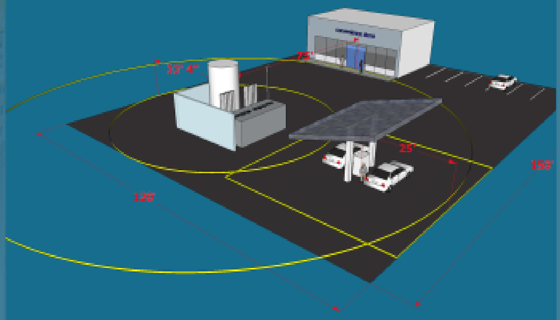
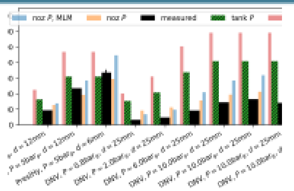
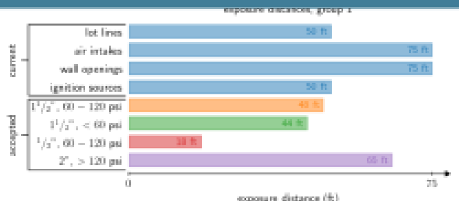
SAND2022-12498C

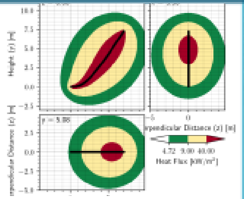
Sandia National Laboratories

Basis for Updated Bulk Liquid Hydrogen Separation Distances in NFPA 2









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U.S. DEPARTMENT OF ENERGY NNSA

Current distances in NFPA 2 between bulk liquid hydrogen storage lack documentation of basi

- Distances are based on storage volume
- Air intakes required to be 75 ft from bulk storage
  - Distance independent of size
  - Unable to be reduced through the use of barrier walls
- Exposures placed in groups (in 2016 update to NFPA2) but distance to each exposure is not consistent within the group
- Have served industry well over half a century of use, but can be improved using modern modeling tools and experience

Δ 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 noncombustible contents	5[a]	1.5	5[a]	1.5	5[a]	1.5
(2) Unsprinklered building or structure with combustible contents						
i. Adjacent wall(s) with fire resistance rating less than 3 hours	25	7.6	50	15	75	23
ii. Adjacent wall(s) with fire resistance rating of 3 hours or greater[b]	5	1.5	5	1.5	5	1.5
(b) Buildings of combustible construction						
(1) Sprinklered building or structure	50	15	50	15	50	15
(2) Unsprinklered building or structure	50	15	75	23	100	30.5
8. Flammable gas storage or systems (other than hydrogen) above or below ground	50	15	75	23	75	23
9. Between stationary liquefied hydrogen containers	5	1.5	5	1.5	5	1.5
10. All classes of flammable and combustible liquids (above ground and vent or fill openings if below ground)[c]	50	15	75	23	100	30.5
11. Hazardous materials storage or systems including liquid oxygen storage and other oxidizers, above or below ground	75	23	75	23	75	23

Previous approach to determine compressed gaseous storage setbacks in NFPA 2 (analogous approach used as a starting basis for liquid hydrogen)

Quantitative risk assessment on representative refueling station

- No direct, mathematical link to setback distances, but did inform if 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 setbacks 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

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.

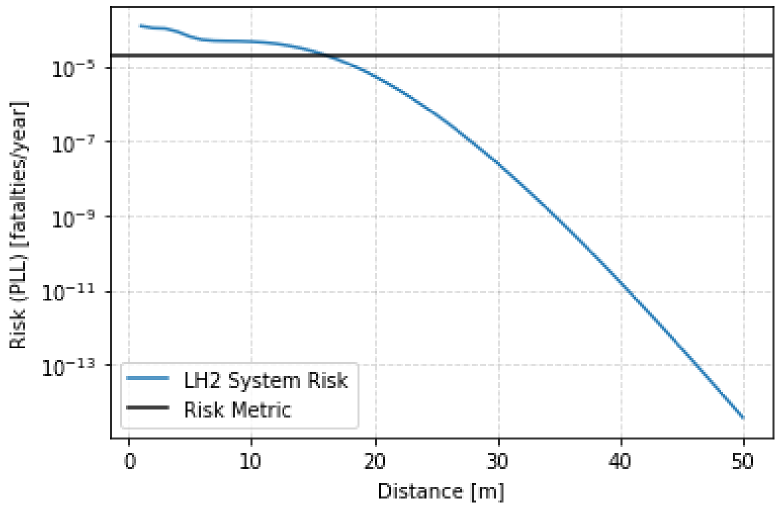
Basis for a characteristic leak size was informed by quantitative risk assessment

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

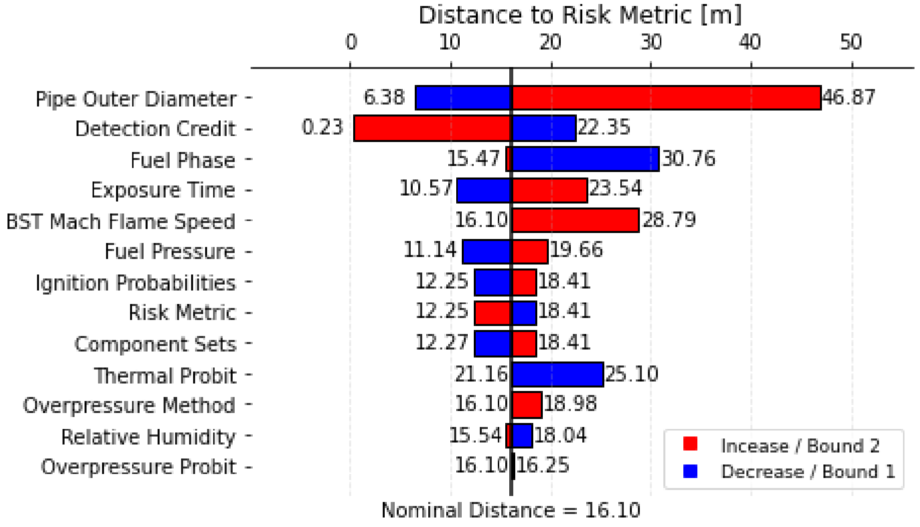
Risk acceptance metric can give a risk-based distance from a leak point based on a full QRA

- Varying QRA inputs can affect this distance significantly

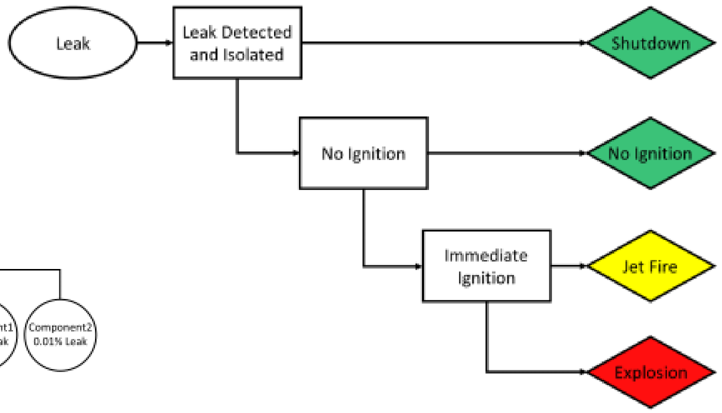
Potential Loss of Life (PLL) Risk Metric at Distances Away from Leak



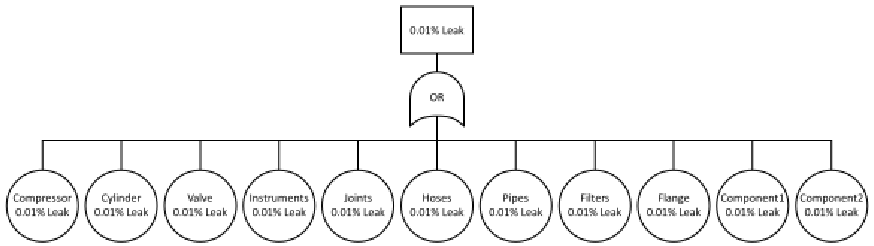
Sensitivity of Risk-Based Distances



Leak Outcome Event Tree



Component Leak Fault Tree



Sensitivity study enabled selection of a characteristic fractional leak area

QRA varied single input value, then calculated equivalent fractional leak area for a range of system pipe diameters

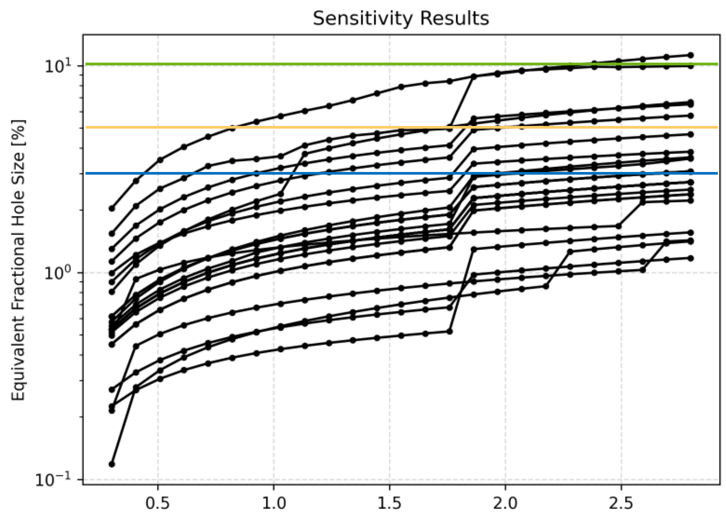
Sensitivity results are mostly below 10% fractional leak area

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

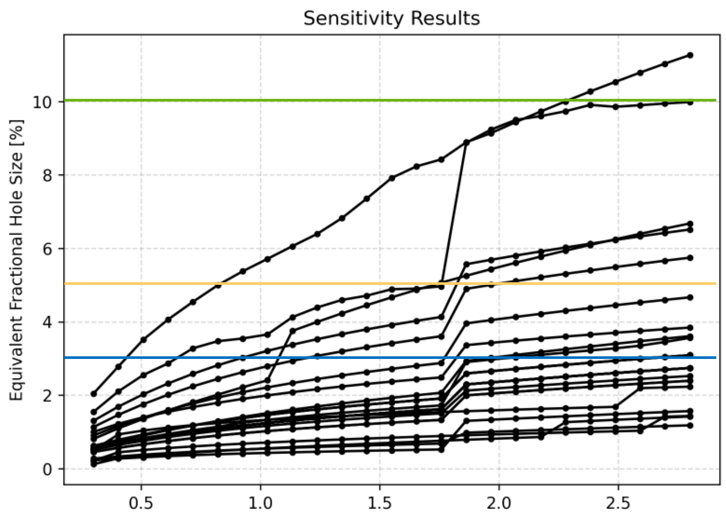
Possibilities considered:

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

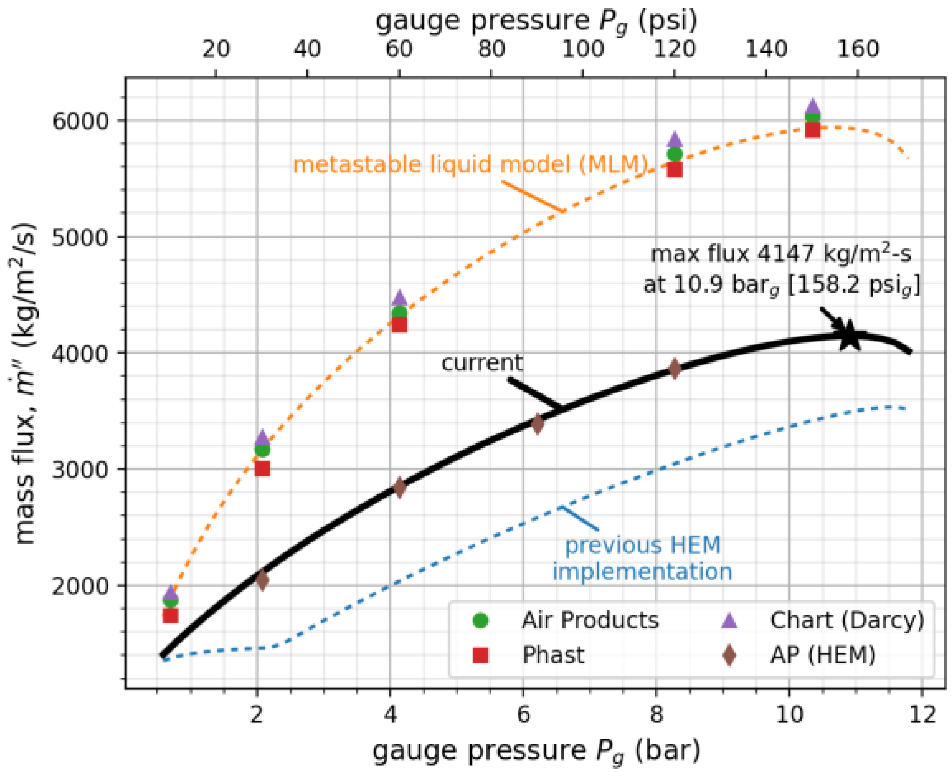
Log-Scale



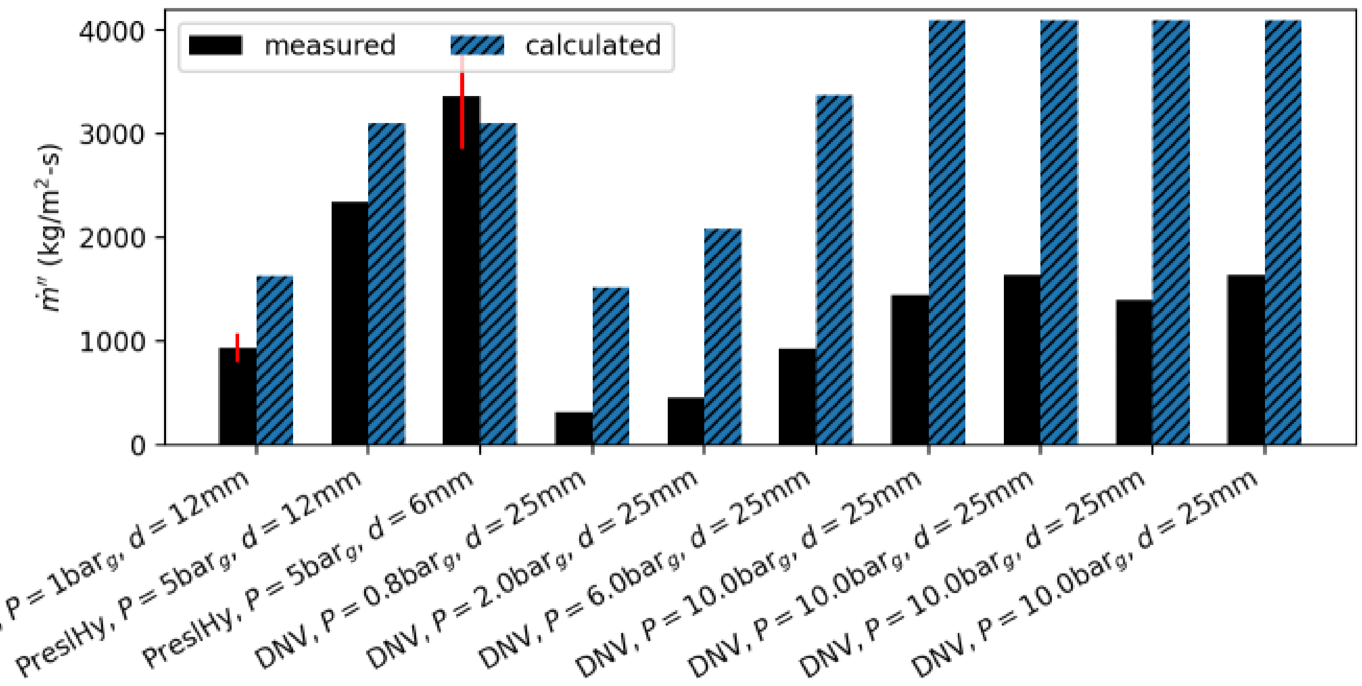
Linear-Scale



Liquid hydrogen mass flow model was updated from a previous version in HyRAM+



- Calculations use homogenous equilibrium model (HEM) with updated implementation
- HEM model generally overpredicts experiments (experiments attempting to get high liquid flows are greatly overpredicted when using MLM)



In addition:

- Other models (dispersion, flame, overpressure) were validated against experiments
- Flame model updated for risk analysis to include the capability to simulate effect of cross-wind

The team regrouped the liquid hydrogen exposure groups

Group	Exposure	Should avoid
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 distance to an average unignited concentration

Exposures considered (Group 1):

- Air intakes
- Sewer inlets
- People (fireball)

NFPA 2 GH2 uses 8% by volume

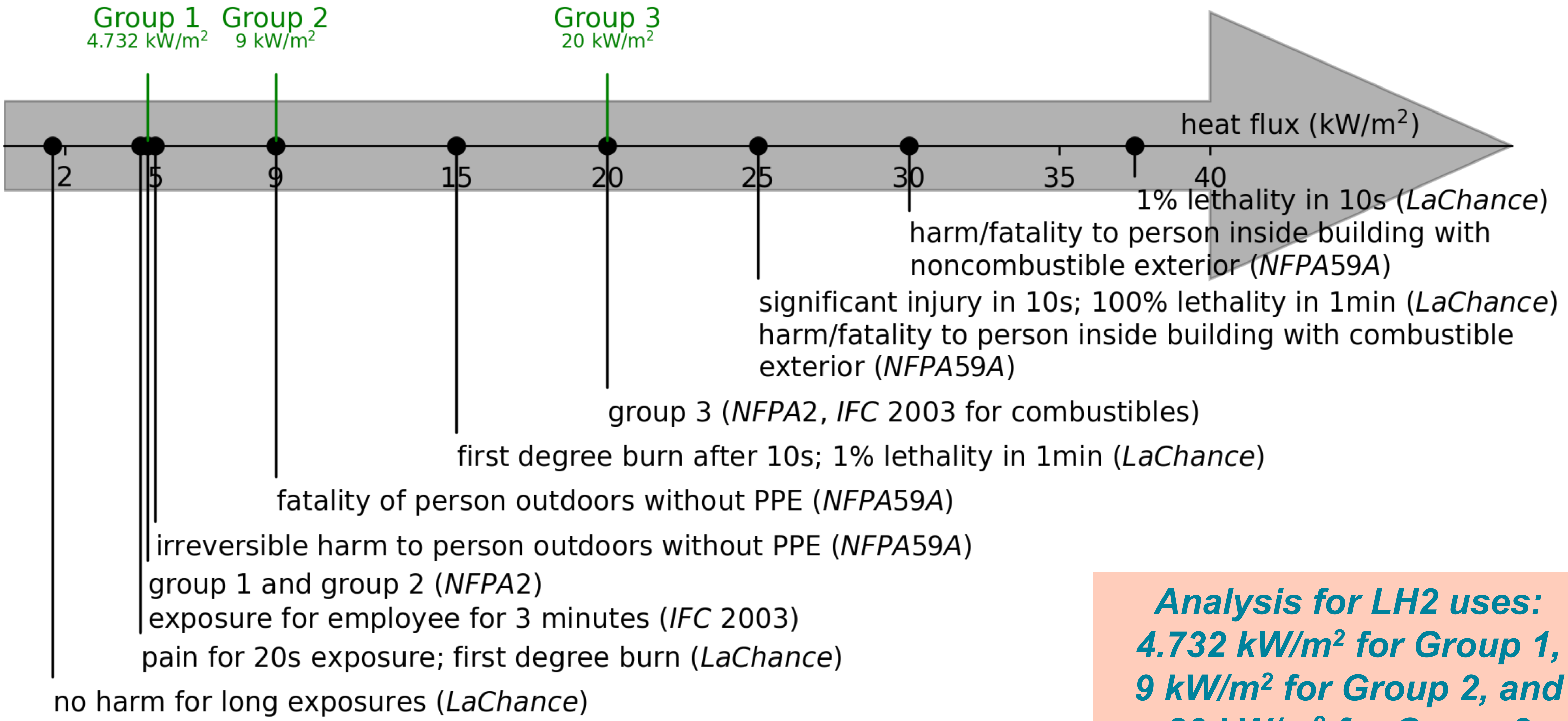
- Based on ability to sustain ignition
- Rather than 4% by volume lower flammability limit

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

- Also considers higher concentrations for oxygen displacement

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

Criteria for distances to jet flame heat flux levels



Analysis for LH2 uses: 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

Criteria for distance to a peak overpressure

Exposures considered:

- 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 uses:

- ***1 psi (7 kPa) for Group 1 exposures***
- ***2 psi (14 kPa) for Group 2 exposures***
- ***3 psi (21 kPa) for Group 3***

Table 1. Effect of overpressure on humans (highlighted in red) and structures, as well as selected Groups 1 and 2 overpressure criteria (highlighted in blue)

