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Analysis to support revised distance between bulk liquid hydrogen systems and exposures

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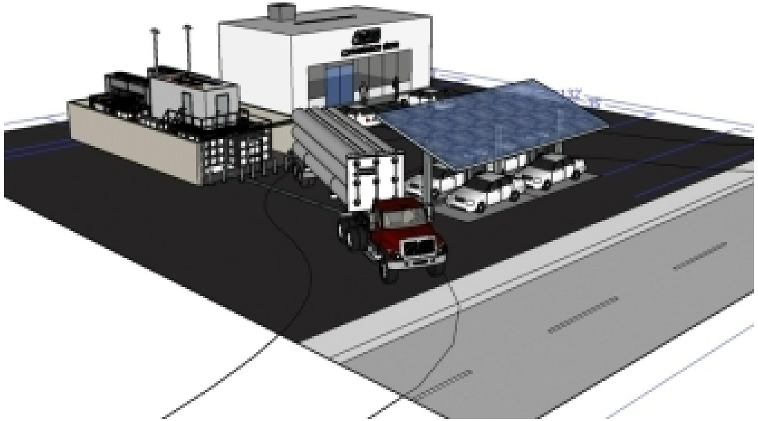
Current separation distances for liquid hydrogen systems in NFPA 2 are based on consensus without a documented scientific analysis

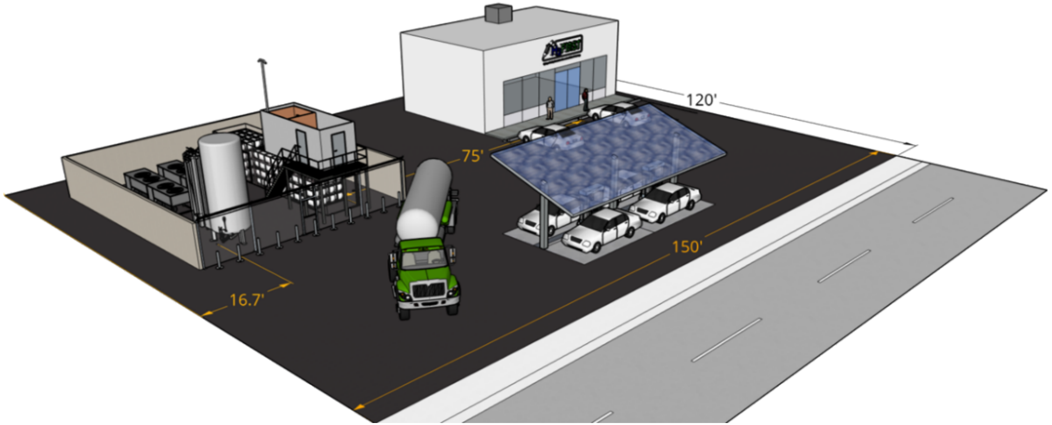
Compressed H_2 storage

- Previous work by Sandia led to science-based gaseous H_2 separation distances



Liquid H_2 storage

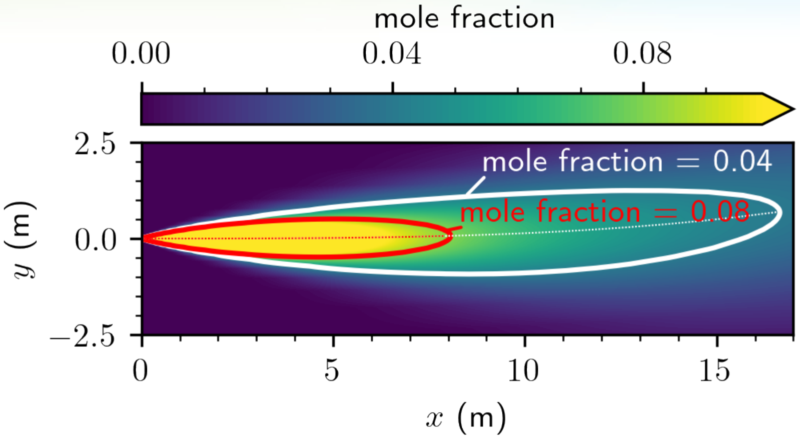
- Even with credits for insulation and fire-rated barrier wall, 75 ft. offset to building intakes and parking make footprint large



Lab-scale validated models have been used to perform an analysis for updated LH_2 separation distances in NFPA 2

- Same criteria as for bulk gaseous setbacks
  - Aside from cryogenic burns, hazards from liquid hydrogen leaks/flames are similar to gaseous hydrogen
  - Considers flammable region (dispersion of unignited hydrogen), and hazards from jet flames
  - Added unconfined overpressure from a delayed ignition
- Leak scenario
  - 1% of flow area (same as current gaseous setbacks)
  - Multiple pipe sizes (0.1” – 3”, 2.5 - 76mm) and pressures (60 – 180 psi, 414 – 1240 kPa)
- Distance criteria
  - Group 1: greater of the distances to 8% concentration or 4.732 kW/m^2
  - Group 2: distance to a heat flux of 4.732 kW/m^2
  - Group 3: distance to visible flame length or heat flux of 20 kW/m^2
- Safety factor of 2 (current gaseous setbacks use 1.5)

