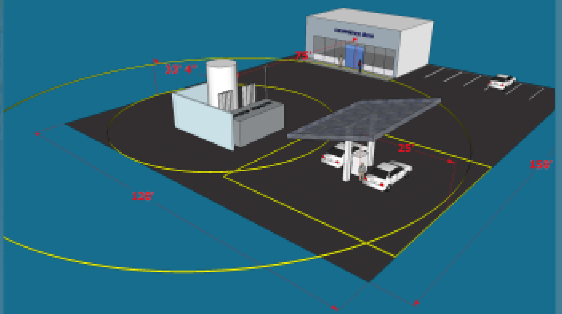
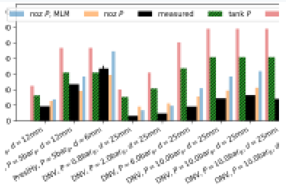
This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

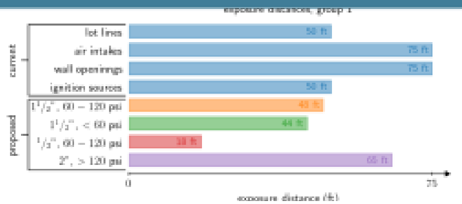
SAND2022-8323C

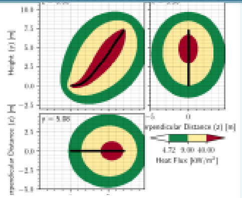
Sandia National Laboratories

Quantitative Risk Assessment Sensitivity Study as the Basis for Risk-Informed Consequence-Based Setback Distance Requirements for Liquid Hydrogen Storage Systems









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

Probabilistic Safety Assessment and Management (PSAM) 16

Honolulu, HI, USA

June 26 - July 1, 2022

U.S. DEPARTMENT OF ENERGY NNSA

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Background

- Currently, **NFPA 2** (Hydrogen Technologies Code) has **prescriptive requirements** for **setback distances** from **bulk liquid hydrogen** outdoor storage
  - Some distances vary with total stored quantity of liquid hydrogen, but not all
  - No known documented basis for the distances used
- **Past work** on **gaseous hydrogen** setback distances resulted in **revised requirements**
  - Distances vary with storage pressure and size of interconnecting pipe, rather than stored quantity
  - Informed by quantitative risk assessment on representative hydrogen system and leak frequency analysis
- Some concerns with using previous approach on liquid hydrogen system
  - Lack of extensive operating data, especially for liquid hydrogen
  - Leak size may be non-conservative
  - Overpressure consequences not considered

NFPA 2, Hydrogen Technologies Code, 2011 Edition. National Fire Protection Association, Quincey, MA.
NFPA 2, Hydrogen Technologies Code, 2020 Edition. National Fire Protection Association, Quincey, MA.
LaChance, et al. Analysis to support development of risk-informed separation distances for hydrogen codes and standards. Sandia National Laboratories, SAND2009-0874

Goal and Approach

Goal:

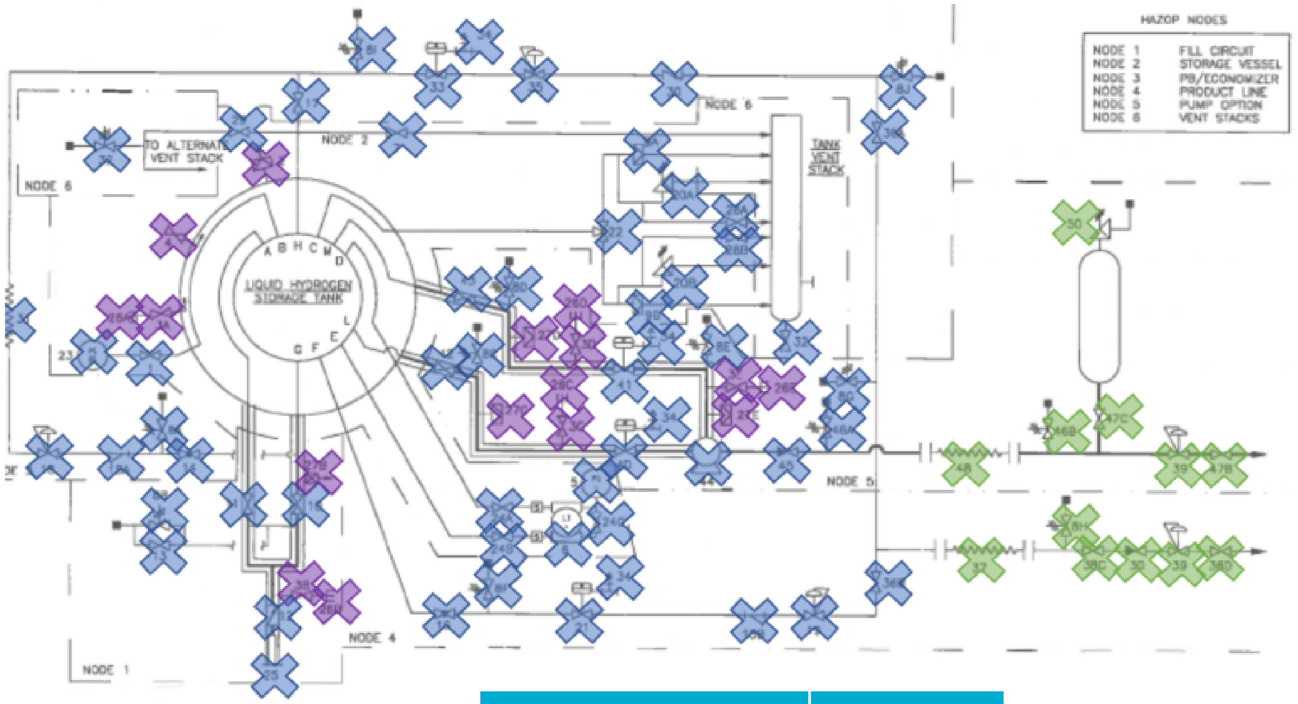
To use **risk-informed methods** to **justify a hydrogen release leak size** that allows for calculation of **consequence-based separation distances** that **vary with pressure and pipe size**

Approach

- Estimate risk-based separation distances for representative system
- Calculate equivalent hole size for consequence-based distances
- Select conservative hole size and use to calculate table values

Representative Liquid Hydrogen System

- Informative process schematic from CGA P-28 (2014) Standard used as base representative system
  - Included liquid hydrogen-wetted components only
- Storage system only
  - Not industrial process plant
  - Not refueling station
- Number of components varied in sensitivity study (details to follow)

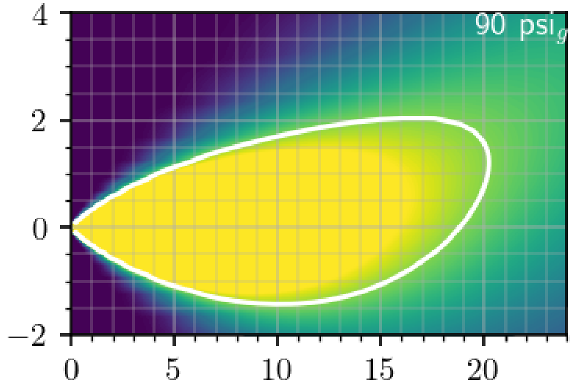


Component	Count
Pump	1
Pipe (m)	10
Vessel	1
Filter	2
Valve	44
Flange	8
Instrument	3

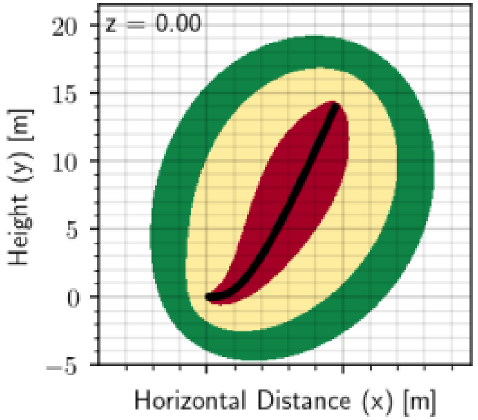
HyRAM+ Physics/Consequence Models

HyRAM+
Hydrogen Plus Other Alternative Fuels Risk Assessment Models

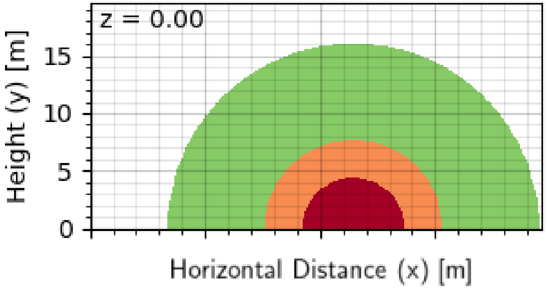
- Unignited Concentration
  - 1-D streamline model with buoyancy
  - Hazard for ignition source in flammable region



- Jet Flame
  - 1-D multi-point radiation model
  - Heat flux hazard



- Unconfined Overpressure
  - Uses unignited plume model
  - Different overpressure models: TNT, BST, Bauwens/Dorofeev
  - Overpressure hazard

