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RISK SENSITIVITY STUDY AS THE BASIS FOR RISK-INFORMED CONSEQUENCE-BASED SETBACK DISTANCES

For Liquid Hydrogen Storage System

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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**

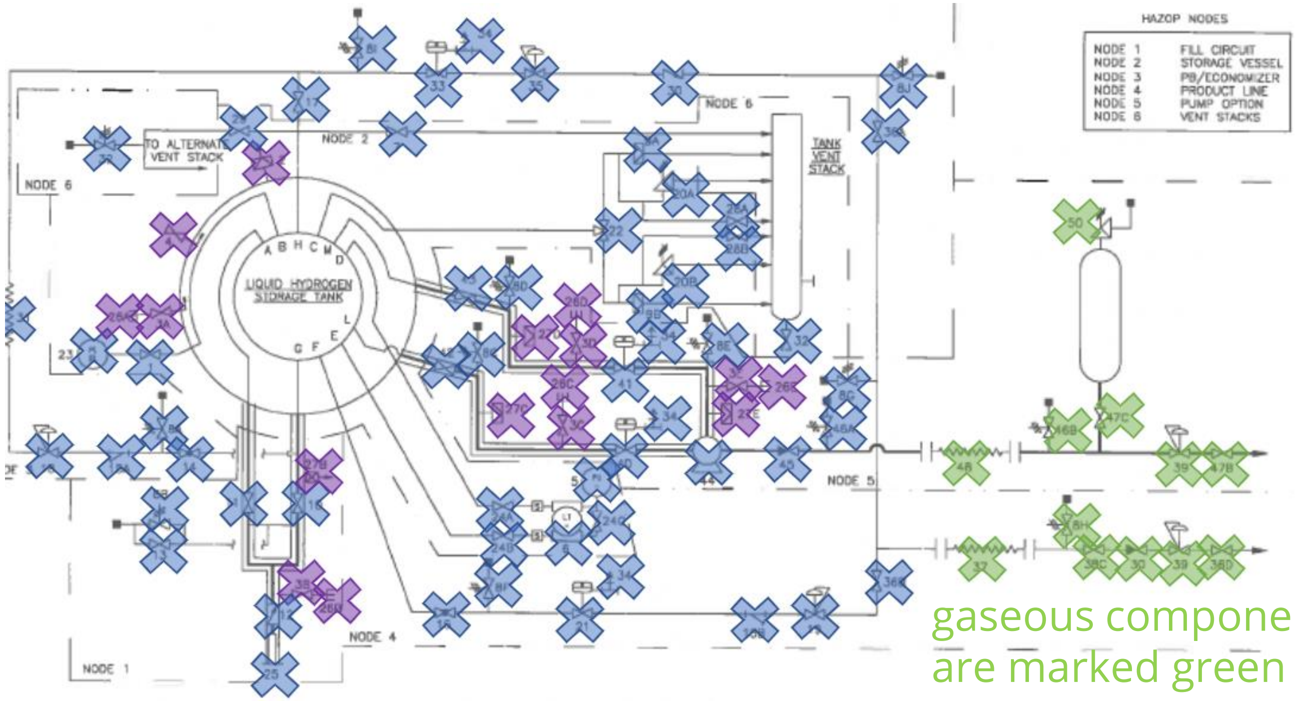
Approach

- 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 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)

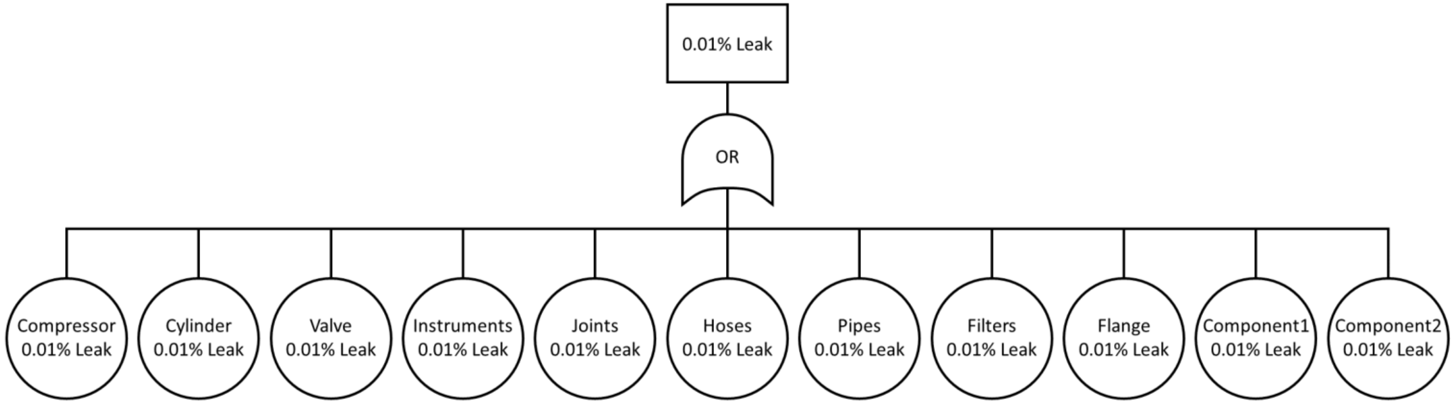
Component	Count
Pump	1
Pipe (m)	10
Vessel	1
Filter	2
Valve	44
Flange	8
Instrument	3

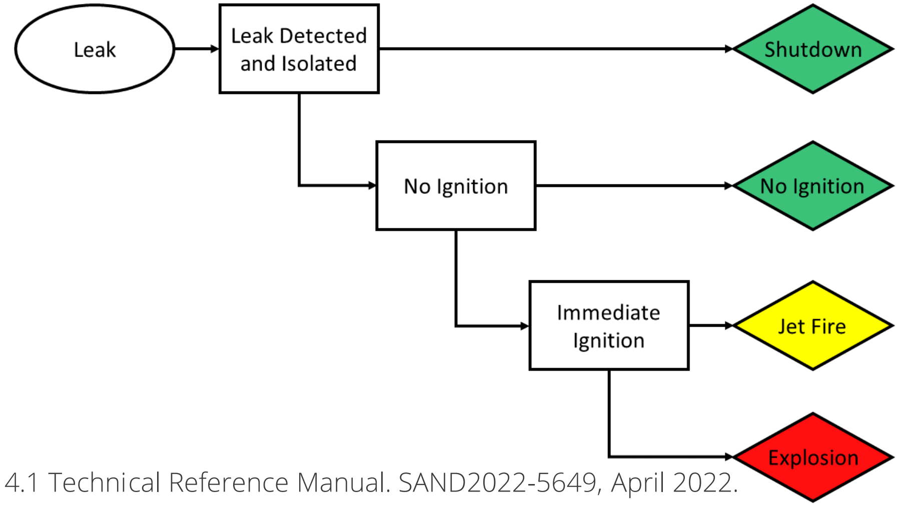


gaseous components are marked green

HYRAM+ QUANTITATIVE 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 specific to LH_2
- 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