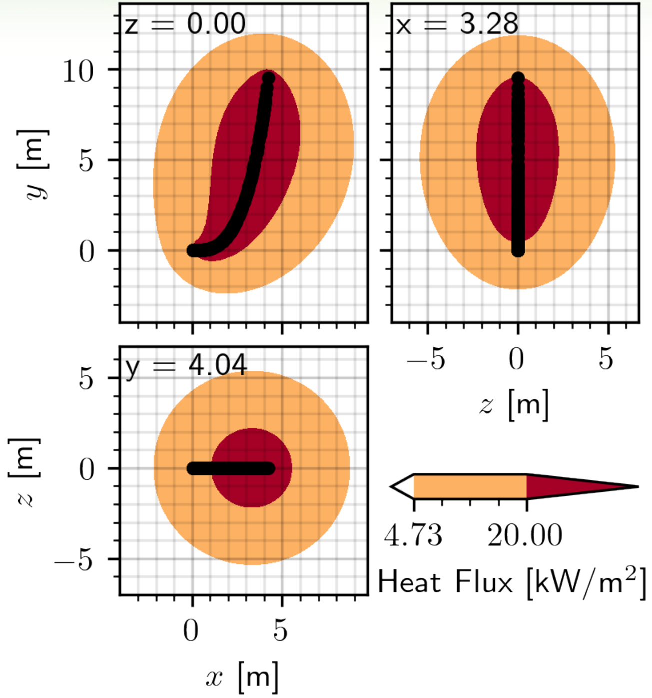
Unignited dispersion simulations show that jets are neutrally buoyant



1% area of 76 mm (3”) diameter pipe, 414 kPa (30 psi), saturated vapor release

- Even for the lowest momentum release, jets do not curve significantly either up or down due to buoyancy
- Conservative streamline (curved) distance to 8% concentration level used to calculate hazard distance

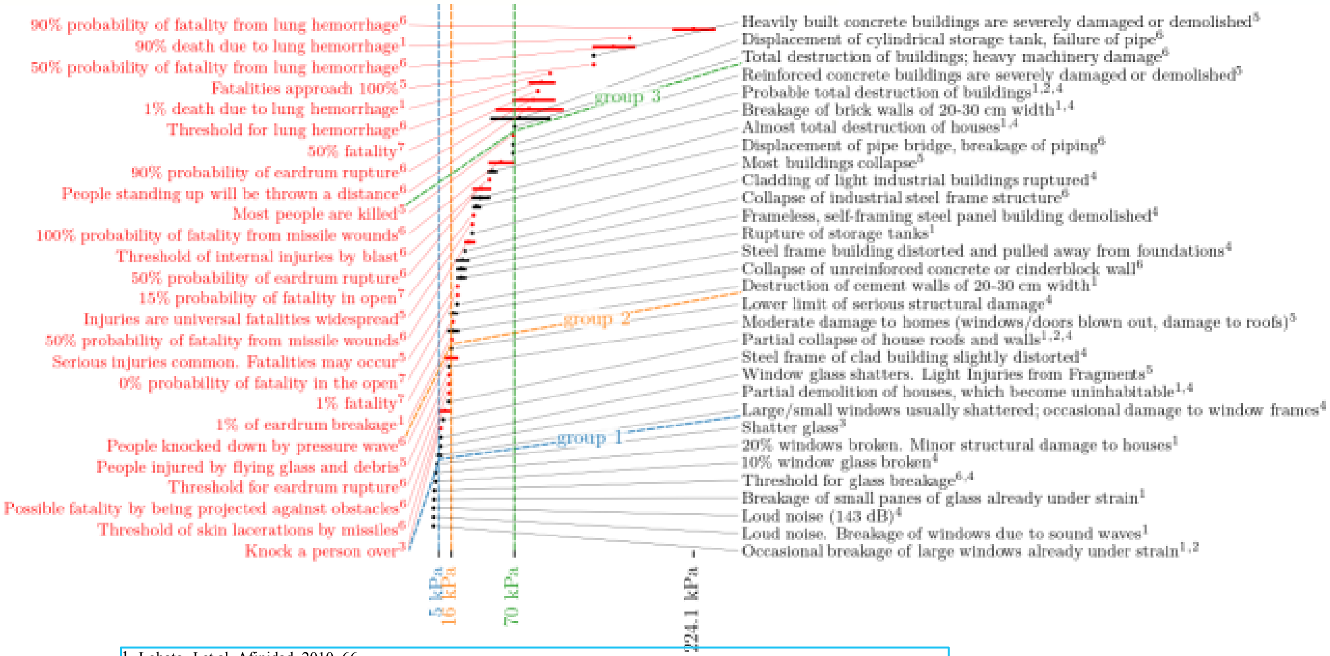
Even high momentum flames are quite buoyant



