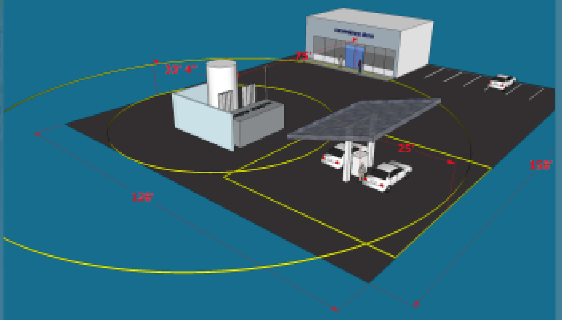
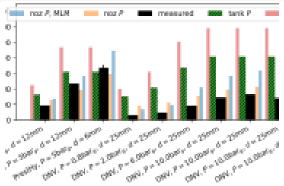
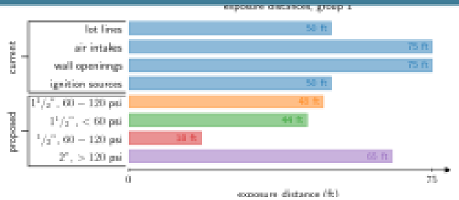
SAND2022-11889C

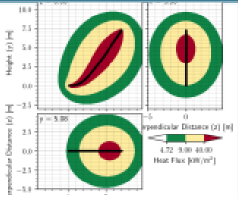
Sandia National Laboratories

Setback Distances for Liquefied Hydrogen Stations









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

8th International Workshop on Hydrogen Infrastructure for Transportation

September 12-13, 2022

U.S. DEPARTMENT OF ENERGY NNSA

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Previous Approach to Determine GH2 Storage Setbacks in NFPA 2; Analogous Approach Used for LH2

Quantitative risk assessment on representative refueling station

- No direct, mathematical link to setback distances, but did inform if overall risk was acceptable

Change 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.

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

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

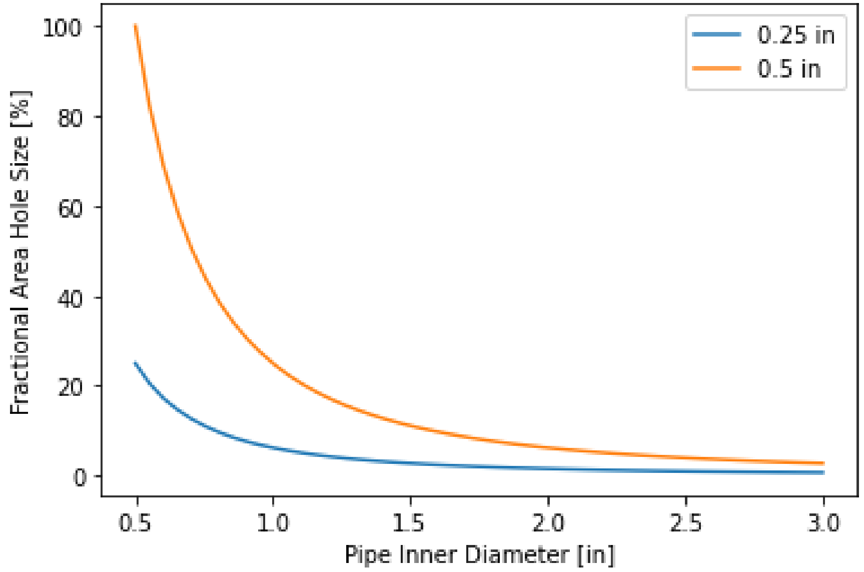
Gives "credit" for using smaller pipe diameters

- Smaller pipes lower risk by limiting the consequences

Allows setbacks to grow for larger pipe diameters

Fractional area leak size:

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



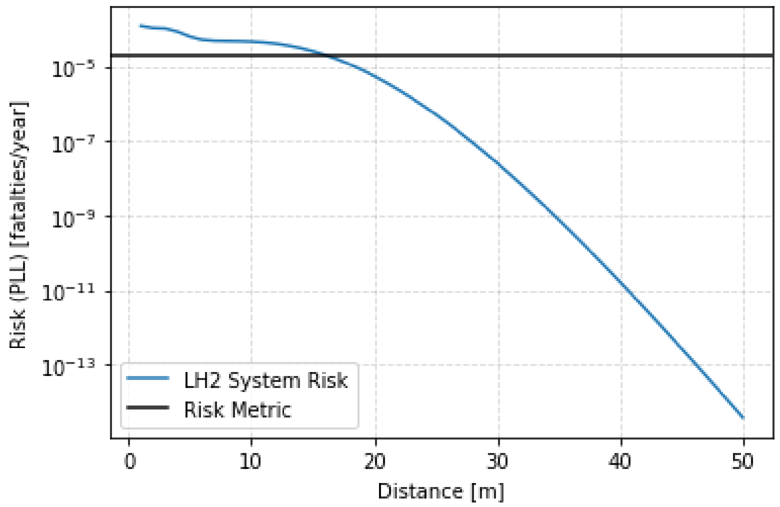
Setback Distance Basis Hole Size Justification: Risk Assessment

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

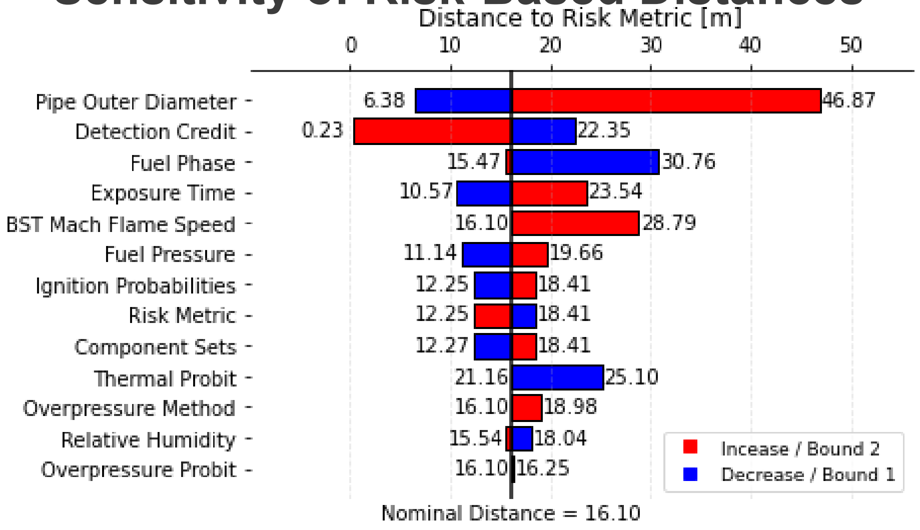
Risk acceptance metric can give a risk-based distance from a leak point based on a full QRA

- Varying QRA inputs can vary this distance significantly

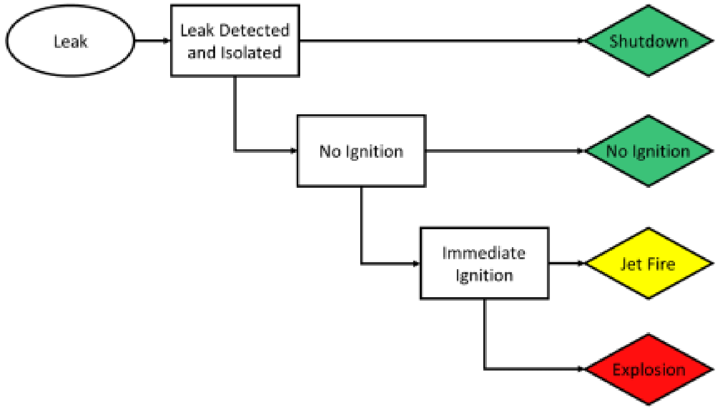
Potential Loss of Life (PLL) Risk Metric at Distances Away from Leak



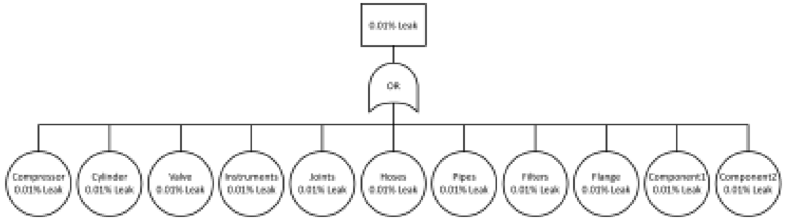
Sensitivity of Risk-Based Distances



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

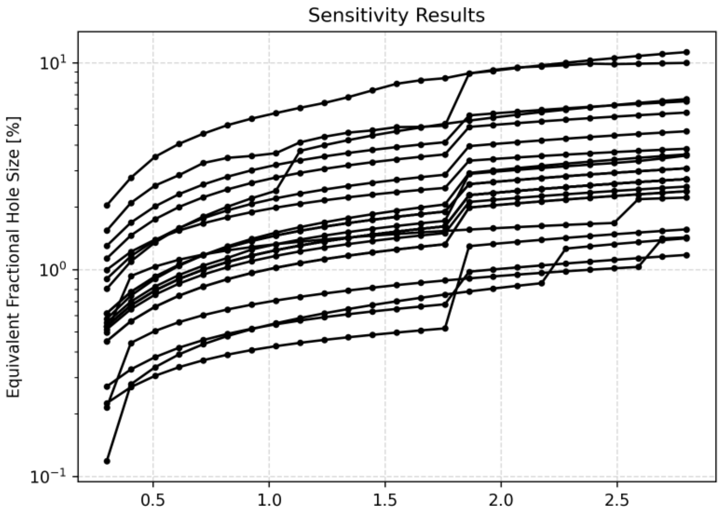
Sensitivity results are mostly below 10% fractional leak area