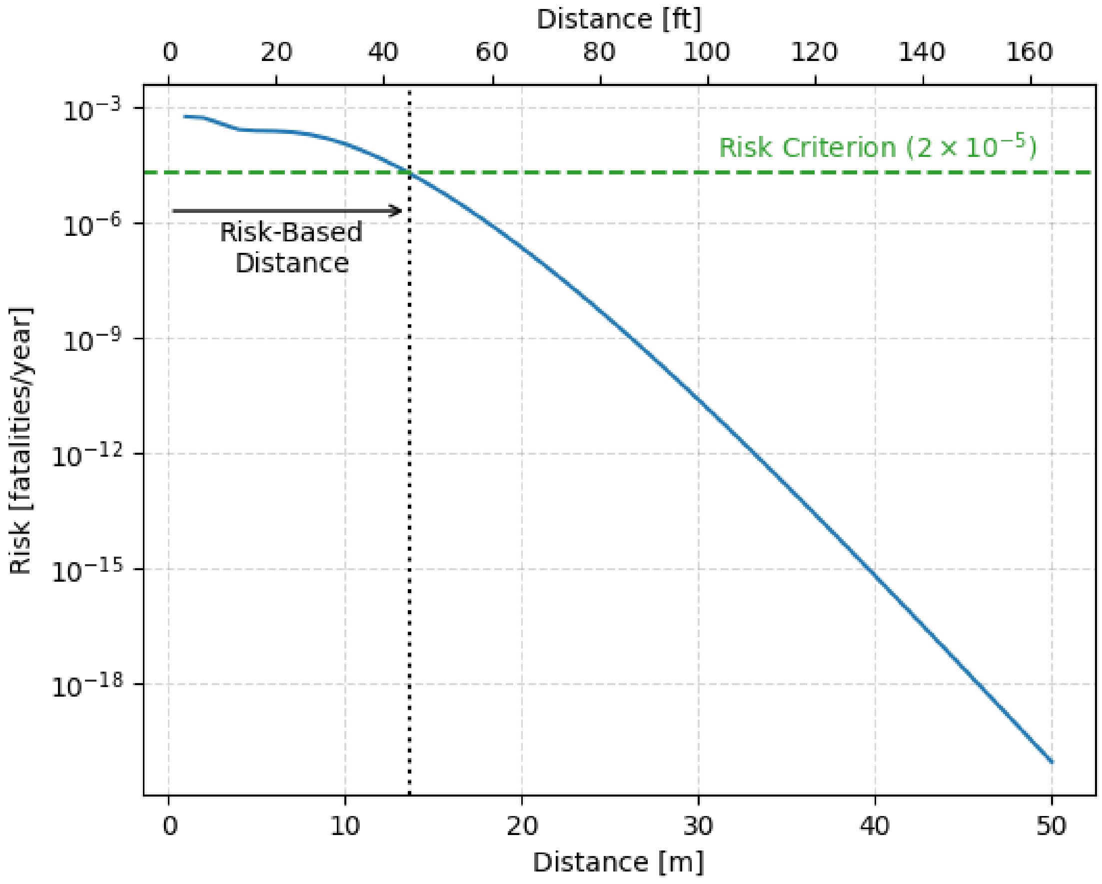




Brian D. Ehrhart and Ethan S. Hecht. Hydrogen Plus Other Alternative Fuels Risk Assessment Models (HyRAM+) Version 4.1 Technical Reference Manual. SAND2022-5649, April 2022.
https://hyram.sandia.gov

RISK-BASED DISTANCE ESTIMATION

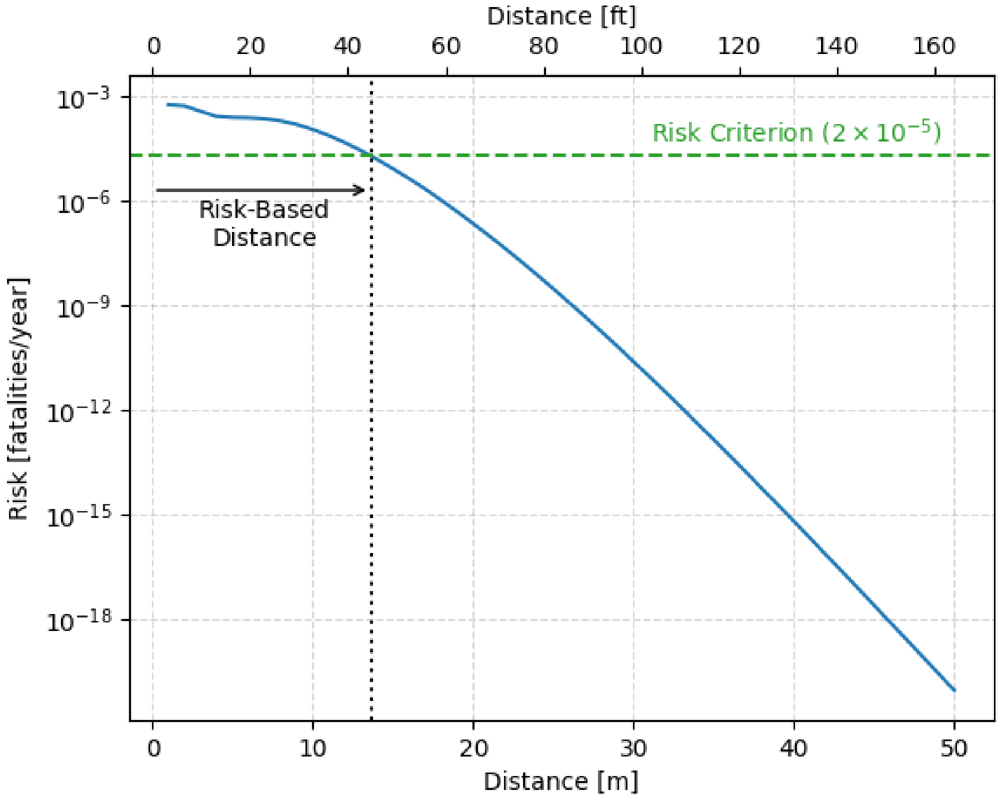
- Risk from system can be quantified as a function of distance away from the leak point
- Point at which the risk falls below a given metric (criterion) yields a risk-based distance
  - Can result in individual risk contours
  - Risk decreases due to distance from thermal and overpressure hazards
  - **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)



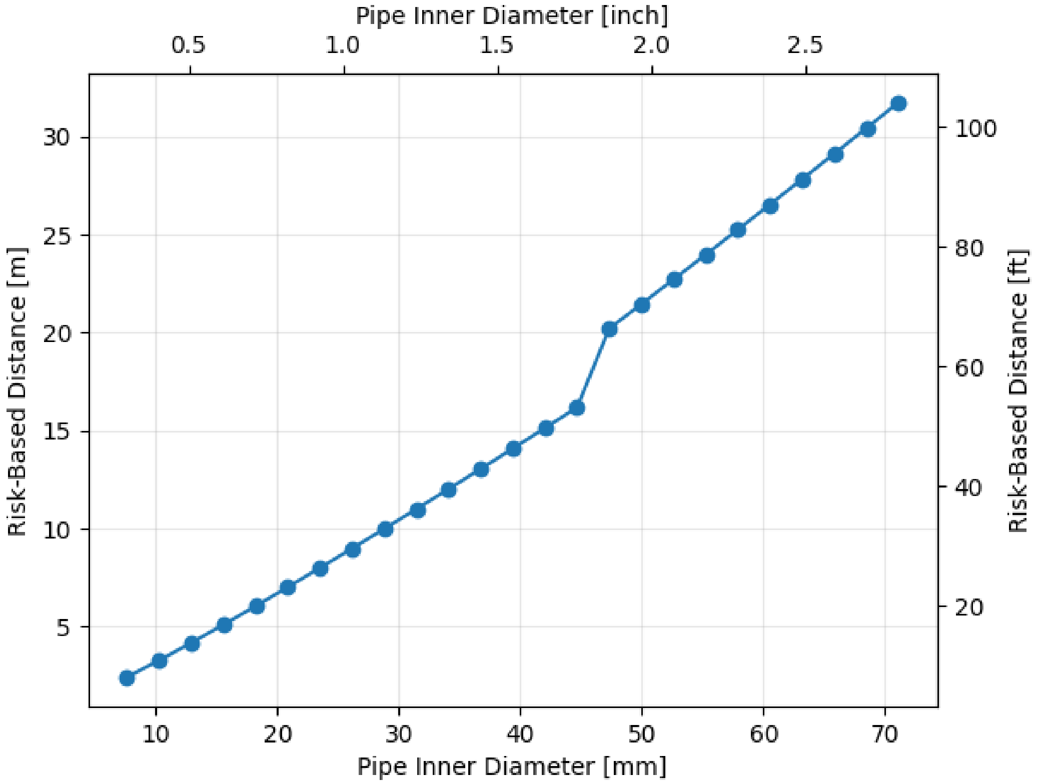
LaChance, et al. Analysis to support development of risk-informed separation distances for hydrogen codes and standards. Sandia National Laboratories, SAND2009-0874