1% area of 76 mm (3”) diameter pipe, 1.2 MPa (180 psi), critical temperature (33.1 K)

- A flame with high momentum curves significantly upwards due to buoyancy
- Flame length and heat flux values for separation distances calculated from bird’s eye view (xz-plane)

Overpressure harm criteria were reviewed, with selection of Groups 1, 2, and 3 criteria



1. Lobato, J.et al. Afinidad, 2010, 66
2. Huang, Ma. Int. J. Hydrog. Energy, 2018, 43, 442-454
3. Jallais et al. Proc. Safety Prog., 2018, 37, 397-410
4. "Preliminary Quantitative Risk Analysis (QRA) of the Texas Clean Energy Project", 2010
5. Argo, & Sandstrom, "Separation Distances in NFPA Codes and Standards" 2014
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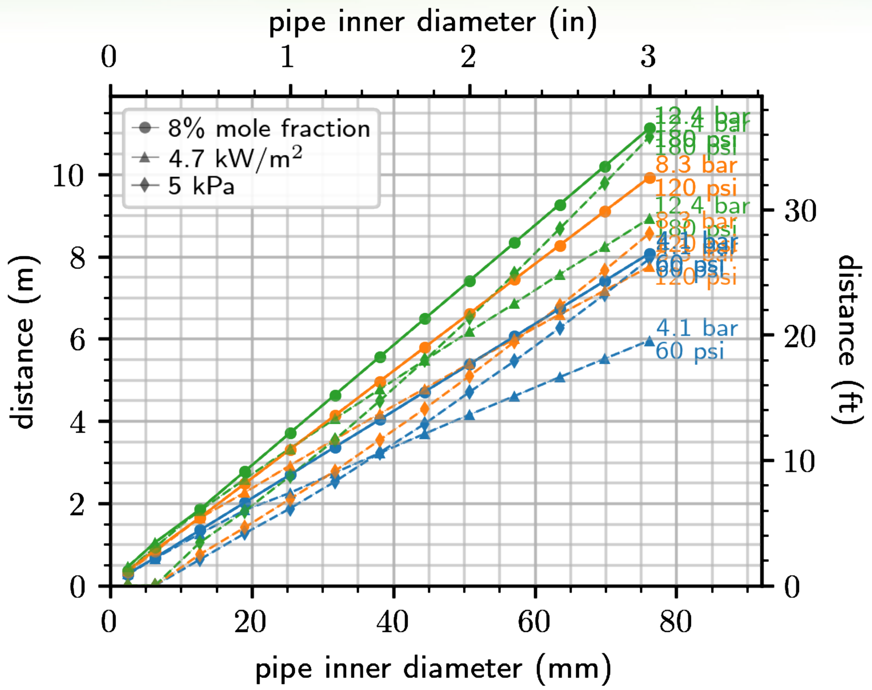
7. "Methods of approximation and determination of human vulnerability for offshore major accident hazard assessment." 2010

- Group 1: no harm to people, small chance of property damage
  - Selected criteria: 5 kPa
- Group 2: small risk of injury to people but negligible risk of fatality, minor property damage
  - Selected criteria: 16 kPa
- Group 3: moderate risk of fatalities, major (but not complete) property damage
  - Selected criteria: 70 kPa