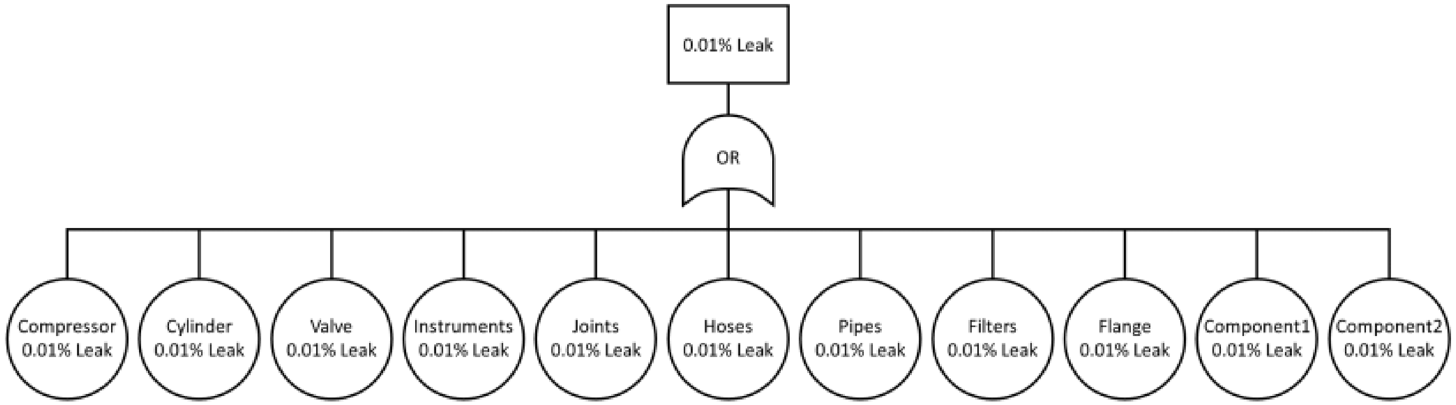


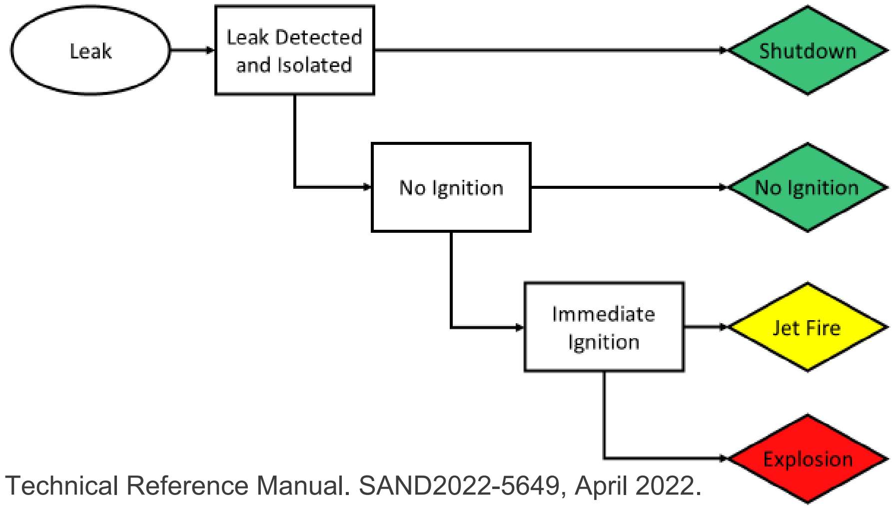
Brian D. Ehrhart and Ethan S. Hecht. Hydrogen Plus Other Alternative Fuels Risk Assessment Models (HyRAM+) Version 4.1 Technical Reference Manual. SAND2022-5649, April 2022.
https://hyram.sandia.gov

HyRAM+ Quantitative Risk Assessment Models

HyRAM+ Hydrogen Plus Other Alternative Fuels Risk Assessment Models

- Fault tree estimates system annual leak frequencies from per-component estimates
  - High uncertainty in leak frequencies due to inherent variability and lack of data
- 5 order of magnitude leak sizes: 0.01%, 0.1%, 1%, 10%, 100% of flow area
- Event tree estimates probability of 4 possible outcomes
- Harm calculated based on thermal effects (jet fire) or overpressure effects (explosion) at fixed location
- Probits used to estimate likelihood of fatality based on estimated harm

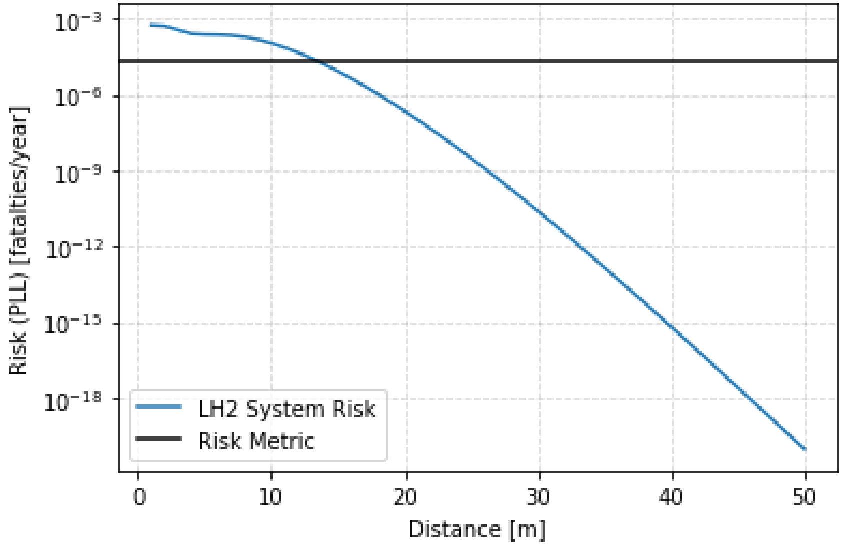




Brian D. Ehrhart and Ethan S. Hecht. Hydrogen Plus Other Alternative Fuels Risk Assessment Models (HyRAM+) Version 4.1 Technical Reference Manual. SAND2022-5649, April 2022.
https://hyram.sandia.gov

Risk-Based Distance Estimation

- Risk from system can be quantified at specific distances away from a leak point
- Point at which the risk falls below a given metric (criterion) yield a risk-based distance
  - Analogous to individual risk contours
  - Risk falls due to distance from thermal and overpressure hazards
  - 2 x 10-5 fatalities/year used as criterion, based on gasoline refueling stations
- Purely risk-based distance not always best for prescriptive requirements
  - Highly sensitive (next slide)
  - Difficult to explain to code committees or authorities having jurisdiction (AHJs)

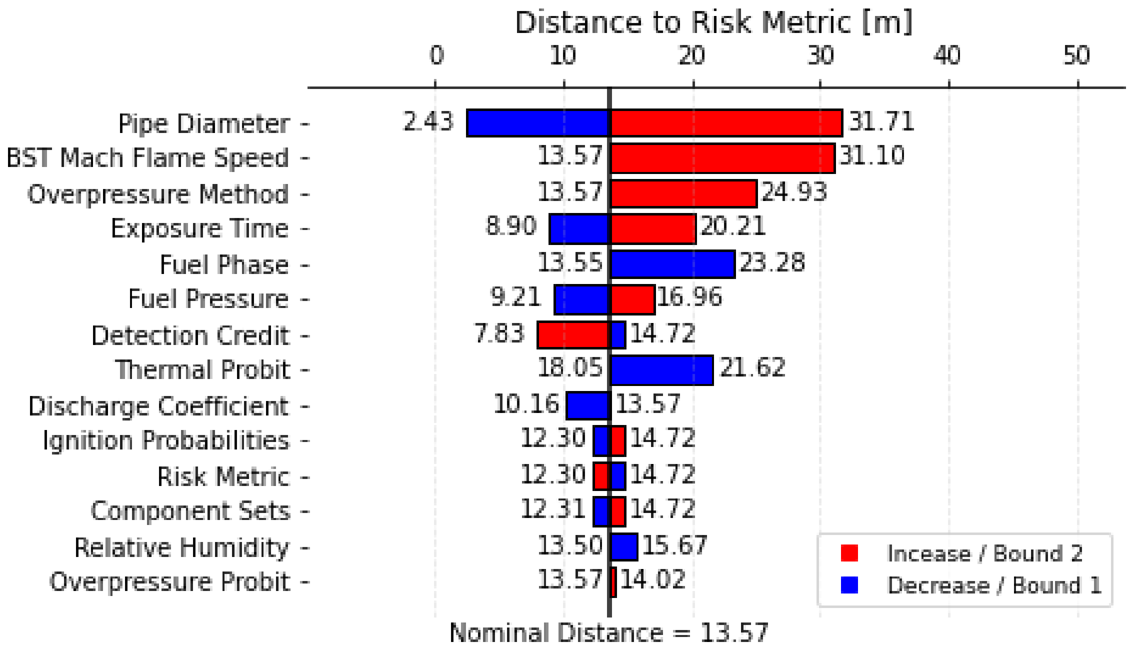


LaChance, et al. Analysis to support development of risk-informed separation distances for hydrogen codes and standards. Sandia National Laboratories, SAND2009-0874

Risk Assessment Sensitivity

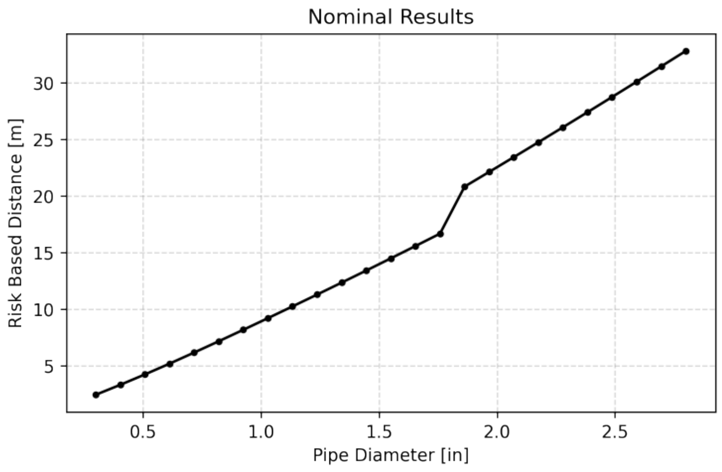
Varied many of the QRA inputs:

- System-specific
  - Pipe diameter
  - Fuel phase
  - Fuel pressure
  - Number of components
- Consequence-specific
  - Overpressure method
  - BST Mach flame speed
  - Discharge coefficient
  - Relative humidity
- Risk-specific
  - Thermal exposure time
  - Detection credit
  - Ignition probabilities
  - Thermal probit
  - Overpressure probit
  - Risk metric



