ANALYSIS TO SUPPORT REVISED DISTANCES BETWEEN BULK LIQUID HYDROGEN SYSTEMS AND EXPOSURES

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ABSTRACT

The minimum distances between exposures and bulk liquid hydrogen listed in the National Fire Protection Agency's Hydrogen Technology Code, NFPA 2, are based on historical consensus without a documented scientific analysis. This work follows a similar analysis as the scientific justification provided in NFPA 2 for exposure distances from bulk gaseous hydrogen storage systems, but for liquid hydrogen. Validated physical models from Sandia's HyRAM software are used to calculate distances to a flammable concentration for an unignited release, the distance to critical heat flux values and the visible flame length for an ignited release, and the overpressure that would occur for a delayed ignition of a liquid hydrogen leak. Revised exposure distances for bulk liquid hydrogen systems are calculated. These distances are related to the maximum allowable working pressure of the tank and the line size as compared to the current exposure distances, which are based on system volume. For most systems, the exposure distances calculated are smaller than the current distances for Group 1, they are similar for Group 2, while they increase for some Group 3 exposures. These distances could enable smaller footprints for infrastructure that includes bulk liquid hydrogen storage tanks, especially when using firewalls to mitigate Group 3 hazards and exposure distances. This analysis is being refined as additional information on leak frequencies is incorporated and changes have been proposed to the 2023 edition of NFPA 2.

1.0 INTRODUCTION

As with any fuel, there are inherent risks in using hydrogen, but with proper protections these risks can be managed. The National Fire Protection Agency (NFPA) Hydrogen Technologies Code, NFPA 2 [1], uses a risk-informed approach described by LaChance and others [2, 3] to justify the separation distances for bulk gaseous hydrogen outdoor storage. The risk-informed approach taken by NFPA to arrive at the separation distances is based on a quantitative risk assessment (QRA), but does not use the QRA results to directly determine the requirements; requirements are not risk-based such as the those provided by the International Organization for Standardization (ISO) [4]. Other means for determining hazardous areas include worst-case consequence and maximum credible event calculations [5]. A risk-informed process takes insights from a QRA, along with deterministic analyses of select accident scenarios, leakage frequency, and uncertainties in the data and methods into account to develop requirements. A risk-based process, on the other hand, uses a QRA to calculate the cumulative risk as a function of separation distance and directly selects the separation distance that enables a chosen risk criteria.

Annex I in NFPA 2 [1] outlines the methodology utilized to develop separation distances, but this methodology has only been fully implemented for bulk compressed gaseous hydrogen storage and not bulk liquid hydrogen storage. In this annex, there are several hazardous scenarios that form the basis for distances to different exposures, aligned into three groups. Some combination of these hazards contributes to separation distances for Group 1, Group 2, and Group 3 exposures. The four Group 1 exposures are lot lines, air intakes, openings in buildings and structures, and ignition sources. At the Group 1 distance, there should be no possibility of igniting leaks (i.e., no ignitable hydrogen), injuries to people at adjacent facilities (i.e., the impact of hazards from an ignited release is negligible), or accumulation of flammable mixtures, which could lead to an explosion hazard (again, no ignitable hydrogen). The two Group 2 exposures are exposed persons other than those involved in servicing of the system and parked cars. The scenario to avoid is the injury to people on-site (i.e., acceptable risk of harm to people on-site). There are ten Group 3 exposures consisting mostly of buildings and other flammable or hazardous materials. For Group 3, fire spread should be avoided (either from or to the hydrogen system), creating unacceptable property damage, or the release of hydrogen or some other hazardous material.

The risk assessment process followed for the gaseous hydrogen setback distances in Annex I of NFPA 2 [1] resulted in the selection of a specific leak size (1% of flow area) from which physical effects are then estimated. Hydrogen release behavior models were then used to estimate the distance to the various exposure groups, which then resulted in the required setback distances. The analysis excluded overpressure events because the systems were located outdoors [3]. In addition to the estimated distance from the models used, a safety factor of 1.5 (50%) was also applied to the distances to account for uncertainties in the analysis and model results.

This work presents an analgous methodology for liquid hydrogen systems to that applied for gaseous hydrogen setback distances. A fractional leak size is used with typical system pipe sizes and pressures to estimate distances to various exposures. Similar criteria to NFPA 2 [1] are used for unignited extent and heat flux hazards. However, this work also considers unconfined overpressure hazards for leaks that ignite after some delay, and incorporate this new harm criteria for the exposure groups.