RISK-BASED DISTANCE FOR VARIABLE PIPE SIZE

- **Pipe diameter** is one of the **most important parameters** for risk-based distance sensitivity
  - 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
  - Pipe risk-based distance discontinuity due to step-change in ignition probability

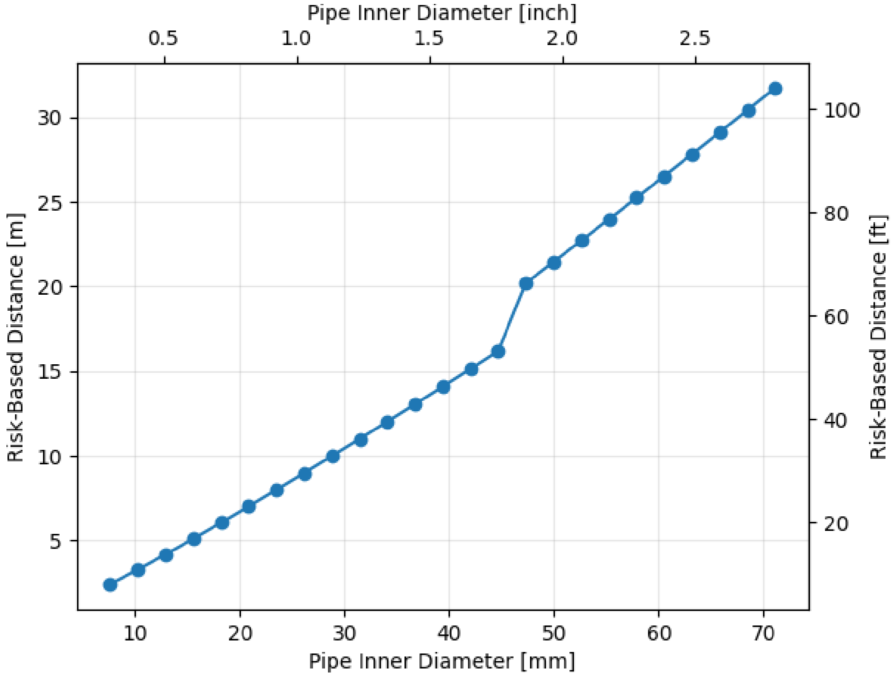


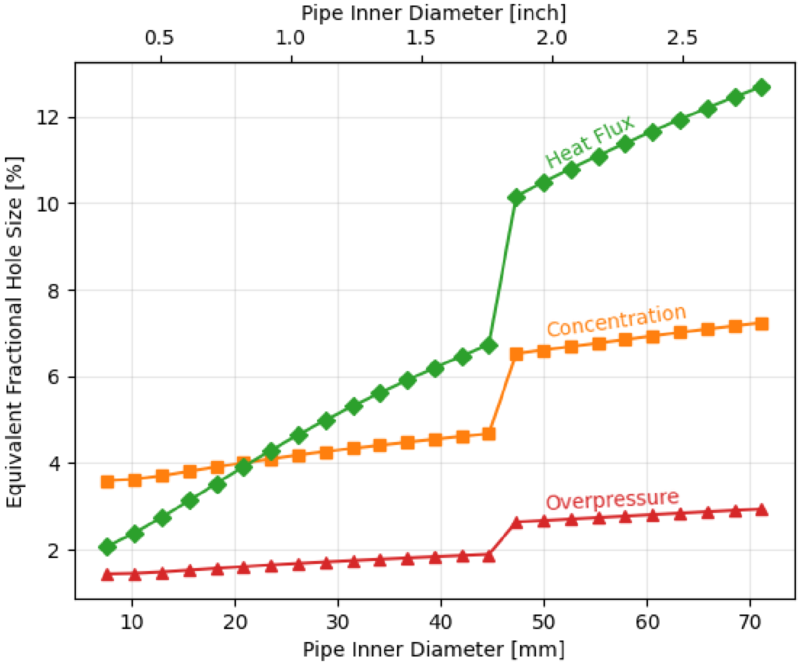
Multiple pipe sizes



EQUIVALENT FRACTIONAL HOLE SIZE

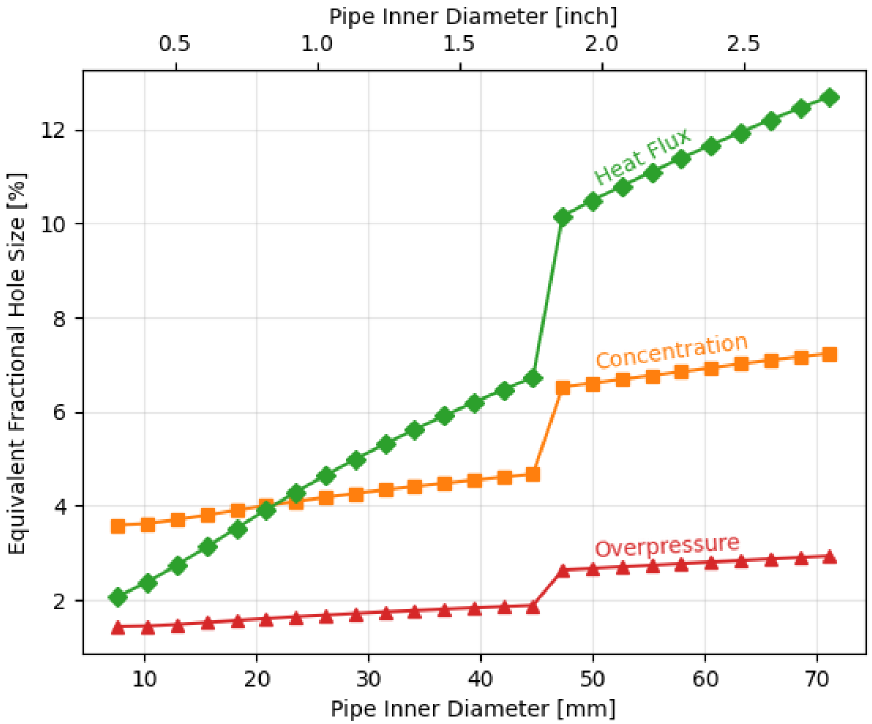
- Calculate **leak hole size** that would give **same consequence-based distance**
  - Based on physical hazard criteria
    - Unignited concentration: 8% by volume
    - Heat flux: 4.7 kW/m2
    - Peak overpressure: 6.9 kPa (1 psi)
- For each **equivalent** hole size, calculate **fractional hole size** based on pipe flow area

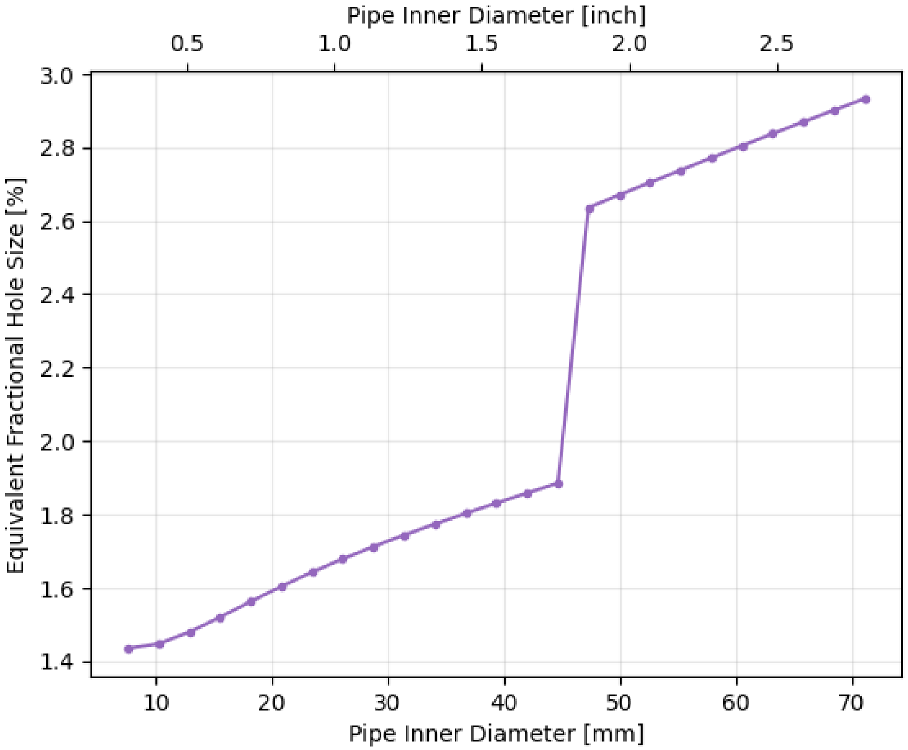




SELECTION OF EQUIVALENT HOLE SIZE

- For each pipe size, select **smallest equivalent fractional hole size**
  - This would be the “driving” hazard for a given setback distance
  - Other consequence models using the same fractional hole size would result in longer distances than the risk-based distance

