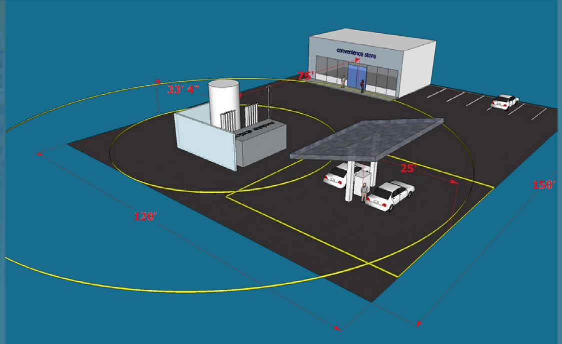
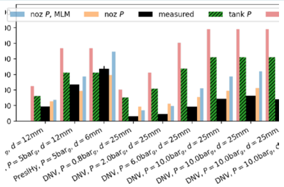
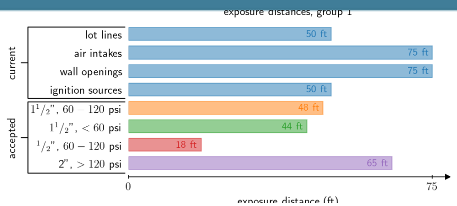
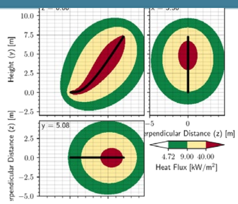
Methodology for consequence-based setback distance calculations for bulk liquid hydrogen storage systems









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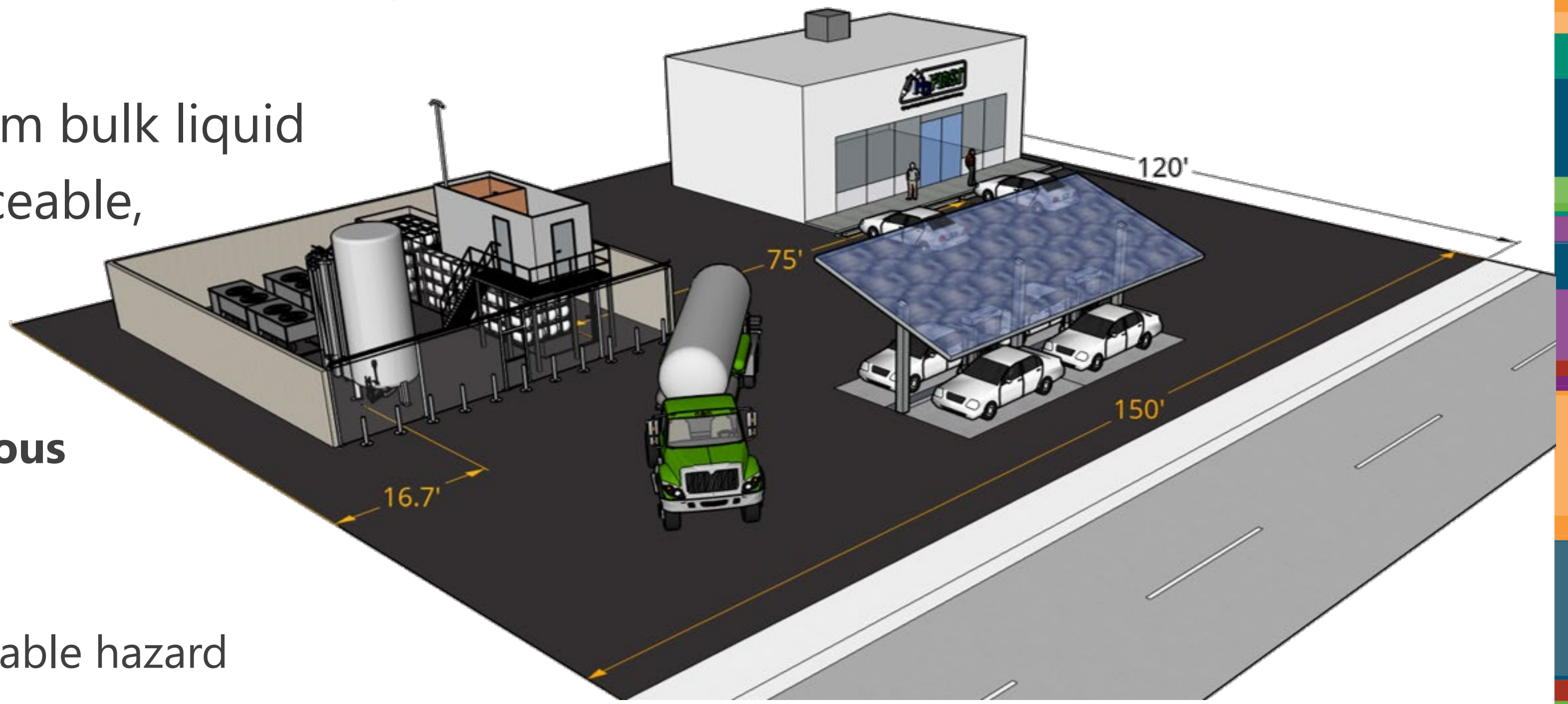
SAND2023-09115C

Previous (2020 edition and before) distances in NFPA 2 for bulk liquid hydrogen storage were large, complex, and lack documentation of basis

Goal: Develop separation distances from bulk liquid hydrogen storage systems that are traceable, defensible, and updatable



Approach (similar to updates for bulk gaseous hydrogen):

1. Verify and validate necessary models
2. Characterize exposure groups and acceptable hazard levels
3. Use quantitative risk assessment to determine characteristic leak size (described in companion paper ID: 119)
4. Calculate consequence based distances using leak size and validated models
5. Get proposed distances approved by building consensus within the technical committee

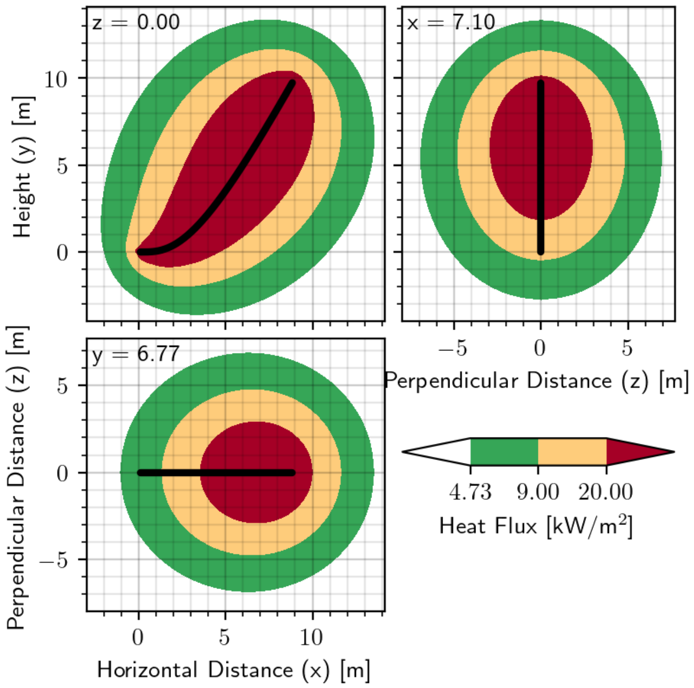
Previous distances were:

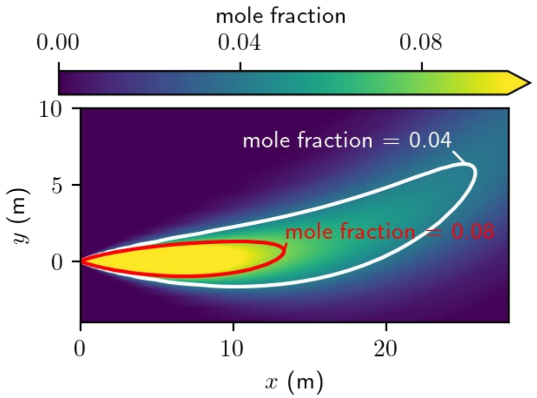
- Based on storage volume
- 23 m (75 ft) from air intakes
- Distances to exposures vary within group
- Served industry well for half a century

The Sandia developed HyRAM+ toolkit was used for calculations

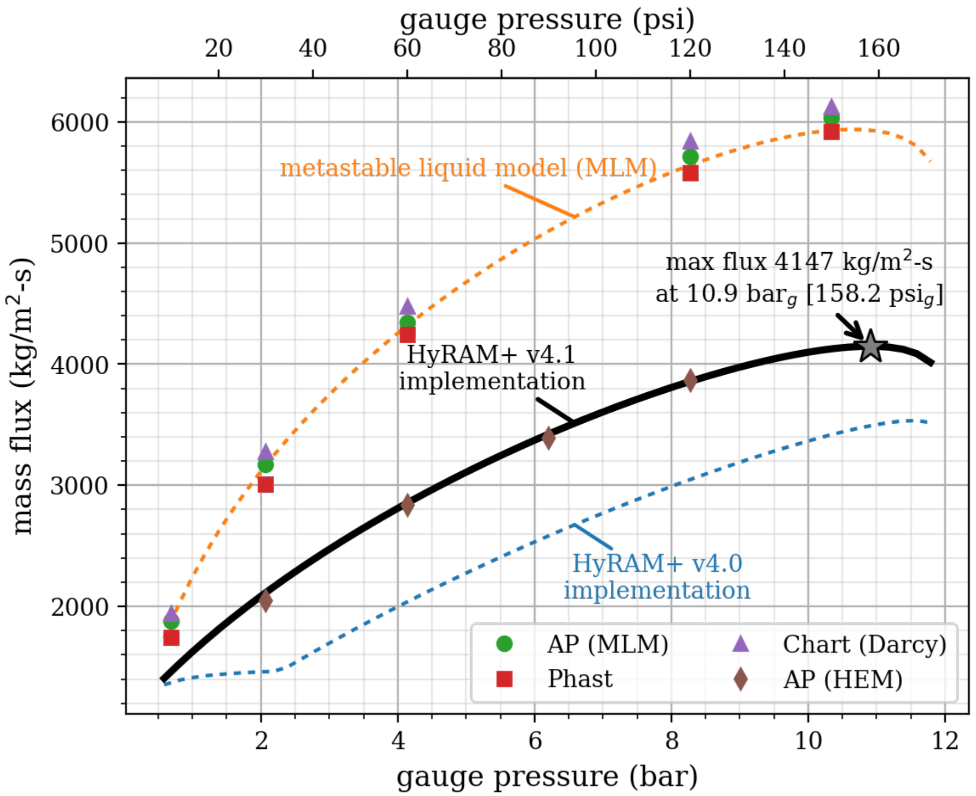
Available at hyram.sandia.gov, from PyPI and conda-forge

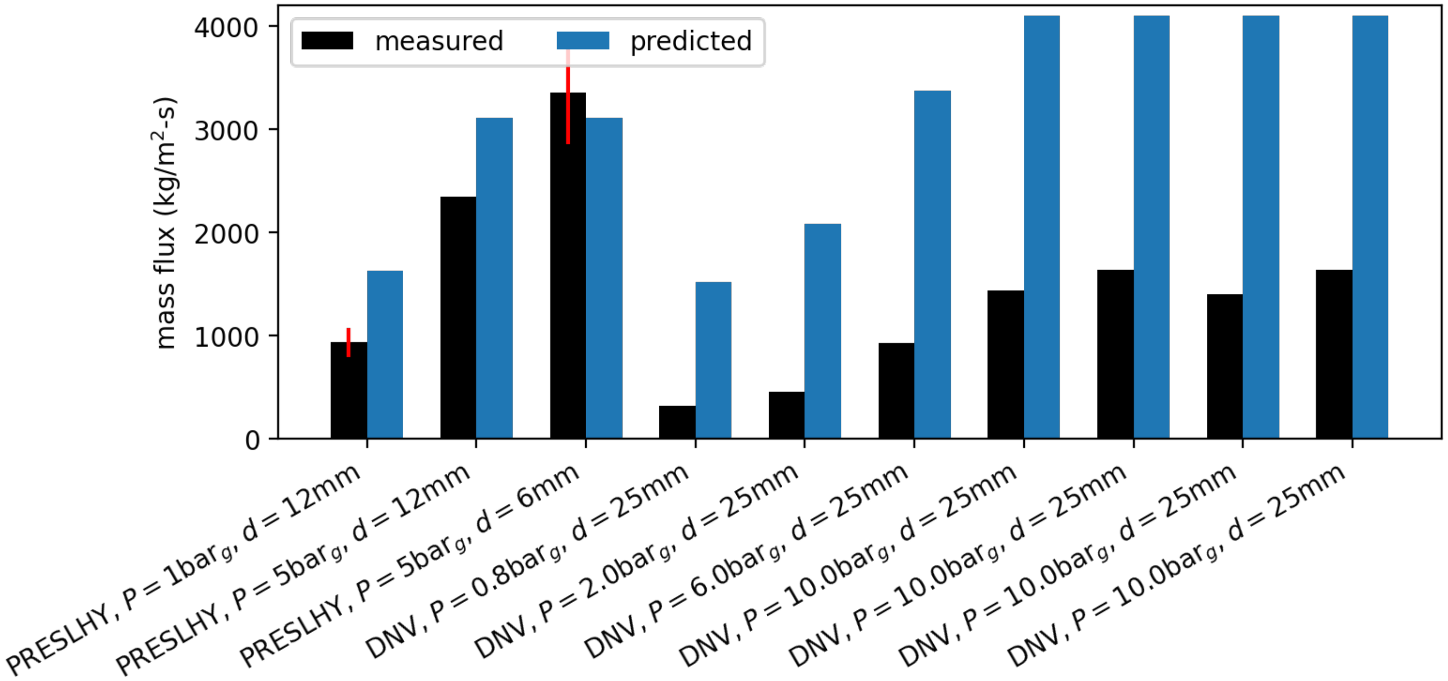
- Fast running, reduced order models
  - Unignited dispersion
  - Flame: trajectory and heat flux
  - Unconfined overpressure
- Behavior models used standalone (this analysis) or for quantitative risk assessment (see companion paper ID: 119)
- Python backend enables flexibility of modeling
- Version 4.1 used for these calculations