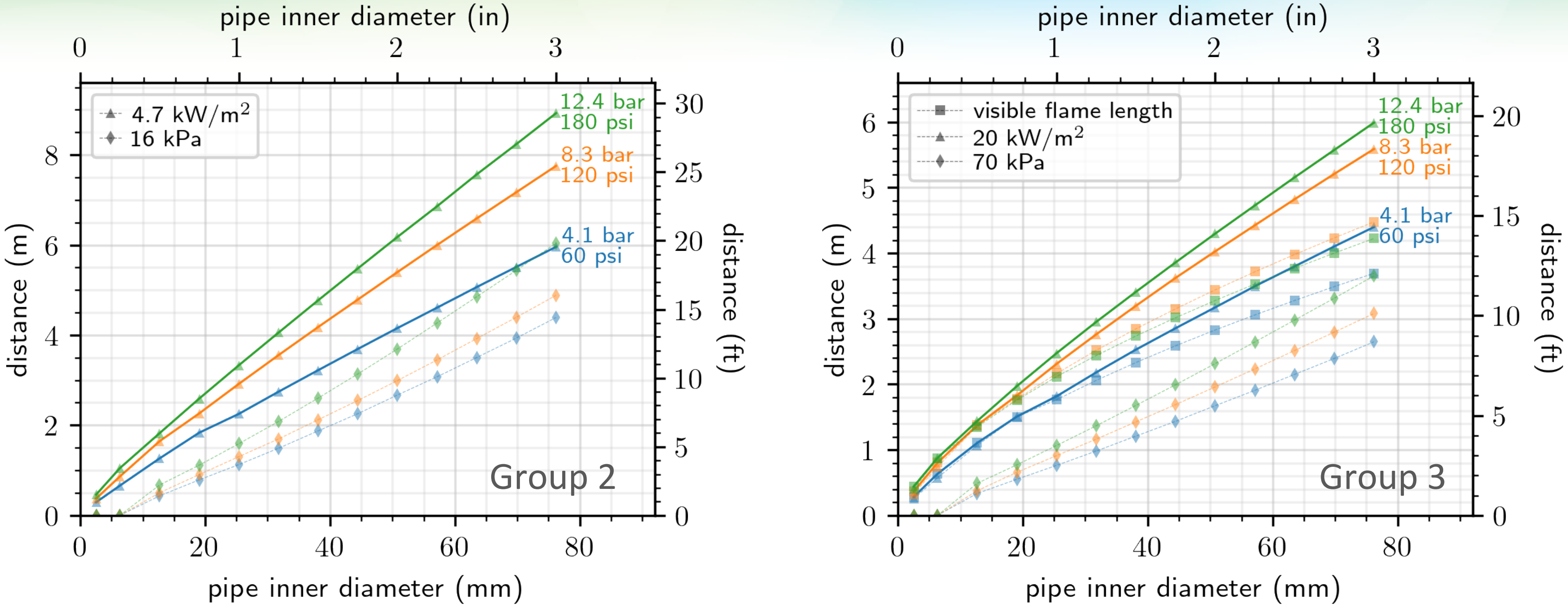
The distance to an 8% mole fraction is limiting for group 1 exposures



- Distance is the largest of:
  - Mole fraction of 8%
  - Heat flux of 4.7 kW/m^2
  - Overpressure of 5 kPa

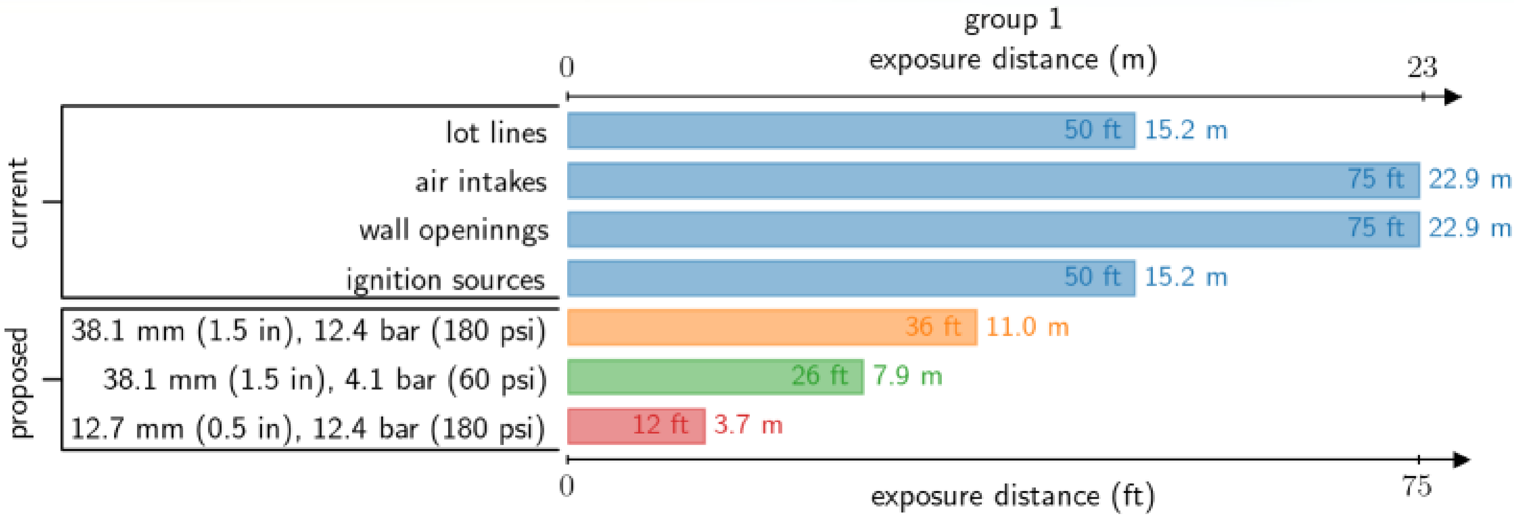
> Even at maximum system pressure and diameter, hazard distance (11 m) is less than current air intake/parking distance (23 m)
>
> - Most systems have smaller pipes (≤ 38 mm) and operate at lower pressures (≤ 8 bar)
> - Safety factor increases for actual exposure distance