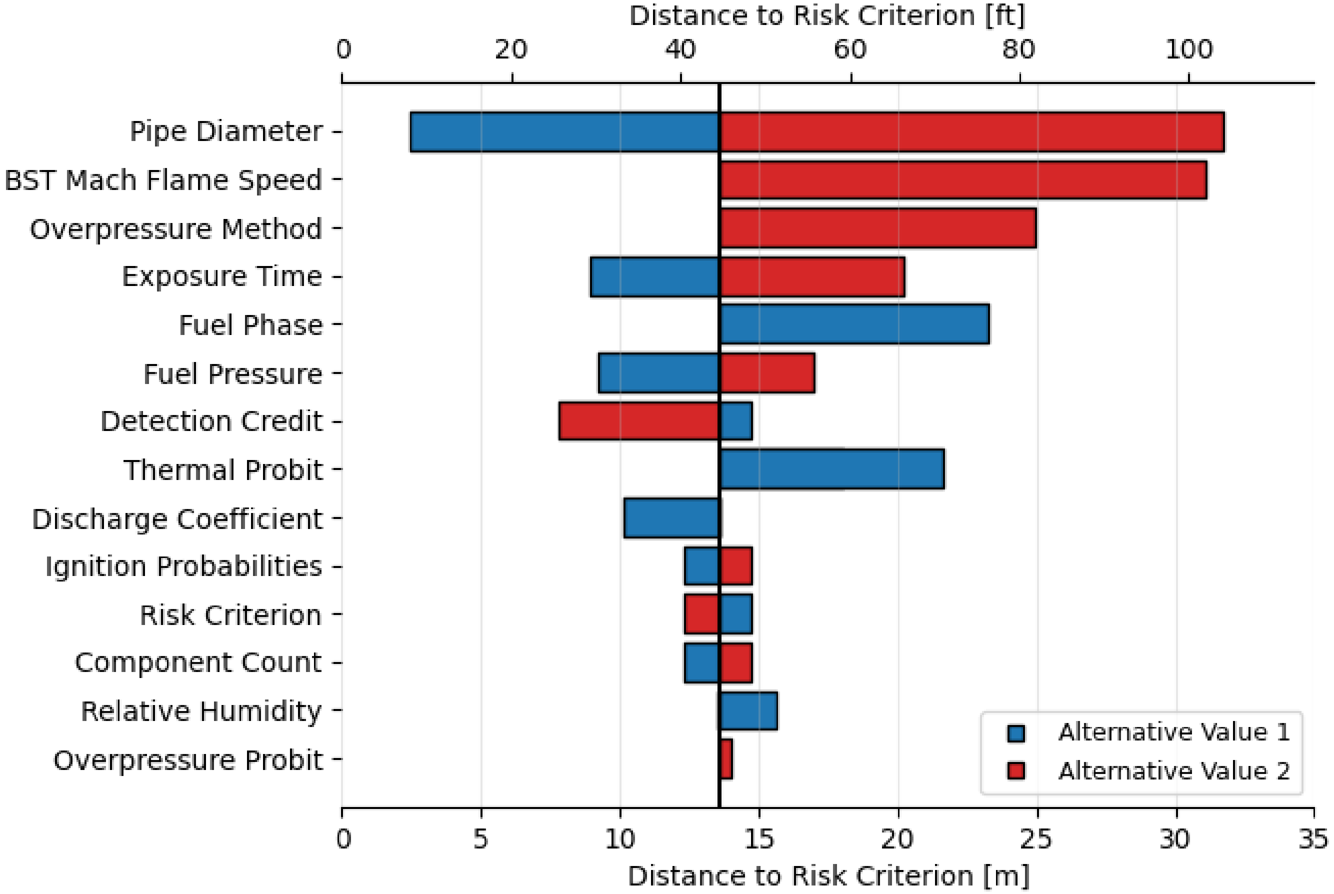




RISK ASSESSMENT SENSITIVITY

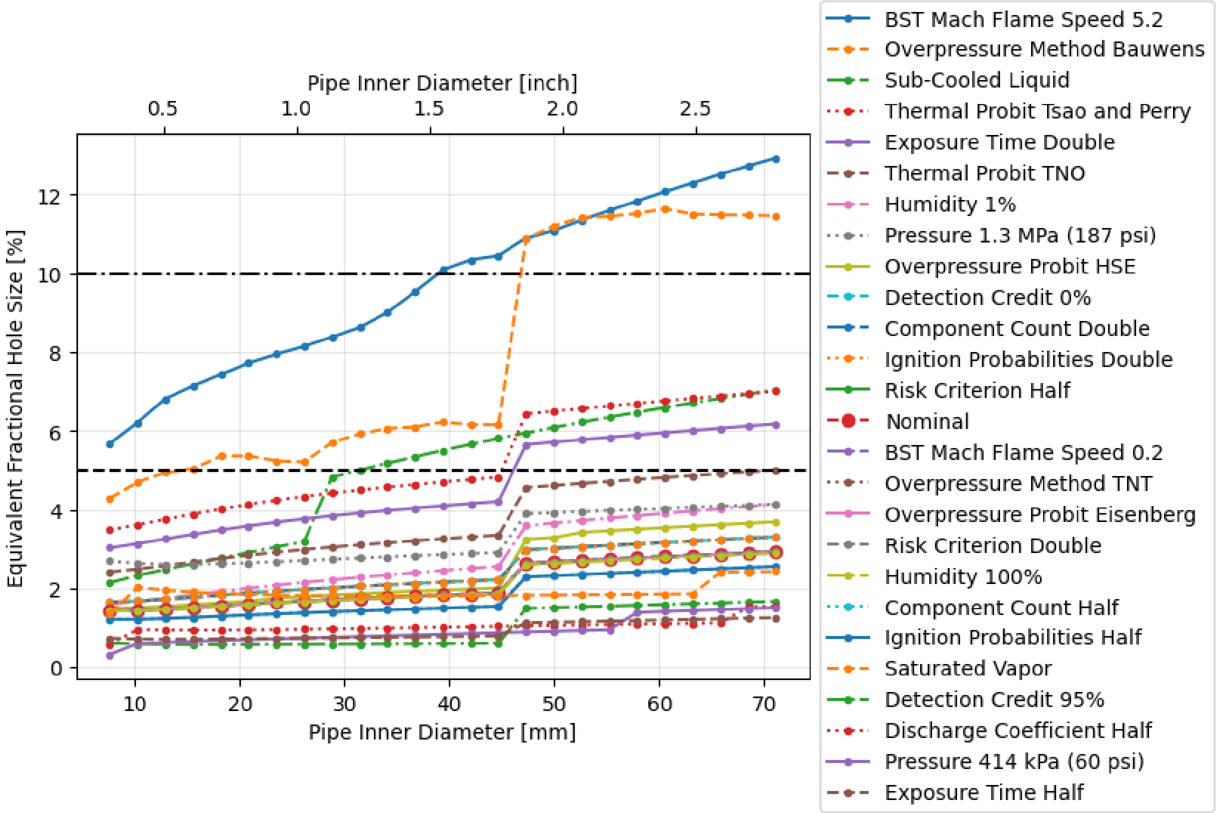
Individually varied many of the QRA inputs:

- System-specific
  - Pipe diameter (previously shown)
  - 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

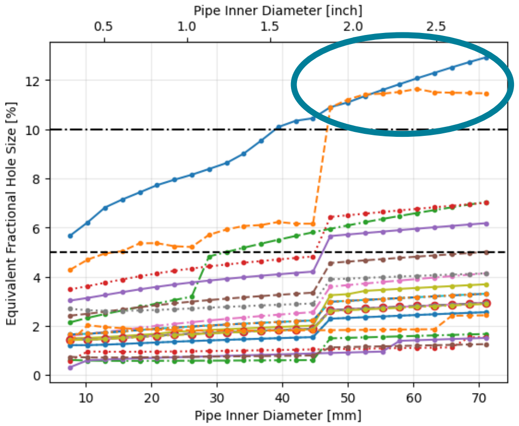


EQUIVALENT HOLE SIZE SENSITIVITY

- 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: DETONATION OVERPRESSURE



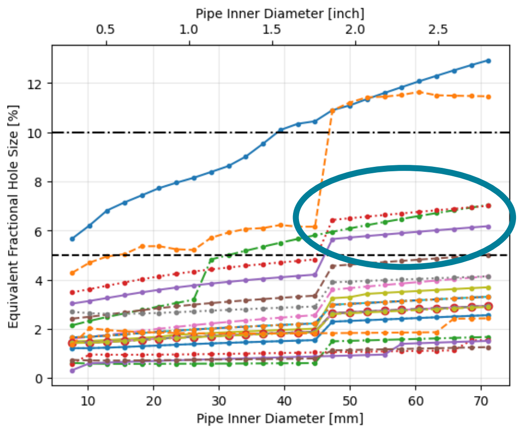
2 cases exceed 10% equivalent fractional hole size at largest pipe diameter:

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

OVERLY-CONSERVATIVE CASES:
SUB-COOLED LIQUID, EXPOSURE TIME, AND THERMAL PROBIT



3 cases exceed 5% equivalent fractional hole size at largest diameter:

- Sub-cooled liquid source
  - HyRAM+ **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
- 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**
- Thermal exposure time: 60 seconds (double nominal)
  - **Multiple sources recommend** 30 second (or less) response time to move away from flame
  - Weakly-radiating hydrogen flame can **decrease harm over distance quickly**

SELECTION OF 5% FRACTIONAL LEAK AREA

Sensitivity results are almost all below 10% fractional leak area

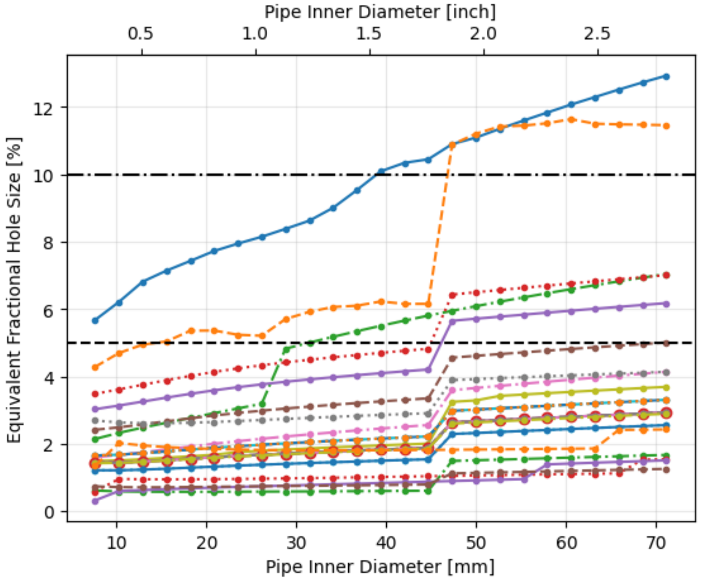
- **Only 2 of 26 cases exceed 10%** at largest pipe inner diameters
- **Only 3 of 26 additional cases exceed 5%** at largest pipe inner diameters
- **21 of 26 cases are below 5%** fractional hole size for all inputs and pipe diameters considered

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)

5% fractional hole area selected as basis for consequence-based setback distances

- *See ICHS Paper #140 for details on calculation of setback distances*



CONCLUSIONS

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

Sensitivity study of risk-based distances quantified variability, and led to conservative but not unrealistic choice in leak size

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

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?

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BACK UP SLIDES

FRACTIONAL HOLE SIZE

Fractional instead of absolute hole size

- NFPA 2 GH2 tables use 1% of flow area

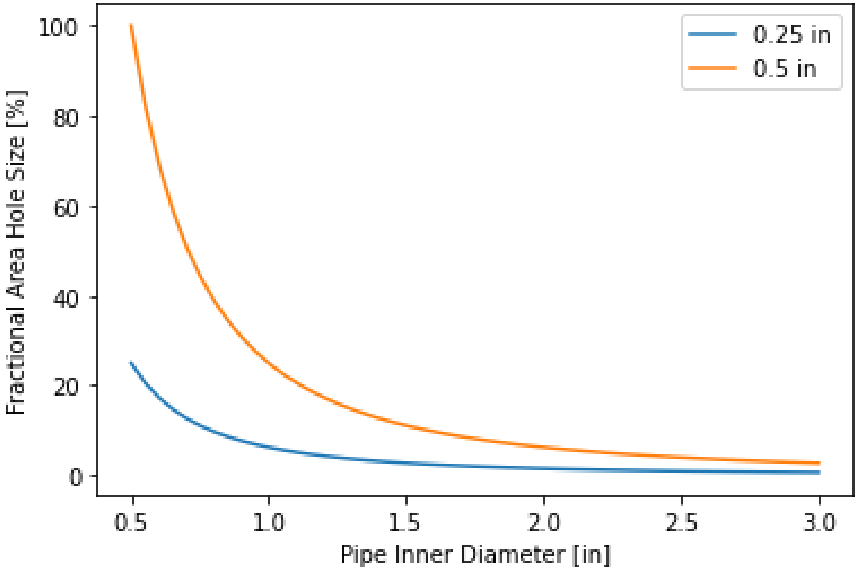
Gives “credit” for using smaller pipe diameters

- Smaller pipes lower risk by limiting the consequences

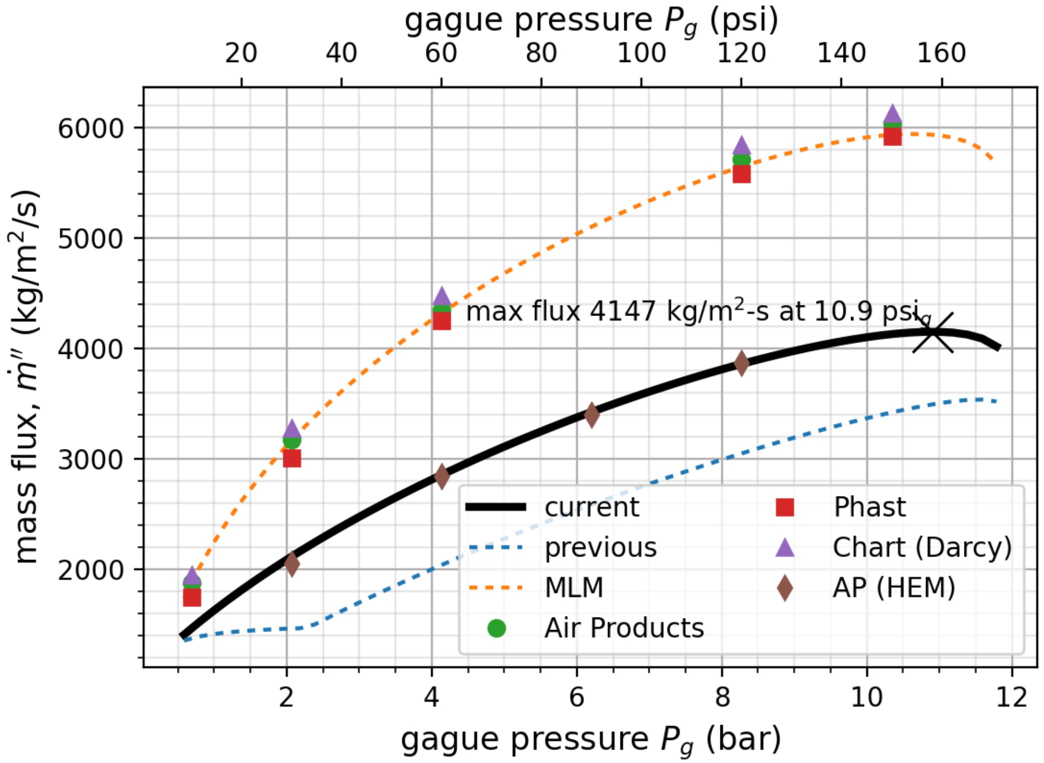
Allows setbacks to grow for larger pipe diameters

