Sandia National Laboratories | Combustion Research Facility | H_2FC Hydrogen and Fuel Cells Program

SAND2020-6054PE

HyRAM simulations of LH_2 hazard distances

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Background: Gaseous separation distances are broken into groups and exposure distances are related to specific hazards

Table I.1(a) Hazard Scenario

Row	Group 1 Exposures [greater of a or b]	Hazard Scenario Rationale[c]
(a)	Lot lines	1, 2, 3, 4, 5
(b)	Air intakes (HVAC, compressors, other)	1
(c)	Operable openings in buildings and structures	1, 2
(d)	Ignition sources such as open flames and welding	3, 5
Row	**Group 2 Exposures[d]**	**Hazard Scenario Rationale[c]**
(a)	Exposed persons other than those involved in servicing of the system	4
(b)	Parked cars	4
Row	**Group 3 Exposures[e]**	**Hazard Scenario Rationale[c]**
(a)	Buildings of noncombustible non-fire-rated construction	2
(b)	Buildings of combustible construction	2
(c)	Flammable gas storage systems above or below ground	2
(d)	Hazardous materials storage systems above or below ground	6, 7, 8, 9
(e)	Heavy timber, coal, or other slow-burning combustible solids	2
(f)	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	2
(g)	Unopenable openings in buildings and structures	1, 2
(h)	Encroachment by overhead utilities (horizontal distance from the vertical plane below the nearest overhead electrical wire of building service)	2, 10
(i)	Piping containing other hazardous materials	6, 7, 8, 9
(j)	Flammable gas metering and regulating stations such as natural gas or propane	6, 7, 8, 9

[a]Unignited jet concentration decay distance to 4 percent mole fraction (volume fraction) hydrogen.
[b]Drad – radiation heat flux level of 1577 W/m^2.
[c]See Table E.1(b) of NFPA 55 for explanation of notes.
[d]Drad for heat flux level of 4732 W/m^2 exposure to employees for a maximum of 3 minutes.
[e]The greater of Drad for combustible heat flux level of 20,000 W/m^2 or the visible flame length.

