

Questions?

Contact: Brian Ehrhart (bdehrha@sandia.gov), Ethan Hecht (ehecht@sandia.gov)

Backup Slides

Previous vs. New LH2 Exposures

Previous Liquid Hydrogen Exposure Groups

Group 1

1. Lot lines
2. Air intakes [heating, ventilating, or air-conditioning equipment (HVAC), compressors, other]
3. Wall openings Operable openings in buildings and structures
4. Ignition sources such as open flames and welding

Group 2

5. Places of public assembly
6. Parked cars (distance shall be measured from the container fill connection)

Group 3

7. Buildings or structure
   a) Buildings constructed of noncombustible or limited combustible materials
      1) Sprinklered building or structure or unsprinklered building or structure having noncombustible contents
      2) Unsprinklered building or structure with combustible contents
         i. Adjacent wall(s) with fire resistance rating less than 3 hours
         ii. Adjacent wall(s) with fire resistance rating of 3 hours or greater
   b) Buildings of combustible construction
      1) Sprinklered building or structure
      2) Unsprinklered building or structure
8. Flammable gas storage or systems (other than hydrogen) above or below ground
9. Between stationary liquefied hydrogen containers
10. All classes of flammable and combustible liquids (above ground and vent or fill openings if below ground)
11. Hazardous materials storage or systems including liquid oxygen storage and other oxidizers, above or below ground
12. Heavy timber, coal, or other slow-burning combustible solids
13. Wall openings Unopenable openings in buildings and structures
14. Inlet to underground sewers
15. Utilities overhead, including electric power, building services, or hazardous materials piping systems
   a) Horizontal distance from the vertical plane below the nearest overhead wire of an electric trolley, train, or bus line
   b) Horizontal distance from the vertical plane below the nearest overhead electrical wire
   c) Piping containing other hazardous materials
16. Flammable gas metering and regulating stations above grade

New Liquid Hydrogen Exposure Groups

- Group 1
  1. Lot lines
  2. Air intakes
  3. Operable openings in buildings
  4. Ignition sources such as open flames/welding
- Group 2
  5. Exposed persons other than those servicing the system
  6. Parked cars
  7. Buildings of combustible construction
  8. Hazardous materials storage systems above ground or fill/vent openings for below ground storage systems
  9. Ordinary combustibles, including fast-burning solids such as ordinary lumber, excelsior, paper, or combustible waste and vegetation other than that found in maintained landscaped areas
- Group 3
  10. Buildings of non-combustible non-fire-rated construction
  11. Flammable gas storage systems above or below ground
  12. Heavy timber, coal, or other slow-burning combustible solids
  13. Unopenable openings in buildings and structures
  14. Encroachment by overhead utilities (horizontal distance from the vertical plane below the nearest overhead electrical wire of building service
  15. Piping containing other hazardous materials
  16. Flammable gas metering and regulating stations such as natural gas or propane

Gaseous vs. Liquid Hydrogen Exposure Groups

Gaseous Hydrogen Exposure Groups

Group 1

- Lot lines
- Air intakes (HVAC, compressors, other)
- Operable openings in buildings and structures
- Ignition sources such as open flames and welding

Group 2

- Exposed persons other than those servicing the system
- Parked cars

Group 3

- Buildings of non-combustible non-fire-rated construction
- Buildings of combustible construction
- Flammable gas storage systems above or below ground
- Hazardous materials storage systems above or below ground
- Heavy timber, coal, or other slow-burning combustible solids
- Ordinary combustibles, including fast-burning solids such as ordinary lumber, excelsior, paper, or combustible waste and vegetation other than that found in maintained landscaped areas
- Unopenable openings in building and structures
- Encroachment by overhead utilities (horizontal distance from the vertical plane Below the nearest overhead electrical wire of building service)
- Piping containing other hazardous materials
- Flammable gas metering and regulating stations such as natural gas or propane

Liquid Hydrogen Exposure Groups

Group 1

1. Lot lines
2. Air intakes
3. Operable openings in buildings
4. Ignition sources such as open flames/welding

Group 2

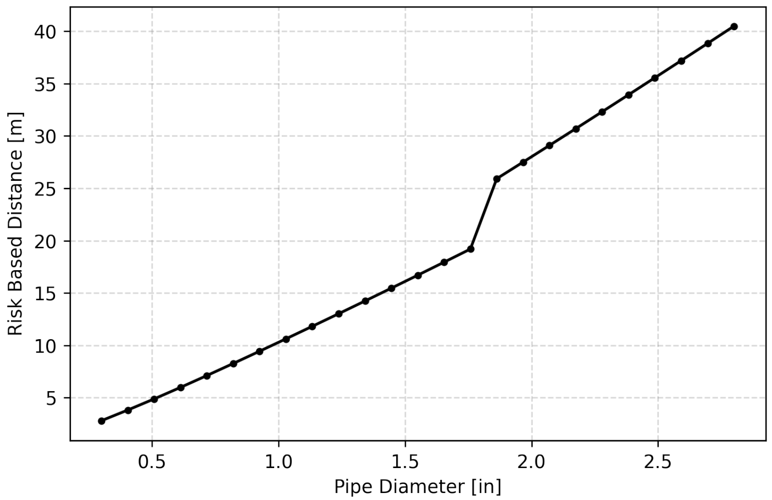
5. Exposed persons other than those servicing the system
6. Parked cars
7. Buildings of combustible construction
8. Hazardous materials storage systems above ground or fill/vent openings for below ground storage systems
9. Ordinary combustibles, including fast-burning solids such as ordinary lumber, excelsior, paper, or combustible waste and vegetation other than that found in maintained landscaped areas