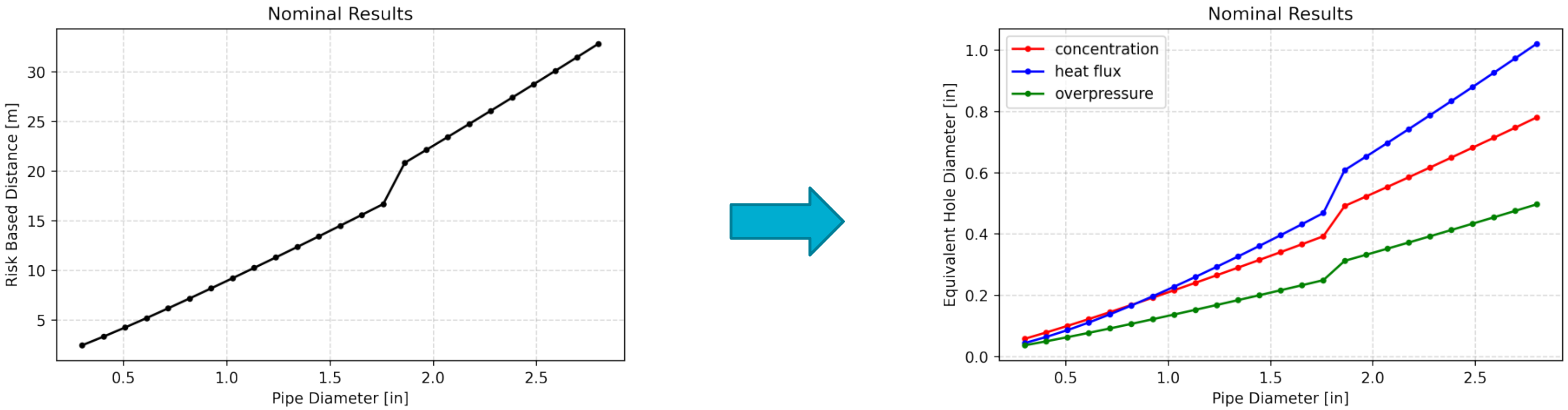
Risk-Based Distance for Variable Pipe Size

- **Pipe diameter** is one of the **most sensitive parameters** for risk-based distance
  - Pipe size relatively easy for AHJ review as a basis for prescriptive requirements
- Calculate a **risk-based distance** for set of inputs, varying only the pipe size



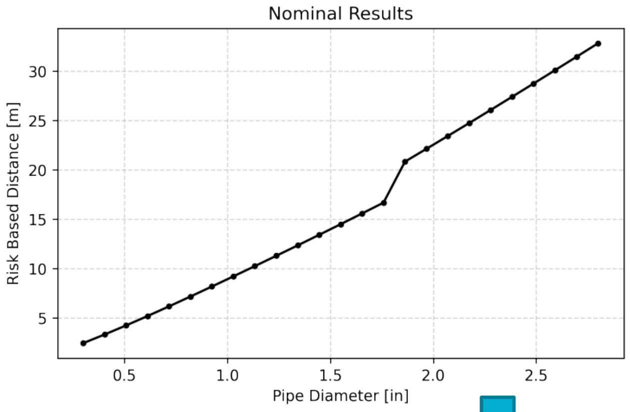
Equivalent Hole Size Estimation

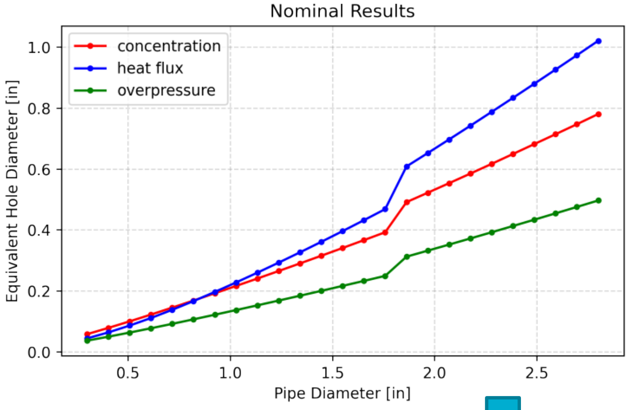
- Equivalent hole size can then be estimated using on risk-based distance
  - For each risk-based distance value:
  - Calculate **leak hole size** that would give **same consequence-based distance**
  - Based on physical hazard criteria
    - Unignited concentration: 8% by volume
    - Heat flux: 4.7 kW/m2
    - Peak overpressure: 6.9 kPa (1 psi)

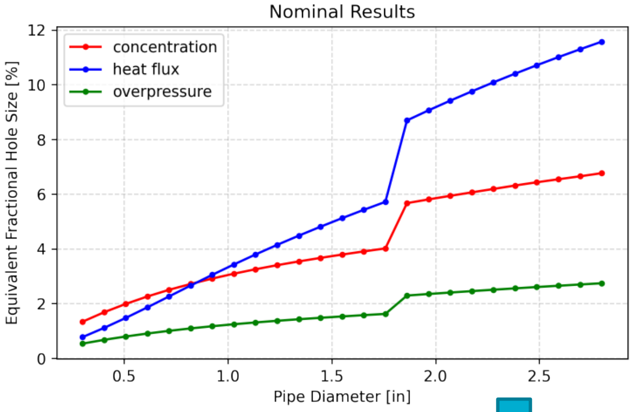


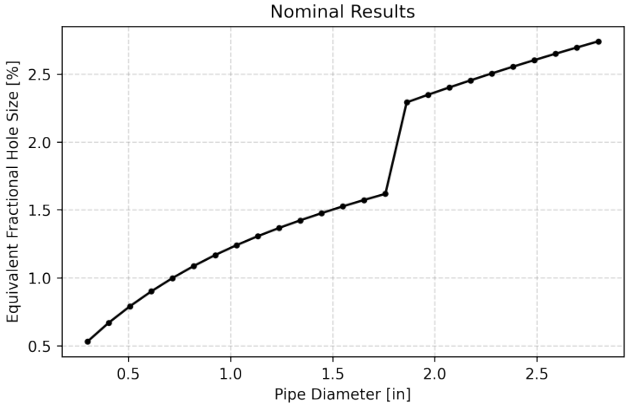
Equivalent Hole Size for Variable Pipe Size

- For each equivalent hole size, calculate **fractional hole size** based on pipe flow area
- For each pipe size, select **smallest fractional hole size**
  - This would be the “driving” hazard for a given setback distance



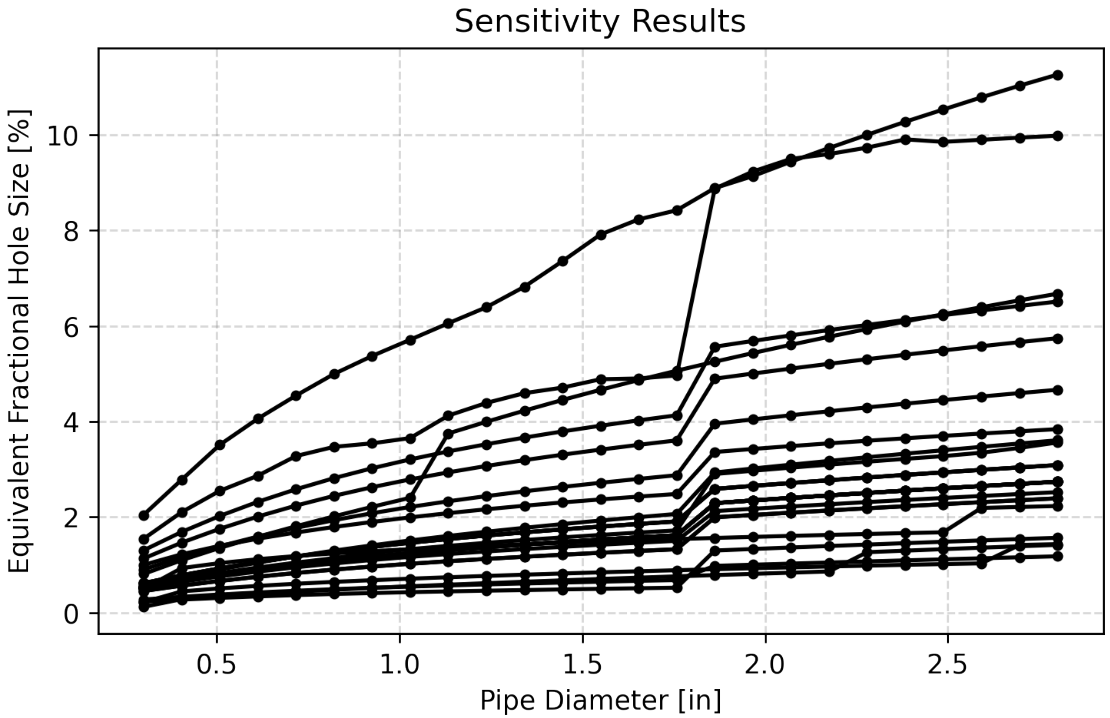






Equivalent Hole Size Sensitivity

- The equivalent fractional hole size can then be repeated for each item of the sensitivity case study
  - Results in 26 individual lines, each of which vary with pipe diameter
- **Almost all cases cluster below 5-10%** equivalent fractional hole size



Overly-Conservative Cases: Sub-Cooled Liquid and Detonation

- 3 cases exceed 5-10% equivalent fractional hole size at largest pipe diameter:
- Sub-cooled liquid source
  - HyRAM+ consequence models assume a release directly to atmosphere
  - **Neglects piping effects** (e.g., flow losses and heat transfer) that would heat up cryogenic hydrogen (≈20 K)
  - Experiments that were intentionally trying to release liquid hydrogen could only get a two-phase mixture, not even a saturated liquid
- Detonation-based overpressure methods
  - BST method with Mach flame speed of 5.2 too high for non-premixed jet
  - Bauwens/Dorofeev model assumes detonation of fraction of flammable mass, but model has limited validation data
  - These **methods tend to overpredict experimental measurements** based on delayed ignition of unconfined hydrogen

K. Lyons, S. Coldrick, and G. Atkinson. Summary of experiment series E3.5 (rainout) results. Technical report, PRESLHy deliverable number D3.6, 2020.
C. Huescar Medina, A. Halford, and J. Stene. Liquid hydrogen safety data report: Outdoor leakage studies. Technical report, DNV-GL. Report 853182, Rev. 2, 2008.
S. Jallais, E. Vyazmina, D. Miller, and J. K. Thomas, “Hydrogen jet vapor cloud explosion: A model for predicting blast size and application to risk assessment,” Process Safety Progress, vol. 37, no. 3, pp. 397–410, 2018.
C. R. L. Bauwens and S. B. Dorofeev, “Modeling detonation limits for arbitrary non-uniform concentration distributions in fuel–air mixtures,” Combustion and Flame, vol. 221, pp. 338–345, 2020.