Fractional area leak size:

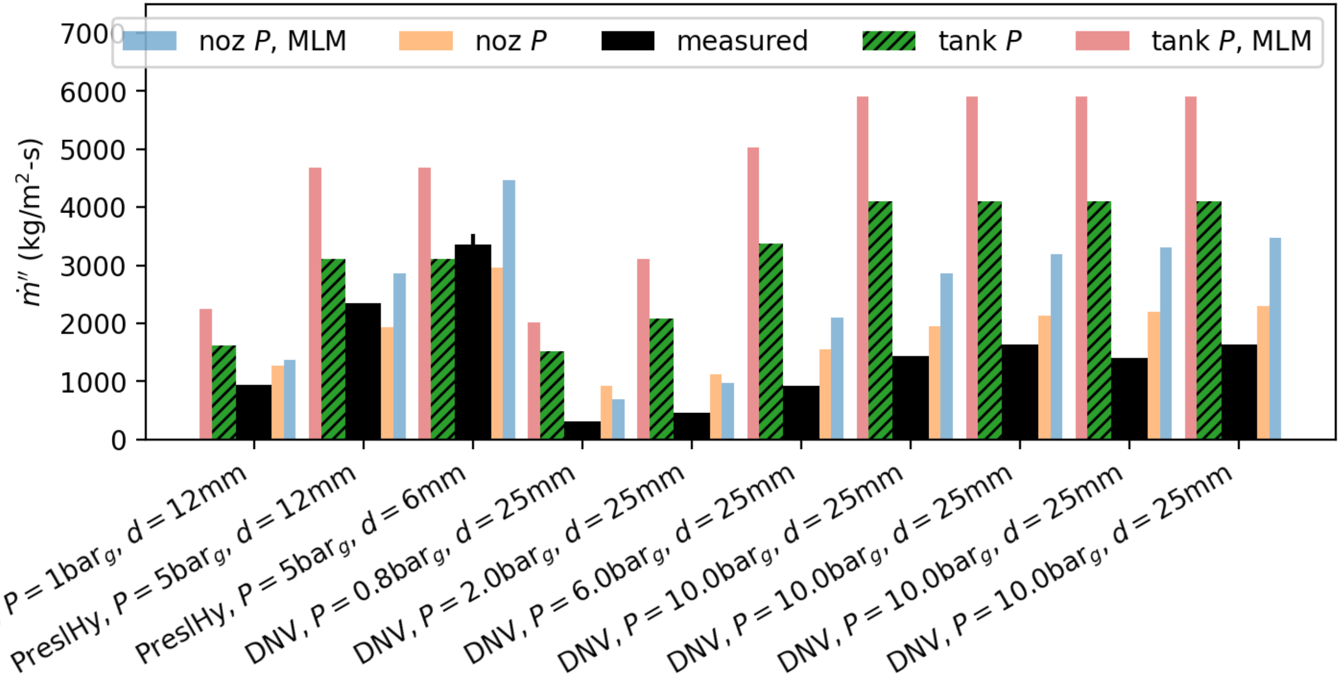
- $Fraction = \frac{A_{leak}}{A_{pipeID}} = \frac{\frac{\pi}{4}d_{leak}^2}{\frac{\pi}{4}d_{pipeID}^2} = \left(\frac{d_{leak}}{d_{pipeID}}\right)^2$



MASS FLOW RATE–COMPARISON AND JUSTIFICATION

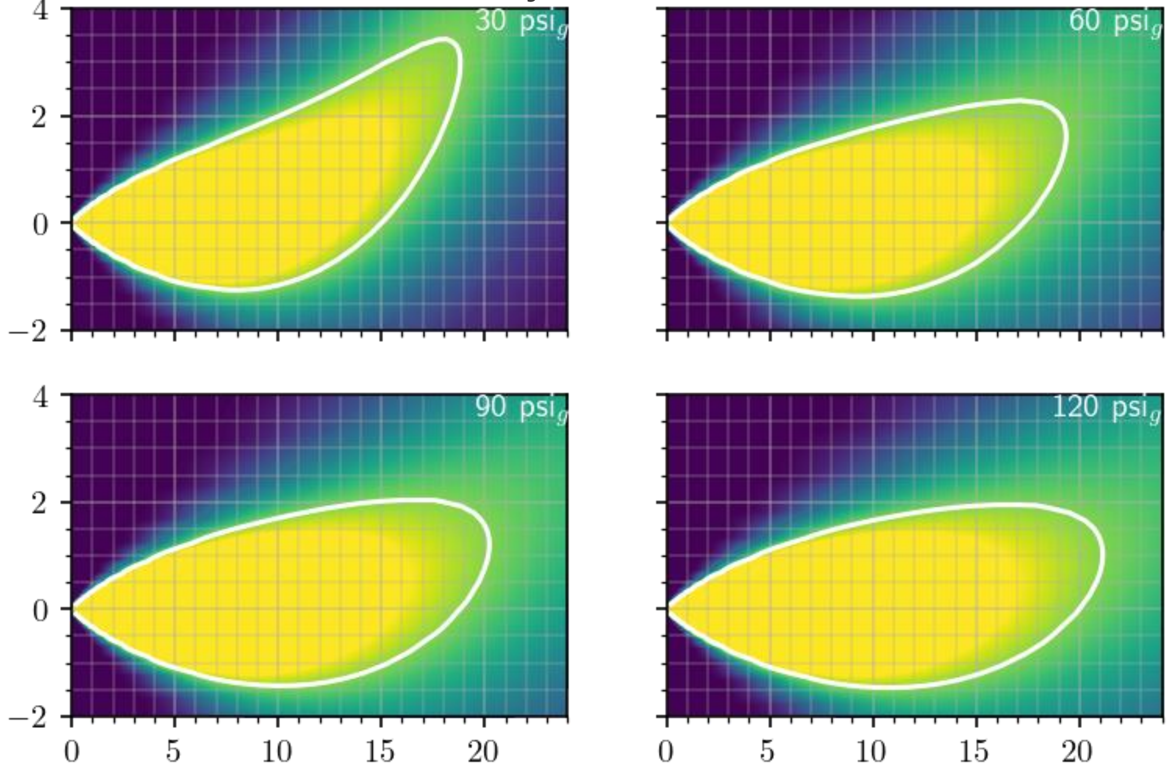


- Calculations use homogenous equilibrium model (with search for maximum mass flux)
- Experiments attempting to get maximum liquid don't see flows approaching metastable liquid model (MLM)