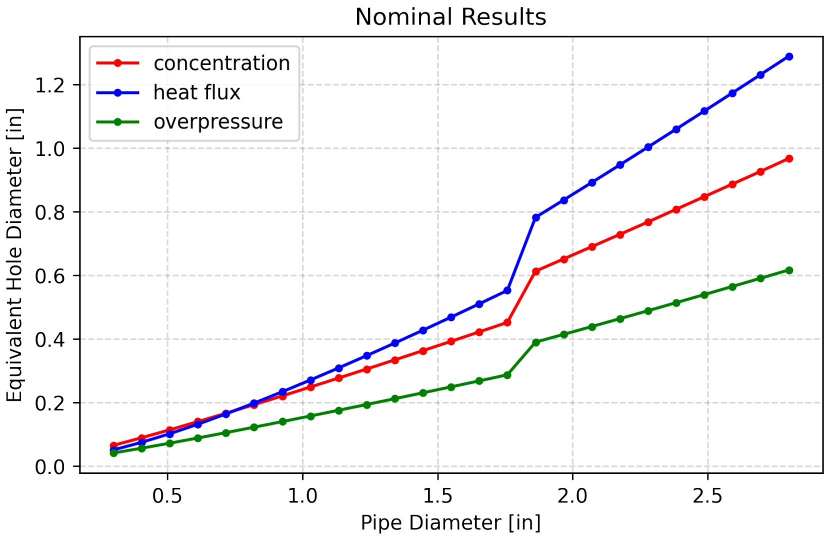
Group 3

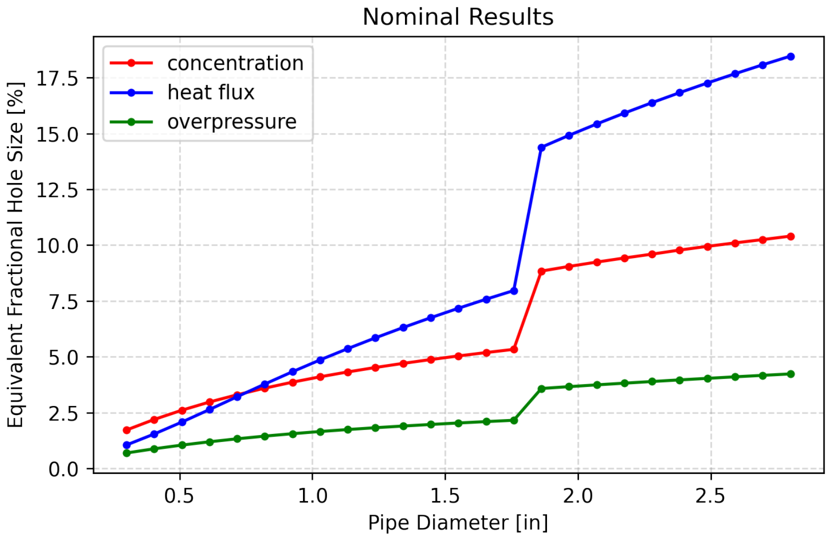
10. Buildings of non-combustible non-fire-rated construction
11. Flammable gas storage systems above or below ground
12. Heavy timber, coal, or other slow-burning combustible solids
13. Unopenable openings in buildings and structures
14. Encroachment by overhead utilities (horizontal distance from the vertical plane below the nearest overhead electrical wire of building service
15. Piping containing other hazardous materials
16. Flammable gas metering and regulating stations such as natural gas or propane

Fractional Hole Size May Serve as Better Proxy to Risk Calculations

- Using HyRAM quantitative risk assessment (QRA), can calculate the distance to individual risk based on some criterion (e.g., 2e-5)
- Risk-based distances (distance to risk criteria) increase with increasing pipe diameter
  - This makes intuitive sense, but single hole size would have constant distance with increasing pipe diameter
- Can then use HyRAM consequence-based models to calculate hole size that would give equivalent distance to Group 1 exposures
  - Equivalent hole size based on risk-based distance also increases with increasing system pipe diameter
- Then can take the smallest fractional hole size of harm criteria, since that is the hazard driving the distance

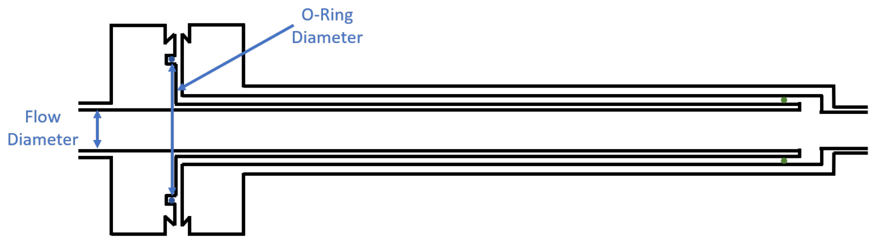






Sensitivity study can help inform what fractional leak size % to pick

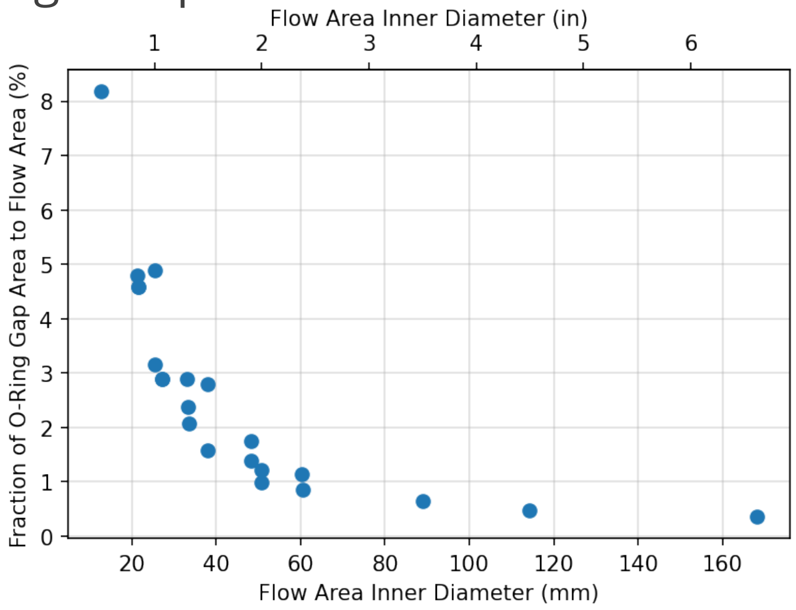
Hole Size Justification: Bayonet Geometry