Overpressure kPa	psi	Damage
0.2	0.0	Occasional breakage of large windows already under strain [9, 10]
0.3	0.0	Loud noise. Breakage of windows due to sound waves [9]
0.3	0.0	Loud noise (143 dB) [11]
0.7	0.1	Breakage of small panes of glass already under strain [9]
1.0	0.1	Threshold for glass breakage [11, 12]
2.0	0.3	10% window glass broken [11]
2.0	0.3	20% windows broken. Minor structural damage to houses [9]
3.5	0.5	Shatter glass [13]
3.5–6.9	0.5–1.0	Large/small windows usually shattered; occasional damage to window frames [11]
6.8	1.0	Partial demolition of houses, which become uninhabitable [9, 11]
6.9	**1.0**	**Selected Group 1 Criteria**
7.0	1.0	Window glass shatters. Light Injuries from Fragments [14]
7.0	1.0	Knock a person over [13]
9.0	1.3	Steel frame of clad building slightly distorted [11]
6.9–13.8	1.0–2.0	Threshold of skin lacerations by missiles [12]
13.6	2.0	Partial collapse of house roofs and walls [9–11]
13.7	**2.0**	**Selected Group 2 Criteria**
13.8	2.0	Threshold for eardrum rupture [12]
13.8	2.0	Possible fatality by being projected against obstacles [12]
14.0	2.0	Moderate damage to homes (windows/doors blown out, damage to roofs) [14]
14.0	2.0	People injured by flying glass and debris [14]
10.3–20.0	1.5–2.9	People knocked down by pressure wave [12]
15.8	2.3	Lower limit of serious structural damage [11]
16.2	2.3	1% of eardrum breakage [9]
13.1–20.4	1.9–3.0	Destruction of cement walls of 20–30 cm width [9]
17.0	2.5	1% fatality [15]
15.0–20.0	2.2–2.9	Collapse of unreinforced concrete or cinderblock wall [12]
20.7	**3.0**	**Selected Group 3 Criteria**
20.7	3.0	Steel frame building distorted and pulled away from foundations [11]
21.0	3.0	Serious injuries common. Fatalities may occur [14]
21.0	3.0	0% probability of fatality in the open [15]
20.4–27.7	3.0–4.0	Rupture of storage tanks [9]
20.7–27.6	3.0–4.0	Frameless, self-framing steel panel building demolished [11]
20.0–30.0	2.9–4.4	Collapse of industrial steel frame structure [12]
27.6	4.0	Cladding of light industrial buildings ruptured [11]
27.6–34.5	4.0–5.0	50% probability of fatality from missile wounds [12]
34.0	4.9	Injuries are universal fatalities widespread [14]
34.0	4.9	Most buildings collapse [14]
35.0	5.1	15% probability of fatality in open [15]
35.0–40.0	5.1–5.8	Displacement of pipe bridge, breakage of piping [12]
34.0–47.6	4.9–6.9	Almost total destruction of houses [9, 11]
34.5–48.3	5.0–7.0	50% probability of eardrum rupture [12]
48.3	7.0	Threshold of internal injuries by blast [12]
47.7–54.4	6.9–7.9	Breakage of brick walls of 20–30 cm width [9, 11]
48.3–68.9	7.0–10.0	100% probability of fatality from missile wounds [12]
68.9	10.0	Probable total destruction of buildings [9–11]
69.0	10.0	Reinforced concrete buildings are severely damaged or demolished [14]
69.0	10.0	Most people are killed [14]
70.0	10.2	Total destruction of buildings; heavy machinery damage [12]
50.0–100.0	7.3–14.5	Displacement of cylindrical storage tank, failure of pipe [12]
55.2–110.3	8.0–16.0	People standing up will be thrown a distance [12]
68.9–103.4	10.0–15.0	90% probability of eardrum rupture [12]
90.0	13.1	50% fatality [15]
82.7–103.4	12.0–15.0	Threshold for lung hemorrhage [12]
101.0	14.6	1% death due to lung hemorrhage [9]
138.0	20.0	Heavily built concrete buildings are severely damaged or demolished [14]
138.0	20.0	Fatalities approach 100% [14]
137.9–172.4	20.0–25.0	50% probability of fatality from lung hemorrhage [12]
169.2	24.5	90% death due to lung hemorrhage [9]
206.8–241.3	30.0–35.0	90% probability of fatality from lung hemorrhage [12]
300.0	43.5	95% fatality [15]
482.6–1379.0	70.0–200.0	Immediate blast fatalities [12]

Distances are calculated using chosen criteria and models

5% fractional leak area for 4 characteristic pipe sizes (0.5”, 1”, 1.5”, and 2” [12.7 – 50.5 mm])

3 characteristic pressures for bulk liquid tanks

- 60 psi_g [404 kPa_g]
- 120 psi_g [827 kPa_g]
- up to the critical pressure (173 psi_g [1195 kPa_g]) – max mass flux pressure of 158 psi_g [1091 kPa_g] used for these calculations

Group 1:

- Concentration: 8 mol% (streamline)
- 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)
- Peak Overpressure: 13.790 kPa (2 psi)

Group 3:

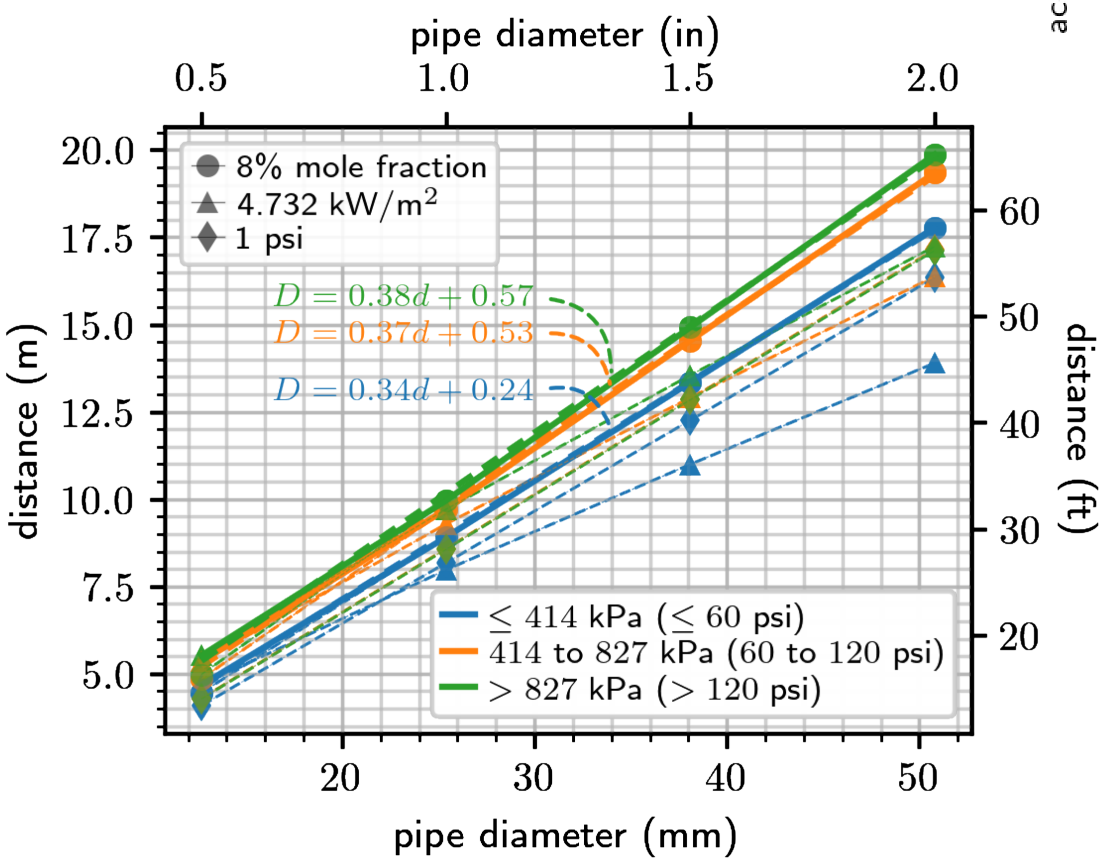
- Heat Flux: 20 kW/m^2 (6,340 BTU/hr/ft^2) (bird's eye)
- Peak Overpressure: 20.7 kPa (3 psi)
- Visible Flame Length (bird's eye)

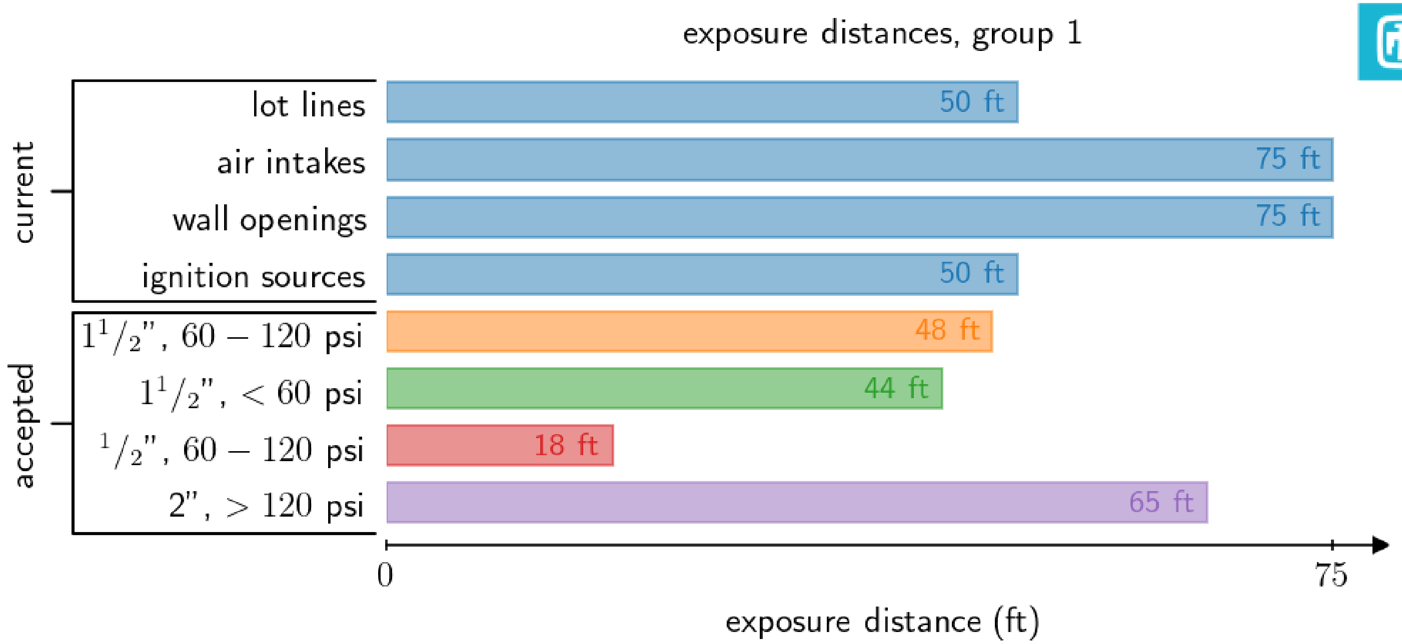
Safety factor = 1 (models and leak area have built-in conservativism)

1. Calculate distances for each criteria
2. Select maximum distance within a group for a given pipe size
3. Develop linear correlation for variations in pipe size

Group 1

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





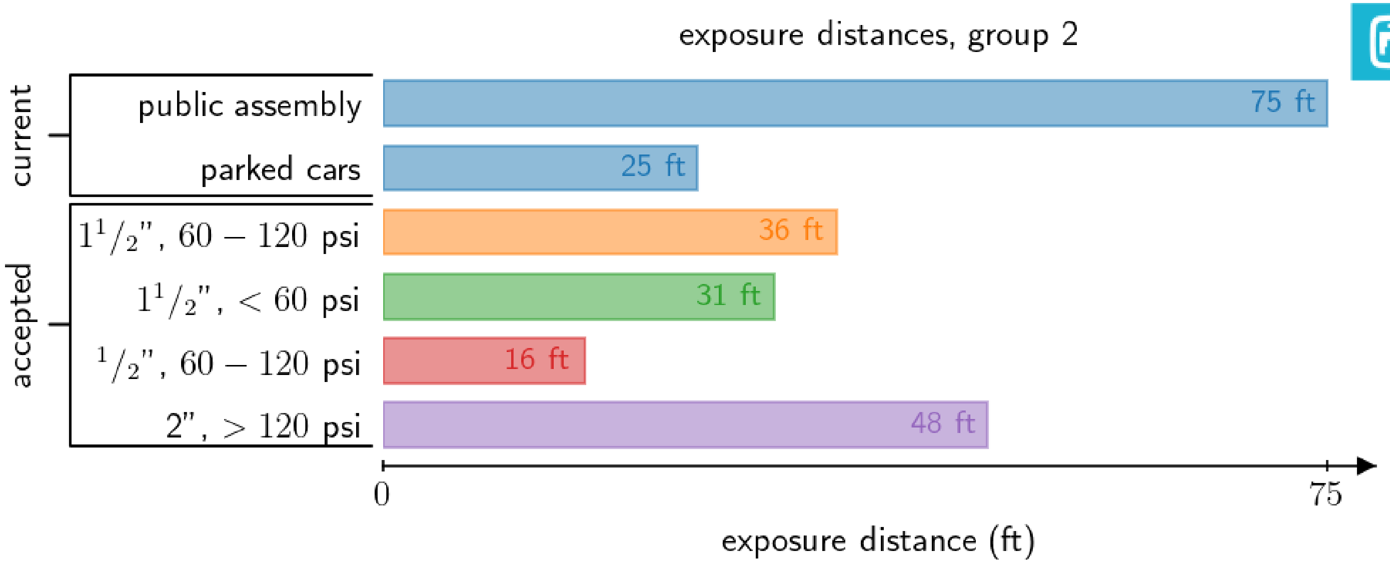
Protects against:

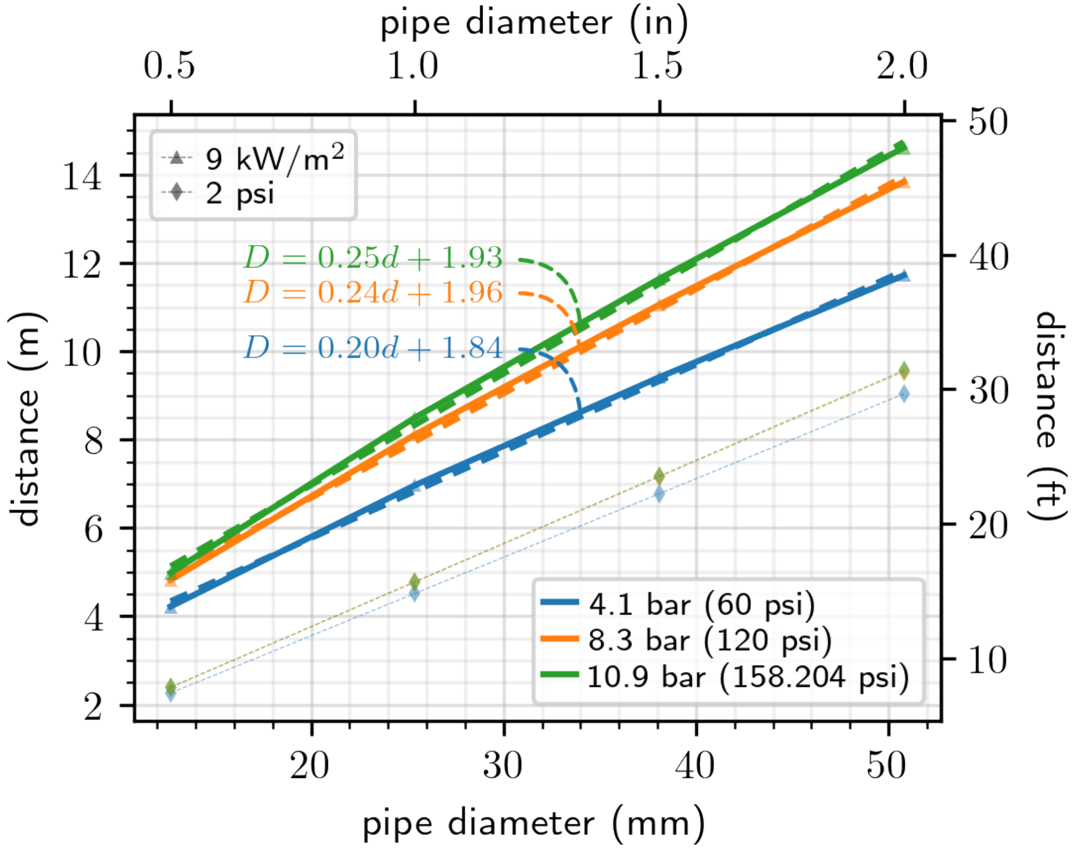
- Flammable concentration
- Damage from heat flux
- Damage from overpressure
- General public

8 mol% (streamline) dominates distance

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





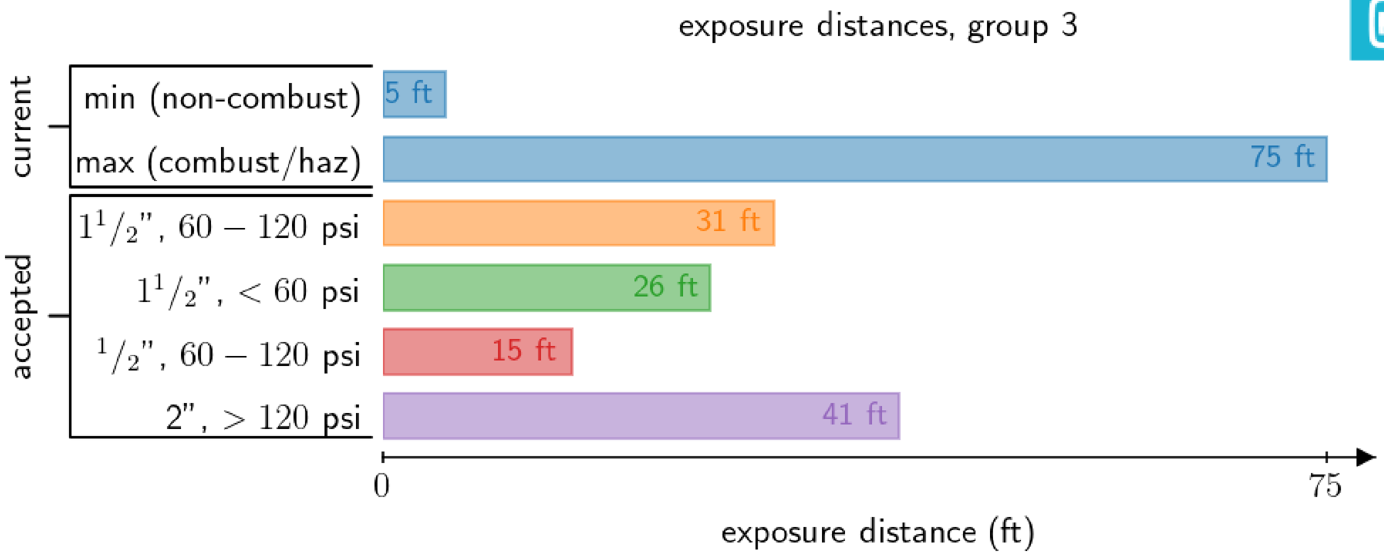
Protects against:

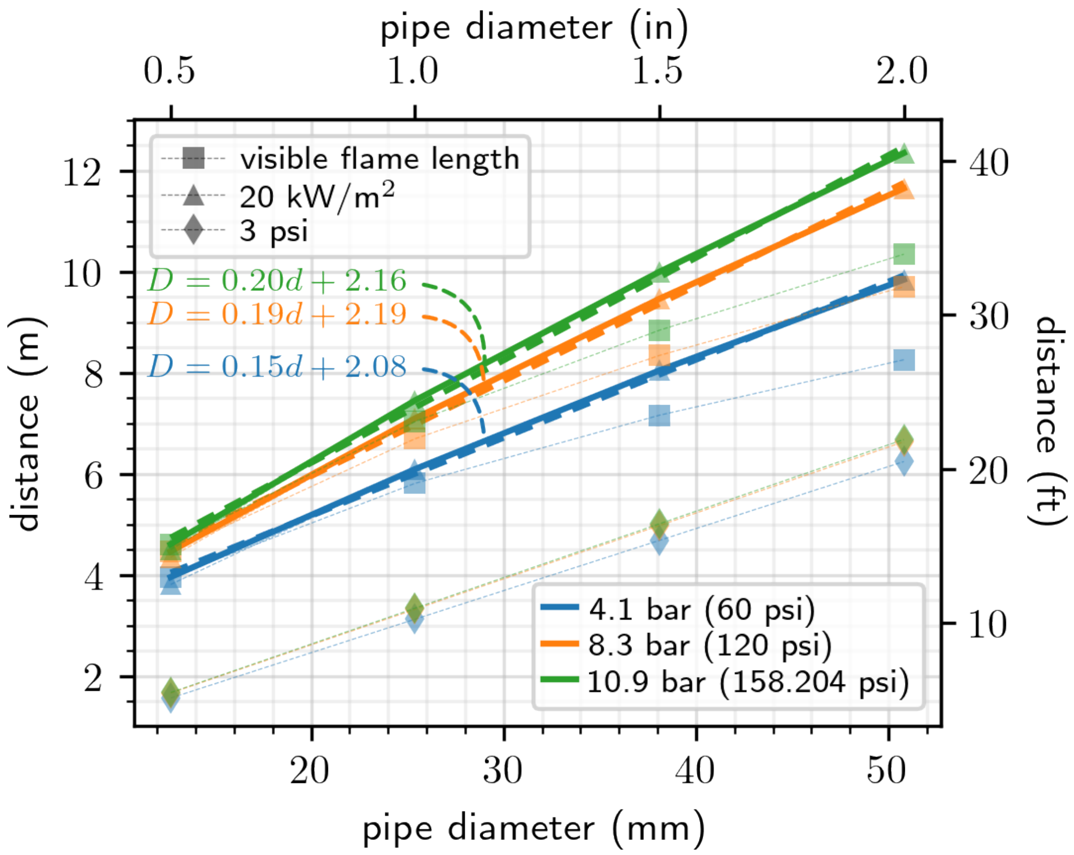
- Fire spread to ordinary combustibles
- Significant damage to buildings
- Harm to people informed of risk (people at the fueling station)

Heat Flux: 9 kW/m² (2,853 BTU/hr/ft²) (bird's eye) dominates distance

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





Protects against:

- Escalation of event (fire spread)

Heat Flux: 20 kW/m^2 (6,340 BTU/hr/ft^2) (bird's eye) dominates distance

Updated tables are similar to gaseous hydrogen

- Single distances for each exposure group
- Pressure ranges do not show large differences, but may be useful in some cases
- Pipe size can make a significant difference

Table 8.3.2.3.1.6(a) Minimum Distance from Outdoor Bulk Liquefied Hydrogen [LH2] Systems to Exposures, up to 75000 gallons— Typical Inner Diameter (1.5 in [38.1 mm])

Maximum Tank Operating Pressure (gauge)	≤ 60 psi ≤ 414 kPa		60 to 120 psi 414–827 kPa		>120 psi >827 kPa	
Exposures Group 1	**m**	**ft**	**m**	**ft**	**m**	**ft**
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	13.3	44	14.5	48	14.9	49
Exposures Group 2	**m**	**ft**	**m**	**ft**	**m**	**ft**
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	9.4	31	11.1	36	11.6	38
Exposures Group 3	**m**	**ft**	**m**	**ft**	**m**	**ft**
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	8.0	26	9.5	31	10.0	33

Table 8.3.2.3.1.6(b) Minimum Distance from Outdoor Bulk Liquefied Hydrogen LH2 Systems to Exposures by Maximum Inner Diameter