The mass flow rate model was updated and compared to data



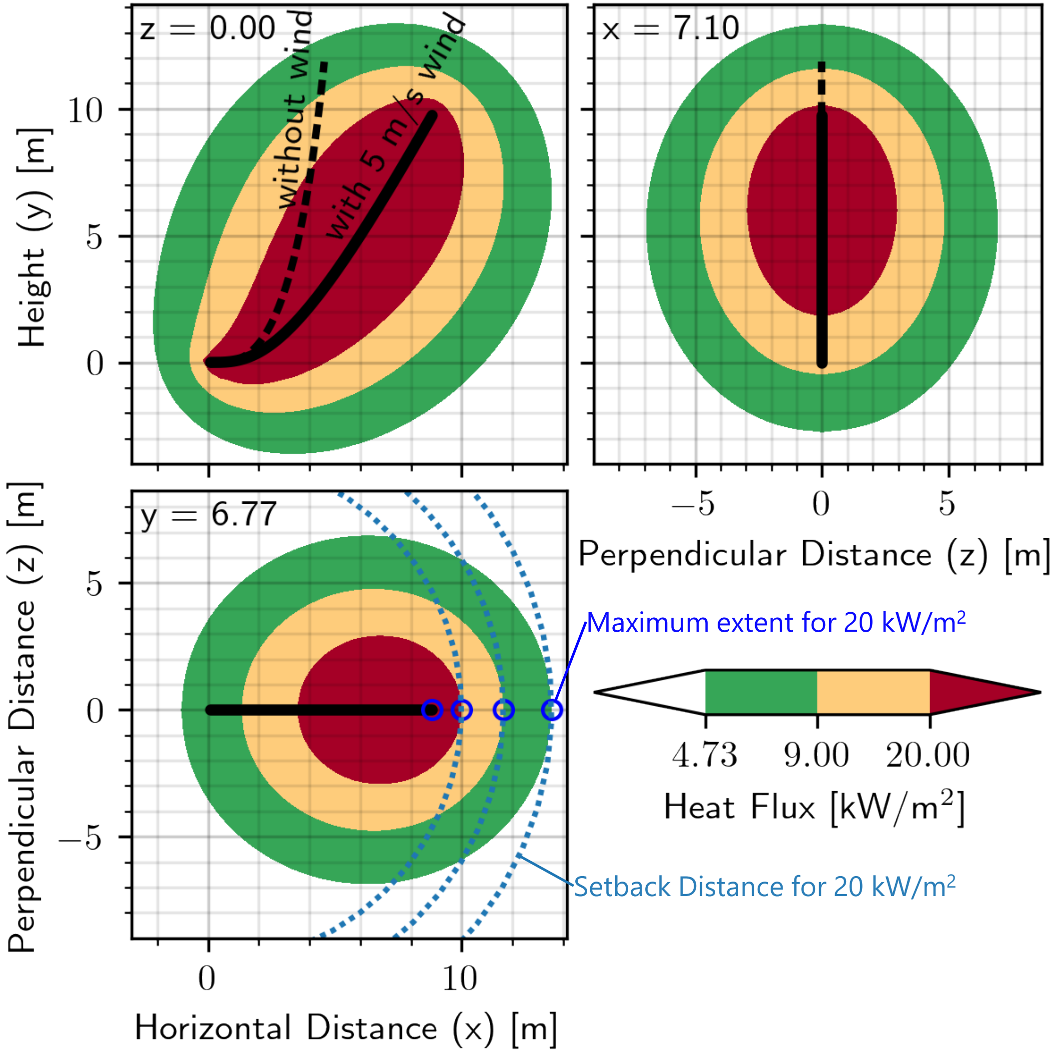


- HyRAM v4.1 mass flow rate calculations were updated – resulted in increased mass flow for liquid hydrogen
  - No longer relies on uncertain calculation of speed of sound for two-phase fluids
  - Verified by comparing to other models
  - Metastable liquid model (constant density flow instead of isentropic) considered too conservative
- Updated model compares well to data from two experimental campaigns attempting to maximize liquid H_2 flows

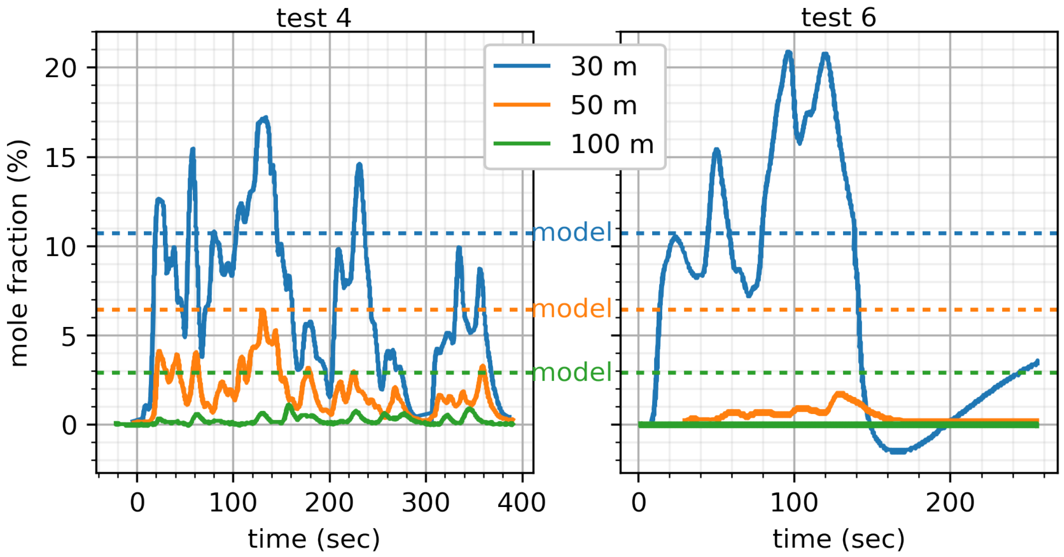
Data from (PRESLHy): Lyons et al., 2020 and (DNV): Huescar-Medina et al. 2020, report #853182, rev 2

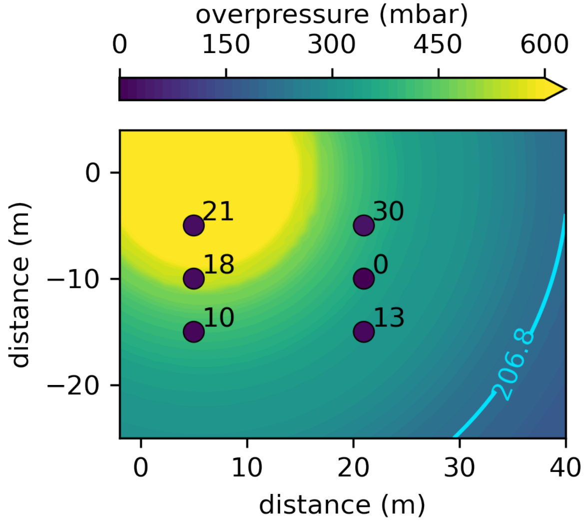
Some wind effects were added to the Python flame model to improve heat-flux calculations

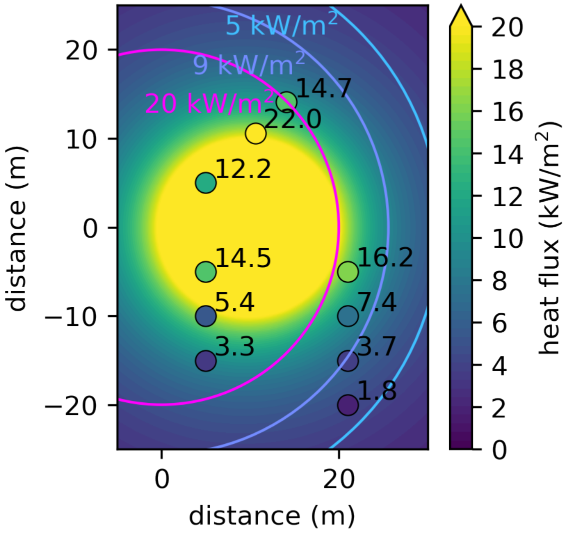
- Model shows significant buoyancy for (relatively) low-pressure LH_2 flames
- Wind only in x-direction (term added to x-momentum equation)
- Birds-eye view used for setback distances
  - Conservative relative to distance at 1m height
  - Maximum extent of heat flux contour becomes setback distance (which is in the positive x-direction) due to unknown direction of flame