2.0 APPROACH

The hazards associated with liquid hydrogen are very similar to those associated with highly compressed gaseous hydrogen. With its low saturation temperature, the liquid will generally flash to vapor due to the heat in the air as it mixes. Heat transfer from an ambient temperature surface will also cause the liquid to vaporize. Rain-out and pooling is possible, but only for very large flowrates and/or long contact times [6–8]. Once the fuel is in vapor form, it will still be cold, yielding a cryogenic hazard (the cold can freeze skin or embrittle normally flexible materials such as o-rings), but otherwise poses the same hazards as a leak from a compressed gaseous system stemming from the fact that the fuel could ignite. The plume itself could ignite, or ignition could occur after accumulation within an enclosure, so the extent to which the flammable concentration of an unignited plume extends is an important consideration. Even without accumulating in an enclosure, if the release does not immediately ignite, there can be some overpressure generated from a delayed ignition of a release. Whether the release ignites immediately or is a delayed process, a cryogenic hydrogen jet flame will radiate heat, which also poses a risk to humans and equipment.

Because the hazards associated with liquid hydrogen are so similar to the hazards from gaseous hydrogen, it is logical to group the exposures from bulk liquid hydrogen in the same manner as the gaseous separation distances in Table 7.3.2.3.1.1(A) in NFPA 2 [1]. In this analysis, updated exposure distances for liquid hydrogen are calculated for each of the 3 groups rather than a distance for each exposure. Further, liquid hydrogen systems have a source valve, similar to gaseous hydrogen systems, that enables the bulk storage tank to be isolated, should a leak develop. While the volume of the tank will impact the duration of an event (should the leak be unable to be isolated with the source valve), it will not change the extent to which a hazard is present. For example, a jet flame from a given leak size with a 13,250 L (3,500 gallon) tank will extend just as far as the same sized leak from a 56,782 L (75,000 gallon) capacity tank (at the same pressure), although the flame will burn longer with the larger tank. Therefore, in this analysis, the distances from liquid hydrogen systems to exposures are based on the parameters of the tank, namely the pipe size and the pressure level (i.e., maximum allowable working pressure [MAWP]) of the tank.

The hazardous criteria for the three different groups of exposures in this work are the same as the hazardous criteria for gaseous hydrogen in NFPA 2 [1]. In this case, an overpressure calculation for a delayed ignition of a leak is also included. Table 1 shows the cutoff overpressure values for each of the three groups. At the Group 1 exposure distance, there should be very little damage to other structures and negligible risk to people. There are no direct links to harm of people at pressures below approximately 14 kPa of overpressure (although a person could be knocked over with approximately 7 kPa [13]), but significant damage can occur to houses at approximately 7 kPa [9, 11]. The Group 1 overpressure value is selected to be slightly below this pressure at 5 kPa (0.7 psi). At the Group 2 exposure distance, people may have a risk of injury, but fatality is unlikely. At 16 kPa (2.3 psi), the selected overpressure for Group 2 exposures, there is some risk of eardrum rupture [12], the possibility of people being projected against obstacles [12], partial collapse of unreinforced walls [9–11, 14], but very little ($< 1\%$) probability of fatality [15]. Finally, for Group 3 exposures, the selected overpressure is 70 kPa (10.2 psi), as this pressure can lead to total destruction of buildings [9–11], severe damage to structures including reinforced concrete [14], and moderate ($\approx$15–50%) probability of fatality [15].

The hazardous criteria from NFPA 2 [1] with the addition of the overpressure criteria described above result in the exposure distances for each of the three groups as:

- Group 1 exposures: the furthest distance to an average mole fraction of 8%, a heat flux of 4.732 kW/m^2 (1,500 BTU/hr-ft^2) or an overpressure of 5 kPa (0.73 psi)
- Group 2 exposures: the furthest distance to a heat flux of 4.732 kW/m^2 (1,500 BTU/hr-ft^2) or an overpressure of 16 kPa (2.32 psi)
- Group 3 exposures: the furthest distance to a heat flux of 20 kW/m^2 (6,340 BTU/hr-ft^2), the visible flame length, or an overpressure of 70 kPa (10.15 psi)

To our knowledge, a comprehensive study on leak sizes and frequencies for components in liquid hydrogen service has not yet been performed. This precludes drawing any conclusions on the cumulative frequency of a certain leak size, as was done for compressed gaseous hydrogen components, where a leak through 1% of the flow area encompassed 95% of the leaks for a hydrogen system. For this work, a 1% flow area leak is assumed for the calculations of the hazards. As information on the leak frequency of liquid hydrogen components is gathered, this assumption can be updated or validated.