Reviewed bayonet connector geometries

Focused on leak size due to o-ring failure

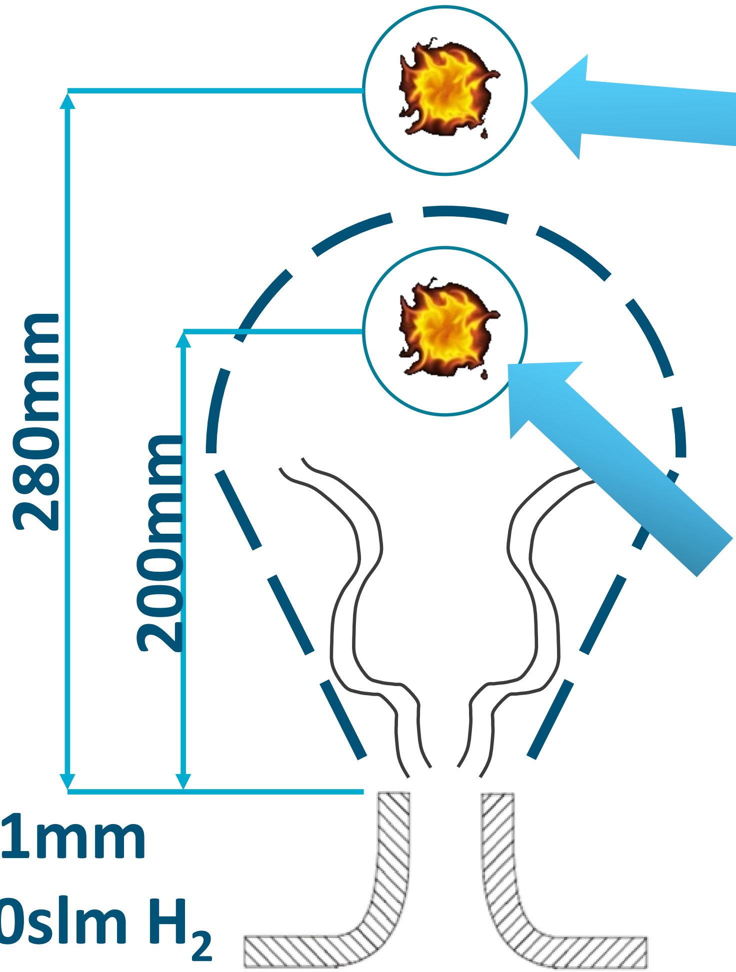
- Leak area equal to flange gap as if o-ring was not there
- 0.9 mm used as a maximum allowed gap height to prevent extrusion

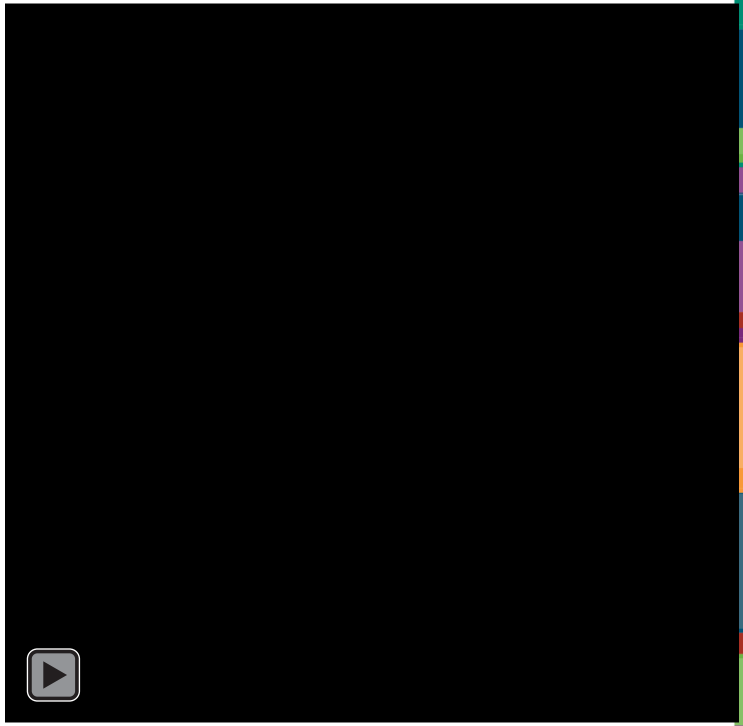


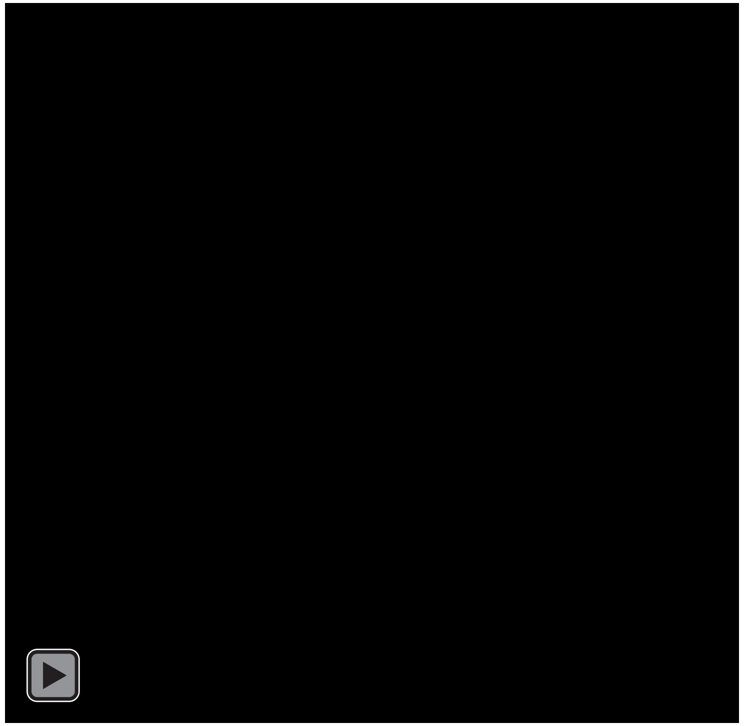
Company	Part Number	O-ring Diam. (in)	O-ring Equiv. Hole Diam (in)	Flow Diam. (in)	O-ring Gap Area/Flow Area (%)	O-ring Gap Area/Flow Area (%) (0.1mm gap)
ACME	0.5 IPS sch 5	1.3	0.4	0.5	74%	8%
ACME	1 IPS sch 5	2	0.5	1	28%	3%
ACME	1.5 IPS sch 10	2.25	0.6	1.5	14%	2%
ACME	2 IPS sch 10	2.52	0.6	2	9%	1%
Cryocomp*	B3049-MB	2.1	0.5	0.85	41%	5%
Cryocomp*	B30412-MB	2.1	0.5	0.85	41%	5%
Cryocomp*	B3069-MB	2.1	0.5	1.07	26%	3%
Cryocomp*	B30612-MB	2.1	0.5	1.07	26%	3%
Cryocomp	B30812-MB	2.3	0.6	1.32	19%	2%
Cryolab-AF	F-BMAFPS12X	4	0.8	1.9	16%	2%
Cryolab-AF	F-BMAFTS12X	4	0.8	1.5	25%	3%
Cyrolab-Lin	F-BFLTPS16X	3.1	0.7	2.38	8%	1%
Cyrolab-Lin	F-BFLTTS16X	3.1	0.7	2	11%	1%
Cyrolab-Lin	F-BFLTPS12X	3.1	0.7	1.3	26%	3%
Cyrolab-Lin	F-BFLTTS12X	3.1	0.7	1	44%	5%
Cyrolab	F-BMCTPS04X	2.15	0.6	0.84	43%	5%
Cyrolab	F-BMCTPS08X	2.6	0.6	1.31	21%	2%
Cyrolab	F-BMCTPS12X	3.2	0.7	1.9	13%	1%
Cyrolab	F-BMCTPS16X	4.1	0.8	2.37	10%	1%
Cyrolab	F-BMCTPS24X	5.1	0.9	3.5	6%	1%
Cyrolab	F-BMCTPS32X	6	0.9	4.5	4%	0%
Cyrolab	F-BMCTPS48X	9.8	1.2	6.62	3%	0%