Dispersion, heat flux and overpressure models were compared to data







- Very limited number of experimental campaigns
- Mole fractions overpredicted on average, especially in far-field where mole fractions are lower
- Unconfined overpressure greatly overpredicted
- Heat flux criteria distances encompass measurements although wind seems to skew direction of high heat flux

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

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

Exposures to consider:

- Air intakes
- Sewer inlets
- People (fireball)

NFPA 2 GH2 uses 8% by volume

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

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

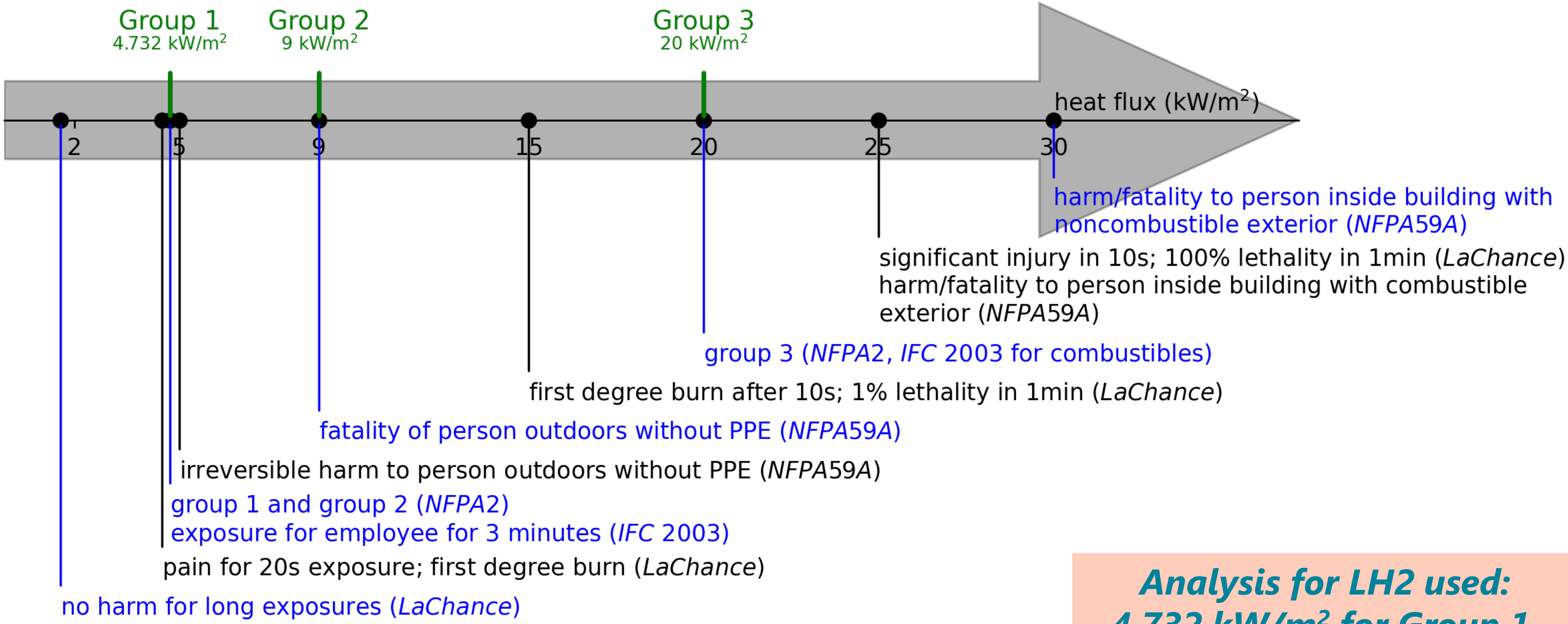
- Also considers higher concentrations for oxygen displacement

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

Ignition kernel forms but does not form jet flame

Jet flame is sustained after ignition

Criteria for heat flux were carefully chosen based on impact to people and structures

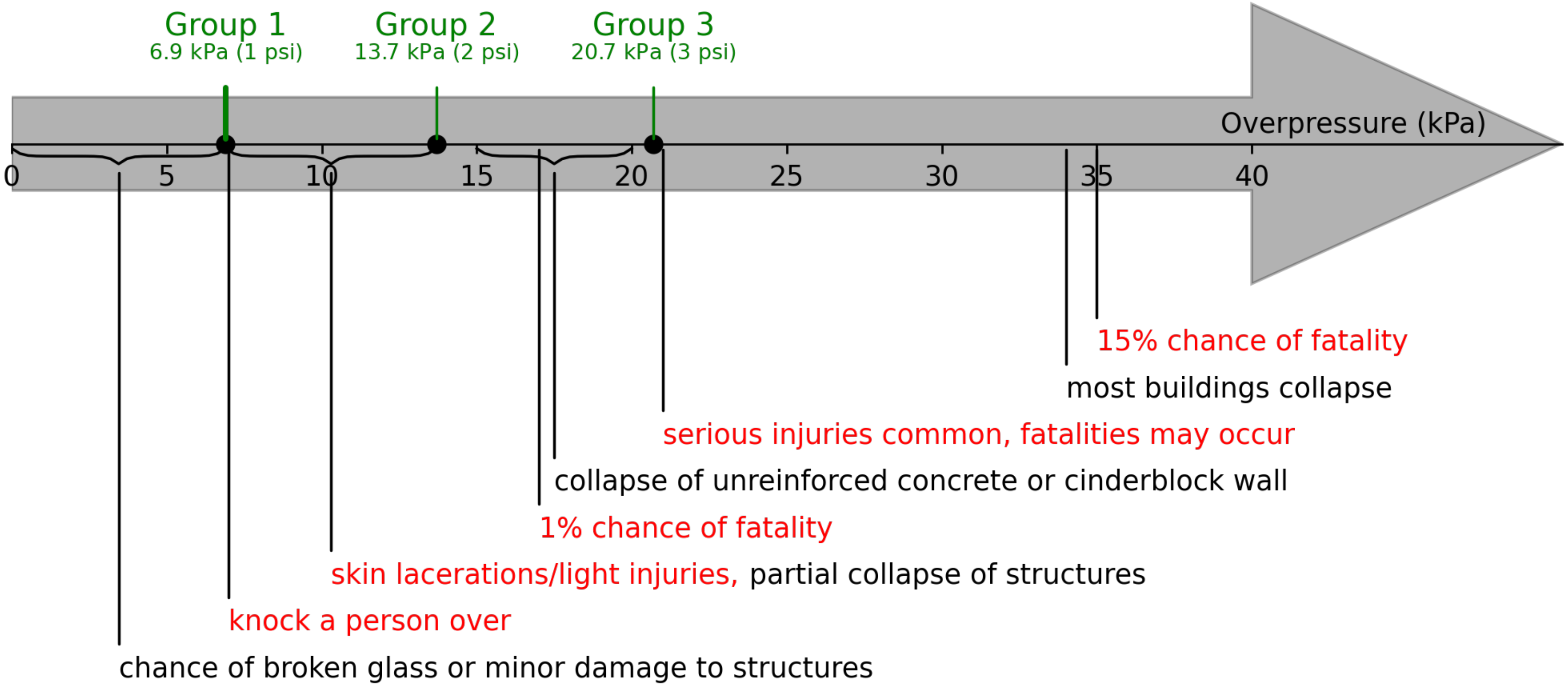


Analysis for LH2 used: 4.732 kW/m² for Group 1, 9 kW/m² for Group 2, and 20 kW/m² for Group 3