For modeling of the hazards, the models from HyRAM version 3.1.0 [16] are used. These models have been validated for cryogenic hydrogen [17]. Within HyRAM, there are models for unignited jet plume dispersion and jet flames. On top of the unignited dispersion model of HyRAM, a model for the overpressure hazard that would develop from a delayed ignition is included, following the work of Bauwens and Dorofeev [18, 19]. The HyRAM model is used to calculate the concentration field and from this, the detonable mass and overpressure that would develop are found based on the correlations given by Bauwens and Dorofeev [18, 19]. The center of the detonable mass is taken as the centerline mole fraction of 30%. Other models for vapor cloud explosions/unconfined overpressure could be used, and different models can give

Table 1. Effect of overpressure on humans (highlighted in red) and structures, as well as selected Group 1, 2, and 3 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]
5.0	**0.7**	**Selected Group 1 Criteria**
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]
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]
13.8	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]
16.0	**2.3**	**Selected Group 2 Criteria**
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	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**	**Selected Group 3 Criteria**
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]

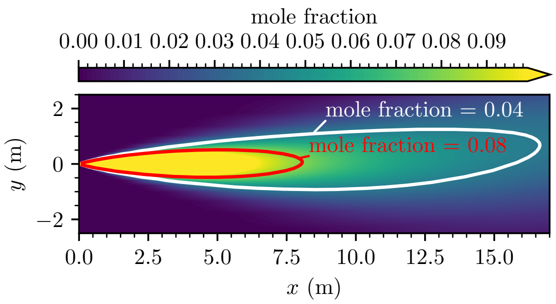


Figure 1. Mole fraction field of a 414 kPa (60 psi) saturated vapor leak from 1% of the flow area of a 76.2 mm (3 inch) diameter pipe

slightly different results. A safety factor is used to account for this model uncertainty, as will be discussed below.

The HyRAM model for unignited dispersion is a one-dimensional conservation of mass, momentum, species, and energy along the streamline of a turbulent flow. This streamline can curve due to the buoyancy of the fluid being transported. This can become important for low-speed hydrogen flows due to the low density of warm hydrogen. While cryogenic hydrogen is much more dense than warm hydrogen, a saturated vapor stream of hydrogen at atmospheric pressure (101,325 Pa) has a density of 1.33 kg/m^3, only slightly higher than the density of air at room temperature (293 K) of 1.21 kg/m^3. Saturated liquid hydrogen is significantly denser than the gas (70.8 kg/m^3 at 101,325 Pa), but as discussed earlier, will vaporize before mixing and dispersing with the air. As the cryogenic hydrogen will quickly mix with the air and warm, the first consideration for these calculations is the extent to which buoyancy affects the dispersion of these plumes. The critical pressure of liquid hydrogen is approximately 1,200 kPa (173 psi) and most liquid hydrogen tanks have a MAWP at or slightly above this value. Bulk cryo-compressed tanks operating are not considered in this analysis. In this work, the critical pressure is encompassed and a range of liquid hydrogen tank pressures are considered, from 414–1,240 kPa (60–180 psi). The dispersion of the lowest pressure simulation, through a 1% leak area of a 76.2 mm (3 inch) diameter pipe is shown in Fig. 1. It is clear, at least when inspecting the 4% mole fraction contour, that the plume is buoyant. Because there is only a small amount of buoyancy for the lowest momentum case considered (especially for the 8% mole fraction contour), to be a bit conservative on the predictions of exposure distances, the (curved) streamline distance to the 8% mole fraction contour was used. This is slightly longer than the horizontal (x) distance to the same contour level.