High speed schlieren inside and outside ignition boundary

Concentration at ignition point can cause local or sustained ignition





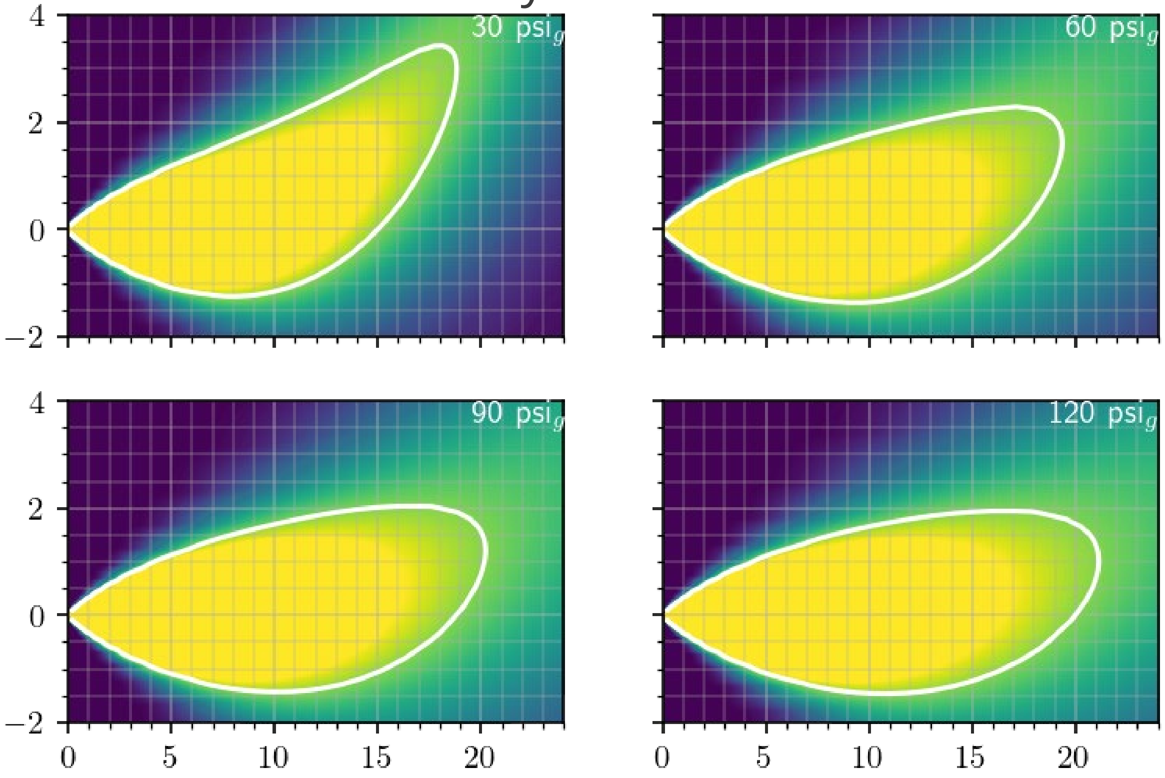


D = Ø1.901mm

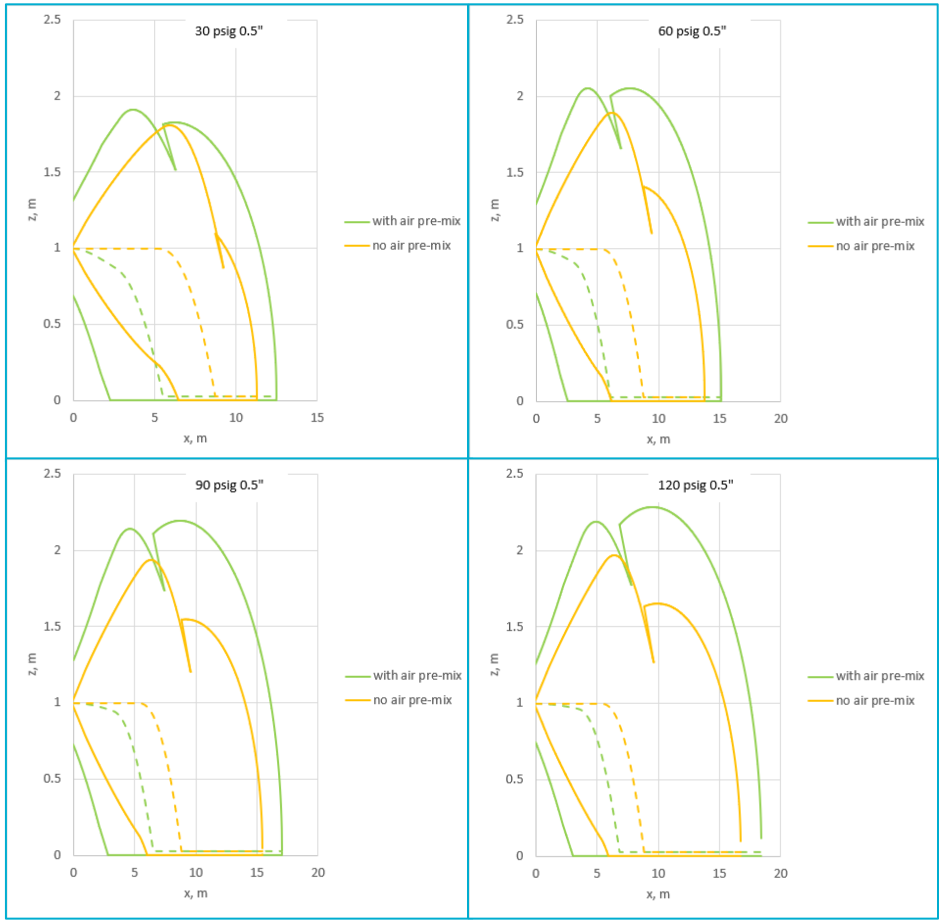
Flow = 100slm H_2

HyRAM+ vs. Air Products VentJet dispersion: 0.5” hole

HyRAM+