- **Only 2 of 26 cases exceed 10%** at largest pipe inner diameters (~3 inch):
  - Overpressure models with detonation (BST Mach 5.2 and Bauwens/Dorofeev)
- **Only 3 of 26 additional cases 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%** fractional hole size for all inputs and pipe diameters considered

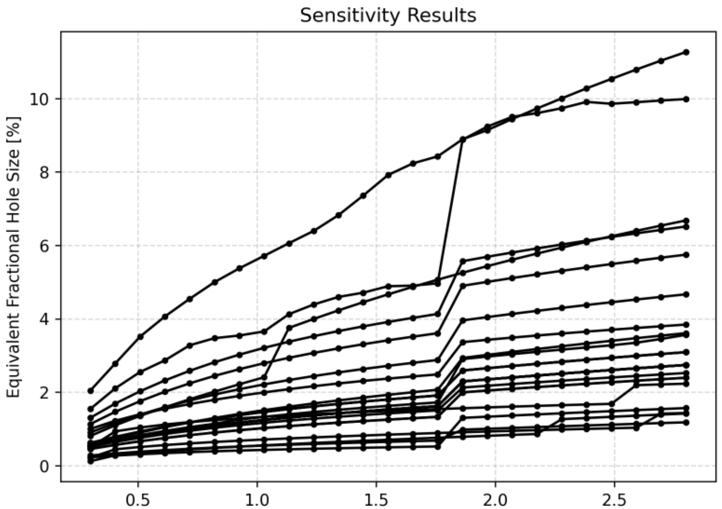
Possibilities considered:

- 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)

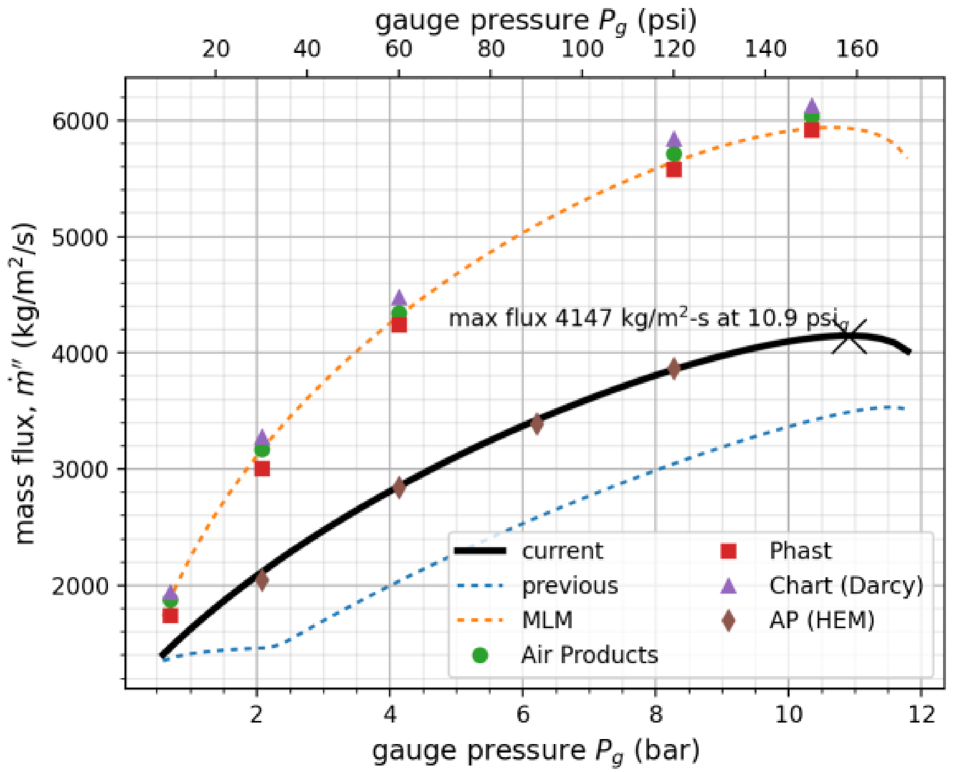
Log-Scale



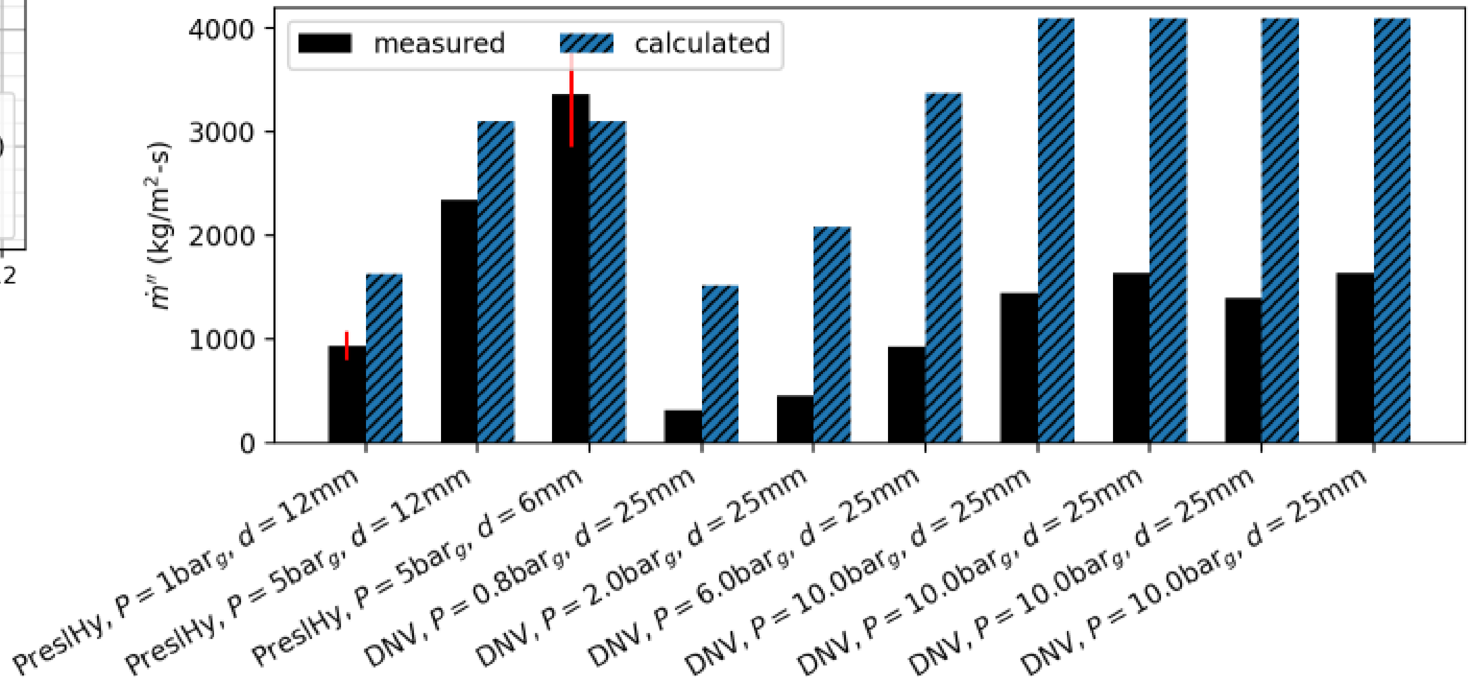
Linear-Scale



Mass Flow Rate–Comparison and Justification



- Calculations use homogenous equilibrium model (with search for maximum mass flux)
- Experiments attempting to get maximum liquid don't see flows approaching metastable liquid model (MLM)



Criteria Justification: Unignited Concentration

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

Will use 8% by volume unignited concentration for Group 1 exposures

Criteria Justification: Jet Flame Heat Flux

Exposure types to consider:

- People
- Cars
- Buildings
- Combustibles

NFPA 2 GH2 currently uses:

- Group 1: 4.732 kW/m^2 (based on IFC 2003 exposure for employee for 3 minutes)
  - Previously was 1.577 kW/m^2 (based on IFC 2003 exposure at property line); now same as Group 2
- Group 2: 4.732 kW/m^2 (based on IFC 2003 exposure for employee for 3 minutes)
- Group 3: 20 kW/m^2 for combustibles, 25.237 kW/m^2 for noncombustibles (IFC 2003)

Visible flame length is currently used for NFPA 2 GH2 Group 3

NFPA 59A Table 19.8.4.2.1:

- 9 kW/m2: fatality of person outdoors without PPE
- 5 kW/m2: irreversible harm to person outdoors without PPE
- 25 kW/m2: harm/fatality to person inside building with combustible exterior
- 30 kW/m2: harm/fatality to person inside building with noncombustible exterior

LaChance et al. (2011):