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

➢ Future work: reconsider exposures in each group for bulk gaseous storage

Credits for mitigations were reviewed and updated

Current (2020 Edition) of NFPA 2 allows for **reduction by 2/3 for insulated** portions of the system

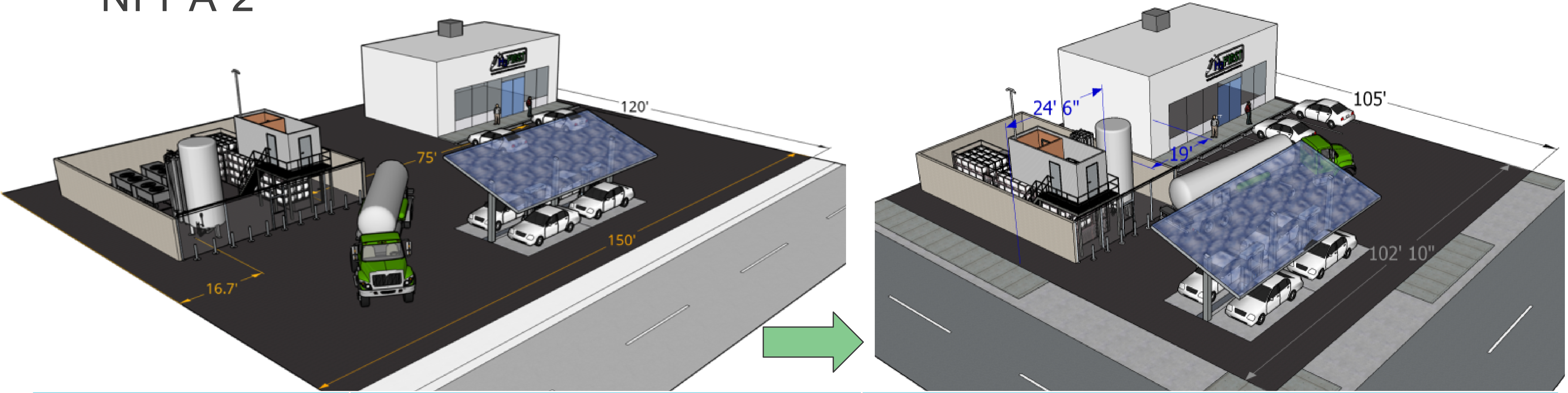
- Welded, double-walled vacuum jacketed pipe typically employed for LH_2 flows reduces potential leak points
- Credit remains, but language was clarified to: *vacuum insulated portions of the system with no mechanical connections, joints, or leak sources*

Current (2020 Edition) of NFPA 2 allows for **reduction to 0 ft (0 m) from fire barrier walls** for some exposures

- Fire barrier walls prevent heat flux and overpressures from reaching exposures
- Walls can also directionally reduce dispersion or flows of unignited gas
- Fire barrier walls enable reduction for bulk gaseous storage as well
- In approved version, fire barrier walls enable:
  - Reduction of distances to air intakes by ½ but not less than 15 ft (4.6m)
  - Reduction of other Group 1 and Group 2 exposures by ½
  - Reduction of Group 3 exposures to 0 ft (0 m)

Reaffirmed importance of **automatic emergency shutdown system** for public refueling stations

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



Characteristic	NFPA 2 (2016)	This work
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 separation distances as liquid system	Treated separately, divided by source valve (changed in 2020 version of NFPA 2)
Driver of separation distance to building	Air intakes	Distance to building /parking spaces (19 ft - group 2 exposure [38 ft reduced by half due to barrier wall])

- Using accepted separation distances, DOE goal of 40% reduction in footprint can be met (18,000 ft^2 -> 10,800 ft^2)

Thank you!

Questions?

ehecht@sandia.gov

Thanks for funding support from:

- United States Department of Energy, Energy Efficiency & Renewable Energy, Fuel Cell Technologies Office, Safety, Codes, and Standards subprogram managed by Laura Hill

Backup Slides

Benefits of Fractional Hole Size Rather than Absolute Hole Size as Setback Distance Basis

Fractional hole size instead of absolute hole size

- NFPA 2 GH2 tables use 1% of flow area

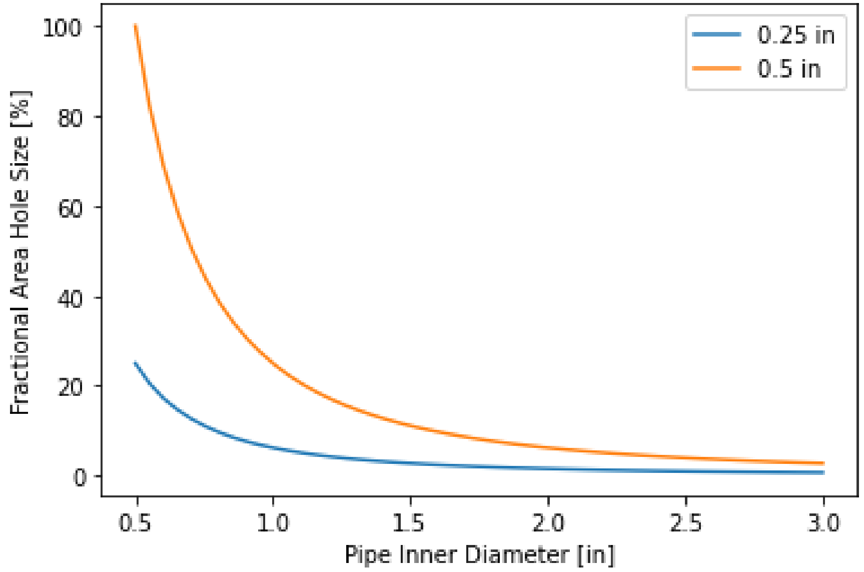
Gives "credit" for using smaller pipe diameters

- Smaller pipes lower risk by limiting the consequences

Allows setbacks to grow for larger pipe diameters

Fractional area leak size:

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



Current vs. Accepted LH2 Exposures

Current 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

Accepted 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

Current Approach: Exposure Groups

Current 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

Accepted 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
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Group 3

10. Buildings of non-combustible non-fire-rated construction
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15. Piping containing other hazardous materials
16. Flammable gas metering and regulating stations such as natural gas or propane

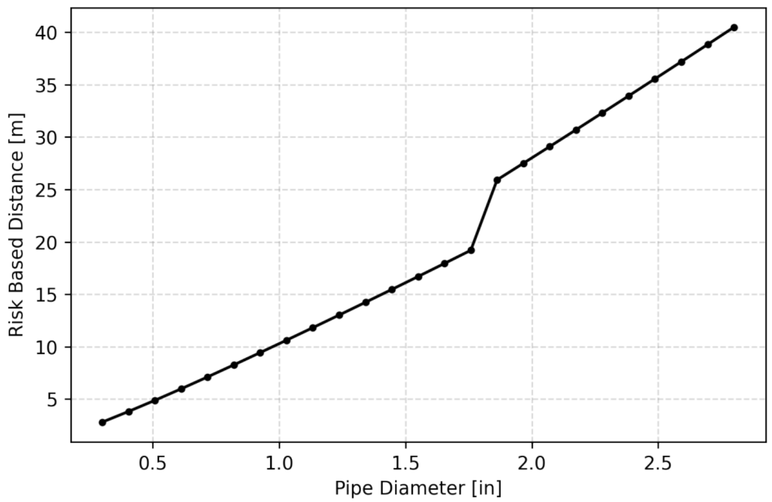
Fractional Hole Size May Serve as Better Proxy to Risk Calculations

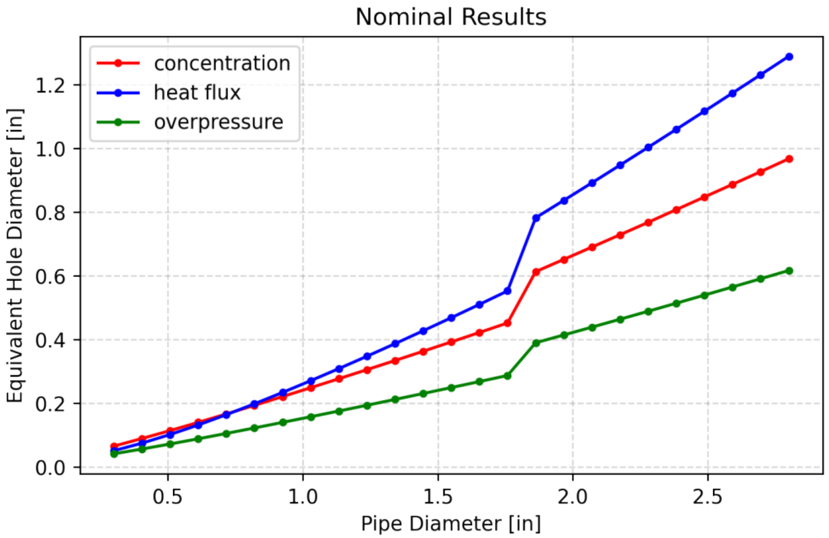
- Using HyRAM quantitative risk assessment (QRA), can calculate the distance to individual risk based on some criteria (e.g., 2e-5)

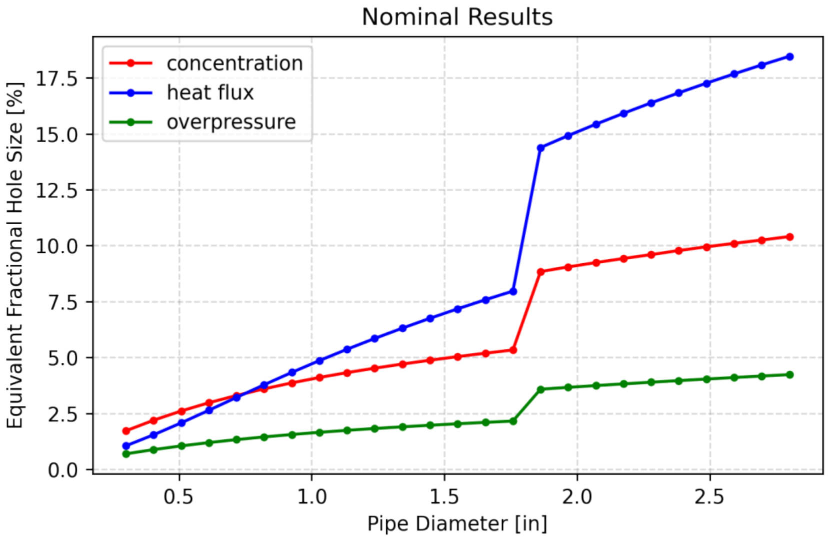
- Risk-based distances (distance to risk criteria) increase with increasing pipe diameter
  - This makes intuitive sense, but single hole size would have constant distance with increasing pipe diameter