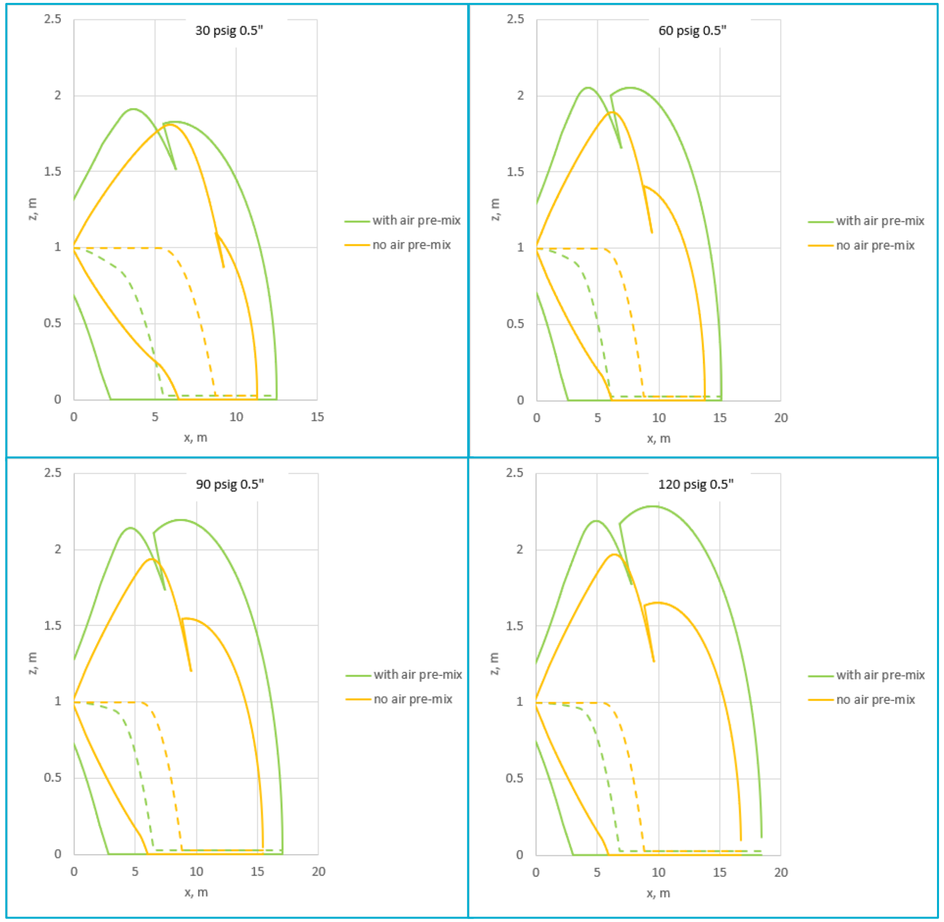


HYRAM+ VS. AP VENTJET DISPERSION: 0.5" HOLE

HyRAM+



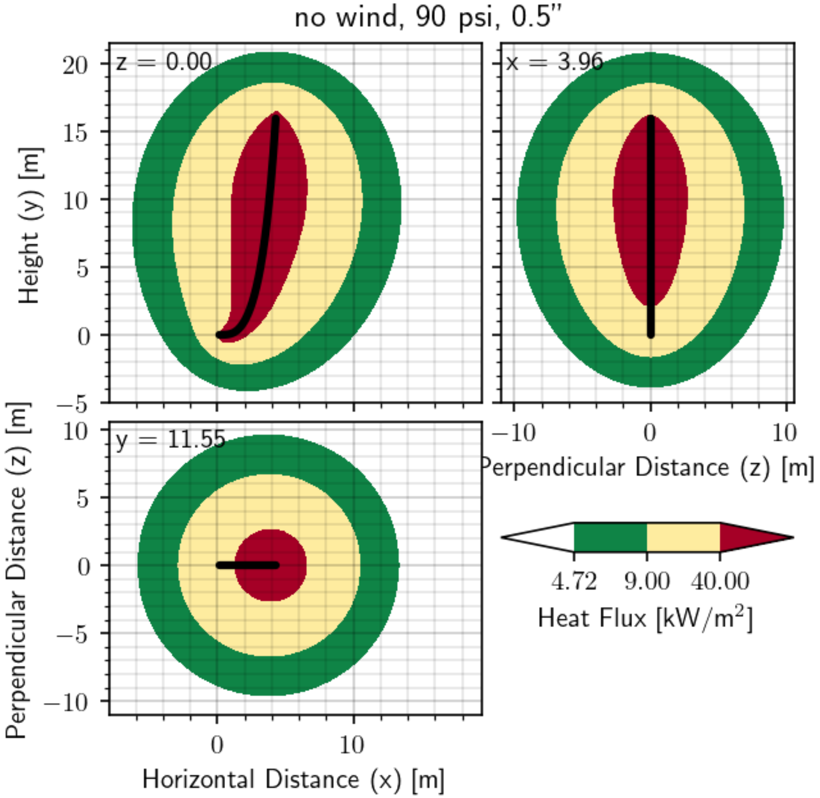
AP VentJet

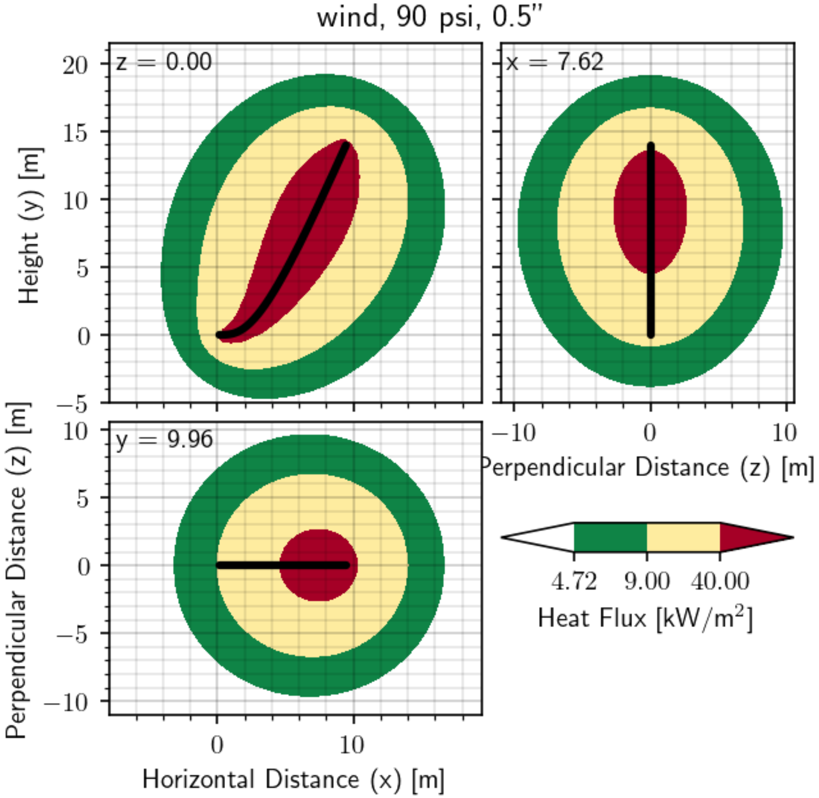


- VentJet is affected by ground while HyRAM+ does not account for this
- HyRAM+ distances are slightly longer (more conservative) than VentJet
- Distances calculated along streamline rather than just x-distance adding additional conservativism