- 1.6 kW/m2: No harm for long exposures
- 4-5 kW/m2: Pain for 20s exposure; first degree burn
- 9.5 kW/m2: Second degree burn after 20s
- 12.5-15 kW/m2: First degree burn after 10s; 1% lethality in 1min
- 25 kW/m2: Significant injury in 10s; 100% lethality in 1min
- 35-37.5 kW/m2: 1% lethality in 10s

Will use:
4.732 kW/m^2 for Group 1,
9 kW/m^2 for Group 2, and
20 kW/m^2 for Group 3

Criteria Justification: Peak Overpressure

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

Will use:

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

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]

Using chosen criteria and models – distances are calculated

5% Fractional Leak Area

Group 1:

- Concentration: 8 mol% (streamline) – *dominates setback distance*
- Heat Flux: 4.732 kW/m2 (1,500 BTU/hr/ft^2) (bird's eye)
- Peak Overpressure: 6.895 kPa (1 psi)

Group 2:

- Heat Flux: 9 kW/m2 (2,853 BTU/hr/ft^2) (bird's eye) – *dominates setback distance*
- Peak Overpressure: 13.790 kPa (2 psi)

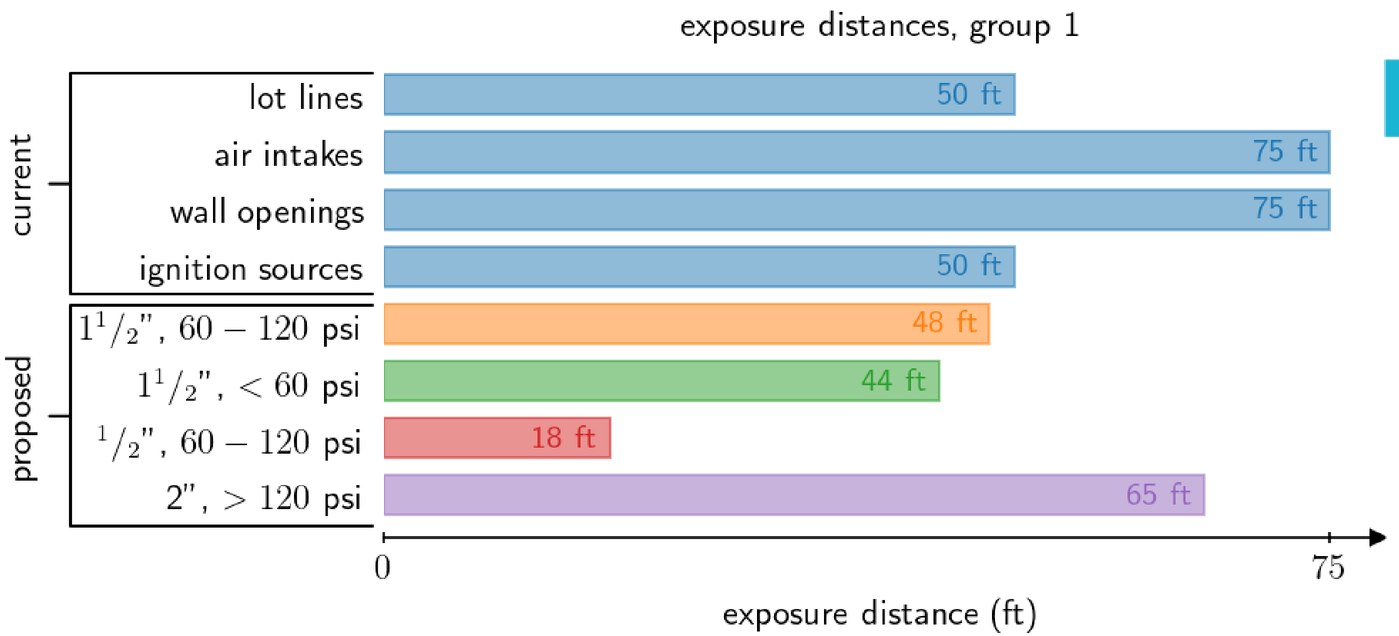
Group 3:

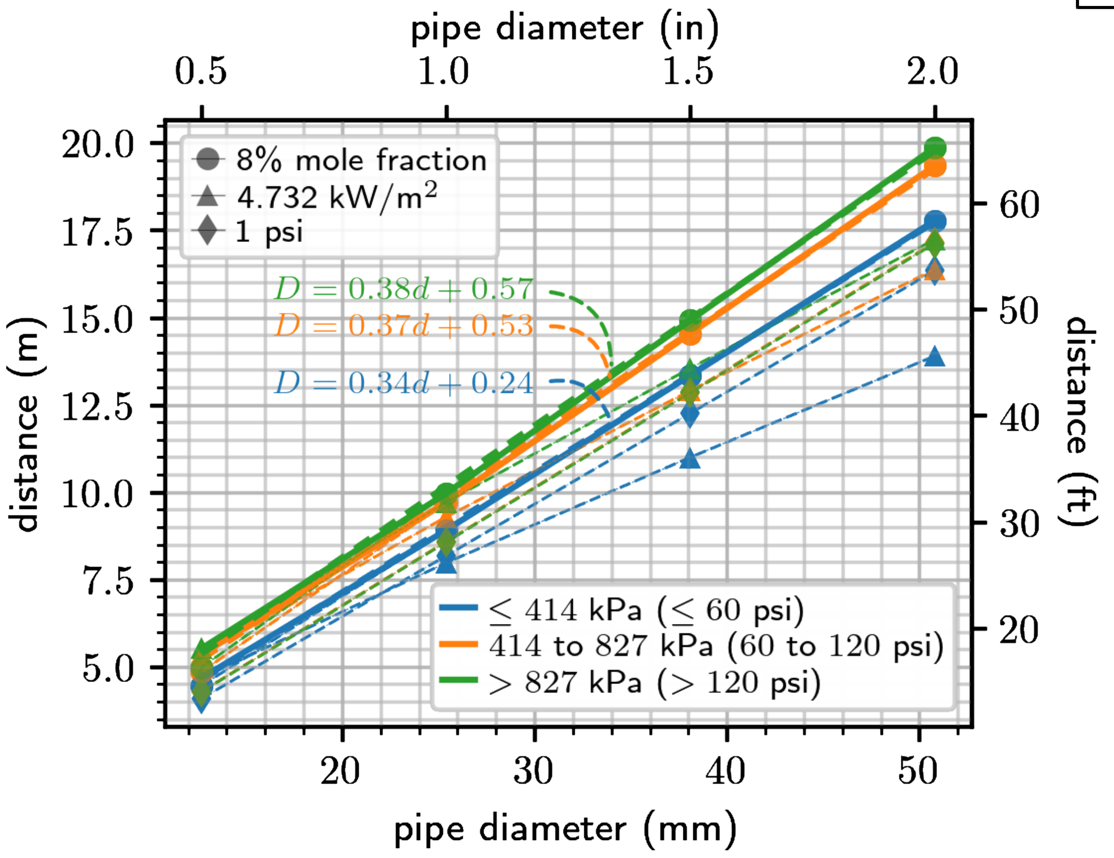
- Heat Flux: 20 kW/m2 (6,340 BTU/hr/ft^2) (bird's eye) – *dominates setback distance*
- Peak Overpressure: 20.7 kPa (3 psi)
- Visible Flame Length (bird's eye)