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

Criteria for peak overpressure were based on impact to people and structures

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



Exposures to consider:

- People
- Cars
- Buildings

Hecht and Ehrhart, ICHS 2021

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

NFPA 59A Table 19.8.4.3.1

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

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

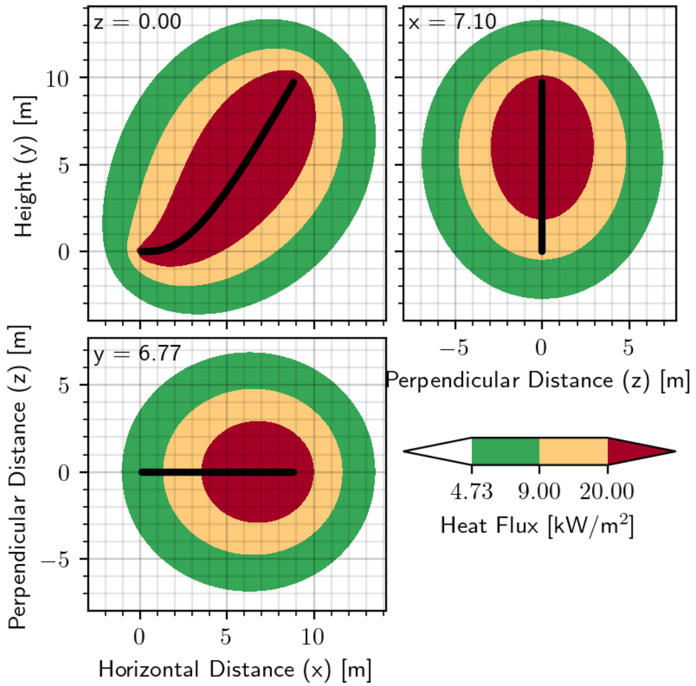
Distances were calculated using chosen criteria and models

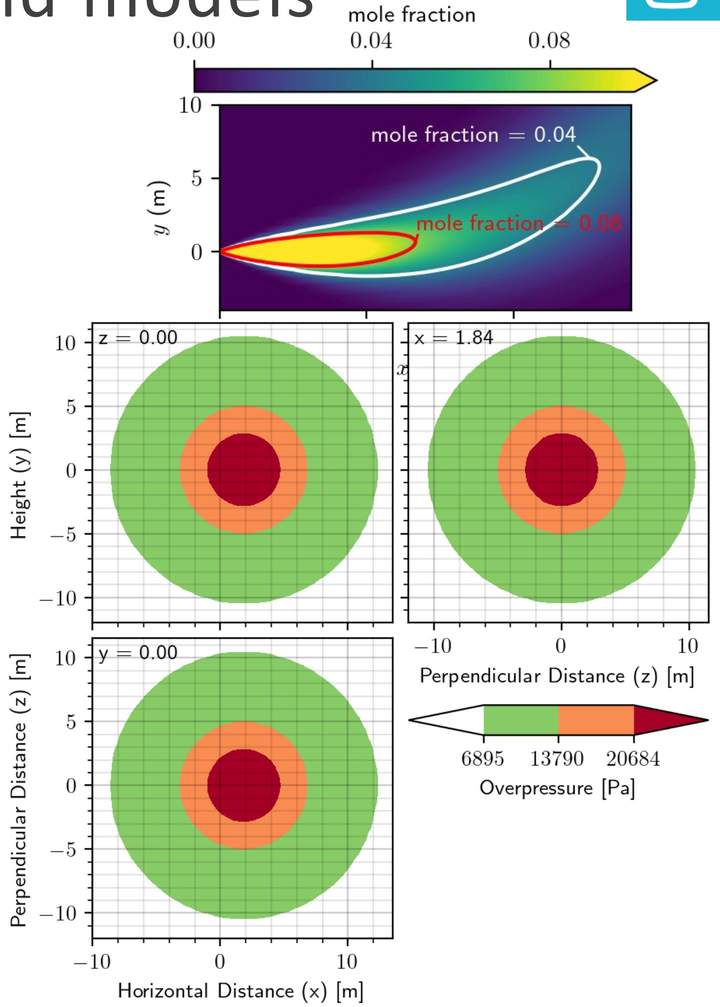
Calculations for:

- 5% fractional leak area (from risk analysis – see paper ID: 119)
- 4 characteristic pipe sizes (0.5- 2”)
- 3 characteristic pressures for bulk liquid tanks (60-173 psi$_g$ [P_{crit}])

Consequence criteria:

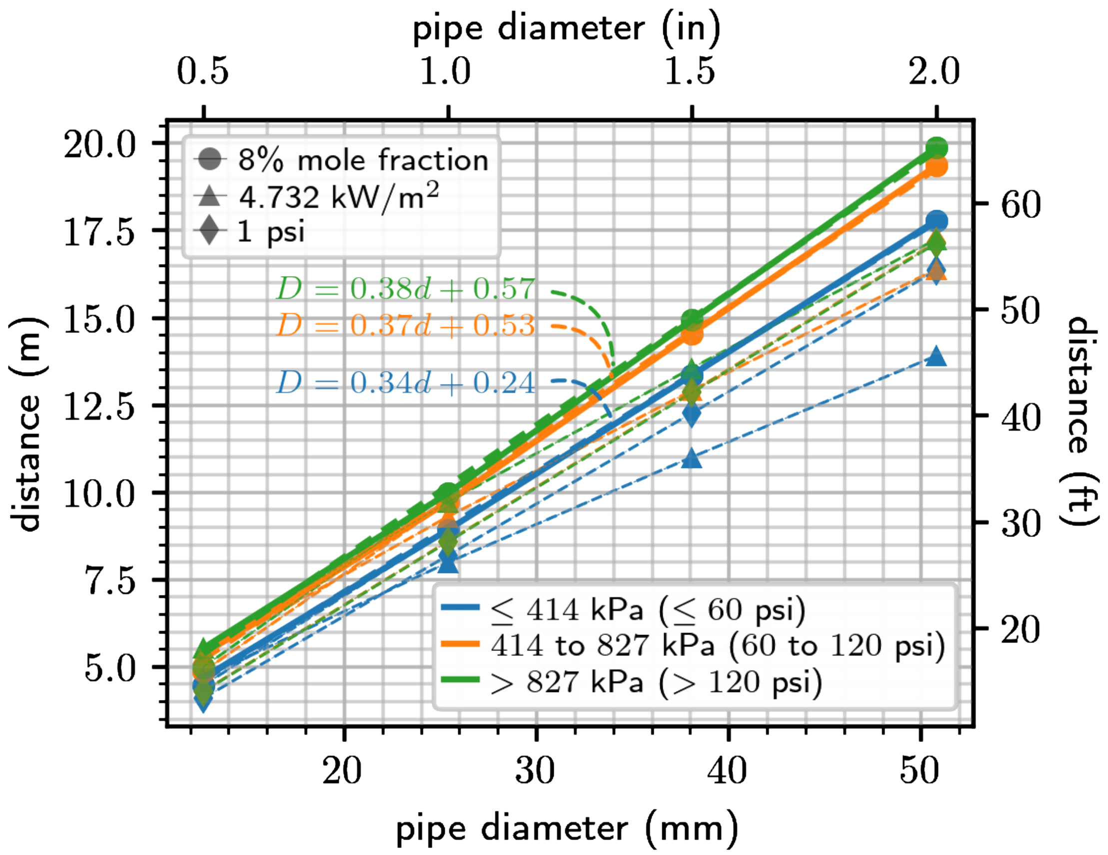
- Group 1:
  - Concentration: 8 mol% (streamline)
  - Heat Flux: 4.732 kW/m^2 (bird's eye)
  - Peak Overpressure: 6.895 kPa (bird’s eye)
- Group 2:
  - Heat Flux: 9 kW/m^2 (bird's eye)
  - Peak Overpressure: 13.790 kPa (bird’s eye)
- Group 3:
  - Heat Flux: 20 kW/m^2 (bird's eye)
  - Peak Overpressure: 20.7 kPa (bird’s eye)
  - Visible Flame Length (bird's eye)