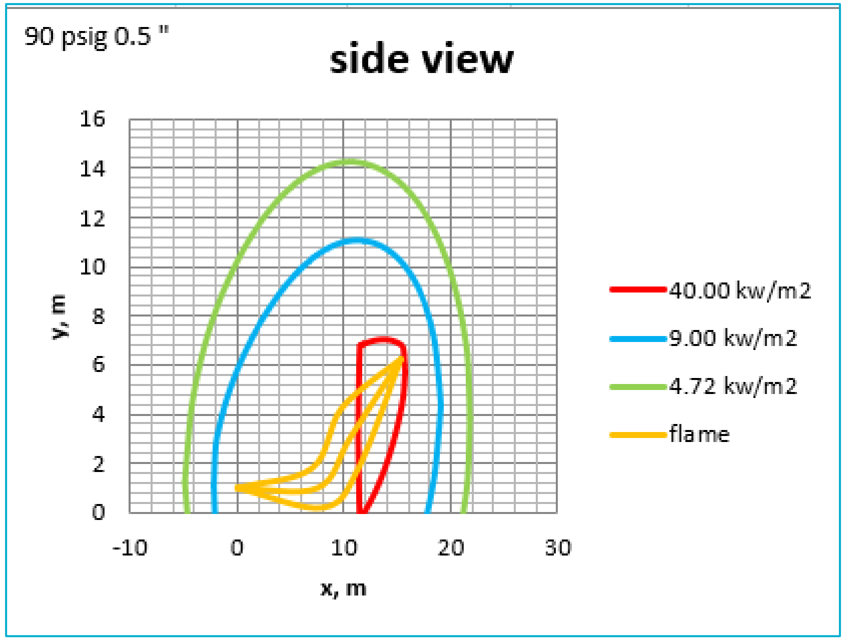
HYRAM+ VS AP FLAME: 90 PSI, 0.5” HOLE

HyRAM+





AP VentJet

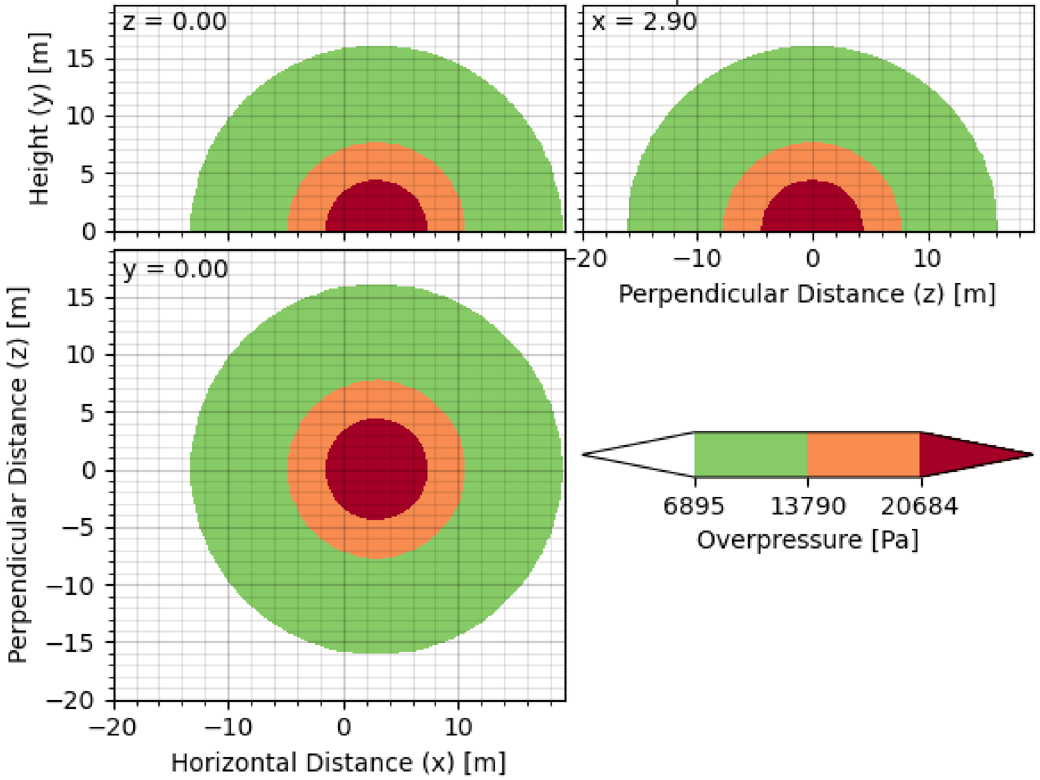


- High density of LH2 results in low momentum release rates
- HyRAM+ modified to include the effect of wind; results in similar distances to AP flame
- Largest projected heat fluxes onto the ground are used as exposure distances

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)

HyRAM+
0.5″ hole, 90 psi



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***

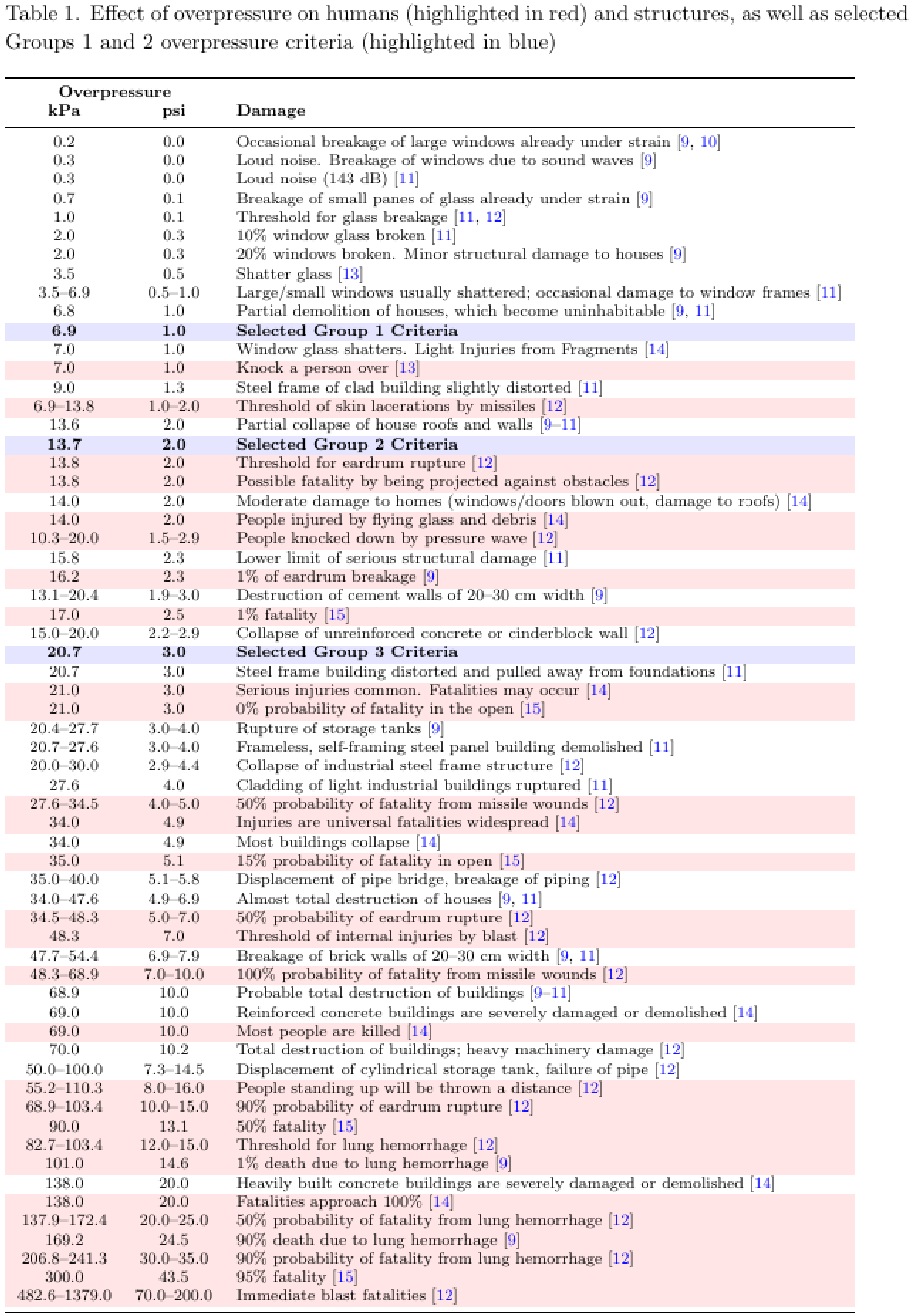


Table 1. Effect of overpressure on humans (highlighted in red) and structures, as well as selected Groups 1 and 2 overpressure criteria (highlighted in blue)

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]

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