Safety factor = 1

Group 1

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



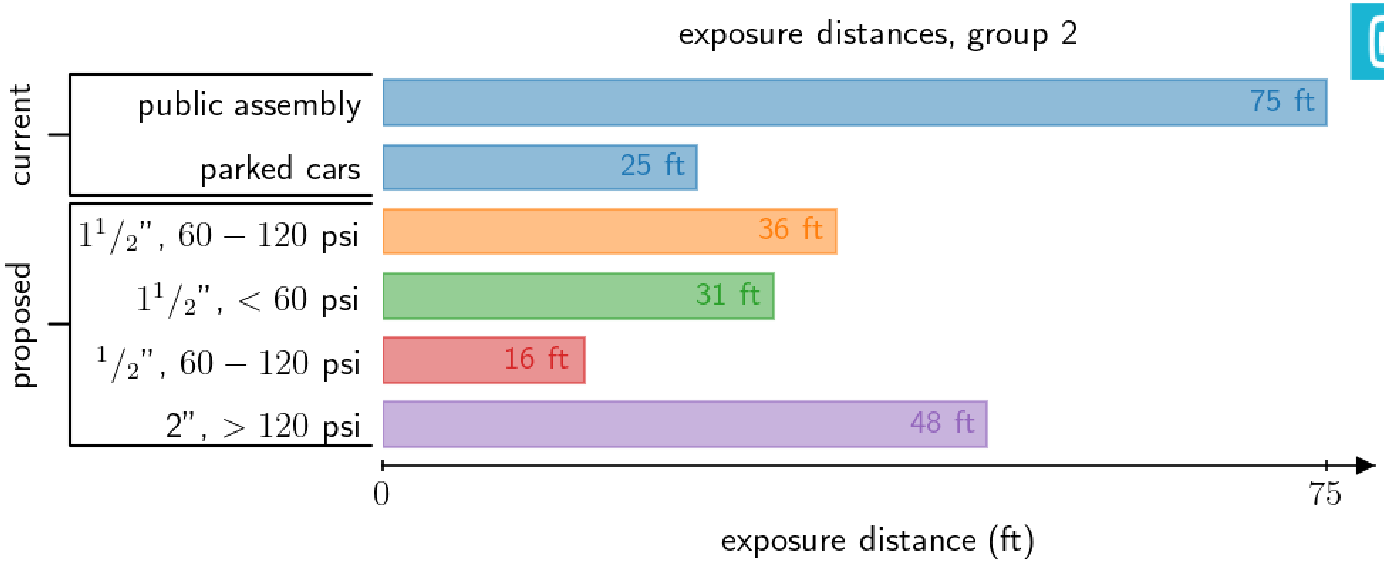


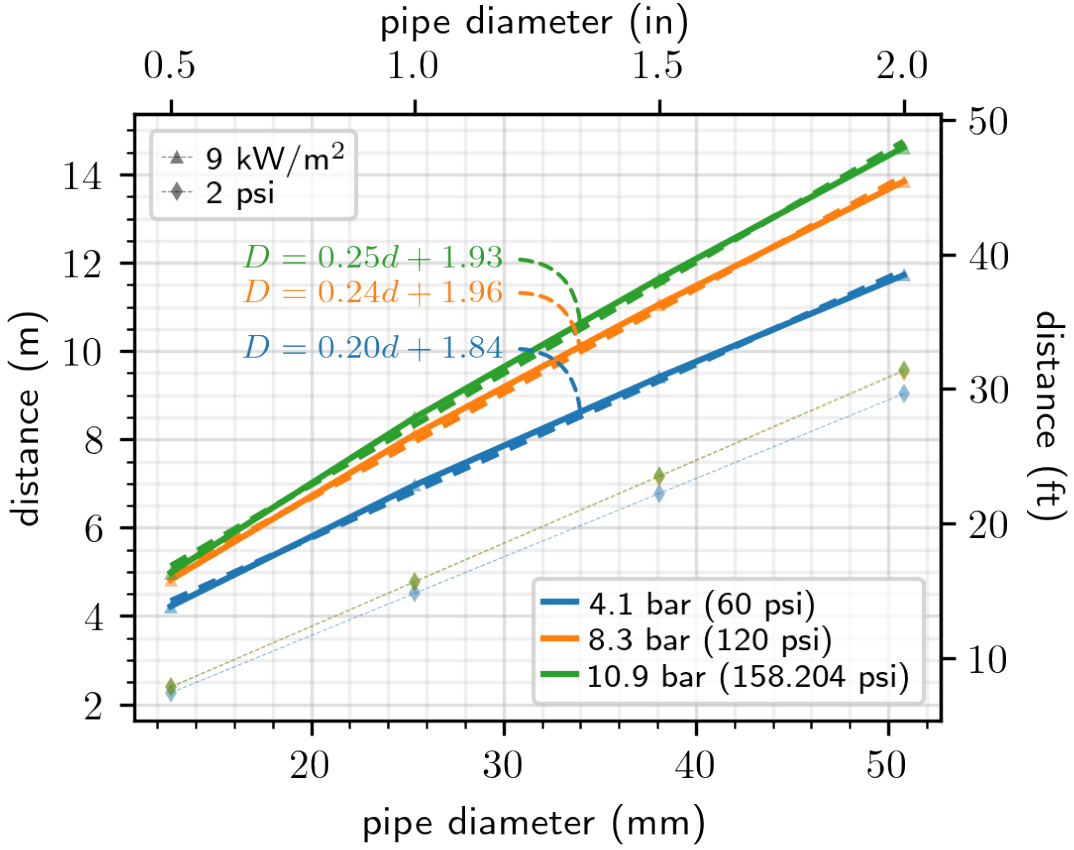
Protects against:

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

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



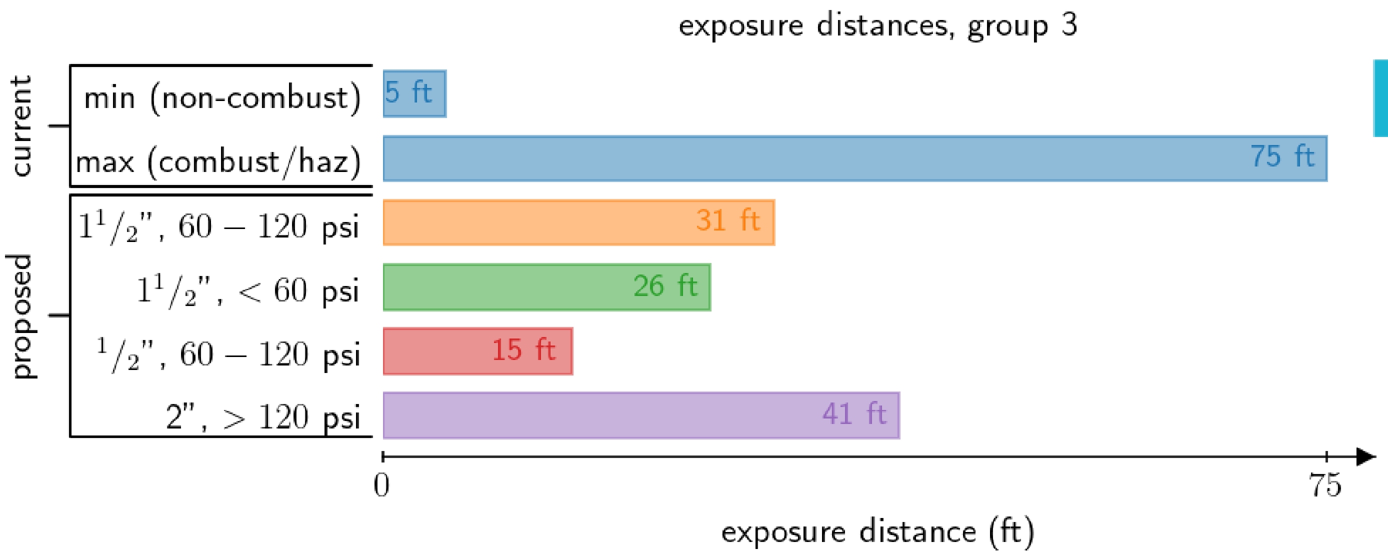


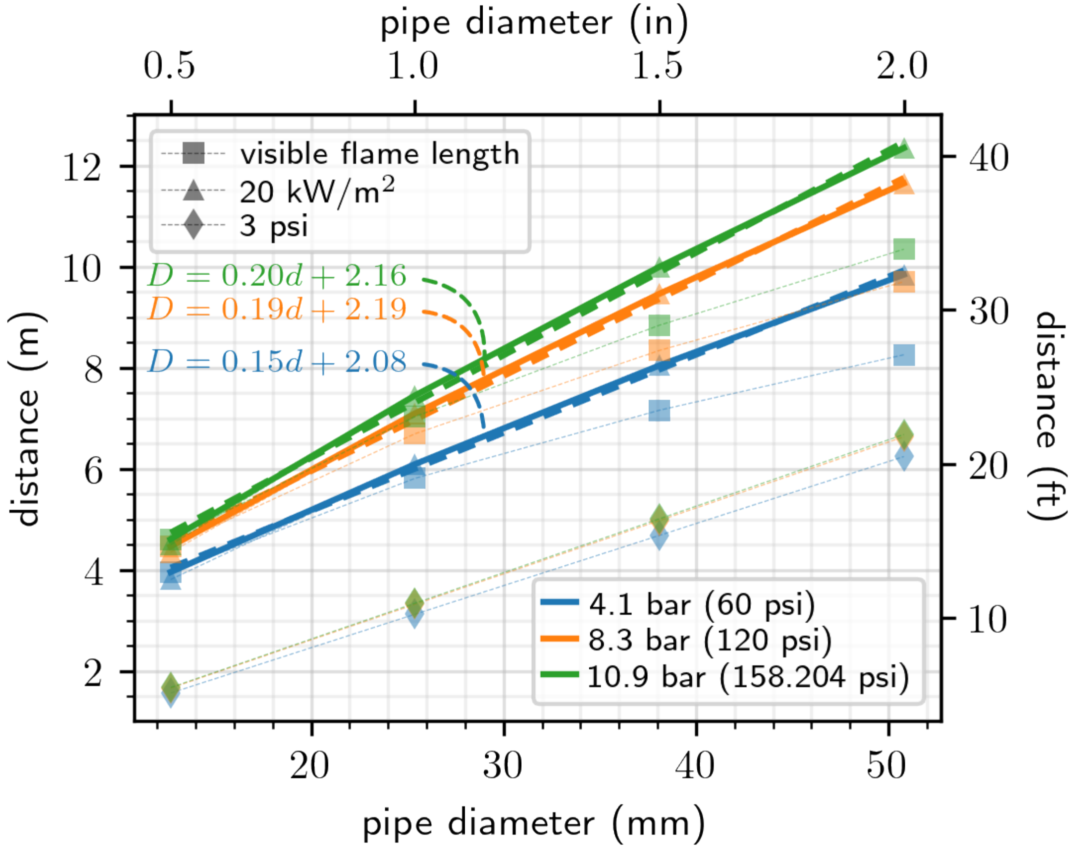
Protects against:

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

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)

Typical Inner Diameter

Distances for each exposure group

Pressure ranges do not show large differences, but may be useful in some cases

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		60 to 120 psi		>120 psi	
	≤ 414 kPa		414–827 kPa		>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

Range of pipe diameters and pressures

Table 8.3.2.3.1.6(b) Minimum Distance from Outdoor Bulk Liquefied Hydrogen LH_2 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					
Inner Diameter		Group 1		Group 2		Group 3		Group 1		Group 2		Group 3		Group 1		Group 2		Group 3	
		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

Thank you!