Table I.1(b) Hazard Scenario Rationale Notes to Table E.1(a) of NFPA 55

Note Number	Statement	Performance Criteria	Hazardous Materials Design Scenario
1	Gas release and subsequent entrainment or accumulation by the receptor	Exp…	
2	Fire spread to or from adjacent equipment or structure	Pro…	
3	Gas explosion hazard on site or affecting adjacent property	Exp…	
4	Threat of injuries on site or adjacent property	Haz…	
5	Ignition of an unignited release/ vented hydrogen	Exp…	
6	Damage to exposed components of underground system that are exposed above ground	**Property Protection.** The facility design shall limit the effects of all required design scenarios from causing an unacceptable level of property damage. [1:5.2.2.4]	**Hazardous Materials Design Scenario 1.** Hazardous Materials Design Scenario 1 involves an unauthorized release of hazardous materials from a single control area. This design scenario shall address the concern regarding the spread of hazardous conditions from the point of release. [1:5.4.4.1]
7	Damage to aboveground system due to function of explosion control system used to vent underground vault or structure	**Property Protection.** The facility design shall limit the effects of all required design scenarios from causing an unacceptable level of property damage. [1:5.2.2.4] **Explosion Conditions.** The facility design shall provide an acceptable level of safety for occupants and for individuals immediately adjacent to the property from the effects of unintentional detonation or deflagration. [1:5.2.2.2]	**Hazardous Materials Design Scenario 3.** Hazardous Materials Design Scenario 3 involves the application of an external factor to the hazardous material that is likely to result in a fire, explosion, toxic release, or other unsafe condition. This design scenario shall address the concern regarding the initiation of a hazardous materials event by the application of heat, shock, impact, or water onto a hazardous material being stored, used, handled, or dispensed in the facility. [1:5.4.4.3]
8	Fire or explosion in other hazardous materials resulting in release of hydrogen	**Hazardous Materials Exposure.** The facility design shall provide an acceptable level of safety for occupants and for individuals immediately adjacent to the property from the effects of an unauthorized release of hazardous materials or the unintentional reaction of hazardous materials. [1:5.2.2.3]	**Hazardous Materials Design Scenario 3.** Hazardous Materials Design Scenario 3 involves the application of an external factor to the hazardous material that is likely to result in a fire, explosion, toxic release, or other unsafe condition. This design scenario shall address the concern regarding the initiation of a hazardous materials event by the application of heat, shock, impact, or water onto a hazardous material being stored, used, handled, or dispensed in the facility. [1:5.4.4.3]
9	Fire or explosion in hydrogen system resulting in release of other hazardous materials	**Hazardous Materials Exposure.** The facility design shall provide an acceptable level of safety for occupants and for individuals immediately adjacent to the property from the effects of an unauthorized release of hazardous materials or the unintentional reaction of hazardous materials. [1:5.2.2.3]	**Hazardous Materials Design Scenario 2.** Hazardous Materials Design Scenario 2 involves an exposure fire on a location where hazardous materials are stored, used, handled, or dispensed. This design scenario shall address the concern regarding how a fire in a facility affects the safe storage, handling, or use of hazardous materials. [1:5.4.4.2]
10	Failure of equipment exposing hydrogen system to electrical hazard, physical, or health hazard; failure of system exposing utilities to failure	**Property Protection.** The facility design shall limit the effects of all required design scenarios from causing an unacceptable level of property damage. [1:5.2.2.4]	**Hazardous Materials Design Scenario 3.** Hazardous Materials Design Scenario 3 involves the application of an external factor to the hazardous material that is likely to result in a fire, explosion, toxic release, or other unsafe condition.
		Public Welfare. For facilities that serve a public welfare role as defined in 4.1.5 of NFPA 1, the facility design shall limit the effects of all required design scenarios from causing an unacceptable interruption of the facility's mission. [1:5.2.2.5]	This design scenario shall address the concern regarding the initiation of a hazardous materials event by the application of heat, shock, impact, or water onto a hazardous material being stored, used, handled, or dispensed in the facility. [1:5.4.4.3]

Background: Justification for the different exposures is given in both appendix A and I

The exposures integral to Table 7.3.2.3.1.1(A)(a), Table 7.3.2.3.1.1(A)(b), and Table 7.3.2.3.1.1(A)(c) have been arranged into groups based on similar risks. The estimated leak area was changed from 3 percent to 1 percent of the pipe diameter to evaluate separation distances. The thresholds are applicable to the exposures identified in each group, as follows:

(1) *Group 1 Exposures.* The distances specified are those required to reduce the radiant heat flux level to 500 Btu/hr/ft^2 (1577 W/m^2) at the property line or the distance to a point in the unignited hydrogen jet where the hydrogen content is reduced to a 4 percent mole fraction (volume fraction) of hydrogen, whichever is greater. In all cases, the distance required to achieve a 4 percent mole fraction was the greater distance and was used to establish the requirements.

(2) *Group 2 Exposures.* The distances specified are those required to reduce the radiant heat flux level to 1500 Btu/hr/ft^2 (4732 W/m^2) for persons exposed a maximum of 3 minutes.

(3) *Group 3 Exposures.* The distances specified are those required to reduce the radiant heat flux level to 6340 Btu/hr/ft^2 (20,000 W/m^2) or the visible flame length for combustible materials, or a radiant heat flux level of 8000 Btu/hr/ft^2 (25,237 W/m^2) or the visible flame length for noncombustible equipment. In both cases, the visible flame length was used to establish the requirements.

A 50 percent safety factor was added to all resulting separation distance values.