Overly-Conservative Cases: Exposure Time and Thermal Probit

- 2 cases exceed 5% equivalent fractional hole size at largest diameter:
- Thermal exposure time: 60 seconds (double nominal)
  - **Multiple sources recommend** 30 second response time to move away from flame
  - Weakly-radiating hydrogen flame can **decrease harm over distance quickly**
- Tsao and Perry thermal probit
  - **Includes infrared effects** in addition to ultraviolet
    - Hydrogen flames radiate weakly, meaning infrared radiation likely to be low
  - Does **not account** for protection from **clothing**

TNO Green Book, Methods for the Determination of Possible Damage. CPR 16E. Published by the Director-General of Labour, Netherlands, 1992.
Phani K. Raj. A review of the criteria for people exposure to radiant heat flux from fires. Journal of Hazardous Materials, 159:61–71, 2008.
Jeffrey LaChance, Andrei Tchouvelev, and Angunn Engebø. Development of uniform harm criteria for use in quantitative risk analysis of the hydrogen infrastructure. International Journal of Hydrogen Energy, 36(3): 2381–2388, February 2011.

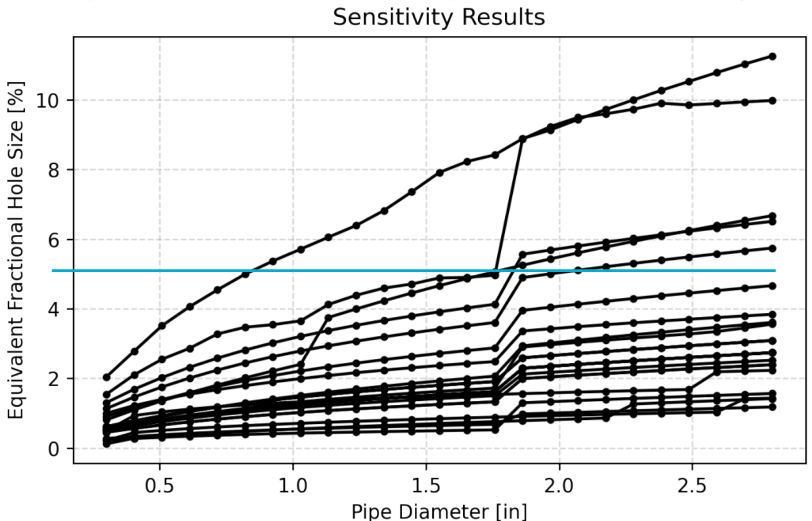
Selection of 5% Fractional Leak Area

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

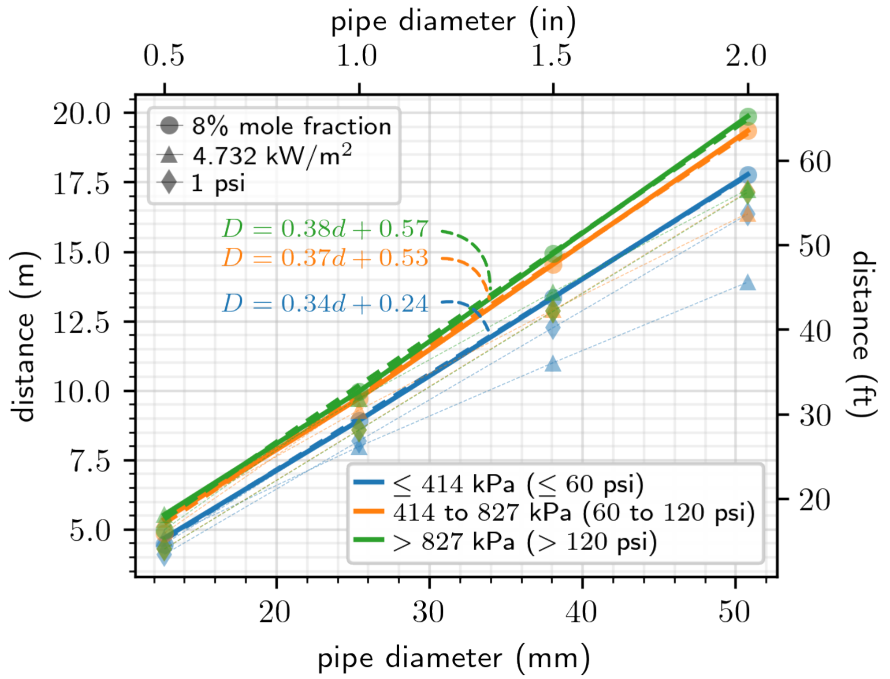
Possibilities considered:

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



Use of Fractional Hole Size for Setback Distance Calculation

- 5% fractional hole size used as source
- Pressure and pipe size were varied
  - This affected release flow rate
  - Thus varied distance to hazard
- For each exposure group (types of exposure), furthest distance was selected
- Resulted in distances that vary with pressure and pipe size



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□+ 0.24		0.20□+ 1.84		0.15□+ 2.08		0.37□+ 0.53		0.24□+ 1.96		0.19□+ 2.19		0.38□+ 0.57		0.25□+ 1.93		0.20□+ 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

Conclusions

Risk-based distances can be highly sensitive to system parameters and modeling assumptions

Sensitivity study of risk-based distances showed amount of variability, and leads to conservative but not unrealistic choice in leak size

Fractional leak size can allow “credit” for differences in pipe size and fuel pressure

Risk-informed justification for consequence-based setback distances can utilize useful aspects of consequence-based distances while still incorporating trends from risk assessment

Potential Future Work

Use same methodology to revisit gaseous hydrogen requirements

Include cryogenic pooling scenarios

- Improved validation from upcoming experiments

Better characterize hydrogen-specific overpressure

Use similar methodology to assess liquid transfer points

Thank you!
Questions?

bdehrha@sandia.gov

Back Up Slides

Fractional Hole Size

Fractional instead of absolute hole size

- NFPA 2 GH2 tables use 1% of flow area

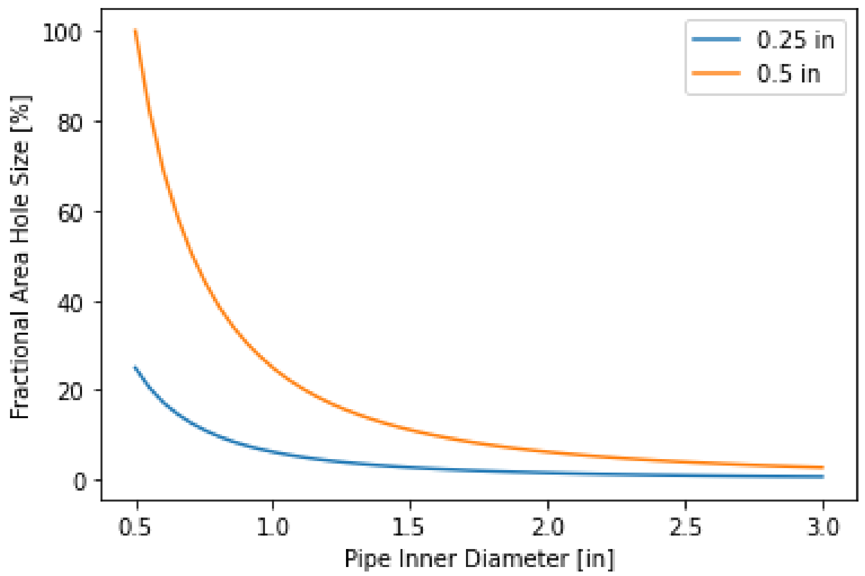
Gives "credit" for using smaller pipe diameters

- Smaller pipes lower risk by limiting the consequences

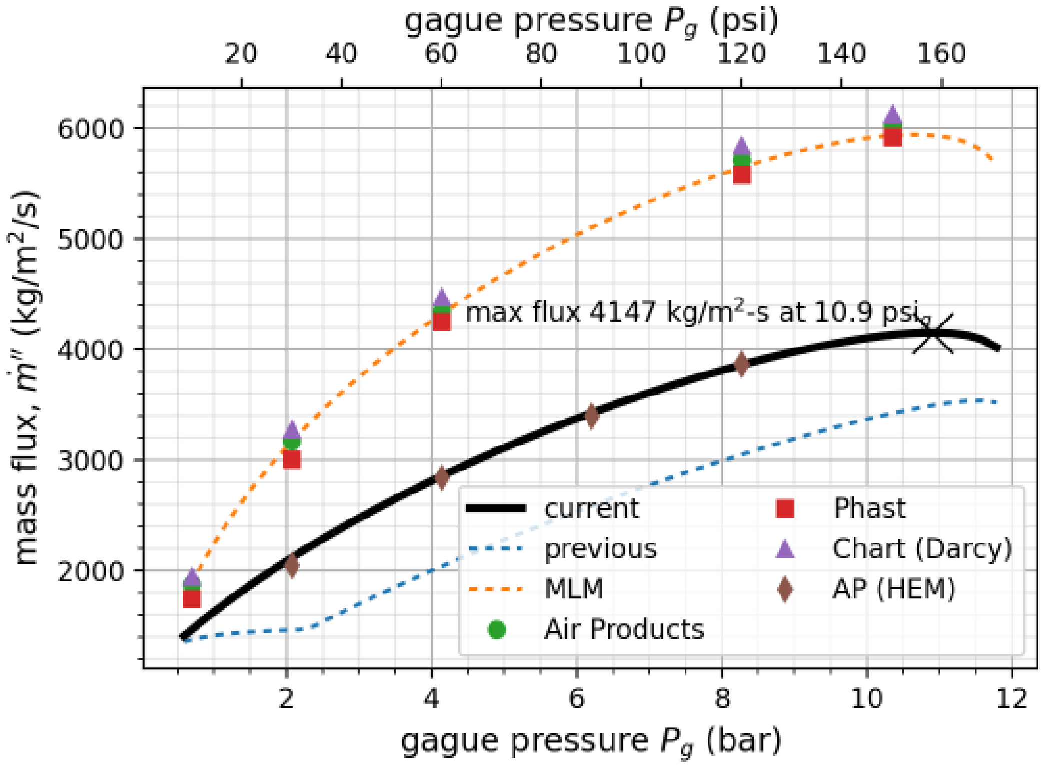
Allows setbacks to grow for larger pipe diameters

Fractional area leak size:

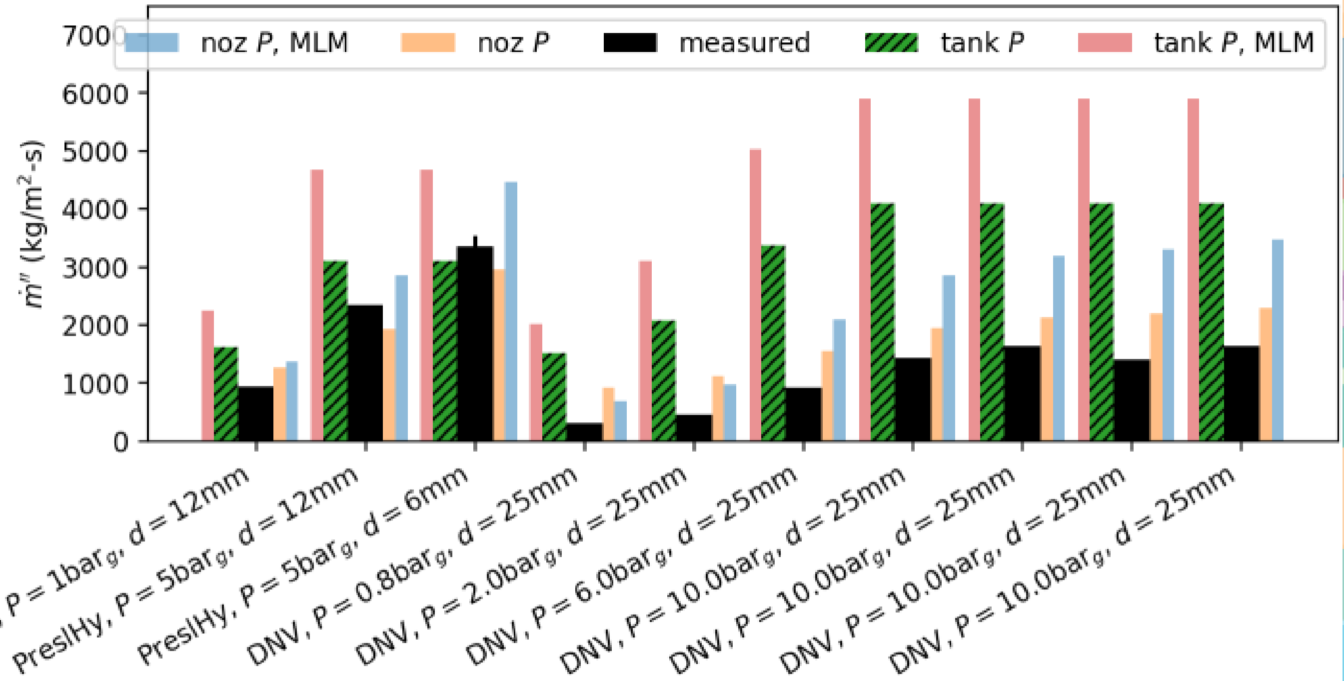
- $Fraction = \frac{A_{leak}}{A_{pipeID}} = \frac{\frac{\pi}{4}d_{leak}^2}{\frac{\pi}{4}d_{pipeID}^2} = \left(\frac{d_{leak}}{d_{pipeID}}\right)^2$



Mass Flow Rate–Comparison and Justification

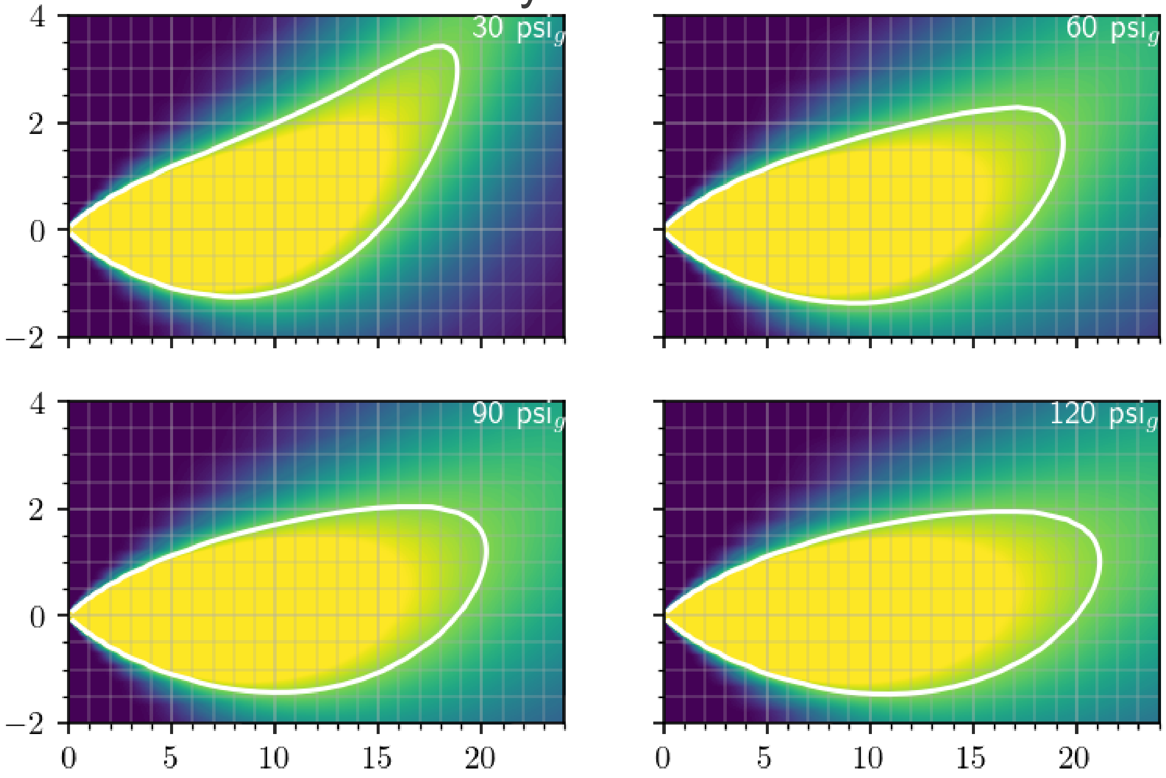


- Calculations use homogenous equilibrium model (with search for maximum mass flux)
- Experiments attempting to get maximum liquid don't see flows approaching MLM