Questions?

Backup Slides

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

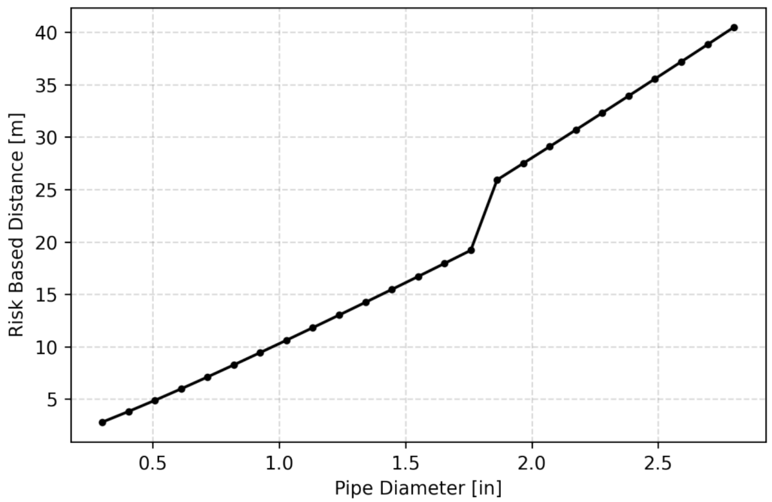
5. Exposed persons other than those servicing the system
6. Parked cars
7. Buildings of combustible construction
8. Hazardous materials storage systems above ground or fill/vent openings for below ground storage systems
9. Ordinary combustibles, including fast-burning solids such as ordinary lumber,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

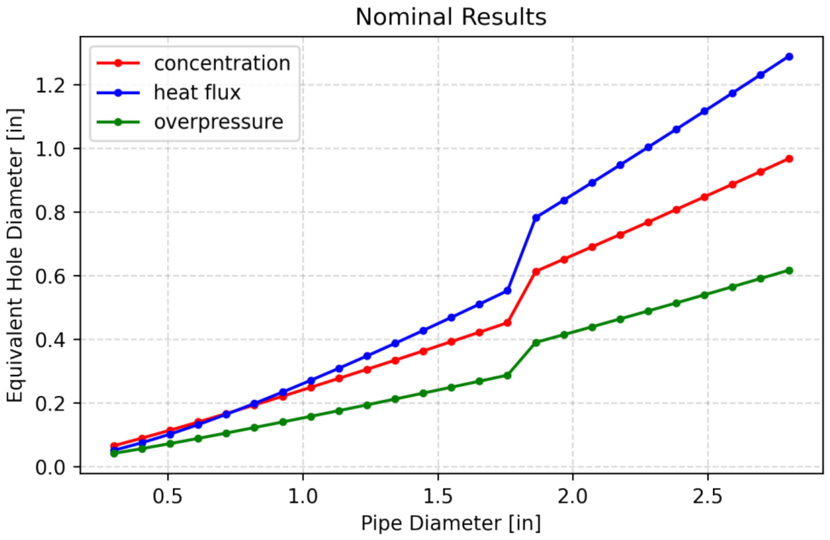
Group 3

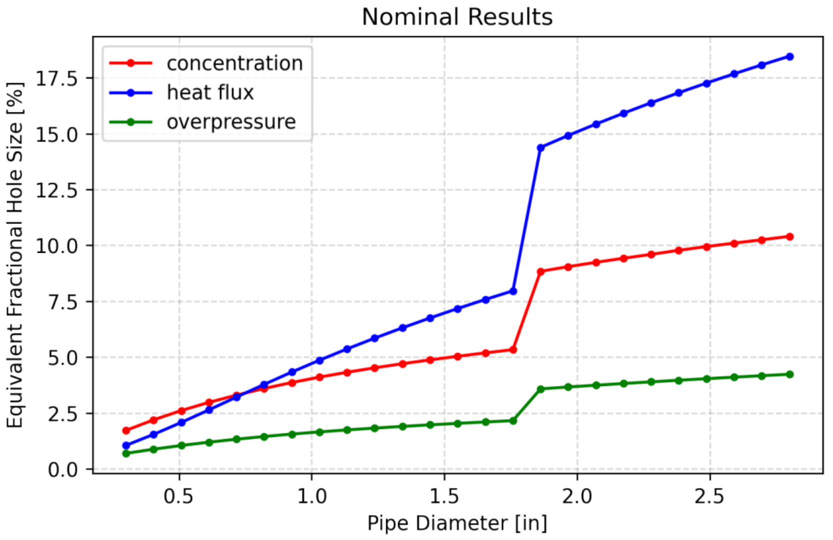
10. Buildings of non-combustible non-fire-rated construction
11. Flammable gas storage systems above or below ground
12. Heavy timber, coal, or other slow-burning combustible solids
13. Unopenable openings in buildings and structures
14. Encroachment by overhead utilities (horizontal distance from the 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 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