- 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

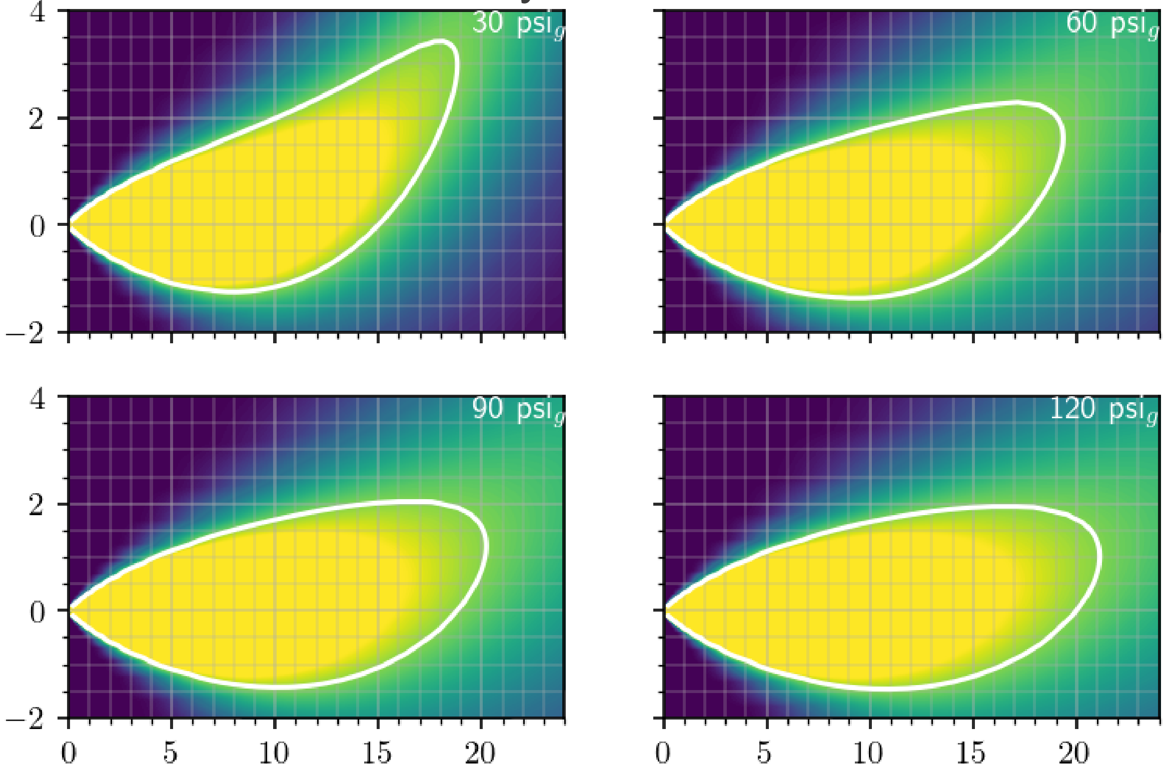
Fractional hole size varies 3-74%

- 0.9 mm may be an over-estimate
- 0.1 mm gap has fractional hole sizes of 0-5% (one 8% value)

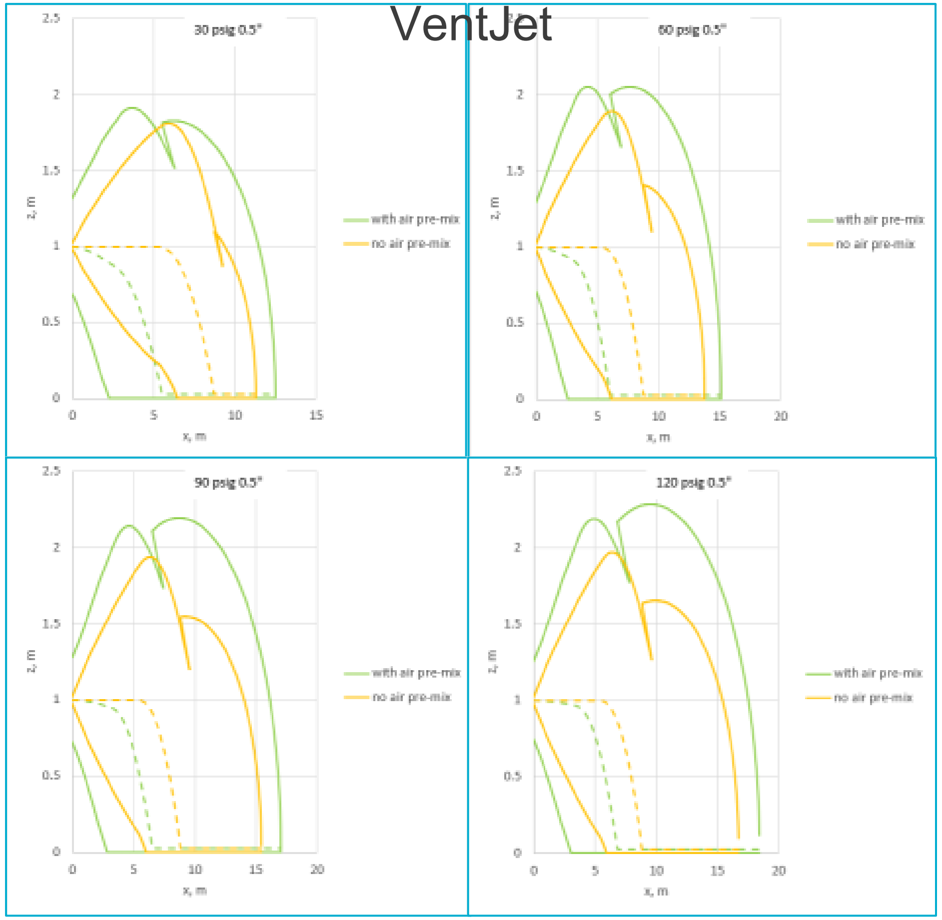
Company	Part Number	O-ring Diam. (in)	O-ring Equiv. Hole Diam (in)	Flow Diam. (in)	O-ring Gap Area/Flow Area (%)	O-ring Gap Area/Flow Area (%) (0.1mm gap)
ACME	0.5 IPS sch 5	1.3	0.4	0.5	74%	8%
ACME	1 IPS sch 5	2	0.5	1	28%	3%
ACME	1.5 IPS sch 10	2.25	0.6	1.5	14%	2%
ACME	2 IPS sch 10	2.52	0.6	2	9%	1%
Cryocomp*	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%

HyRAM+ vs. AP VentJet dispersion: 0.5” hole

HyRAM+



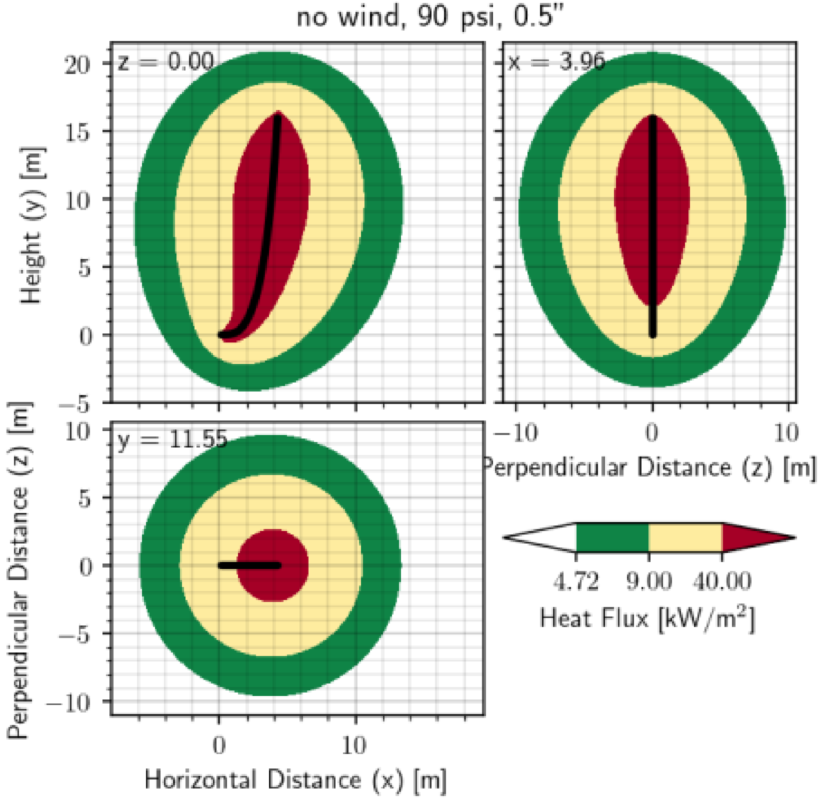
AP VentJet

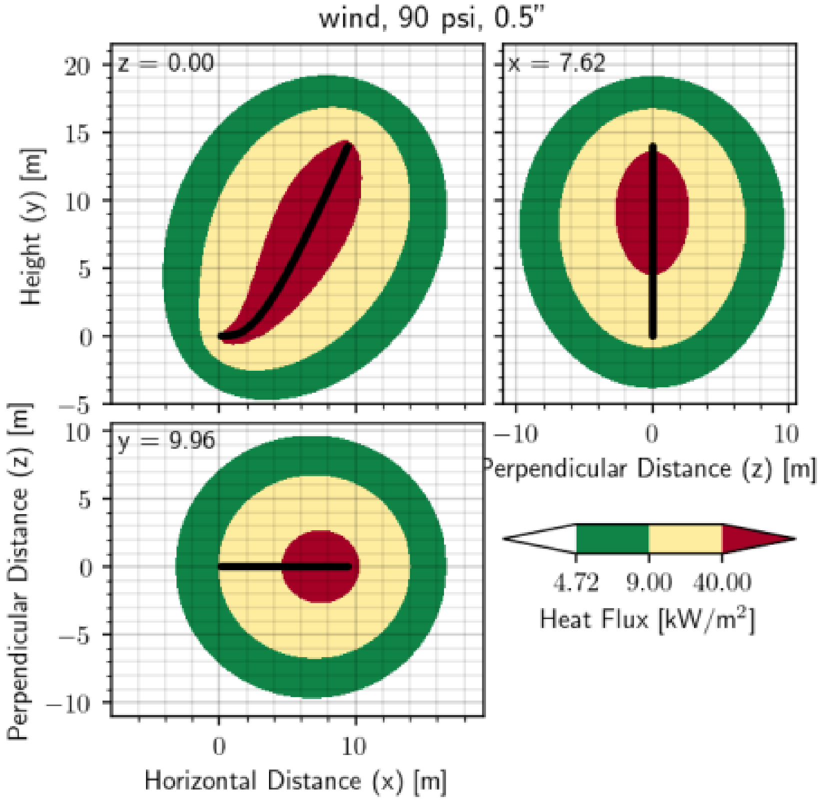


- VentJet is affected by ground while HyRAM+ does not account for this
- HyRAM+ distances are slightly longer (more conservative) than VentJet
- Distances calculated along streamline rather than just x-distance adding additional conservativism