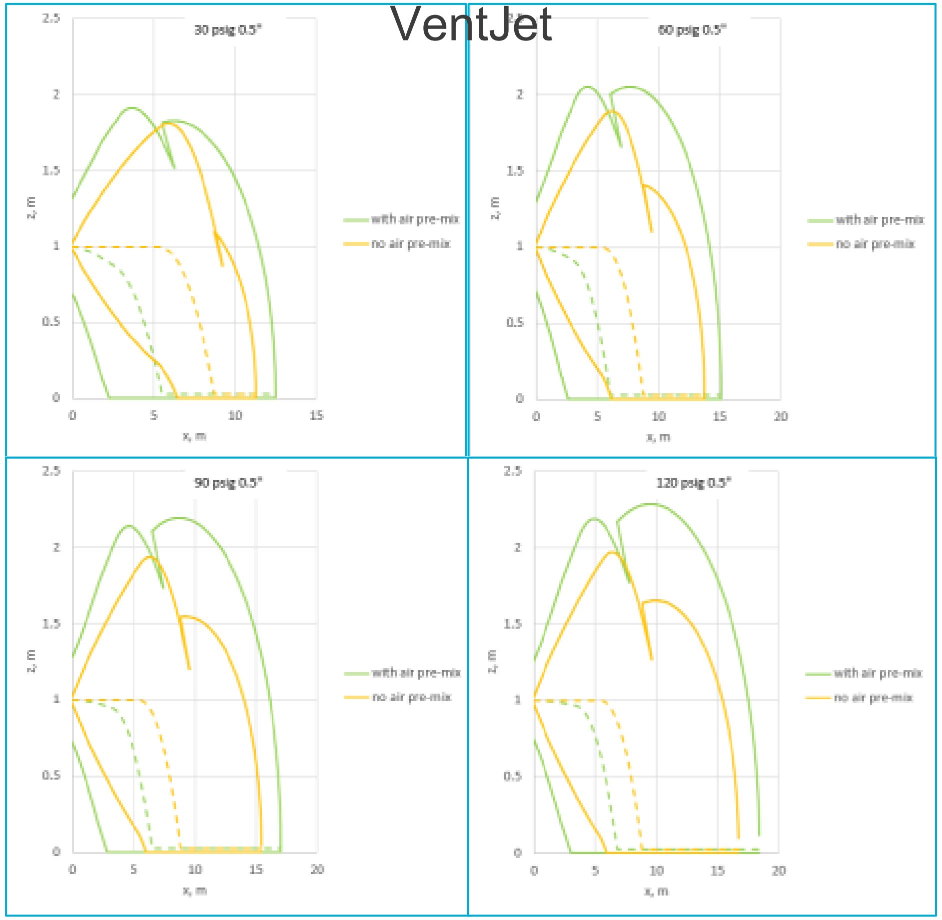


HyRAM+ vs. AP VentJet dispersion: 0.5” hole

HyRAM+

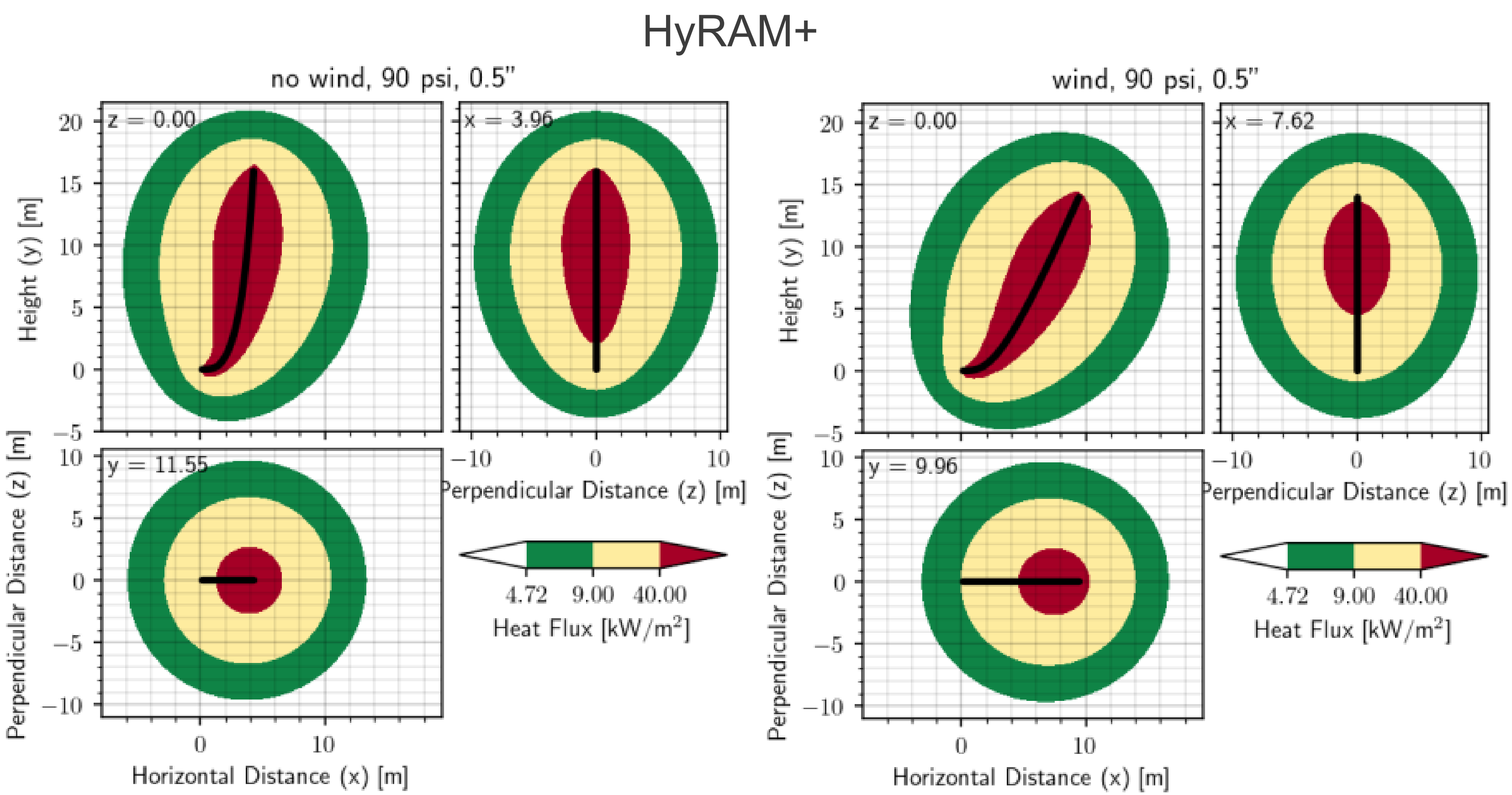


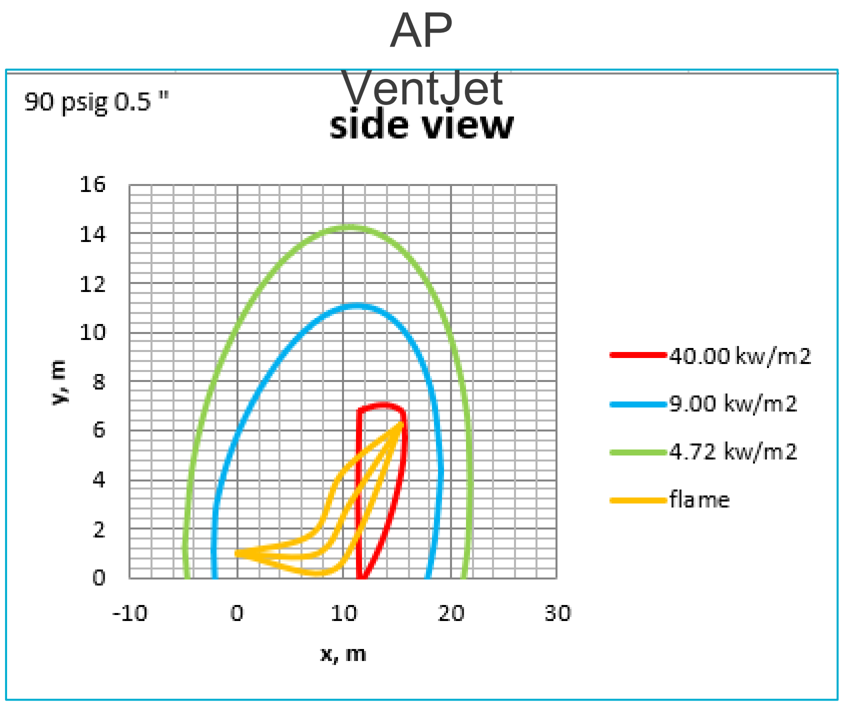
AP VentJet



- 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



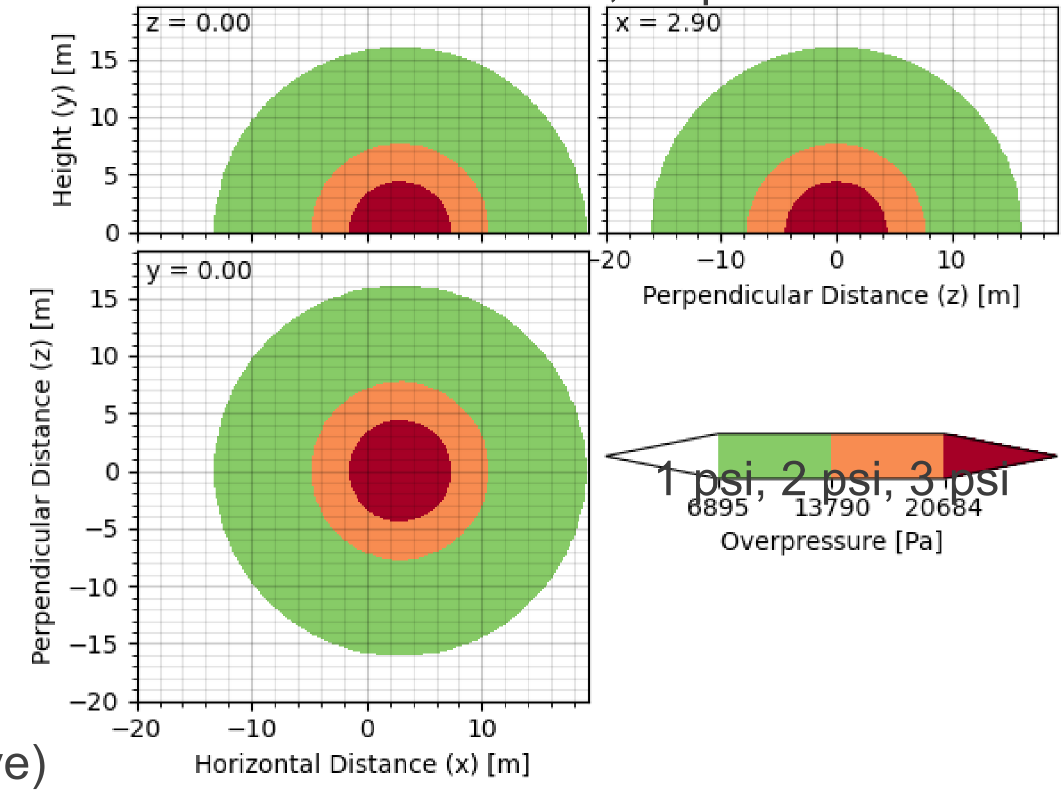


- High density of LH2 results in low momentum release rates
- HyRAM+ modified to include the effect of wind; results in similar distances to AP flame
- Largest projected heat fluxes onto the ground are used as exposure distances

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



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 LFL (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 for Group 1 exposures,***
- ***2 psi for Group 2 exposures,***
- ***3 psi 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]