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

Consequence-based calculations for Group 1

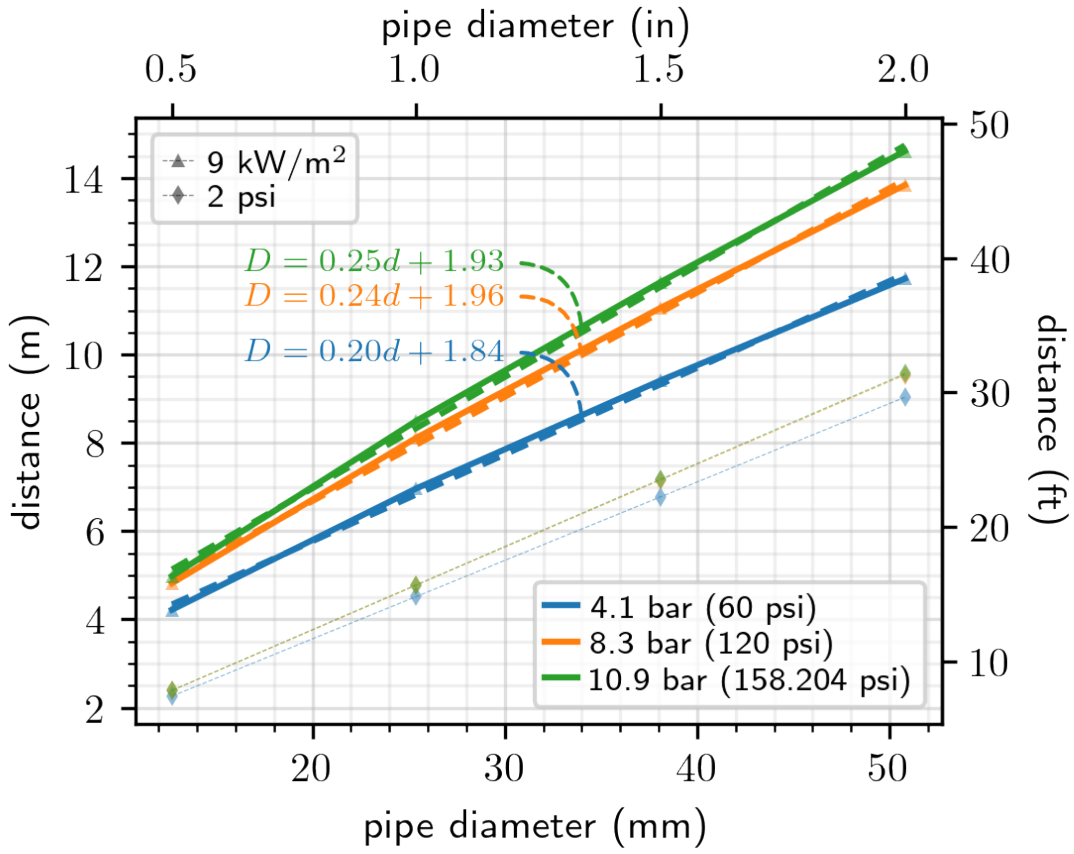


Exposures:
1. Lot lines
2. Air intakes
3. Operable openings in buildings
4. Ignition sources such as open flames/welding

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

Distance to 8% concentration by volume drives setback distance

Consequence-based calculations for Group 2



Distance to 9 kW/m² heat flux drives setback distance

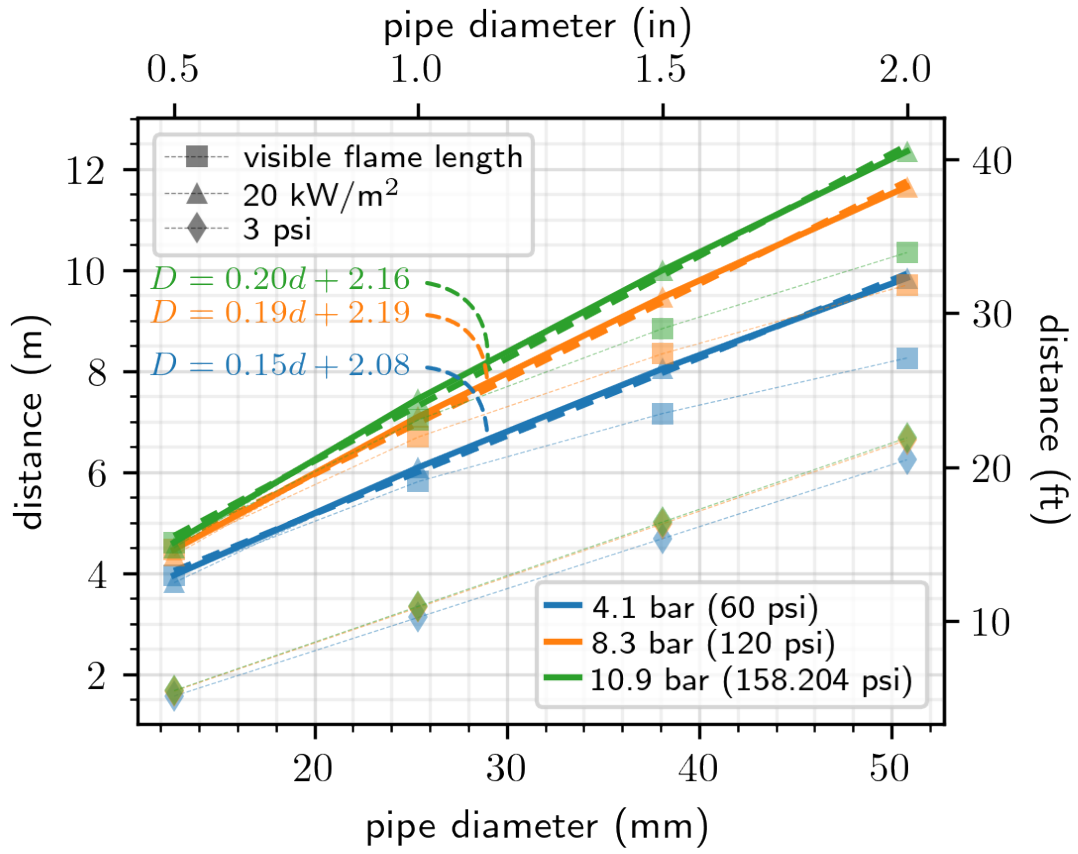
Exposures:

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

Protects against:

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

Consequence based-calculations for Group 3



Distance to 20 kW/m² heat flux drives setback distance

Exposures:

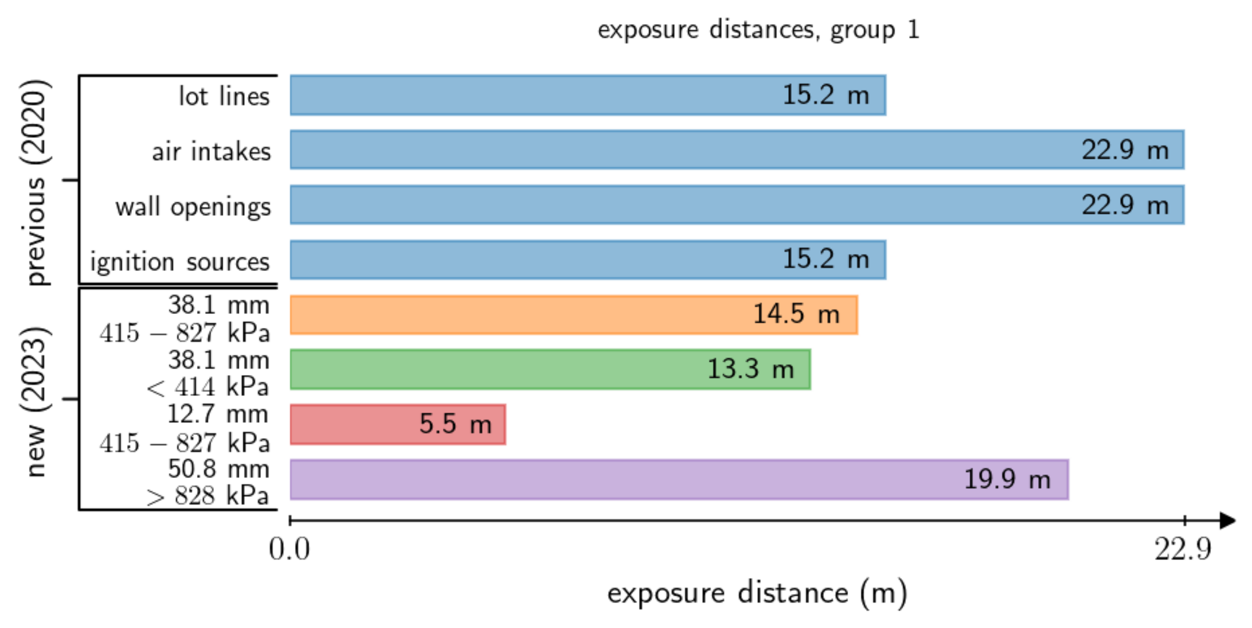
10. Buildings of non-combustible non-fire-rated construction
11. Flammable gas storage systems above or below ground
12. Heavy timber, coal, or other slow-burning combustible solids
13. Unopenable openings in buildings and structures
14. Encroachment by overhead utilities (horizontal distance from the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

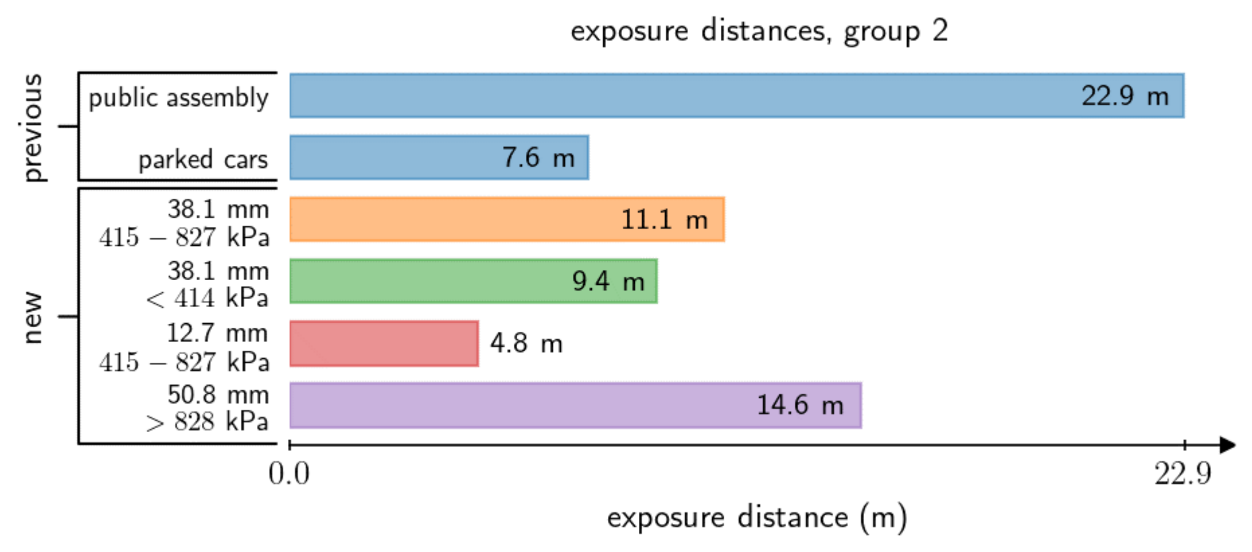
Protects against:

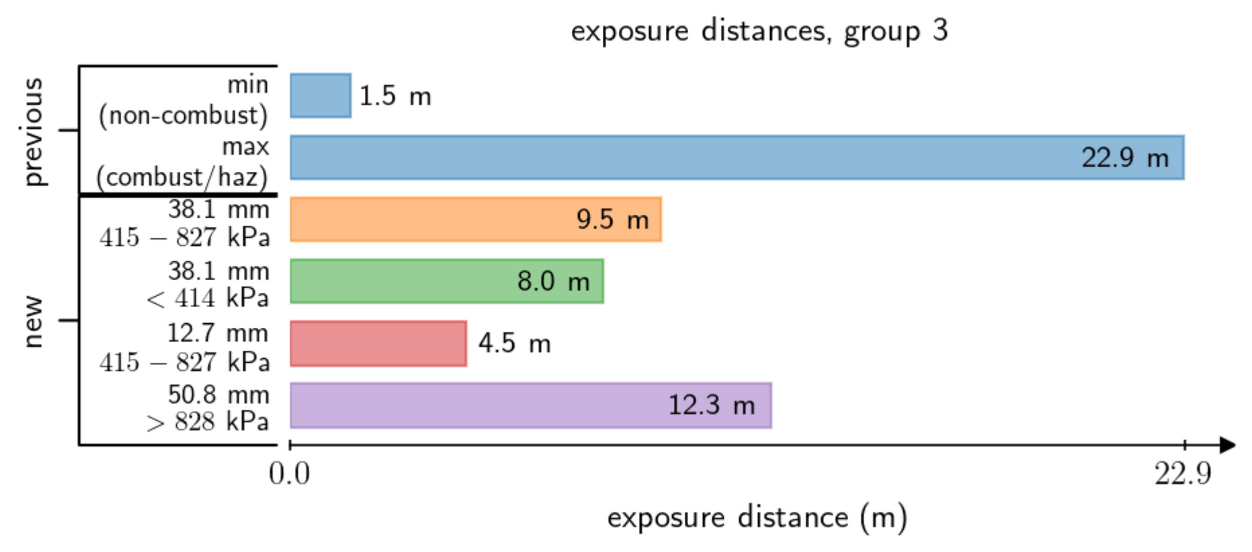
- Escalation of event (fire spread)