Similar calculations result in hazard distances for groups 2 and 3



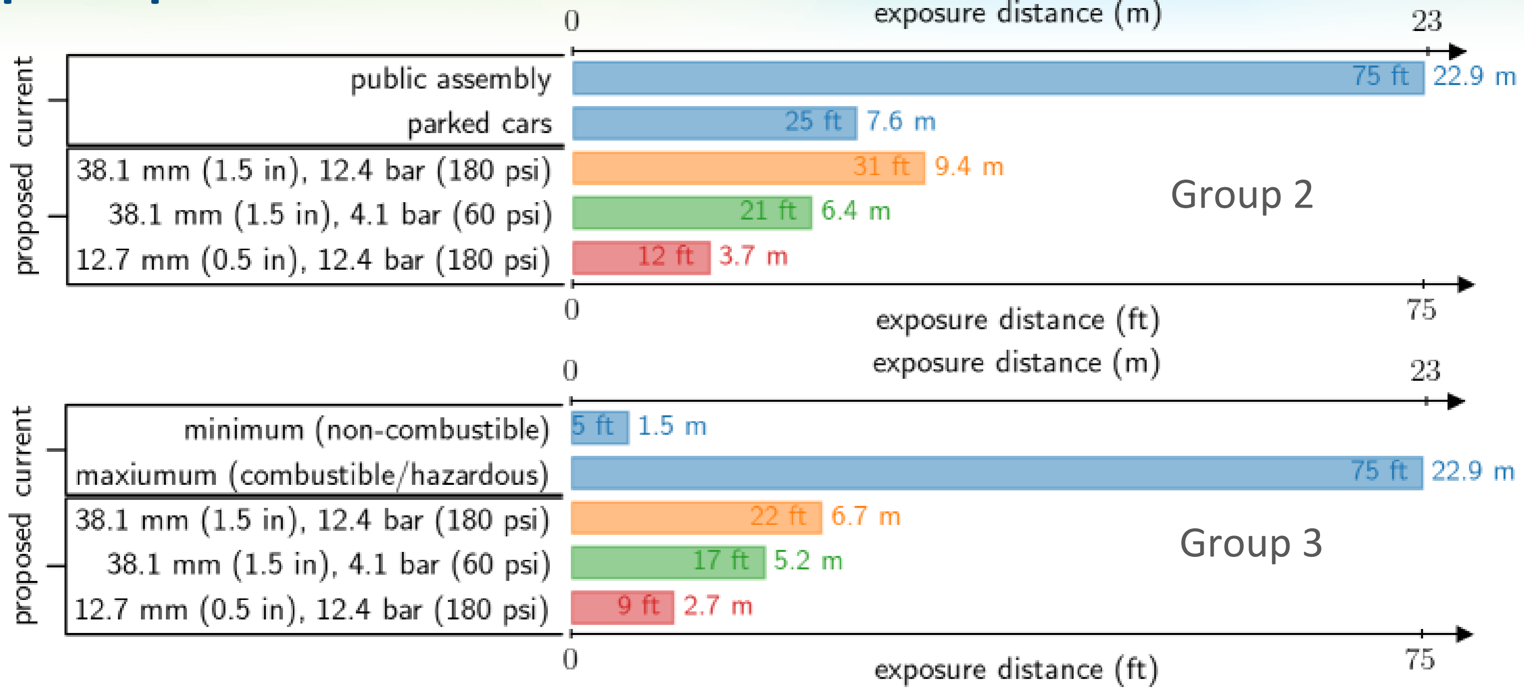
- Distances to specified heat flux tends to be the largest
- Hazard distances for group 3 can be significant

The new group 1 exposure distances can be significantly reduced, depending on the system parameters



- Proposed exposure distances include safety factor of 2 over hazard distances
- Proposed distances based on line size and maximum allowable working pressure of tank
- Typical liquid hydrogen systems (for FCEV refueling) will have reduced group 1 exposure distances

Group 2 exposure distances are generally similar or reduced, while group 3 exposure distances tend to increase



- Group 3 hazard of fire spread (and hence exposure distance) can be mitigated and reduced using fire-rated walls

Proposed changes to NFPA 2 enable flexibility in siting and potentially reduced footprints for liquid hydrogen infrastructure