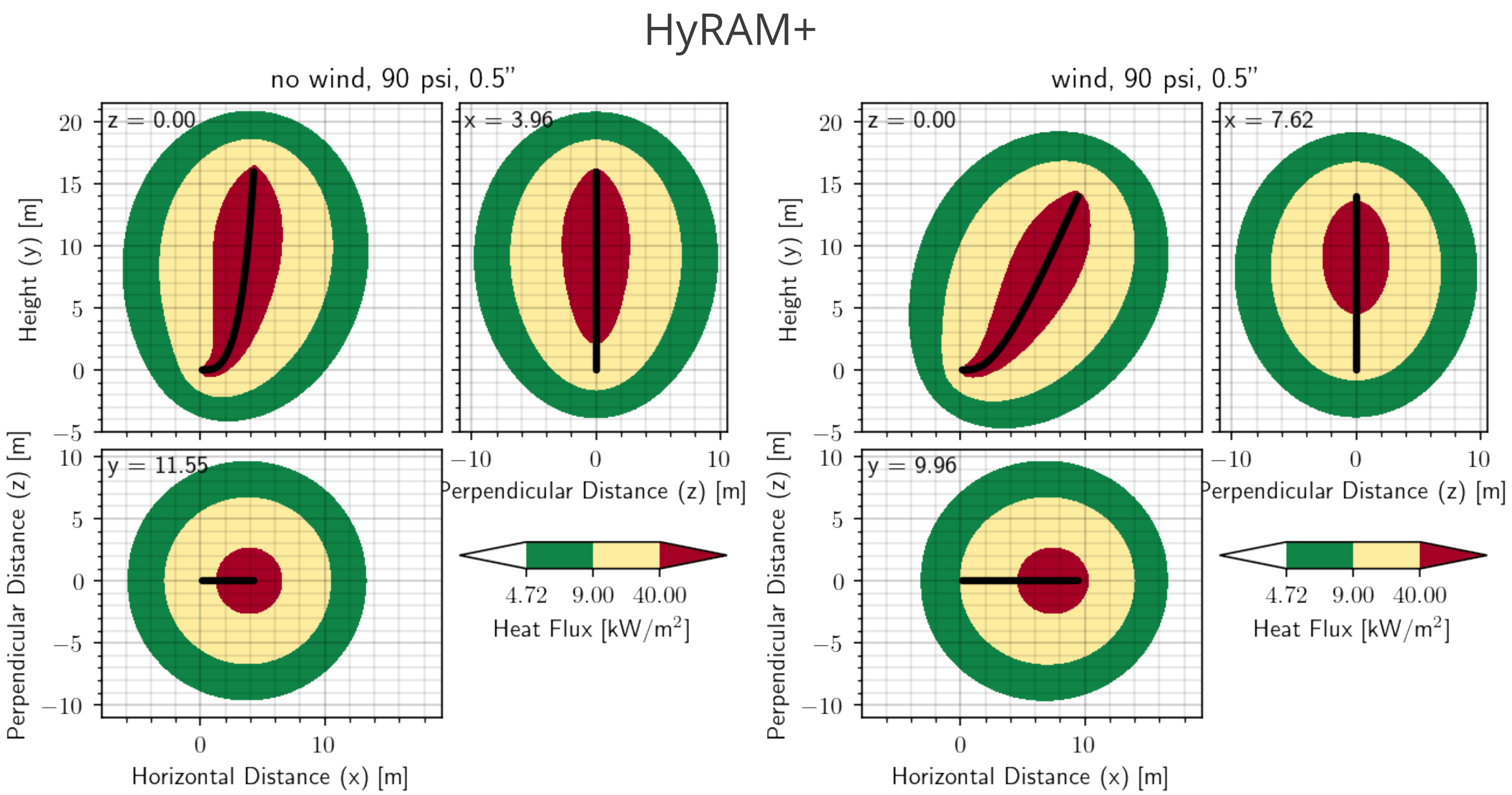


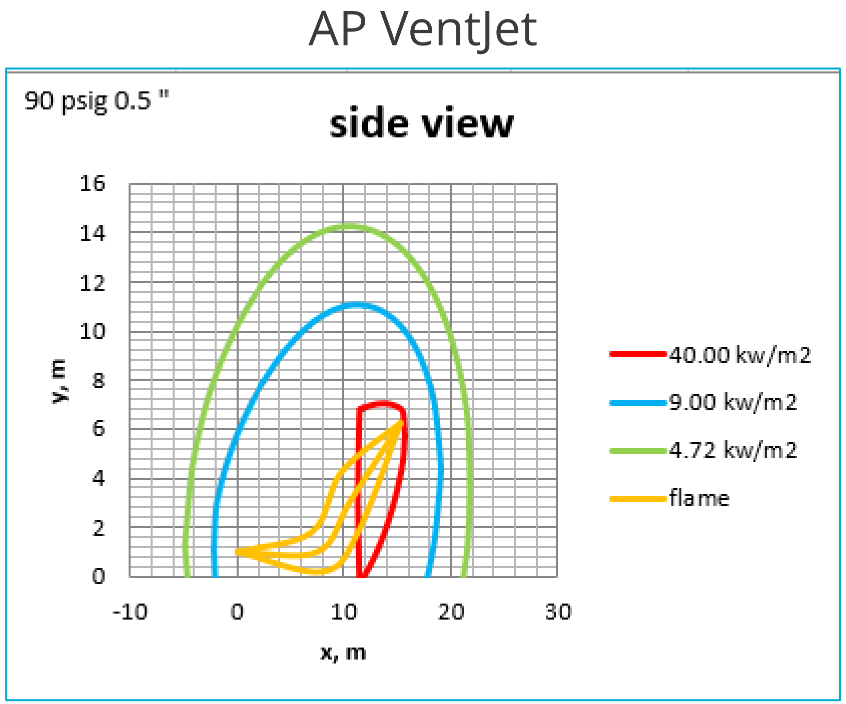
AP VentJet



- VentJet is affected by ground while HyRAM+ does not account for this
- HyRAM+ distances are slightly longer (more conservative) than VentJet
- Distances calculated along streamline rather than just x-distance adding additional conservativism