Similar to the dispersion model, the jet flame model in HyRAM is also a system of ordinary differential equations with a single dependent spatial variable along the streamline. This model also predicts the curvature of a flame due to buoyancy. The trajectory and heat flux contours for the highest momentum flame (cryogenic hydrogen leaking from a 1.2 MPa tank) are shown in Fig. 2. The flame is shown by the black line in the figure and it clearly bends towards near vertical due to buoyancy very near to the horizontal release point. Because these flames are predicted to be so buoyant, exposure distances to both the flame length and the different heat flux contours are based on the overhead projection of the flame trajectory and heat flux contours (i.e., the lower left frame in Fig. 2). Looking for the flame length and heat flux values along the streamline of the flame (rather than the overhead view) would be extremely conservative and lead to large exposure distances.

To account for uncertainty in the leak size distribution for liquid hydrogen systems as well as uncertainty in the model results, a safety factor of 2 (100%) is applied to the calculated hazard distances in this work. This is more conservative than the safety factor of 1.5 (50%) that was

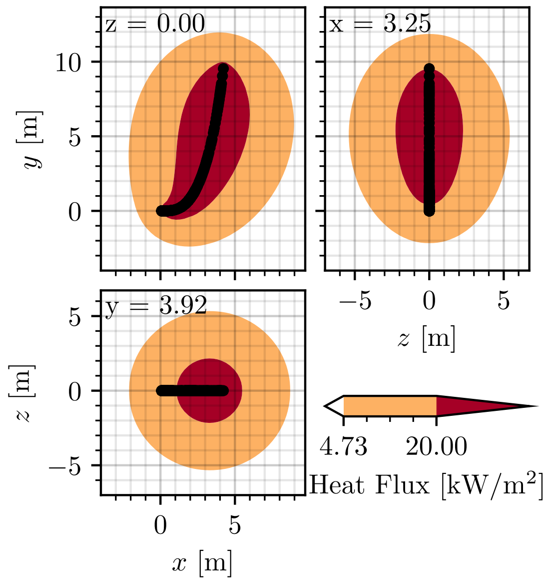


Figure 2. Flame trajectory (black line) and heat flux contours of a 1.2 MPa (180 psi) leak of hydrogen at the critical temperature (33.1 K) from 1% of the flow area of a 76.2 mm (3 inch) diameter pipe. The flame is very buoyant, curving up quickly after the horizontal release.

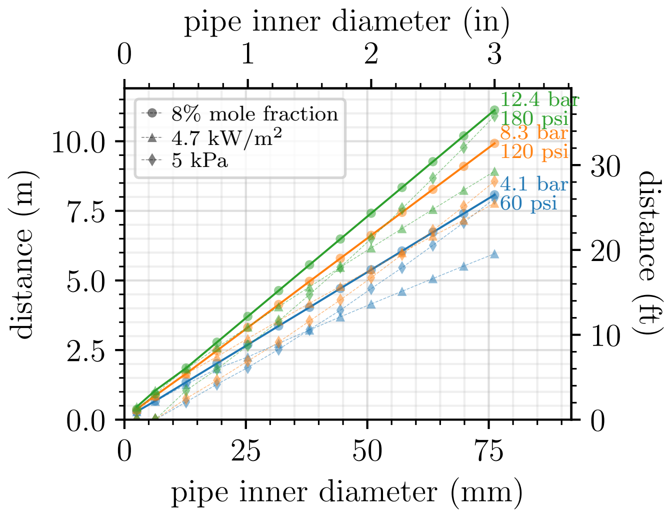
used for the exposure distances from bulk gaseous hydrogen storage in NFPA 2 [1].

3.0 RESULTS AND DISCUSSION

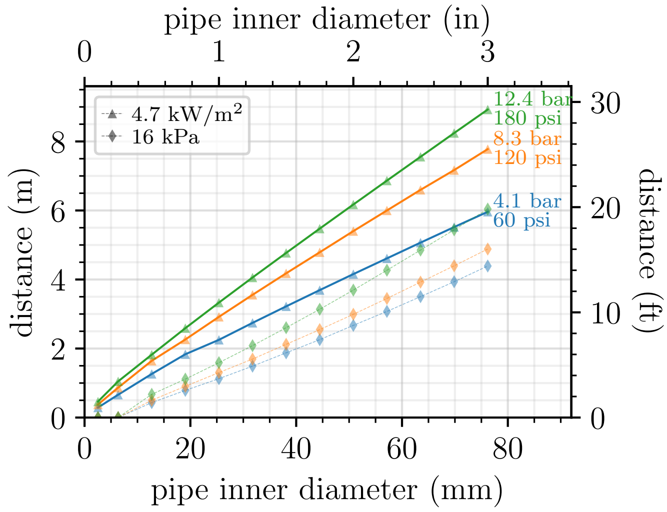
With the approach described previously, the hazard distances for the three different exposure groups were calculated. For Group 1, the furthest distance to an average mole fraction of 8%, a heat flux of 4.732 kW/m^2 (1,500 BTU/hr-ft^2) or an overpressure of 5 kPa (0.73 psi) are shown in Fig. 3a. As would be expected, the shortest hazard distances are for the smallest pipe diameters, and the lowest tank pressures. The figure shows the 5 kPa overpressure distance as diamonds, which are the shortest hazard distances for the smallest pipe diameters, but increase more rapidly than the other hazards as the pipe diameter increases. The 4.7 kW/m^2 heat flux distances are shown as triangles on the plot. The 8% mole fraction distance (circles) is the furthest distance for all of the pipe diameters and tank pressures explored in this work. The solid lines on the plot show the maximum hazard distance for a given tank MAWP, which are aligned with the 8% mole fraction distance in this case.