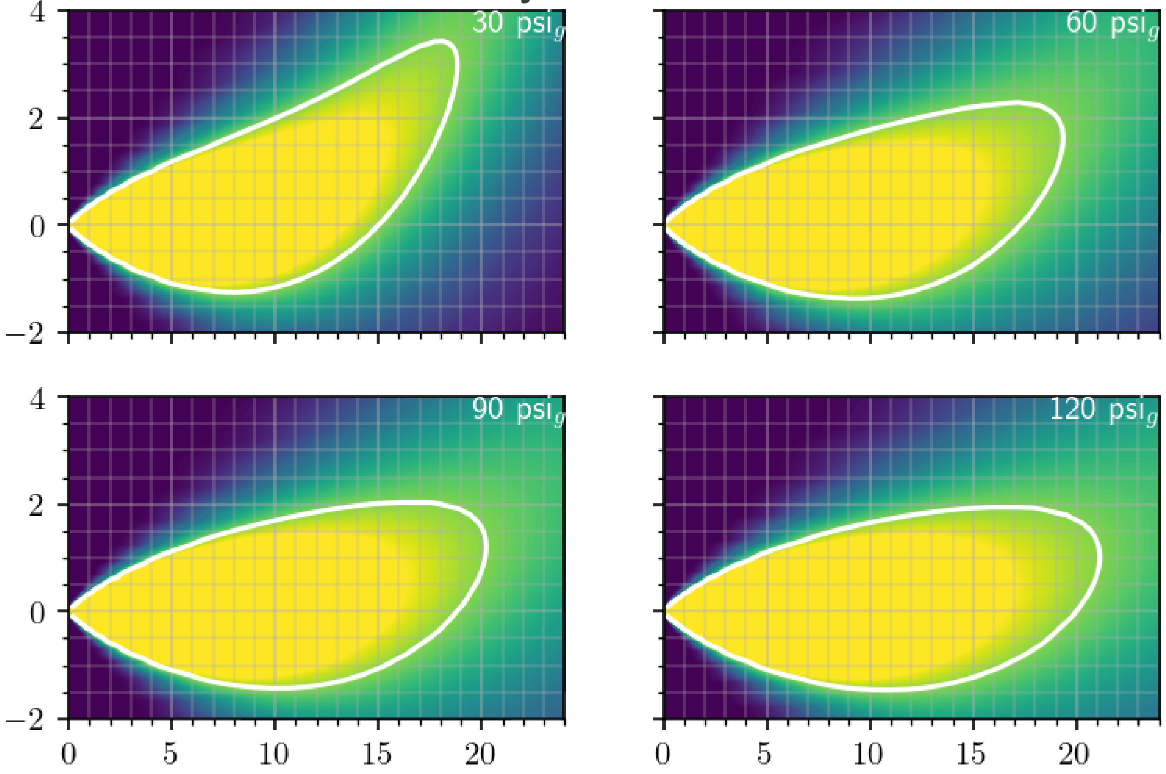
Fractional hole size varies 3-74%

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

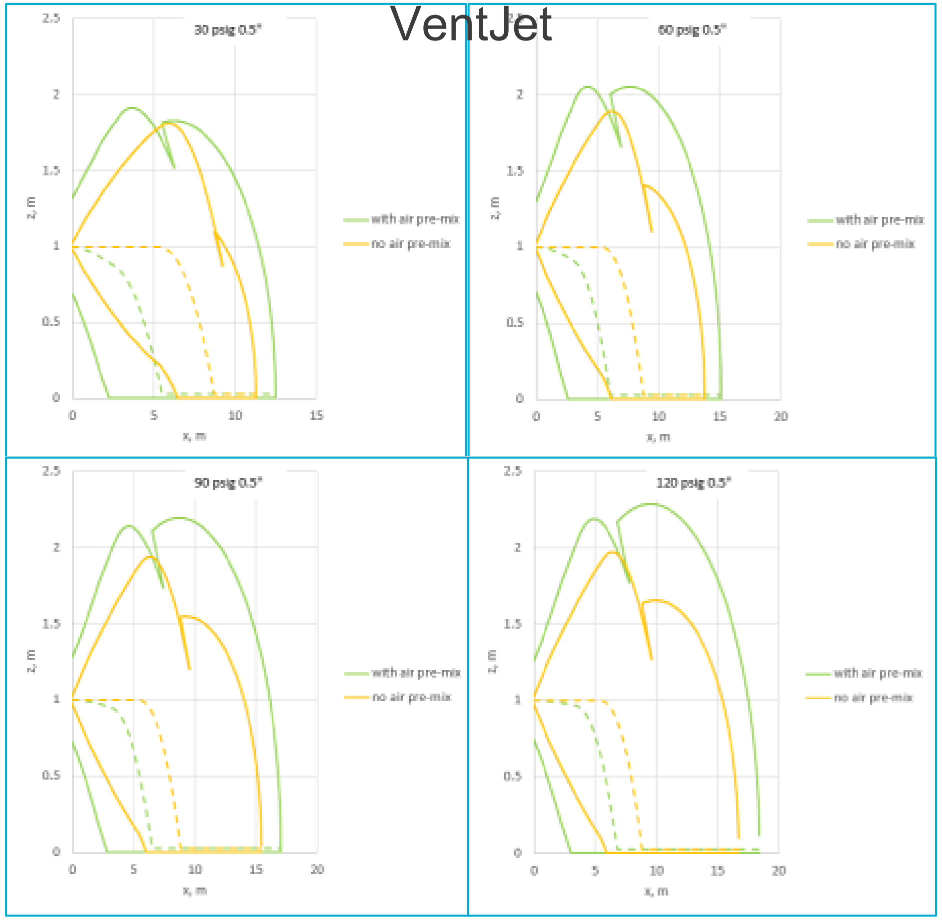
Company	Part Number	O-ring Diam. (in)	O-ring Equiv. Hole Diam (in)	Flow Diam. (in)	O-ring Gap Area/Flow Area (%)	O-ring Gap Area/Flow Area (%) (0.1mm gap)
ACME	0.5 IPS sch 5	1.3	0.4	0.5	74%	8%
ACME	1 IPS sch 5	2	0.5	1	28%	3%
ACME	1.5 IPS sch 10	2.25	0.6	1.5	14%	2%
ACME	2 IPS sch 10	2.52	0.6	2	9%	1%
Cryocomp*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



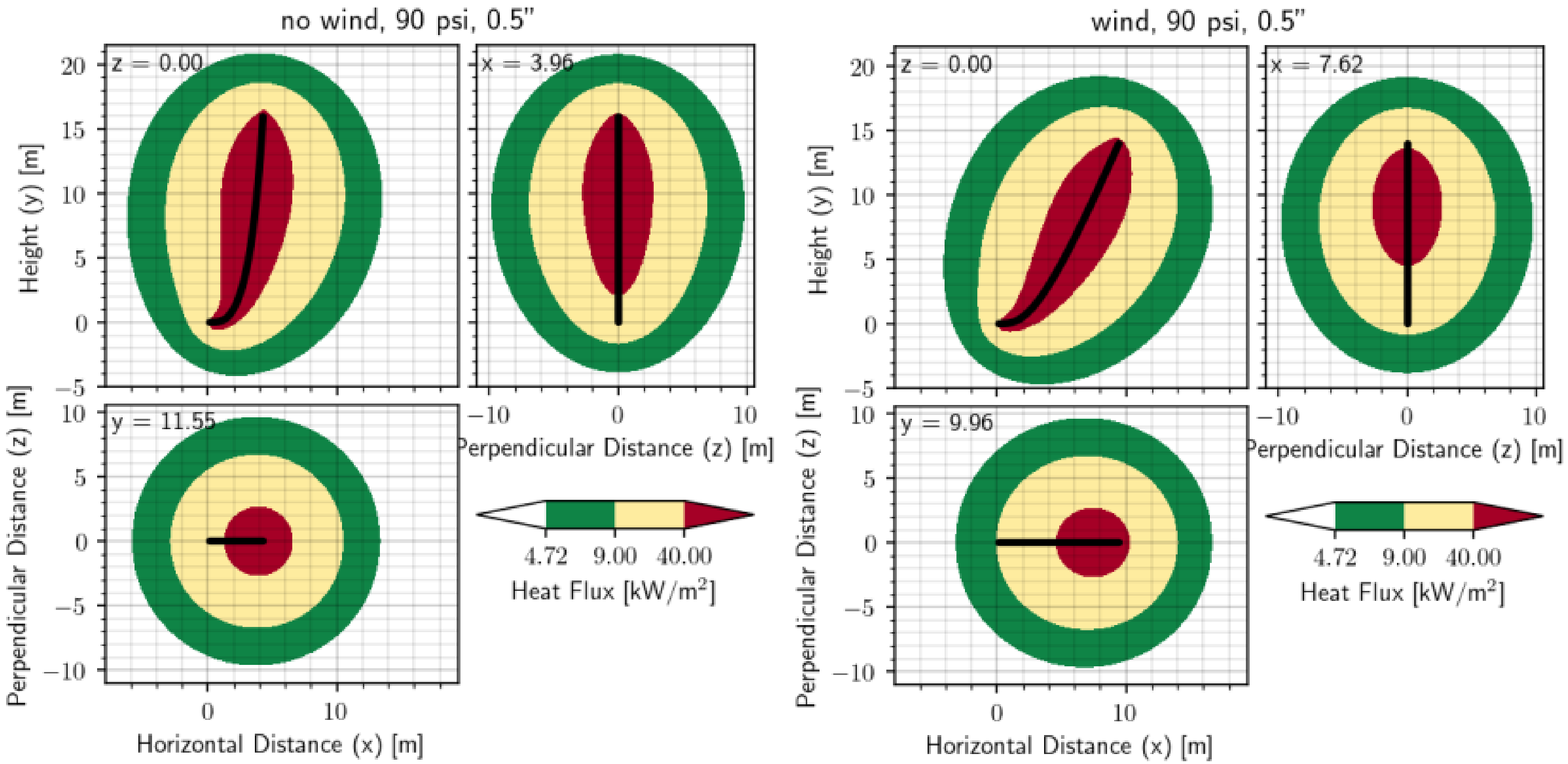
AP VentJet



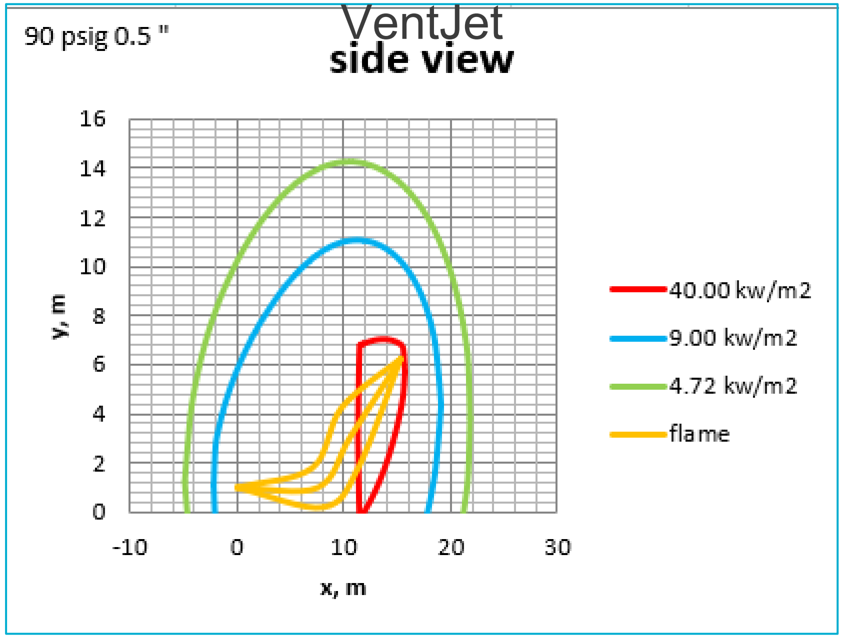
- VentJet is affected by ground while HyRAM+ does not account for this
- HyRAM+ distances are slightly longer (more conservative) than VentJet
- Distances calculated along streamline rather than just x-distance adding additional conservativism