current

Type of Exposure	39.7 gal to 3500 gal (ft)	150 L to 13,250 L (m)	3501 gal to 15,000 gal (ft)	13,251 L to 56,781 L (m)	15,001 gal to 75,000 gal (ft)	56,782 L to 283,906 L (m)
	Total Bulk Liquefied Hydrogen (LH_2) Storage					
Group 1						
1. Lot lines	25	7.6	50	15	75	23
2. Air intakes [heating, ventilating, or air-conditioning equipment (HVAC), compressors, other]	75	23	75	23	75	23
3. Wall openings						
Operable openings in buildings and structures	75	23	75	23	75	23
4. Ignition sources such as open flames and welding	50	15	50	15	50	15
Group 2						
5. Places of public assembly	75	23	75	23	75	23
6. Parked cars (distance shall be measured from the container fill connection)	25	7.6	25	7.6	25	7.6
Group 3						
7. Building or structure						
(a) Buildings constructed of noncombustible or limited-combustible materials						
(1) Sprinklered building or structure or unsprinklered building or structure having noncombustible contents	5[a]	1.5	5[a]	1.5	5[a]	1.5
(2) Unsprinklered building or structure with combustible contents						
i. Adjacent wall(s) with fire resistance rating less than 3 hours	25	7.6	50	15	75	23
ii. Adjacent wall(s) with fire resistance rating of 3 hours or greater[b]	5	1.5	5	1.5	5	1.5
(b) Buildings of combustible construction						
(1) Sprinklered building or structure	50	15	50	15	50	15
(2) Unsprinklered building or structure	50	15	75	23	100	30.5
8. Flammable gas storage or systems (other than hydrogen) above or below ground	50	15	75	23	75	23
9. Between stationary liquefied hydrogen containers	5	1.5	5	1.5	5	1.5
10. All classes of flammable and combustible liquids (above ground and vent or fill openings if below ground)[c]	50	15	75	23	100	30.5
11. Hazardous materials storage or systems including liquid oxygen storage and other oxidizers, above or below ground	75	23	75	23	75	23
12. Heavy timber, coal, or other slow-burning combustible solids	50	15	75	23	100	30.5
13. Wall openings						
Unopenable openings in buildings and structures	25	7.6	50	15	50	15
14. Inlet to underground sewers	5	1.5	5	1.5	5	1.5
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	50	15	50	15	50	15
(b) Horizontal distance from the vertical plane below the nearest overhead electrical wire	25	7.5	25	7.5	25	7.5
(c) Piping containing other hazardous materials	15	4.6	15	4.6	15	4.6
16. Flammable gas metering and regulating stations above grade	15	4.6	15	4.6	15	4.6

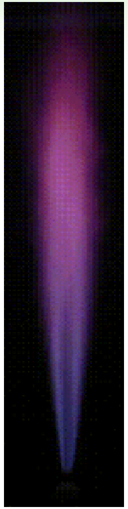
proposed

MAWP (gauge)	< 60 psig < 414 kPa		61 to 120 psig 415 to 827 kPa		121 to 180 psig 828 to 1,241 kPa	
Exposures Group 1	m	ft	m	ft	m	ft
Lot lines Air intakes (HVAC, compressors, other) Operable openings in buildings and structures Ignition sources such as open flames and welding	8.1	26.5	9.9	32.6	11.1	36.5
Exposures Group 2	m	ft	m	ft	m	ft
Exposed persons other than those servicing the system Parked Cars	6.4	21.1	8.4	27.4	9.5	31.3
Exposures Group 3	m	ft	m	ft	m	ft
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 buildings 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	5.1	16.6	6.4	21.0	6.8	22.4

MAWP (gauge)		< 60 psi < 414 kPa						61 to 120 psi 415 to 827 kPa						121 to 180 psi 828 to 1,241 kPa					
Exposures		Group 1		Group 2		Group 3		Group 1		Group 2		Group 3		Group 1		Group 2		Group 3	
Internal Pipe Diameter																			
in	mm	m	ft	m	ft	m	ft	m	ft	m	ft	m	ft	m	ft	m	ft	m	ft
0.1	2.54	0.6	1.9	0.6	1.9	0.6	1.8	0.8	2.5	0.8	2.5	0.7	2.4	0.9	3.0	0.9	3.0	0.9	2.9
0.25	6.35	1.3	4.4	1.3	4.3	1.3	4.2	1.7	5.7	1.7	5.7	1.6	5.3	2.1	6.9	2.1	6.9	1.8	5.7
0.5	12.7	2.7	8.8	2.5	8.3	2.2	7.2	3.3	10.9	3.3	10.8	2.8	9.0	3.7	12.2	3.6	12.0	2.9	9.4
0.75	19	4.0	13.3	3.7	12.0	3.0	9.9	5.0	16.3	4.5	14.8	3.7	12.0	5.6	18.3	5.2	17.0	4.0	13.0
1	25.4	5.4	17.7	4.5	14.8	3.6	11.9	6.6	21.7	5.8	19.1	4.6	15.1	7.4	24.3	6.7	21.9	4.9	16.2
1.25	31.8	6.7	22.1	5.5	18.0	4.4	14.3	8.3	27.1	7.1	23.3	5.5	18.1	9.3	30.4	8.1	26.6	5.9	19.4
1.5	38.1	8.1	26.5	6.4	21.1	5.1	16.6	9.9	32.6	8.4	27.4	6.4	21.0	11.1	36.5	9.5	31.3	6.8	22.4
1.75	44.4	9.4	30.9	7.4	24.2	5.7	18.7	11.6	38.0	9.6	31.4	7.2	23.8	13.0	42.6	10.9	35.9	7.7	25.3
2	50.8	10.8	35.3	8.3	27.3	6.3	20.8	13.2	43.4	10.8	35.4	8.0	26.4	14.8	48.7	12.3	40.5	8.6	28.2
2.25	57.1	12.1	39.8	9.2	30.3	7.0	22.9	14.9	48.9	12.0	39.4	8.9	29.0	16.7	54.7	13.7	45.0	9.5	31.0
2.5	63.5	13.5	44.2	10.1	33.3	7.6	24.9	16.5	54.3	13.2	43.3	9.6	31.6	18.5	60.8	15.1	49.6	10.3	33.8
2.75	69.8	14.8	48.6	11.0	36.2	8.2	26.8	18.2	59.7	14.3	47.0	10.4	34.2	20.4	66.9	16.5	54.1	11.2	36.6
3	76.2	16.2	53.0	11.9	39.1	8.8	28.8	19.8	65.1	15.6	51.0	11.2	36.6	22.2	73.0	17.8	58.6	12.0	39.3