A typical liquid hydrogen pipe is at most 38.1 mm (1.5 inch), according to the Risk Management Plan Guidance Document for Bulk Liquid Hydrogen Systems (CGA P-28) [20]. For this pipe size, the Group 1 hazard distance ranges from about 4 m (13 ft) (for a 4.1 bar [600 psi] MAWP) to 5.5 m (13 ft) (for a 12.4 bar [180 psi] MAWP). Using the conservative safety factor of 2 (doubling the hazard distance) for this pipe size results in exposure distances are well below the current maximum separation distance for Group 1 exposures (for even the maximum tank volume) in NFPA 2 of 22.9 m (75 ft).

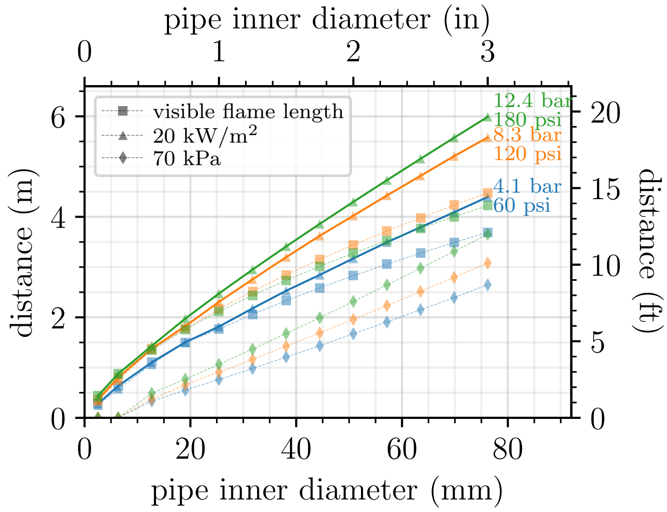
The Group 2 hazard distances (the furthest distance to a heat flux of 4.732 kW/m^2 or an overpressure of 16 kPa) are shown in Fig. 3b. In this case, there are only two hazards considered, and the heat flux is longer than the overpressure hazard distance for all relief pressures. For the typical 38.1 mm (1.5 inch) pipe diameter, the Group 2 hazard distance ranges from about 3.2 m (10.5 ft) (for a 4.1 bar [60 psi] MAWP) to 4.8 m (16 ft) (for a 12.4 bar [180 psi] MAWP). The current exposure distances in NFPA 2 for Group 2 range from 7.6–22.9 m (25–75 ft), so the while



(a) Group 1



(b) Group 2



(c) Group 3

Figure 3. Distances to a mole fraction of 8% (circles), a heat flux given in the legend (triangles), an overpressure given in the legend (diamonds), or the visible flame length (squares), for a 1% leak area of the specified pipe diameter. The maximum hazard distance to each exposure group is shown by the solid lines, and the labels on the end of each line denote the tank (gauge) pressure.