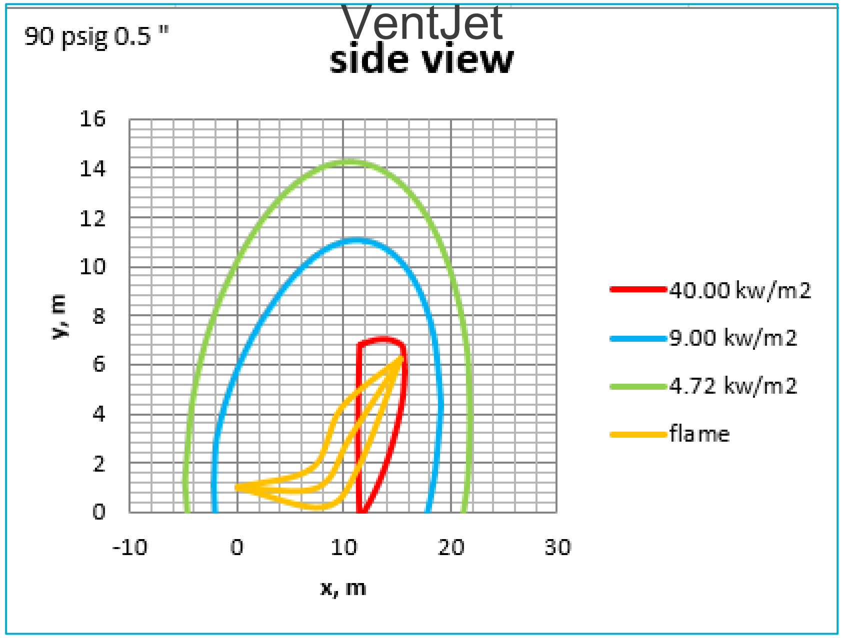
HyRAM+ vs AP flame: 90 psi, 0.5” hole

HyRAM+





AP VentJet

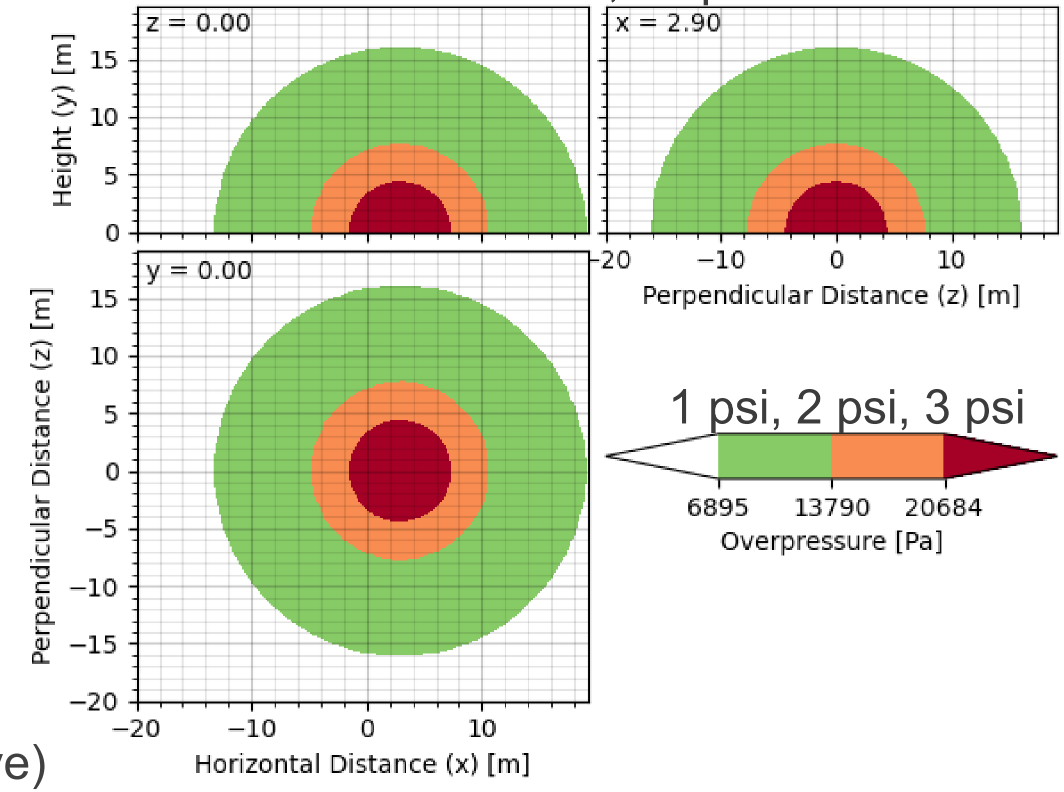


- High density of LH2 results in low momentum release rates
- HyRAM+ modified to include the effect of wind; results in similar distances to AP flame (can be used in Python only)
- Largest projected heat fluxes onto the ground are used as exposure distances

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: Insulated Portions of the System

Current (2020 Edition) of NFPA 2 allow for reduction by 2/3 for insulated portions of the system

- Intended to eliminate potential leak points

Reduction Justification: Walls - Experiments

From Schefer 2009

Fixed quantity of H2 dispensed

Significant reductions in overpressure and heat flux behind the barrier with no entrainment down the back

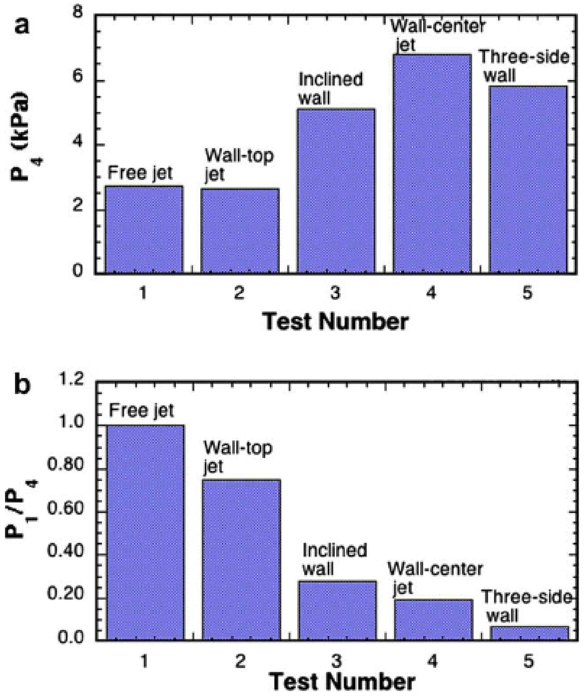


Fig. 12 – Overpressures measured in a free jet and each of four barrier-wall configurations. (a) Maximum overpressure measured prior to wall; (b) ratio of maximum overpressure measured after wall to overpressure behind wall.

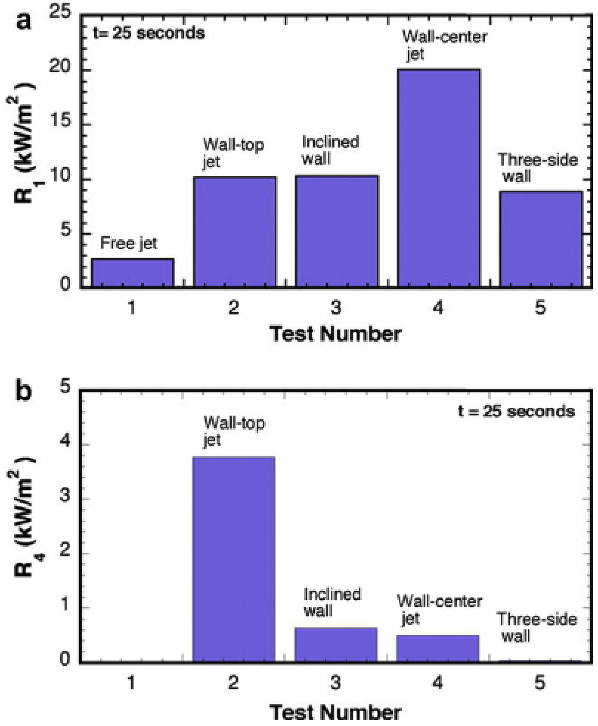
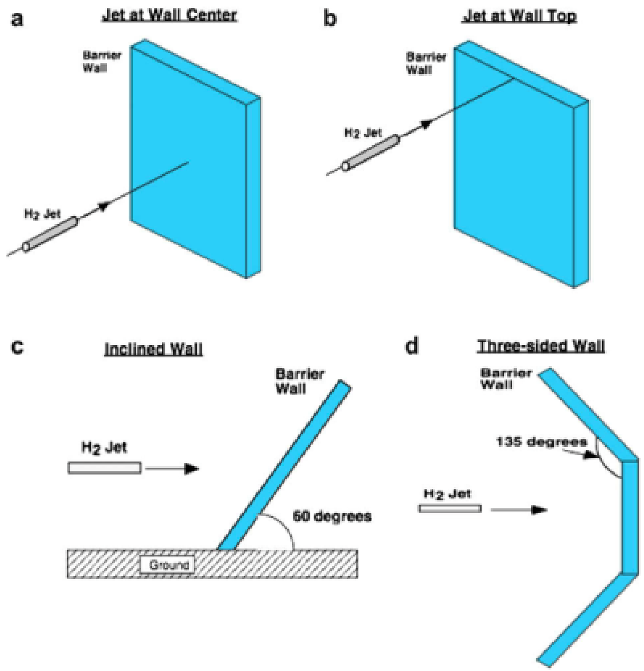
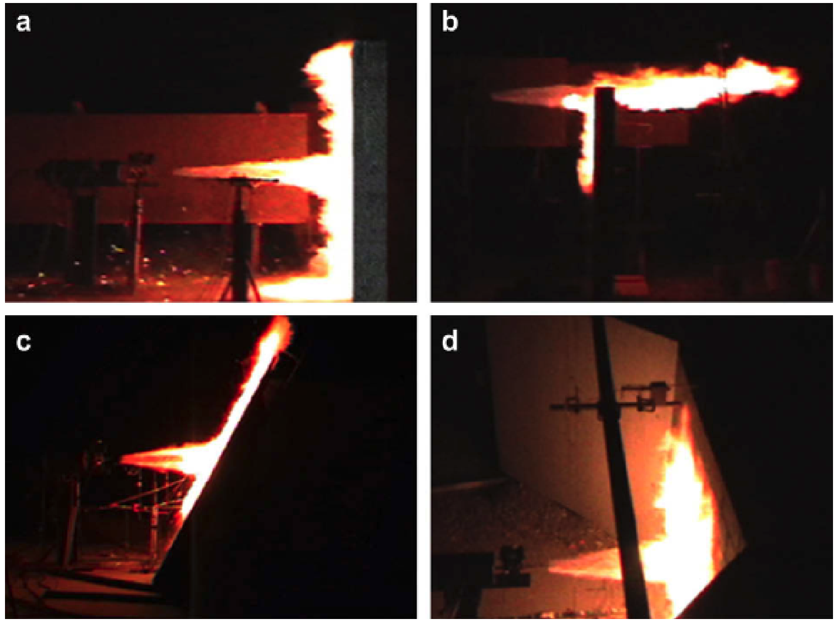


Fig. 17 – Maximum radiative heat flux at 25 s into test measured in a free jet and each of four barrier-wall configurations. (a) Heat flux measured at jet origin; (b) heat flux measured behind wall.





Reduction Justification: Walls - Simulations

- Initial predictions also used for test design (measurement placement)
- Used Schefer 2009 for model validation/calibration
- Simulations from validated model used to determine distances to heat flux criteria and prediction overpressures.
- Simulations also used to estimate concentration envelops for unignited flows
  - Experiments ignited all tests
- Similar results obtained using FLACS to simulate LH2 releases

Houf 2008

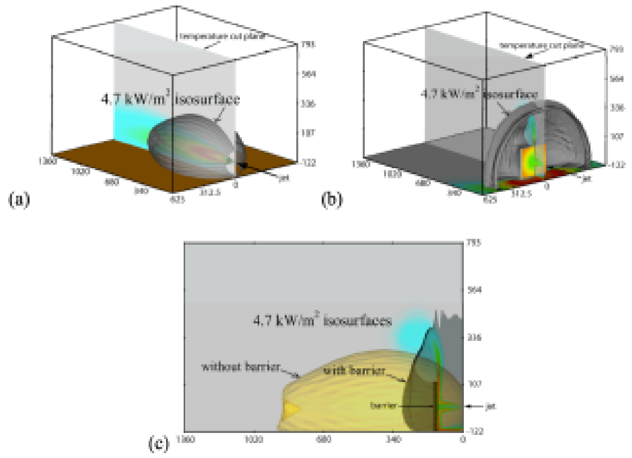


Figure 10. Calculated isosurfaces for radiative heat flux of 4.7 kW/m^2 from hydrogen jet flames; (a) free jet flame with ground plane; (b) jet flame directed toward center of 1-wall vertical barrier; (c) side view of isosurfaces shown in (a) and (b), comparing horizontal and vertical extent of radiation field without and with a barrier; jet flow is from right to left with distances in centimeters.