HyRAM+ vs Air Products flame: 90 psi, 0.5” hole



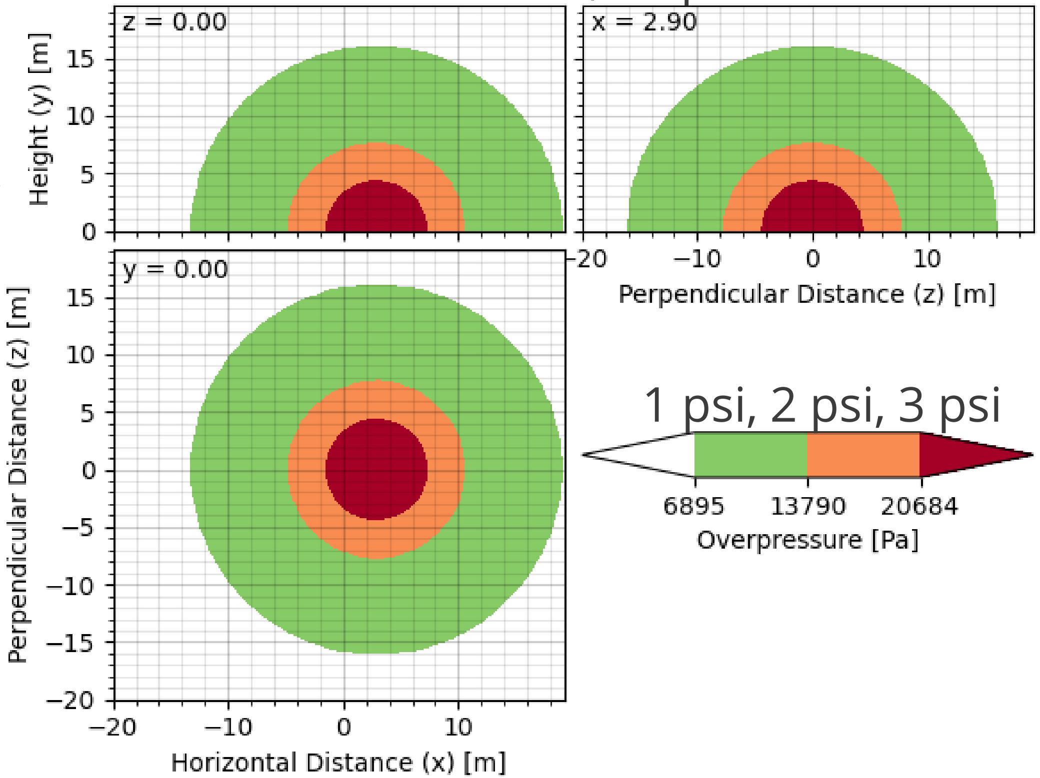


- High density of LH2 results in low momentum release rates
- HyRAM+ modified to include the effect of wind; results in similar distances to AP flame
- Largest projected heat fluxes onto the ground are used as exposure distances

Model Justification: Unconfined Overpressure

- Work by [Jallais et al. (2018)] suggested use of modified TNO ME or BST method for calculating overpressure from delayed ignition of hydrogen jet
  - Source energy of blast wave is calculated from flammable mass from 10-75% (not 4-75%)
  - Blast wave curve (blast intensity) is tied to mass flow rate of leak; deflagration (not detonation)
  - Compared models to experimental data and high-fidelity models
- This approach was implemented using HyRAM+ and compared to AP JetEx model
  - Similar results obtained
- Overpressures compared to DNV-GL release data
  - Peak overpressures overpredicted by 3-10 times (conservative)

HyRAM+
0.5” hole, 90 psi



Reduction Justification: Walls - Risk Reduction

Reduced setback distances based on Individual Risk values found through applying QRA analysis used to support NFPA-2 and 55.

- LaChance 2009
- Used same system configuration with 2.4 m high wall (1.22 m from equipment)

Used QRA to estimate setback distances with risk levels equivalent to those without barriers.

Results demonstrated up to a 66% reduction in setback distance, but revisions of gaseous table in NFPA 2-2011 used conservative 50% reduction.

- From DOE Program Record

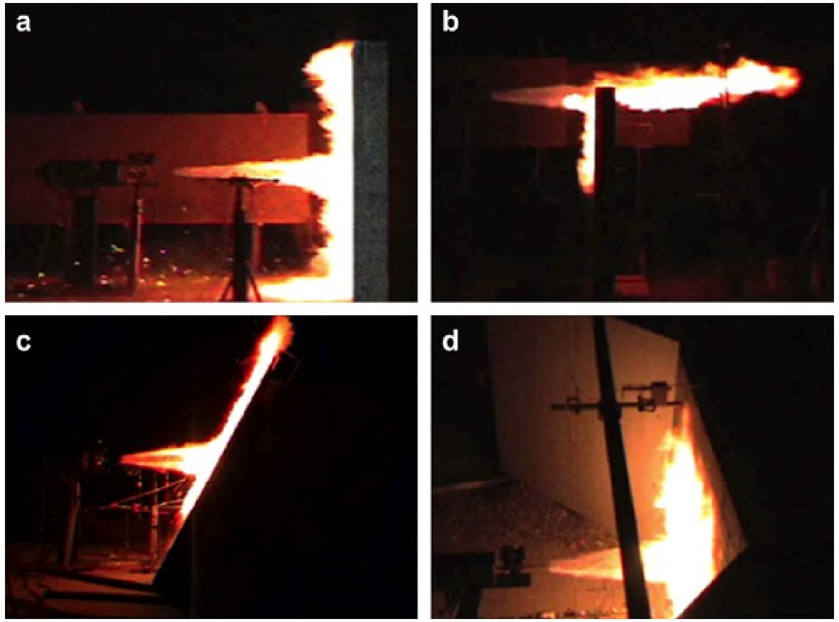
From LaChance 2010

Table 1: Estimated risk reduction from the use of barriers.

System Pressure (MPa)	Leak Diameter[1] (mm)	Separation Distance to Facility Lot Line[2] w/o Barrier (m)	Individual Risk at Facility Lot Line (fatalities /yr)	
			w/o Barrier	Barrier
1.83	9.09	14.0	2.0E-5	5.4E-6
20.78	3.28	14.0	2.1E-5	5.5E-6
51.81	1.37	8.8	3.6E-5	1.1E-5
103.52	1.24	10.4	3.5E-5	1.0E-5

[1] Leak diameter corresponds to 3% of the largest flow area in the system
[2] Separation distance specified in NFPA-55, based on selected leak diameter.

Reduction Justification: Walls



Schefer 2009: Ignited experiments
- Significant reductions in overpressure and heat flux behind the barrier
- No entrainment down the back of the wall

Houf 2008: Modeling for unignited gas clouds
- No entrainment down the back of the wall

Individual risk calculations (not consequence-based) informed distance reductions
- "Results demonstrated up to a 66% reduction in setback distance, but revisions of gaseous table in NFPA 2-2011 used conservative 50% reduction" from DOE Program Record

50% distance reduction from walls will be used for LH2 setbacks also

Table 1: Estimated risk reduction from the use of barriers.