Summary and conclusions

- HyRAM models have been used, with assumptions on leak size, to quantify exposure distances for LH_2 systems
  - Distances related to relief pressure and pipe size
  - Included unconfined overpressure criteria (not limiting for any of the groups)
  - Largest separation distances reduced for typical system
  - Smallest separation distances sometimes increase, but mitigations can be used
  - New tables have been proposed to NFPA 2
- Methods and updated code language currently being reviewed/revised by NFPA 2 storage task group as a committee input



QUESTIONS
OR
COMMENTS:

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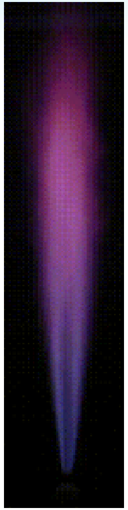

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- Air Liquide and partners

Recent experiments under PreSLHy project show that rainout/pooling unlikely except for vertically downward releases near ground level

- Releases through ¼” – 1” orifices, 0.5m – 1.5m from ground, 1 and 5 bar_g
  - Rainout/pooling only observed for vertically downward releases through ½” pipe 0.5m from ground (105/265 g/s)

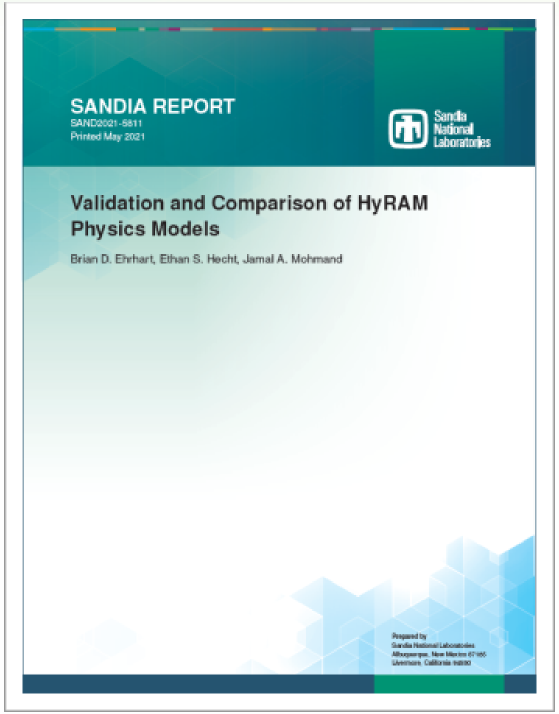
Figure 3-18. Visible cloud during dispersion and rainout tests at HSE facility.

Rainout did not occur during the established flow of these releases, but there was evidence of rainout soon after valve closure (probably liquid air). Further to this, condensed components of air formed around the release point and on impingements for releases from the 6 and 12 mm nozzles. Pools were only formed with low, vertically downward releases. These pools potentially comprised of LH_2, condensed components of air, or a mixture of the two.

https://hysafe.info/wp-content/uploads/sites/3/2021/04/D39_2021-01-PRESLHY_ChapterLH2-v3.pdf
https://hysafe.info/wp-content/uploads/sites/3/2020/08/exp_workshop_260620_WP3_v2.pdf

➢ Pooling is a credible, but unlikely scenario

Verification of HyRAM models against lab-scale and literature data has been completed and published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Validation and Comparison of HyRAM Physics Models