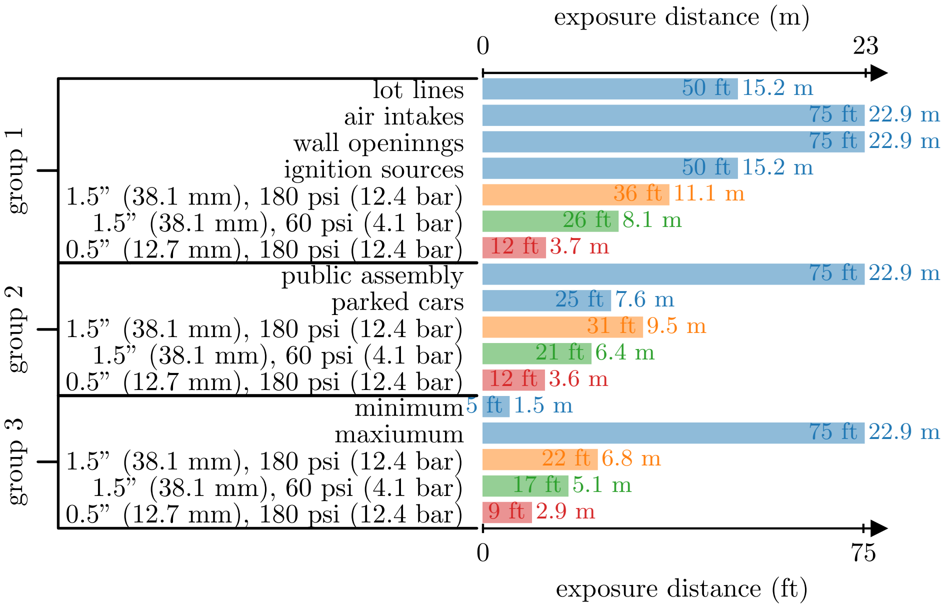


Figure 4. Exposure distances (with a safety factor of 2) calculated in this work are shown by the orange, green, and yellow bars, labeled by the tank parameters, while the current distances in NFPA 2 are shown by the blue bars (for a typical system: a 13,251–56,781 L [3,501–15,000 gallon] tank). For Group 3, only the current minimum and maximum distances in NFPA 2 are shown, since the distances vary widely within the group.

the hazard distances are smaller than the current distances, the exposure distances proposed in this work are in some cases longer than the current exposure distances (when applying a safety factor of 2).

Finally, the Group 3 hazard distances (the furthest distance to the visible flame length, a heat flux of 20 kW/m^2, or an overpressure of 70 kPa) are shown in Fig. 3c. As with the other groups, the distance to a safe overpressure tends to be the shortest distance, which suggests that if the overpressure hazard is calculated for compressed gaseous systems that it will not affect the exposure distances. The visible flame length is generally the next longest distance, and the 20 kW/m^2 hazard distance is the furthest, for most of the conditions shown here. Careful examination shows that the visible flame length is longer than the distance to 20 kW/m^2 for the smallest pipe diameters, but only slightly. For the typical 38.1 mm (1.5 inch) pipe diameter system, the exposure distances range from 2.5–3.4 m (8.5–11 ft). Even without a safety factor, these values are higher than the smallest current Group 3 exposure distance of 1.5 m (5 ft). It should be noted that the general purpose of the Group 3 distances is to prevent fire spread, and therefore these distances can be reduced by using a fire-rated barrier wall. There is no reason that this mitigation would not also be effective for liquid hydrogen systems.

For several typical systems, the calculated distances from exposures, including a safety factor of 2, are graphically compared to the current distances in Fig. 4. The first four exposures (lot lines, air intakes, wall openings, and ignition sources) are in Group 1. For the three different tank conditions plotted here (with variations in pipe size and MAWP), the distances (3.7–11.1 m [12–36 ft]) are less than both the 22.9 m and 15.2 m (75 ft and 50 ft) separation distances for the different exposures within Group 1. However, it should be noted that a larger pipe size, for example a 76.2 mm (3 inch) pipe, with a 828-1,240 kPa (121-180 psig) MAWP, would result in a 22 m (73 ft) exposure distance which is in between the two current exposure distances for Group 1. The two Group 2 exposures (public assembly, and parked cars) have exposure

Table 2. Minimum Distance from Outdoor Bulk Liquefied Hydrogen [LH2] Systems to Exposures — Typical Maximum Pipe Size (1.5 inch [38.1 mm])

MAWP (gague)	< 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

distances of 22.9 and 7.6 m (75 and 25 ft) in the 2020 edition of NFPA 2. The three selected systems in Fig. 4 have exposure distances ranging from 3.6 m (12 ft) to 9.5 m (31 ft). Finally, the current Group 3 exposure distances range widely, from 1.5–22.9 m (5–75 ft). In this work, the selected Group 3 exposure distances range from 2.9 m (9 ft) to 6.8 m (22 ft) for the three selected systems, well above the current minimum exposure distance value. As discussed earlier, the intention of the Group 3 distances is to prevent fire spread, and therefore these distances can be reduced by using a fire-rated barrier wall.