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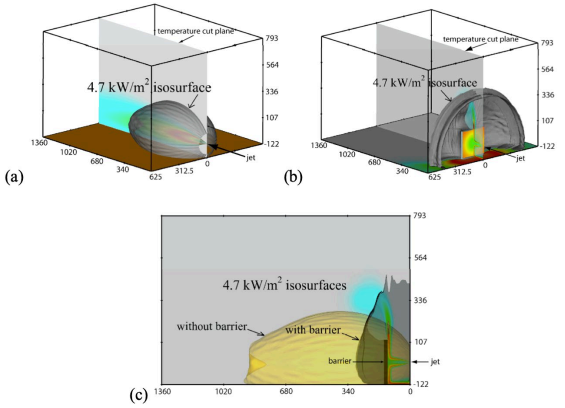
From LaChance 2010



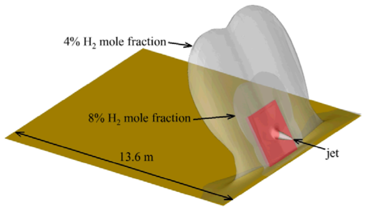


Figure 13. Calculated isosurfaces of 4% and 8% hydrogen mole fraction for a horizontal jet impinging on the 1-wall 2.4 m x 2.4 m (8 ft x 8 ft) tilted barrier. The jet release location is 1.219 m above the ground with the flow from right to left.

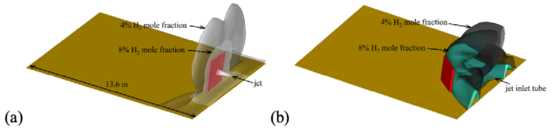
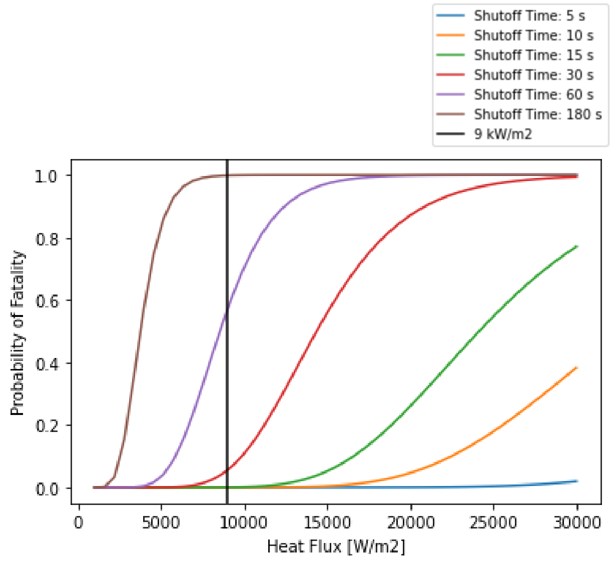
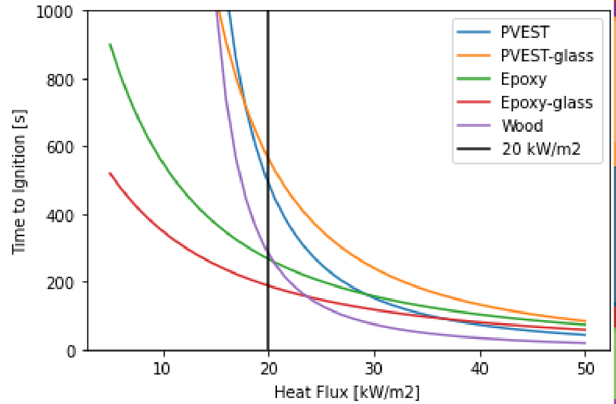


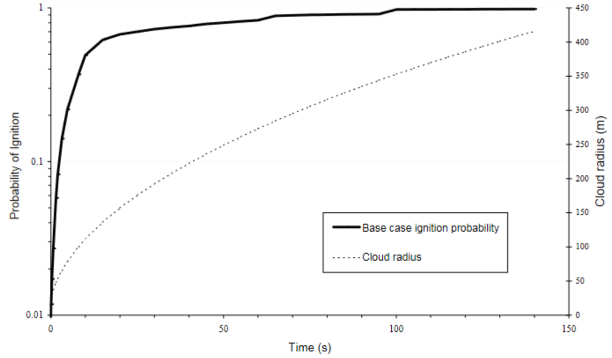
Figure 14. Calculated isosurfaces of 4% and 8% hydrogen mole fraction for unignited horizontal jets impinging on barriers with jet flow from right to left. (a) 1-wall 2.4 m x 2.4 m (8 ft x 8 ft) vertical barrier; (b) 3-wall barrier with 135 degrees between each 2.4 m x 2.4 m (8 ft x 8 ft) wall.

Reduction Justification: Shutdown

- Justification for heat flux to humans:
    - NFPA 2 gives a heat flux criteria of 4.7 kW/m^2 based on exposure to employee for maximum of 3 minutes (Group 1 and 2 exposures)
    - 15 seconds at 9 kW/m^2 has probability of fatality of ~0% whereas 3 minutes at 4.7 kW/m^2 has probability of fatality of ~80%
- Justification for heat flux to buildings/combustibles:
    - Many sources (e.g., SFPE Handbook) give time to ignition at different heat flux values for different materials
    - Group 3 (buildings/combustibles) exposures could be reduced to zero if automatic shutoff can be proven to activate before the time to ignition (3min) at the heat flux criteria chosen (20 kW/m^2)
- Harder to mathematically calculate reductions for unignited concentration or unconfined overpressure
- ***Therefore, automatic retention valves will not give explicit distance-reduction, but will be required at public (refueling) facilities to reduce risk***