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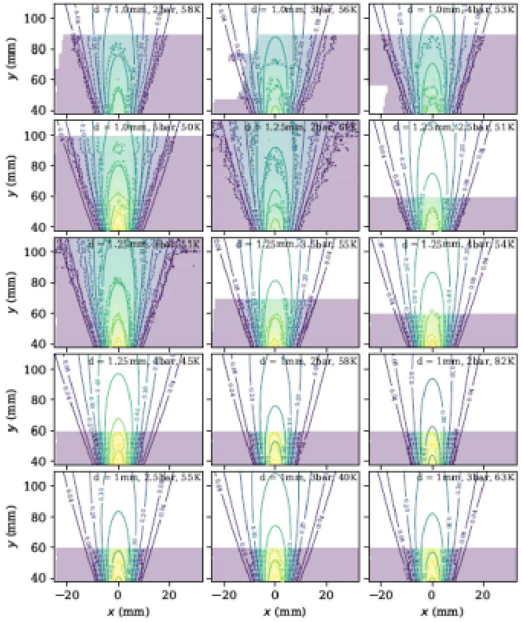


Figure 3-26 Comparison of mole fraction calculated by HyRAM 3.1 (thin, solid lines) to cryogenic hydrogen dispersion data reported by Hecht and Panda [13] (shading and thick, dashed lines) as well as some previously unreported data

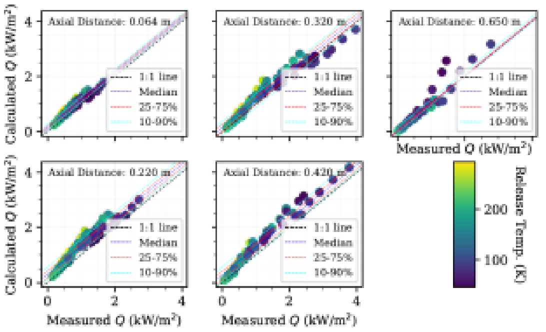


Figure 3-32 Comparison of heat flux (Q) calculated by HyRAM 3.1 to those measured by Panda and Hecht [12]

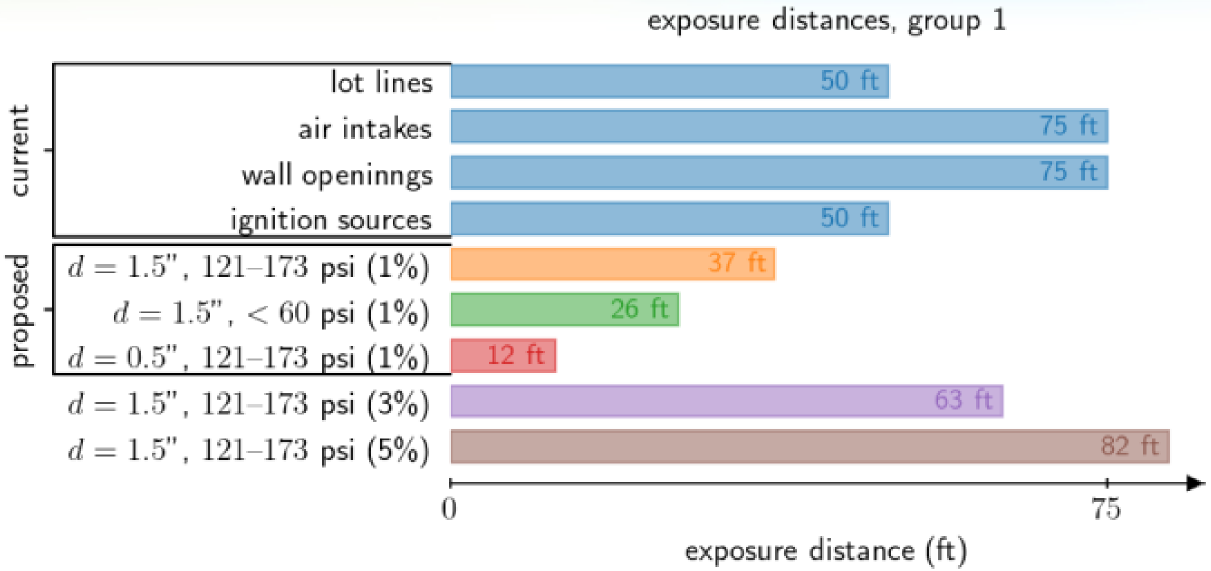
- Distance calculations locked to a specific (3.1), retrievable version of the models

How does the distance change for a 3% leak area vs a 1% leak area?

Group	Criteria	Distance increase
1	8% mole fraction	1.7 times
1	0.7 psi overpressure	2.5-3.3 times
1/2	4.7 kW/m^2	1.7 times
2	2.3 psi overpressure	2.5-3.3 times
3	20 kW/m^2	1.6 times
3	Visible flame length	1.4-1.6 times
3	10.2 psi overpressure	2.5-3.3 times

- Safety factor of 2 on 1% leak area is equivalent to safety factor of 0.15 on 3% leak area
- As calculated distances are conservative for 1% or 3% leak area

Group 1 proposed distances, and calculations with larger leak sizes



Calculations with same safety factor (2)

- 3% leak is 1.54 – 1.77 times further than 1% leak
- 5% leak is 1.91 – 2.40 times further than 1% leak

Groups 2 and 3 proposed distances, and calculations with larger leak sizes

Group 2 →

Group 3 →