The calculated distances from exposures for a typical pipe size of 1.5 inch (38.1 mm) for three different MAWPs are shown in Table 2. This table is analogous to Table 7.3.2.3.1.1(A)(a) within NFPA 2 [1], where for a typical system, the different exposure distances are clearly laid out. The Group 1 distances are well below the 2020 NFPA 2 distances (for all tank volumes), the Group 2 distances are similar, and the Group 3 distances are longer than the current exposure distances. It should be noted that the distances in Table 2 are for a system pipe size of 38.1 mm (1.5 inch). While this may be typical in industrial systems, fueling stations may have smaller liquid hydrogen lines and effectively transfer the amount of hydrogen they need to deliver to vehicles.

Table 3 presents additional exposure distance sizes for a range of pipe sizes (rows) for several MAWPs (columns). This table is analogous to Tables 7.3.2.3.1.1(A)(b) and 7.3.2.3.1.1(A)(c) within NFPA 2 [1] for gaseous hydrogen bulk storage systems. For a smaller liquid hydrogen system with 12.7 mm (0.5 inch) ID liquid hydrogen lines and a tank MAWP of 828–1,241 kPa (121–180 psi), the exposure distances could be reduced to 3.7, 3.6, and 2.5 m (12.2, 12.0, and

Table 3. Minimum Distance from Outdoor Bulk Liquefied Hydrogen [LH2] Systems to Exposures by Maximum Pipe Size

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

9.4 ft) for Groups 1, 2 and 3 exposures, respectively, which would enable the bulk liquid hydrogen storage container to be sited reasonably close to other buildings, lot lines, or equipment, and achieve a small overall station footprint. Other reductions could be possible by further reducing the line size, tank MAWP, building firewalls, or working with the AHJ to get credit for reducing the tank operating pressure (in lieu of reducing the MAWP of the tank itself).

4.0 SUMMARY AND CONCLUSIONS

In this work, simulations of liquid hydrogen dispersion and flame behavior have been performed to justify exposure separation distances from bulk liquid hydrogen storage. The simulations used the models in the HyRAM toolkit, which have been validated for cryogenic hydrogen. The models showed that a small leak from a liquid hydrogen tank is slightly buoyant, while an ignited leak (flame) would have significant buoyancy. Simulations were performed for a range of leak sizes (1% of the flow area from a 2.54–76.2 mm [0.1–3 inch] pipe) and a range of maximum allowable working pressures (414–1,241 kPa [60–180 psi]).

This work follows a similar analysis as the scientific justification provided in NFPA 2 [1] for exposure distances from bulk gaseous hydrogen storage systems, but for liquid hydrogen. A 1% of the flow area leak was assumed and exposures were placed into 3 groups, each with a single exposure distance. The criteria for the exposure distance in each case was the same as for gaseous hydrogen: the maximum distance to an unignited concentration, ignited heat flux value, or visible flame length. In addition, different exposure levels for the overpressure that would develop from a delayed ignition of a hydrogen leak were determined and this criteria was added to the calculation. A more conservative safety factor of 2 (rather than 1.5, which is used for the gaseous exposure distances in NFPA 2) was used to determine distances from different exposures. Rather than basing the exposure distances on tank volume, as is currently done, the exposure distances in this work are based on the MAWP of the tank and the line size.

For most systems, the distance to Group 1 exposures (which includes lot lines and air intakes) is reduced, relative to the values in NFPA 2. In some cases, the Group 2 exposure distances are smaller than those in NFPA 2, but in others the calculated exposure distances are larger. For the majority of systems, the Group 3 exposures that are currently at 1.5 m (5 ft) will increase. However, the Group 3 exposures are flammable or hazardous materials; the exposure distances are meant to prevent fire spread, so fire walls can be used to mitigate this hazard and reduce the necessary distance.

This analysis is being refined as additional information on leak frequencies is gathered and analyzed. This will allow the selection of leak size to be assessed and updated as needed. Pending that analysis, these scientifically justifiable exposure distances could enable much smaller footprints for hydrogen infrastructure with bulk liquid storage tanks.

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