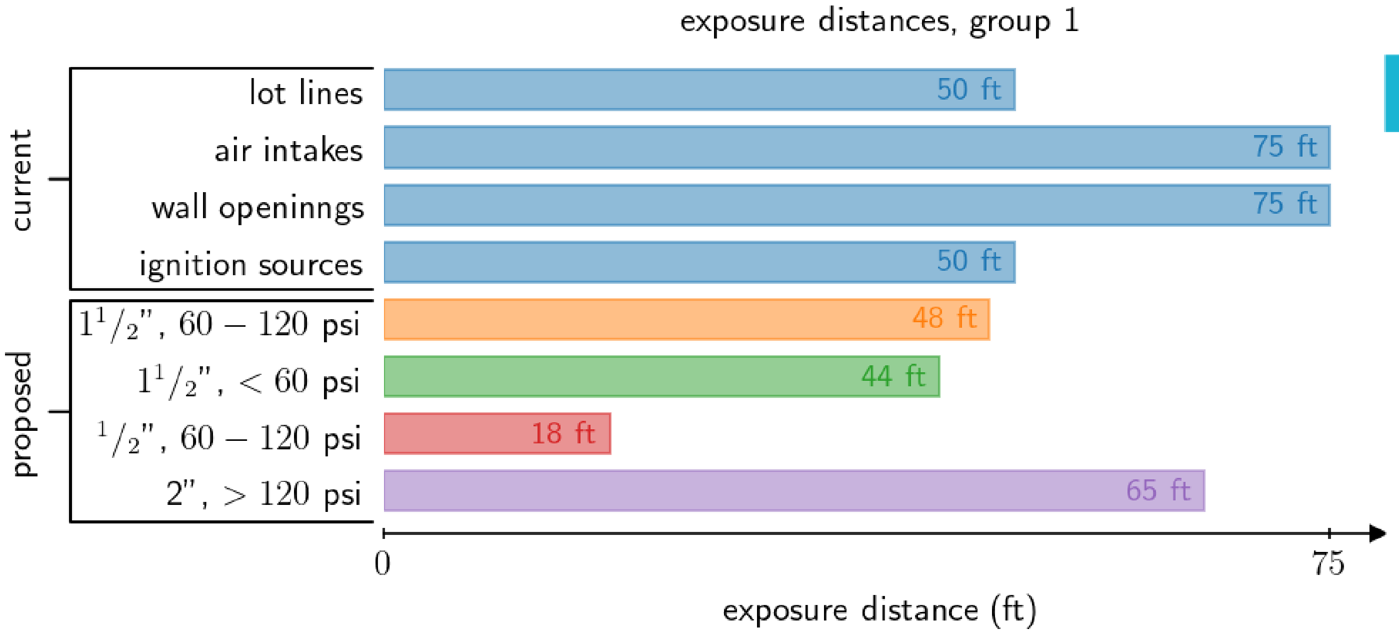
Typical Inner Diameter

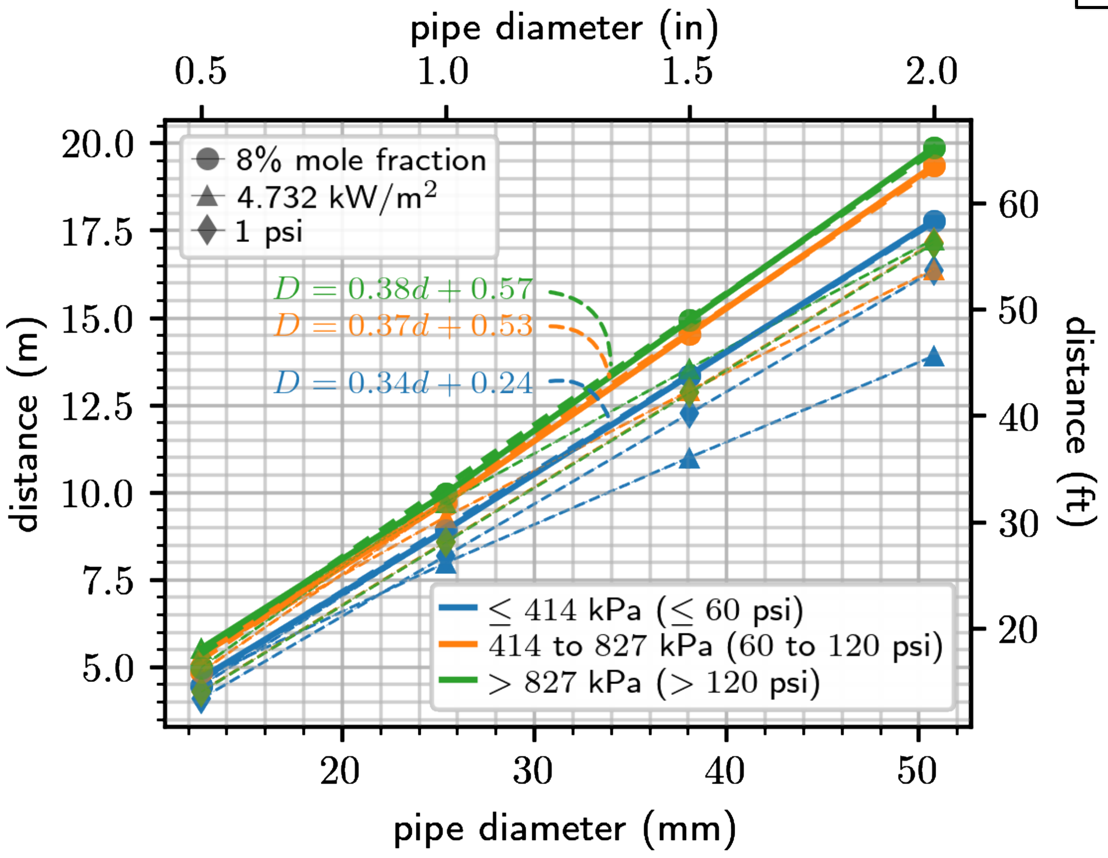
Table 8.3.2.3.1.6(a) Minimum Distance from Outdoor Bulk Liquefied Hydrogen [LH2] Systems to Exposures, up to 75000 gallons— Typical Inner Diameter (1.5 in [38.1 mm])

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

Group 1

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



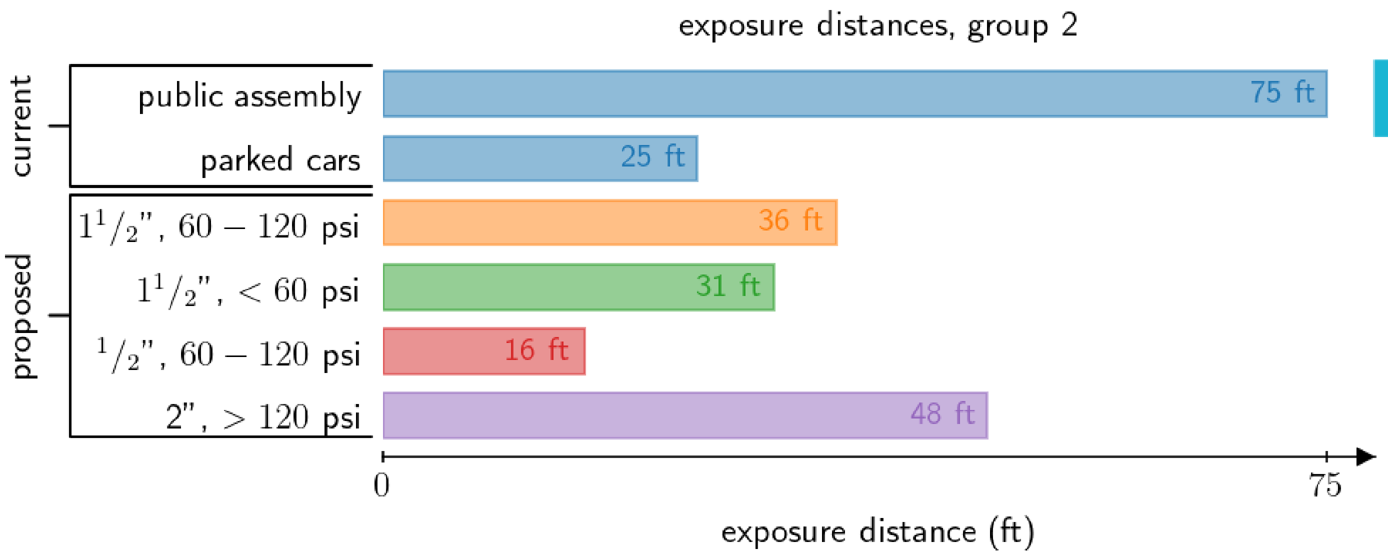


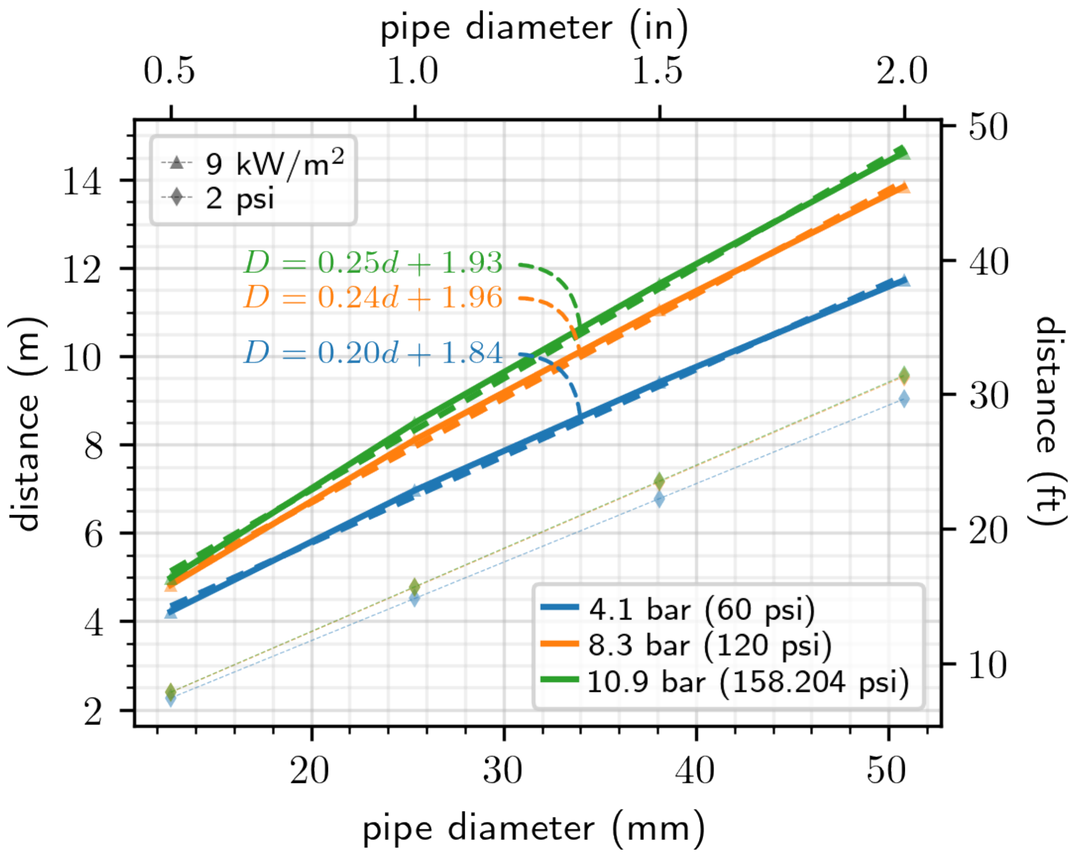
Protects against:

- 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



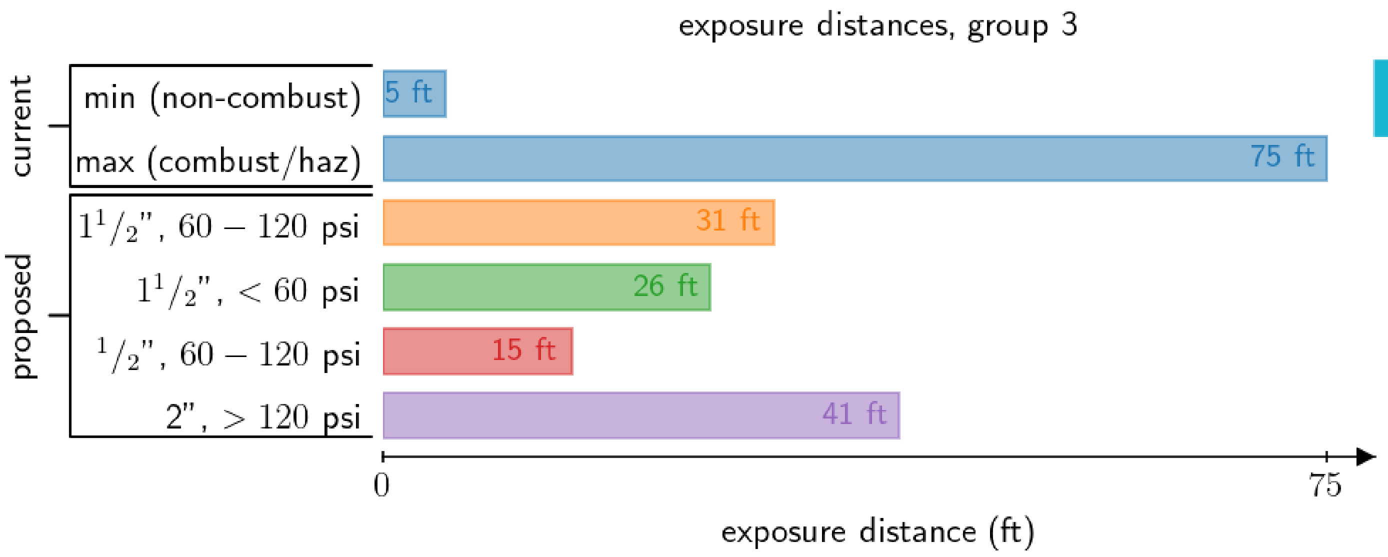


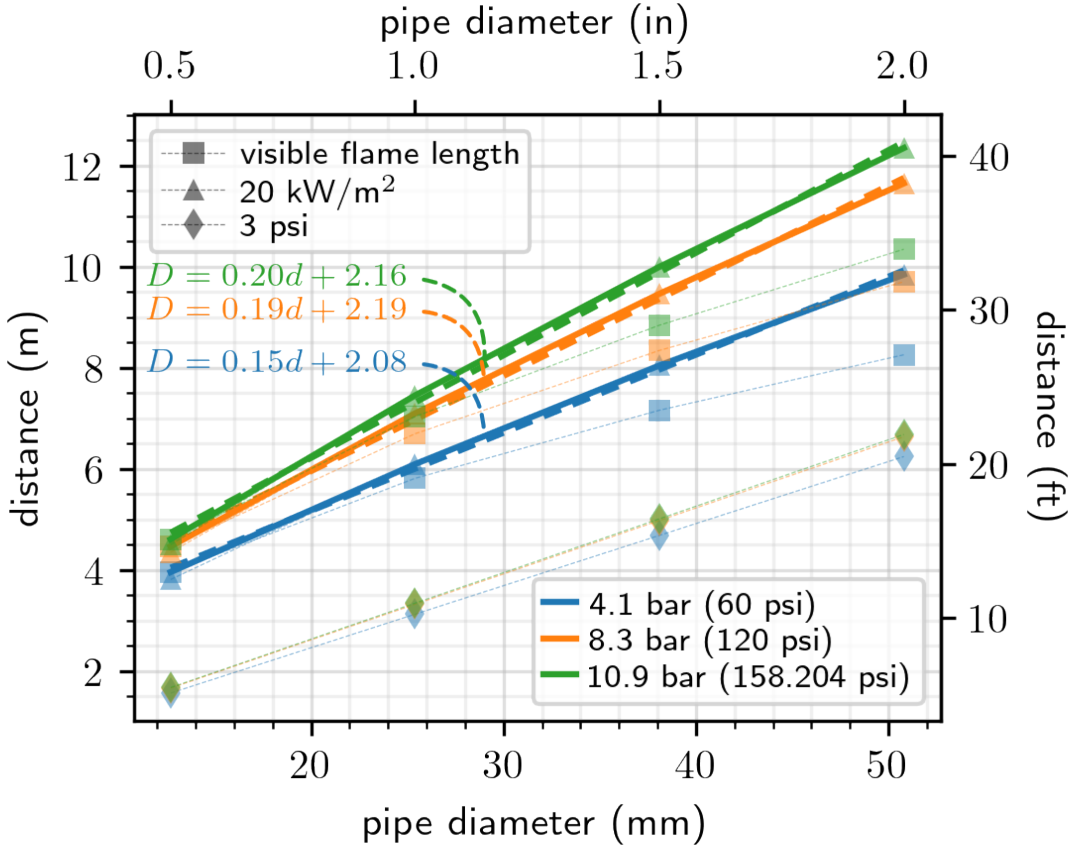
Protects against:

- 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

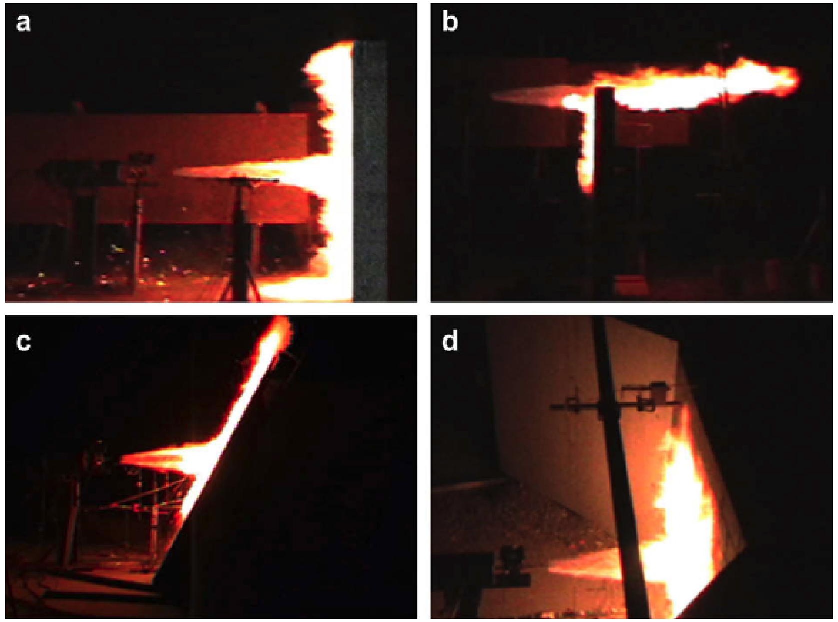




Protects against:

- Escalation of event (fire spread)

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

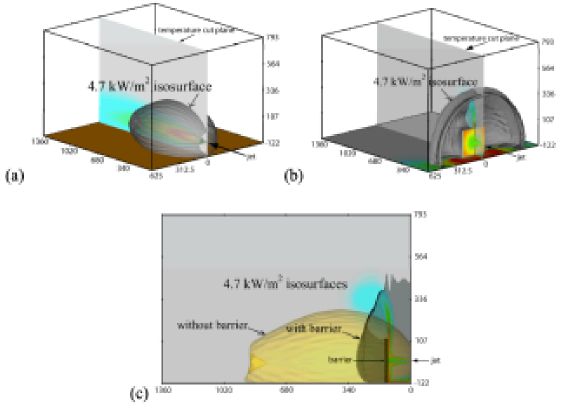
Table 1: Estimated risk reduction from the use of barriers.

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.

From LaChance 2010



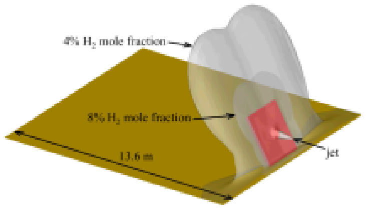


Figure 13. Calculated isosurfaces of 4% and 8% hydrogen mole fraction for a horizontal jet impinging on the 1-wall 2.4 m x 2.4 m (8 ft x 8 ft) tilted barrier. The jet release location is 1.219 m above the ground with the flow from right to left.

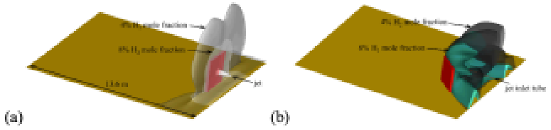
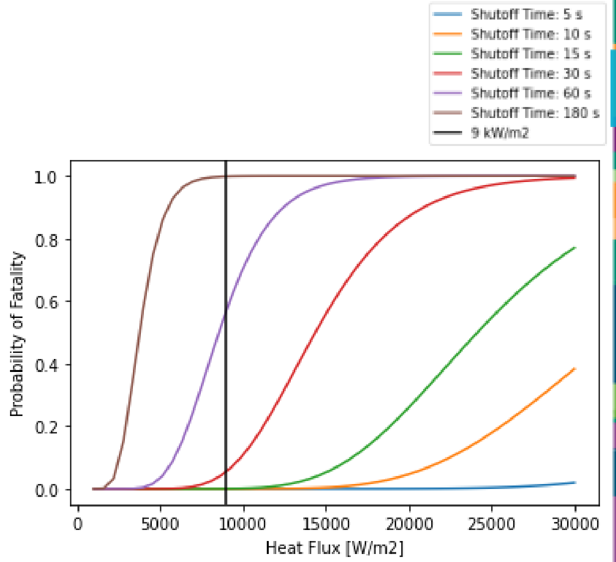
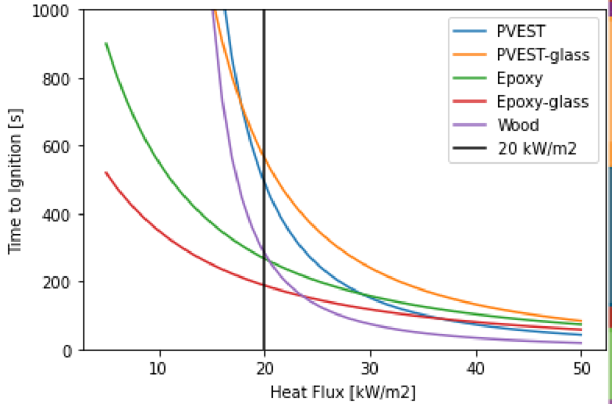


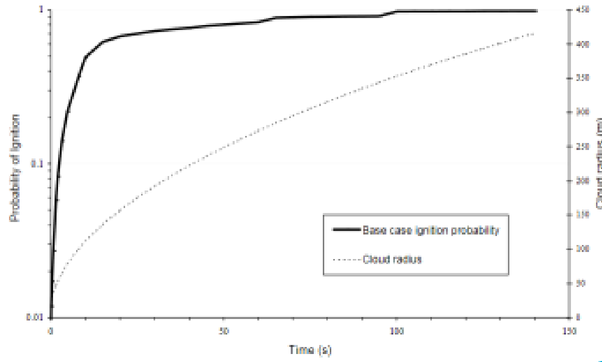
Figure 14. Calculated isosurfaces of 4% and 8% hydrogen mole fraction for unignited horizontal jets impinging on barriers with jet flow from right to left. (a) 1-wall 2.4 m x 2.4 m (8 ft x 8 ft) vertical barrier; (b) 3-wall barrier with 135 degrees between each 2.4 m x 2.4 m (8 ft x 8 ft) wall.

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 8 kW/m^2 instead drops probability of fatality from ~80% to ~0%
- 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

Risk discontinuities from ignition probabilities

- Current ignition probabilities based on mass flow rate
  - Probability step-changes at specific mass flow rate thresholds
- One of the leak sizes passes through two thresholds
  - Causes step-changes in risk
- Need for better characterization of ignition probability