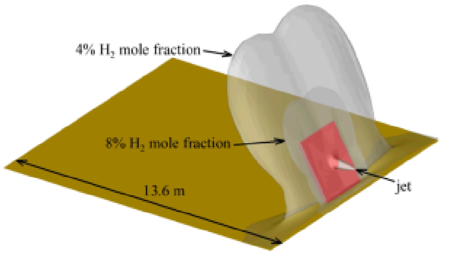


Figure 13. Calculated isosurfaces of 4% and 8% hydrogen mole fraction for a horizontal jet impinging on the 1-wall 2.4 m x 2.4 m (8 ft x 8 ft) tilted barrier. The jet release location is 1.219 m above the ground with the flow from right to left.

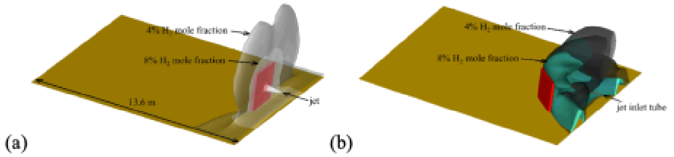


Figure 14. Calculated isosurfaces of 4% and 8% hydrogen mole fraction for unignited horizontal jets impinging on barriers with jet flow from right to left. (a) 1-wall 2.4 m x 2.4 m (8 ft x 8 ft) vertical barrier; (b) 3-wall barrier with 135 degrees between each 2.4 m x 2.4 m (8 ft x 8 ft) wall.

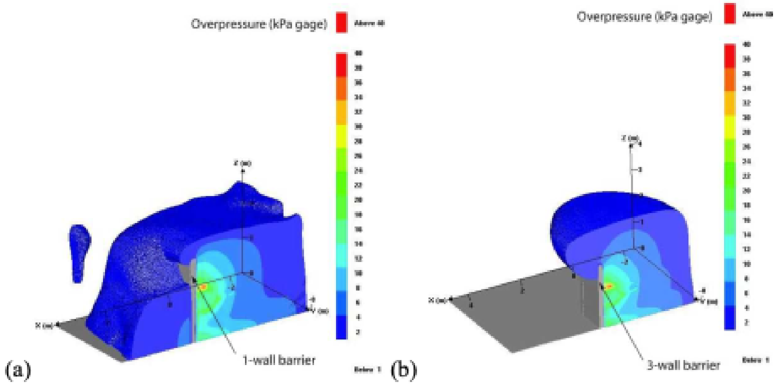


Figure 17. Comparison of maximum overpressure for (a) 1-wall vertical barrier (Test 1) and (b) 3-wall barrier with 135 degrees between each wall (Test 5) for ignition after 1 second from the beginning of the release (1/2 domain shown). Pressure scales are identical on both plots and distances are shown in meters. The outer boundary of the isosurface is 1kPa in both plots and the jet flow is from right to left with ignition on the front side (right) of the barrier.

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 separation 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.

Leak Size Analysis

Industry has significant LH2 operating experience

- Over 1200 operational LH2 tanks
  - ~ 36000 operating "tank-years"
- Over 50 years of transportation and stationary experience
- Estimated 2.2 MM deliveries

Performed review of operating experience of transports, stationary tanks, and deliveries

- Interviews with knowledgeable engineering and operations personnel (anecdotal)
- Search of near miss and incident databases
- Delivery was a focus as expected high risk activity
  - Performed survey of over 30 drivers
  - Requested information about leaks and equipment failures
- Rates of major leaks and fires were estimated from data set

Observations

- Leaks get worse over time if not shut off
- Transportation equipment is very robust
  - Subjected to typical road hazards (impacts, rollovers, etc)
  - Minimal release of product during incidents
- Internal Vessel ruptures: 1 stationary tank, 0 tanker
- No known fatalities related to H2 release, fire, or explosion
- Small leaks are relatively common
  - Industry efforts underway to reduce

Conclusions

- Ignitions are infrequent
- Full line releases/breaks are rare
  - Lines are frequently double walled, and well protected
  - Inadvertent opening of lines is also an issue
- Drivers have been effective to mitigate issues during delivery
- Quick activation of emergency shutdown systems is effective to minimize consequences
- Overpressure should also be considered

Active areas for improvement

- Bayonet design (used for transfer of product) to minimize leakage or failure
- Detection and shutoff systems, particularly to integrate with delivery
- Walls/enclosures reducing consequence becoming more prevalent

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

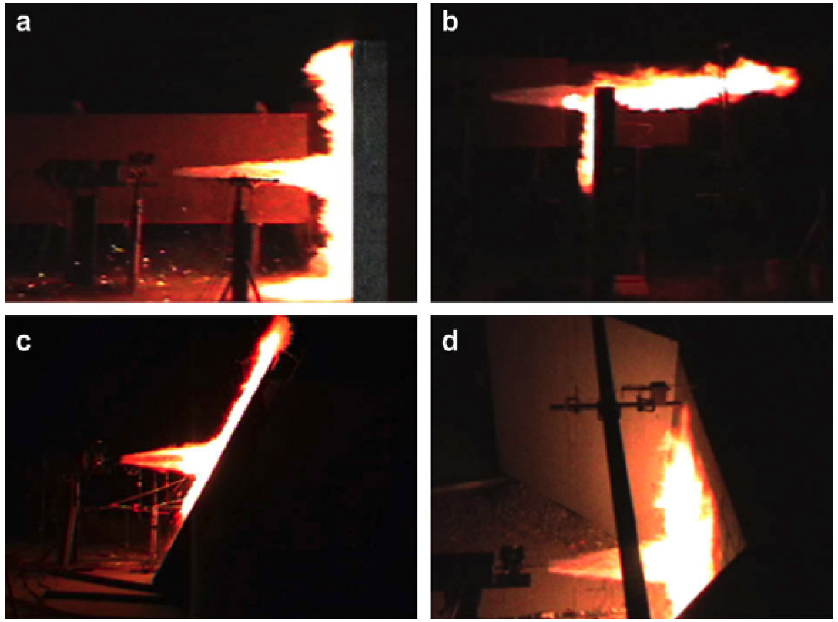
Houf 2008: Modeling for unignited gas clouds

- 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 separation 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



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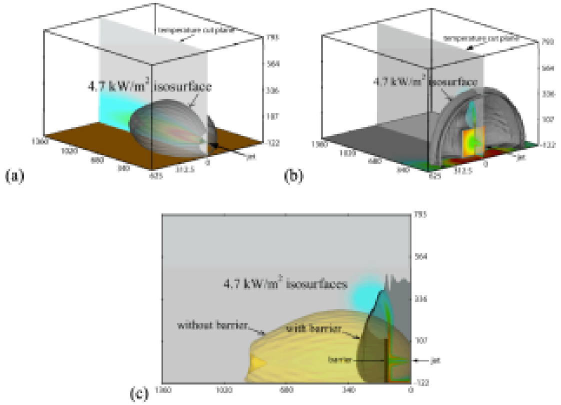
From LaChance 2010



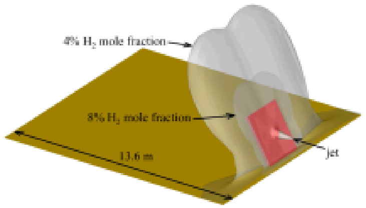
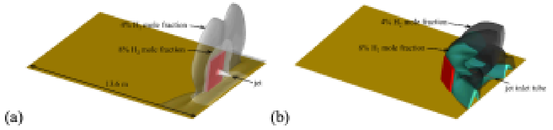


Figure 13. Calculated isosurfaces of 4% and 8% hydrogen mole fraction for a horizontal jet impinging on the 1-wall 2.4 m x 2.4 m (8 ft x 8 ft) tilted barrier. The jet release location is 1.219 m above the ground with the flow from right to left.



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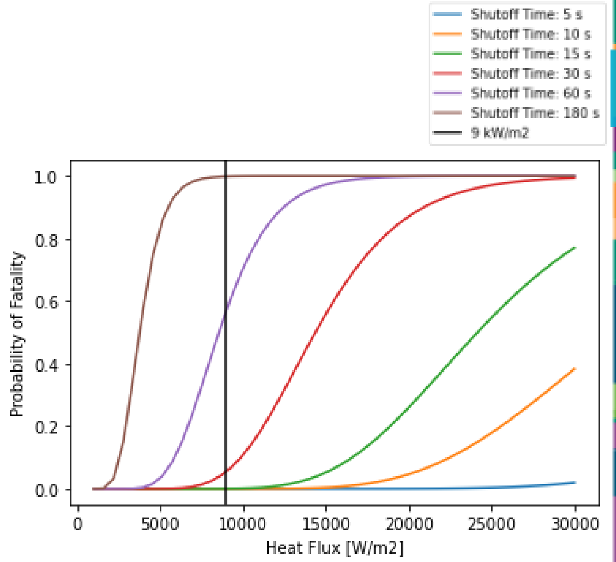
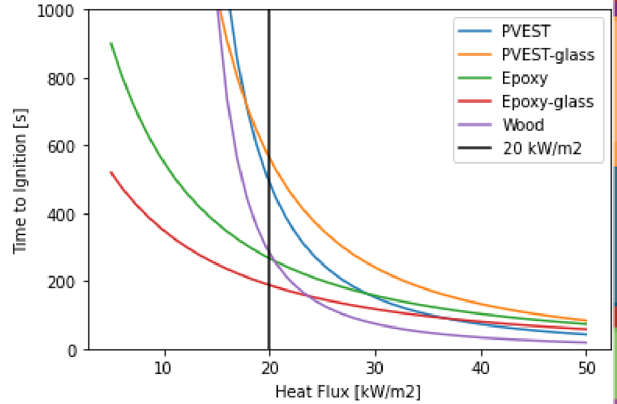
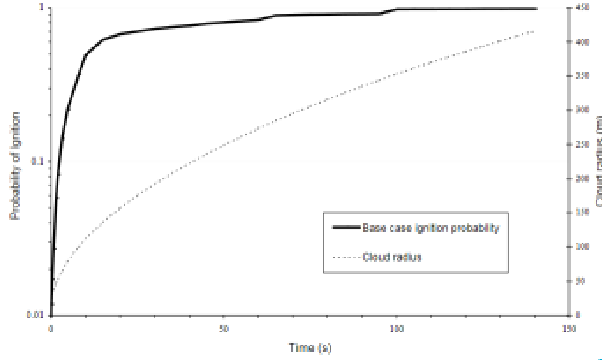
Reduction Justification: Shutdown

- 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]