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

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

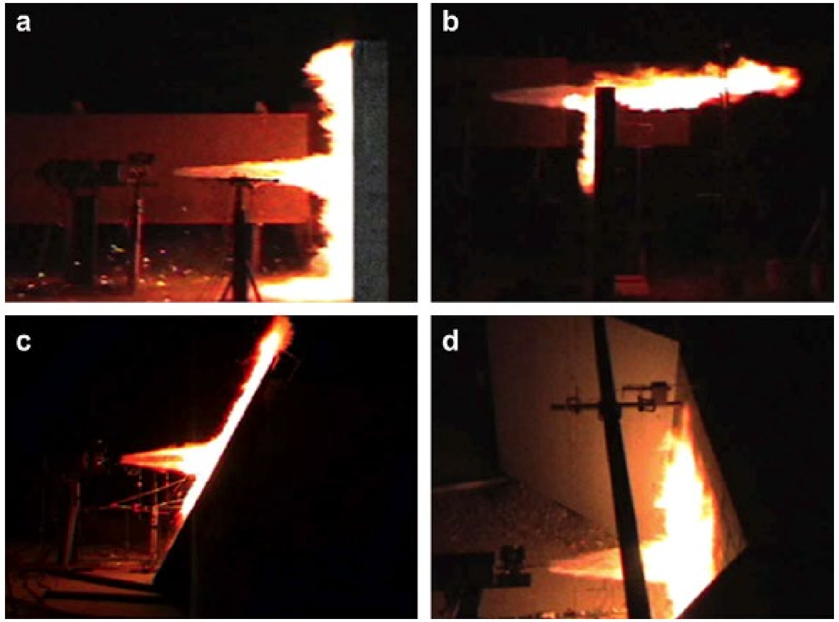






Credits for insulated piping and fire barrier walls remain

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



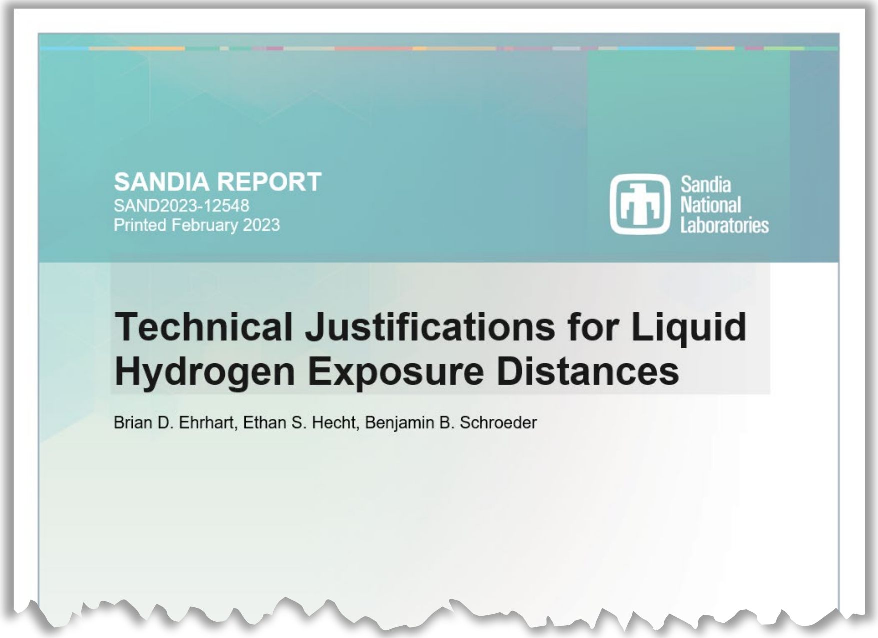
Tests on mitigation from fire barrier walls for gaseous hydrogen flames. From Schefer et al. IJHE 2008.

Acknowledgements and collaboration

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

Summary and future work

- Updated distances are simplified, defensible, and well-documented
- Enables assumptions to be changed and incremental improvements to be made
- Framework could be applied to other setback distances in the future (gaseous setbacks could be revisited)
- Larger systems still need science-based codes and standards (currently separation distances are unspecified for systems larger than about 20 metric tons)
- Additional studies of mitigations from fire barrier walls specific to liquid hydrogen dispersion and flames are needed


SANDIA REPORT
SAND2023-12548
Printed February 2023

Sandia National Laboratories

Technical Justifications for Liquid Hydrogen Exposure Distances

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

Additional documentation available:
SAND2023-12548

Thank you!

Questions?

ehecht@sandia.gov

The team grouped exposures with specific criteria to avoid

Group	Exposure	Criteria
Group 1	1. Lot lines	**Should avoid:** • Harm to the general public • Damage from heat flux • Damage from overpressure • Flammable concentration
	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	**Should avoid:** • Harm to people aware of risk (people at the fueling station) • Significant damage to buildings • Fire spread to ordinary combustibles
	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	**Should avoid:** • Escalation of event (fire spread)
	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	

Distances were tabulated for a typical and range of pipe sizes

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

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

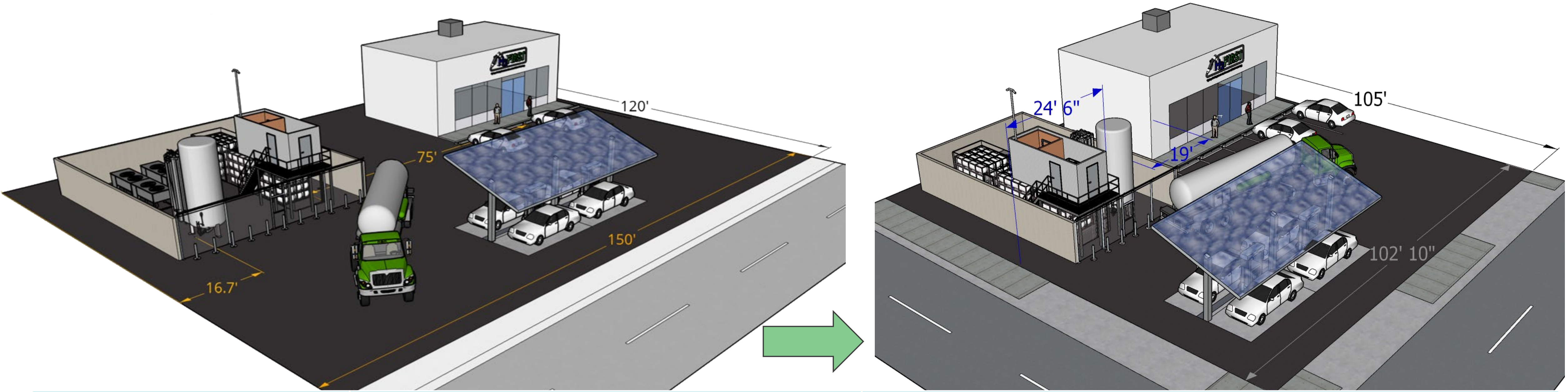
Maximum Operating Pressure (MOP) (gauge)	<60 psi (<414 kPa)		60 to 120 psi (414 kPa to 827 kPa)		>120 psi (>827 kPa)	
Exposures Group 1	**ft**	**m**	**ft**	**m**	**ft**	**m**
1. Lot lines 2. Air intakes (e.g., HVAC, compressors) 3. Operable openings in buildings and structures 4. Ignition sources such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

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

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

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

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



Characteristic	NFPA 2 (2016)	NFPA 2 (2023)
Assumed system	3,500-15,000 gal [950 - 4000 kg] tank	Same tank, 1.5" diameter piping, >120psi
Distance to air intakes	75 ft (unable to reduce with walls)	24'-6" (49 ft reduced by half due to barrier wall)
Lot lines	16.7' (50 ft, reduced by 2/3 due to insulation)	24'-6" (49 ft reduced by half due to barrier wall)
Gaseous portion of system	Same separation distances as liquid system	Treated separately, divided by source valve (changed in 2020 version of NFPA 2)
Driver of separation distance to building	Air intakes	Distance to building /parking spaces (19 ft - group 2 exposure [38 ft reduced by half due to barrier wall])