HyRAM+ vs AP flame: 90 psi, 0.5” hole

HyRAM+



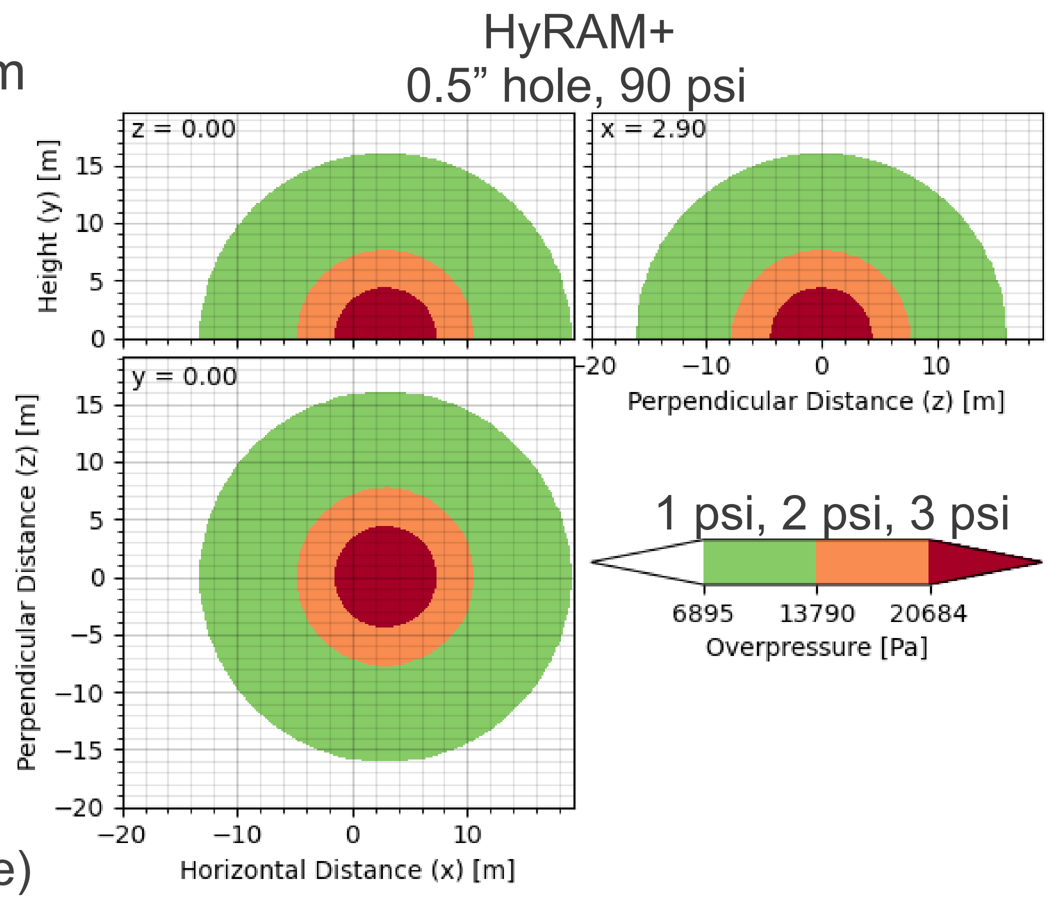
AP VentJet



- 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
- 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)



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

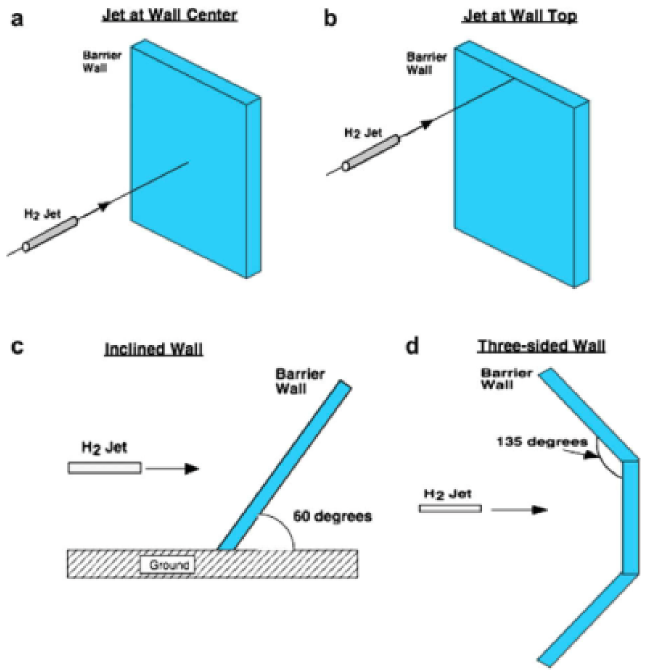
- Intended to eliminate potential leak points

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



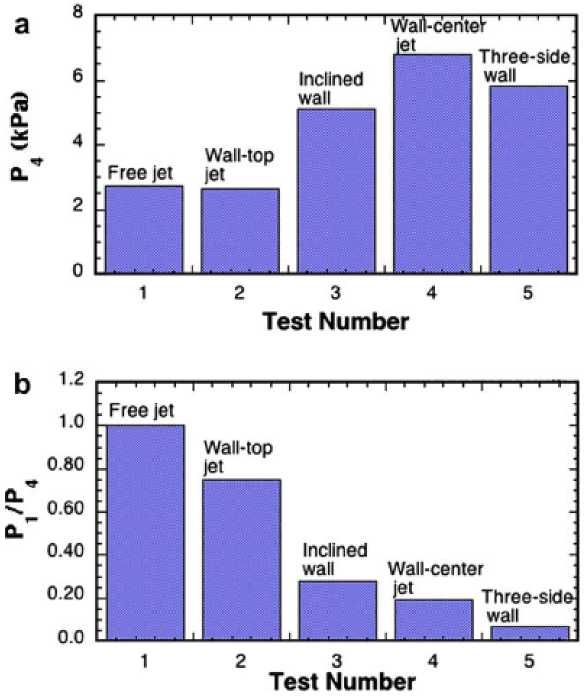


Fig. 12 – Overpressures measured in a free jet and each of four barrier-wall configurations. (a) Maximum overpressure measured prior to wall; (b) ratio of maximum overpressure measured after wall to overpressure behind wall.

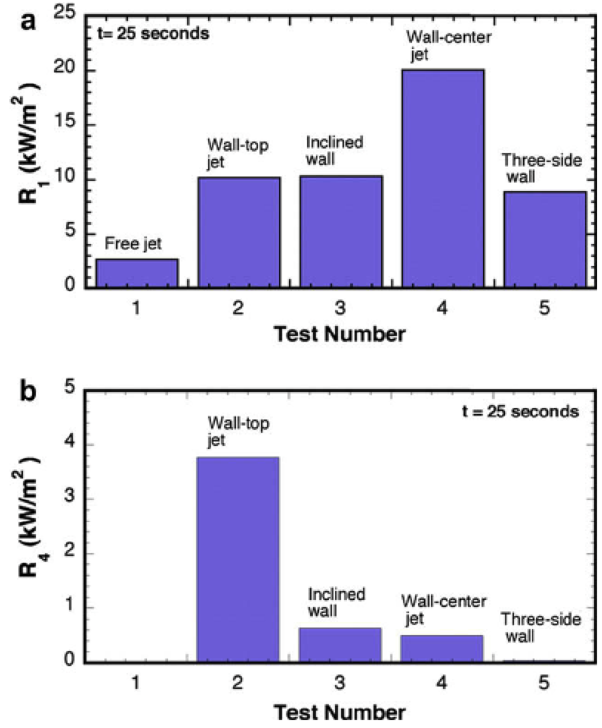
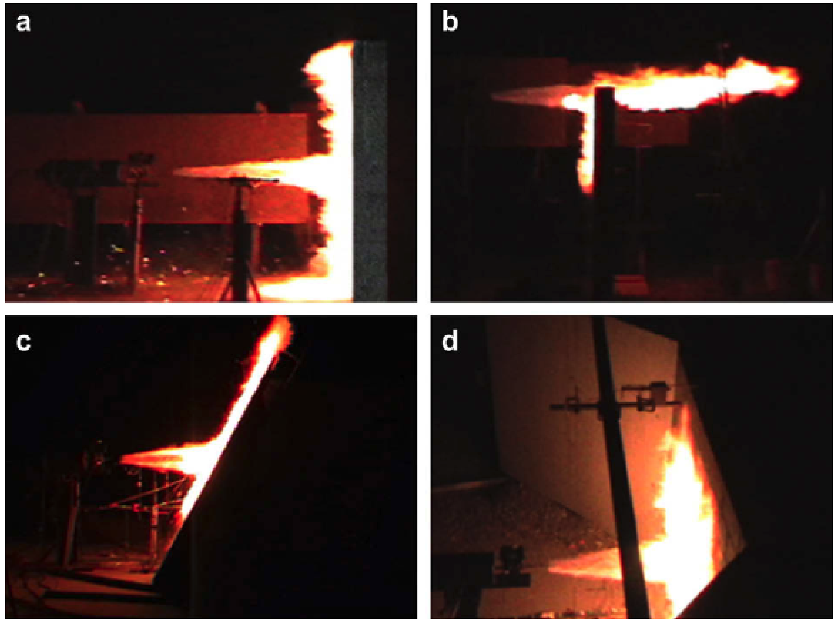


Fig. 17 – Maximum radiative heat flux at 25 s into test measured in a free jet and each of four barrier-wall configurations. (a) Heat flux measured at jet origin; (b) heat flux measured behind wall.



Reduction Justification: Walls - Simulations

Houf 2008

- 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

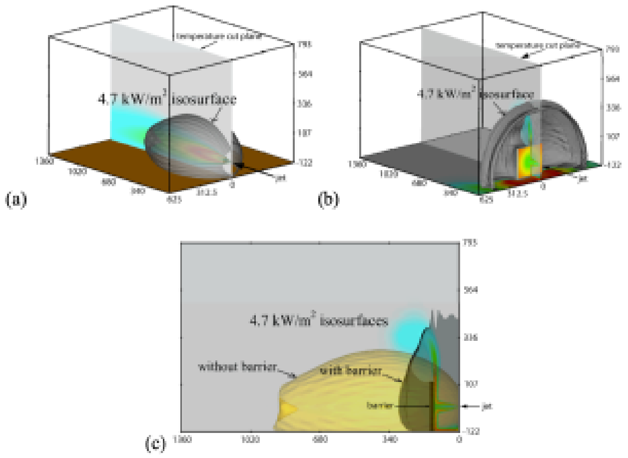


Figure 10. Calculated isosurfaces for radiative heat flux of 4.7 kW/m² from hydrogen jet flames; (a) free jet flame with ground plane; (b) jet flame directed toward center of 1-wall vertical barrier; (c) side view of isosurfaces shown in (a) and (b), comparing horizontal and vertical extent of radiation field without and with a barrier; jet flow is from right to left with distances in centimeters.