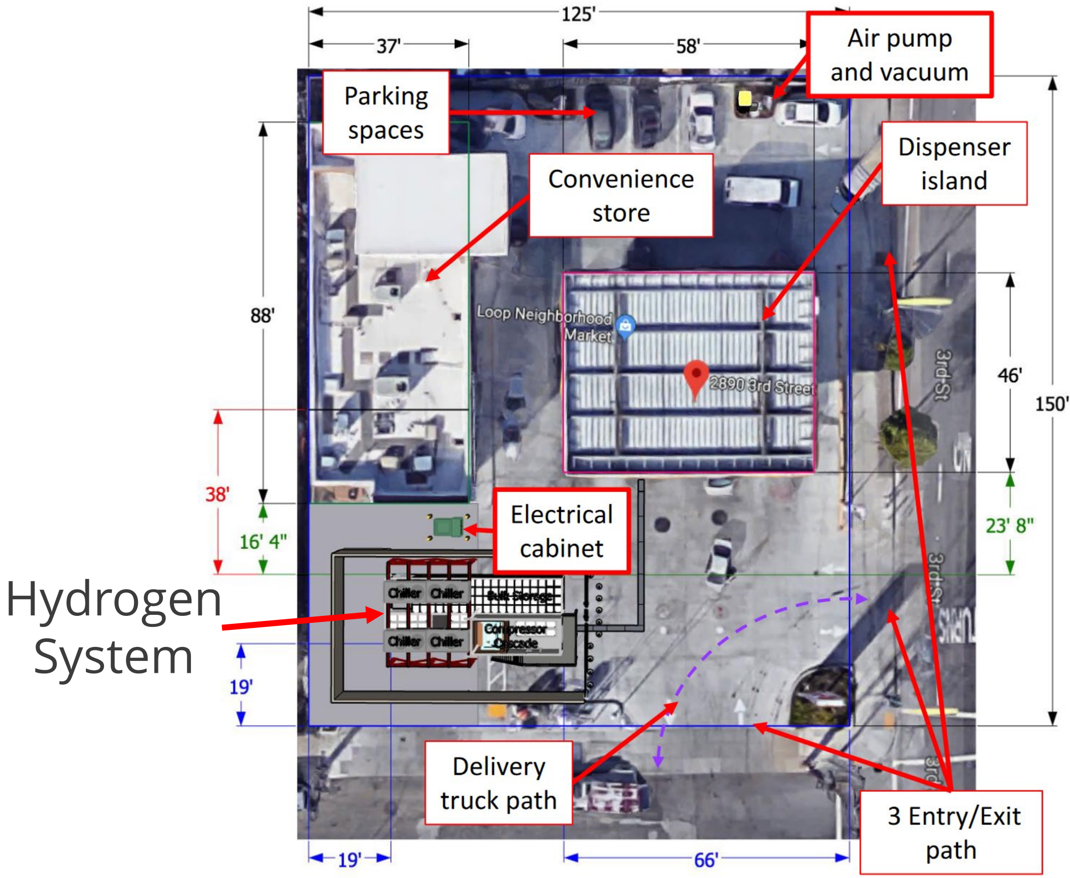




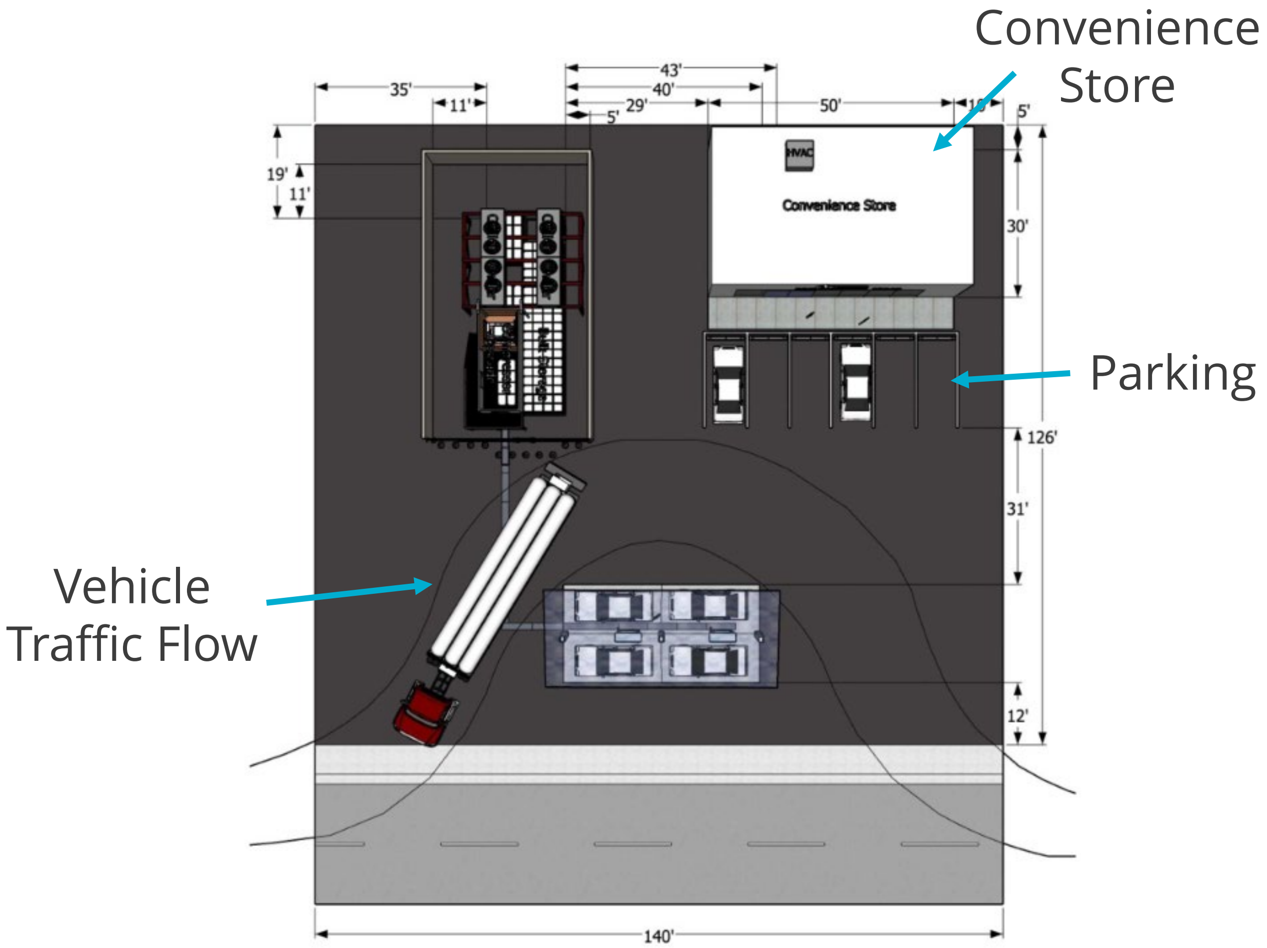


Daycock and Rew, UK HSE Report 226, 2004

How Do Setback Distances Affect Layout and Siting?



Setback distances can affect where hydrogen systems can be located on a property



Setback distances are not the only thing that drives overall footprint

Images from: Ehrhart et al. "[Hydrogen Refueling Reference Station Lot Size Analysis for Urban Sites]." SAND2020-2796