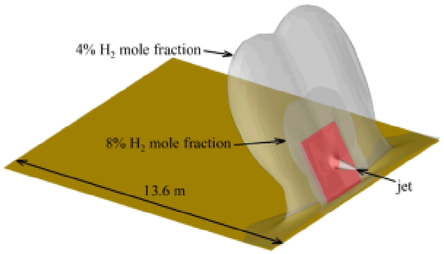


Figure 13. Calculated isosurfaces of 4% and 8% hydrogen mole fraction for a horizontal jet impinging on the 1-wall 2.4 m x 2.4 m (8 ft x 8 ft) tilted barrier. The jet release location is 1.219 m above the ground with the flow from right to left.

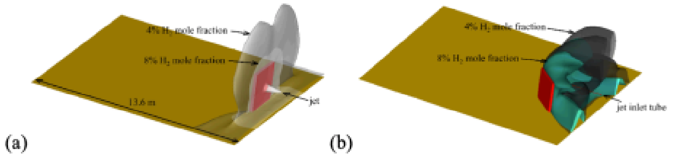


Figure 14. Calculated isosurfaces of 4% and 8% hydrogen mole fraction for unignited horizontal jets impinging on barriers with jet flow from right to left. (a) 1-wall 2.4 m x 2.4 m (8 ft x 8 ft) vertical barrier; (b) 3-wall barrier with 135 degrees between each 2.4 m x 2.4 m (8 ft x 8 ft) wall.

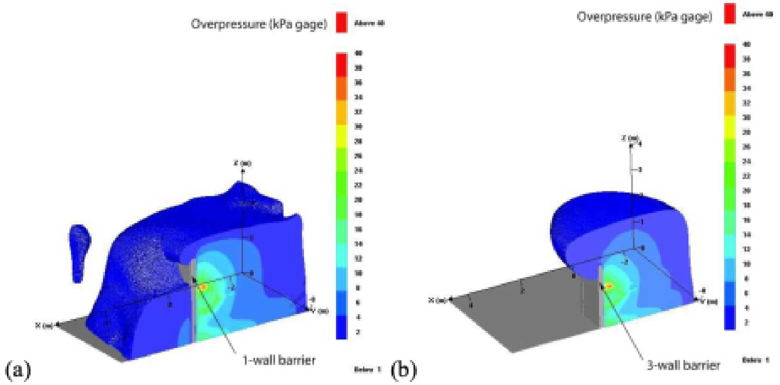


Figure 17. Comparison of maximum overpressure for (a) 1-wall vertical barrier (Test 1) and (b) 3-wall barrier with 135 degrees between each wall (Test 5) for ignition after 1 second from the beginning of the release (1/2 domain shown). Pressure scales are identical on both plots and distances are shown 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

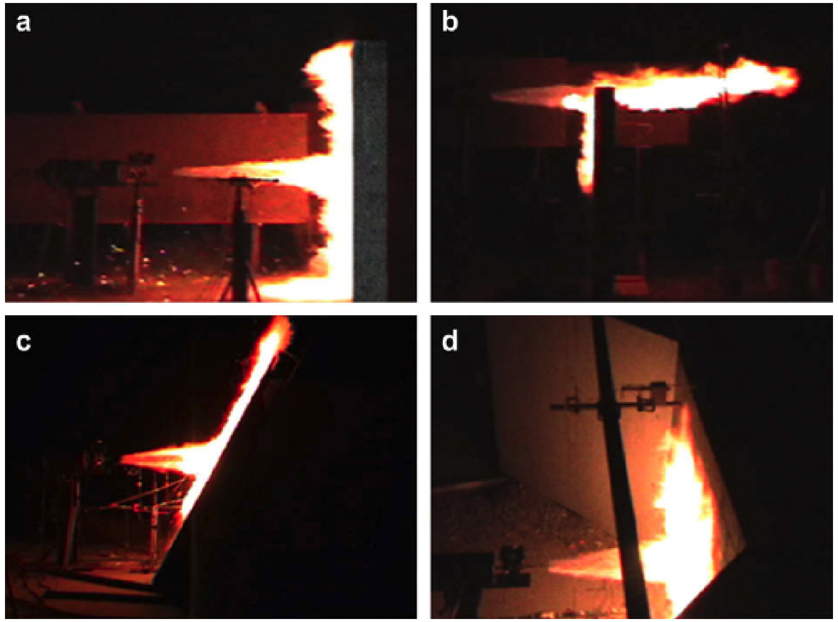
Conclusions

- 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

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)	
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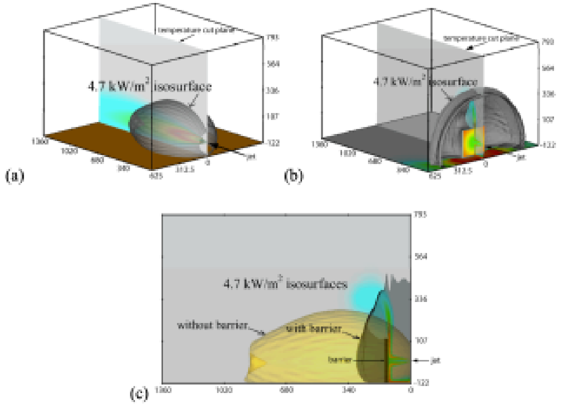
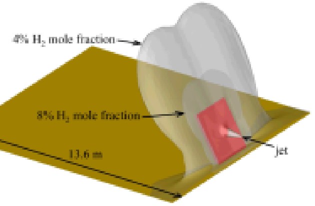
[2] Separation distance specified in NFPA-55, based on selected leak diameter.

From LaChance 2010





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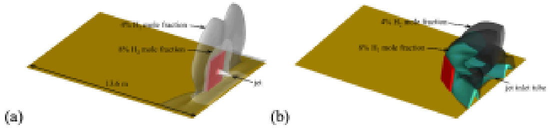

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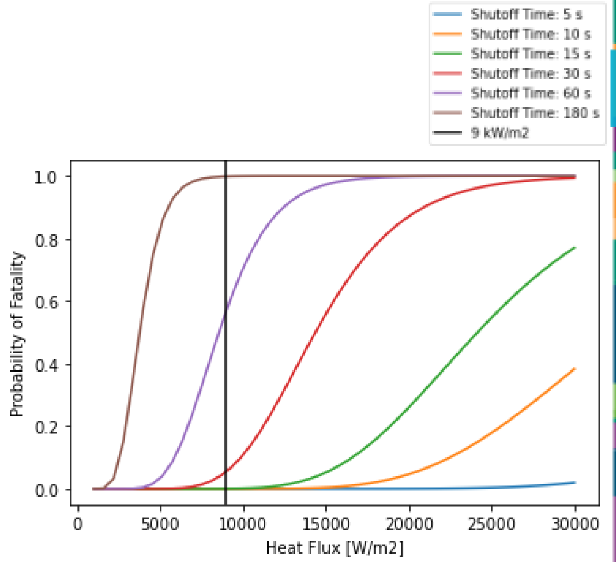
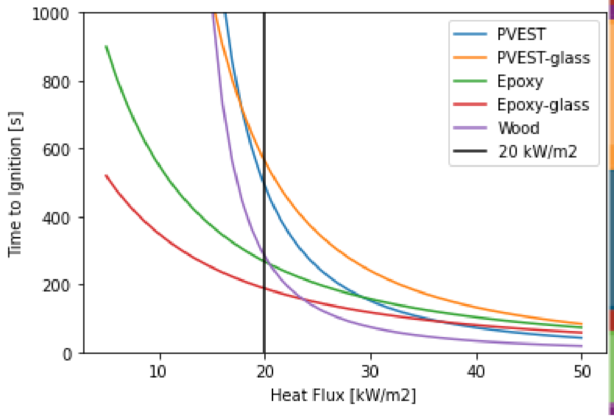
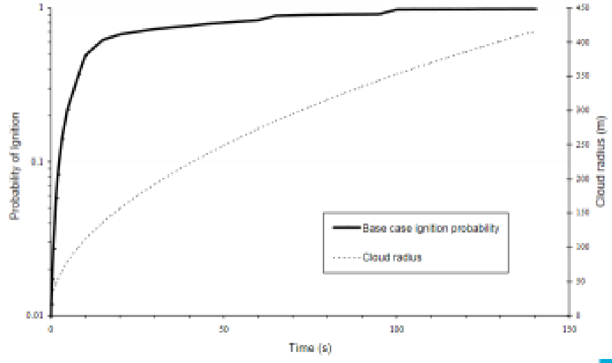
Reduction Justification: Shutdown

- 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