Based on the results of both the system leakage frequency evaluation and the associated risk assessment, a diameter of 3 percent of the flow area corresponding to the largest internal pipe downstream of the highest pressure source in the system is used in the model. The use of a 3 percent leak area results in capturing an estimated 98 percent of the leaks that have been determined to be probable based on detailed analysis of the typical systems employed.

I.4 Selected Heat Flux Values. The values for heat flux used in development of the separation distance tables are as follows:

(1) 1,577 W/m^2 (500 Btu/hr-ft^2)
(2) 4,732 W/m^2 (1,500 Btu/hr-ft^2)
(3) 20,000 W/m^2 (6,340 Btu/hr-ft^2)
(4) 25,237 W/m^2 (8,000 Btu/hr-ft^2)

The basis for using each value is as follows:

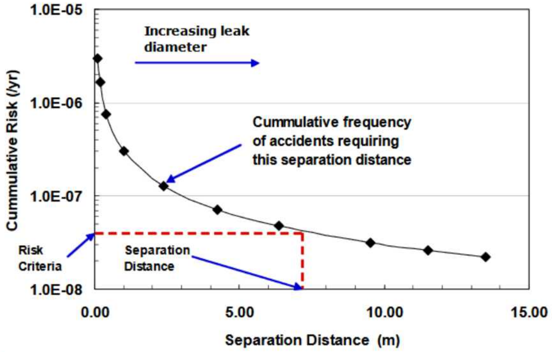
(1) 1,577 W/m^2 (500 Btu/hr-ft^2) is used as the "no harm" value. This heat flux is defined by API 521, *Pressure Relieving and Depressuring Systems,* as the heat flux threshold to which personnel with appropriate clothing can be continuously exposed. [10] This value is slightly less than what the Society of Fire Protection Engineers determined to be the "no harm" heat flux threshold (540 Btu/hr-ft^2), that is, the maximum heat flux to which people can be exposed for prolonged periods of time without experiencing pain. [11]
(2) 4,732 W/m^2 (1,500 Btu/hr-ft^2) is defined by API 521 as the heat flux threshold in areas where emergency actions lasting several minutes might be required by personnel without shielding but with appropriate clothing. [10] It is also defined by the International Fire Code as the threshold for exposure to employees for a maximum of 3 minutes. [12]
(3) 20,000 W/m^2 (6,340 Btu/hr-ft^2) is generally considered the minimum heat flux for the nonpiloted ignition of combustible materials, such as wood. [13]
(4) 25,237 W/m^2 (8,000 Btu/hr-ft^2) is the threshold heat flux imposed by the *International Fire Code* for noncombustible materials. [12]

- With the exception of low temperatures (cryogenic "burns"), there are no additional hazards for LH_2

Possible Ways to Calculate Setback Distances

- Consequence-based
  - Physics/consequence modeling of specified worst-case leak scenario leads to setback distances
  - Criteria and method are conceptually simple and very conservative

- Risk-based
  - Criteria and method are conceptually simple
  - Calculations can be complex and can vary system-to-system



https://www.aiche.org/resources/publications/cep/2020/june/develop-loss-containment-reduction-program-0
SAND2009-0874

Risk-Informed Setback Distances (as per Bulk Gaseous Setbacks)

- Some type of risk analysis informs the scenario selection (leak scenario and criteria)
  - Risk analysis can be HAZOP scenarios, full QRA, or other options
- Physics/consequence modeling on selected scenario leads to setback distances
  - 1% of leak area for gaseous setbacks allowed calculations based on pipe size and pressure
- Setback distance calculation somewhat "uncoupled" from setback distance calculation
  - Setback distance calculation only based on physical modeling of selected scenario
  - ***Scenario selection ultimately a decision by task group/technical committee***
- Risk analysis can "inform" this decision but not "based" on it
  - Scenario differences led to more recent changes in gaseous hydrogen setbacks based on same previous QRA (i.e., 1% instead of 3% leak area, 8% instead of 4% concentration, heat flux values)

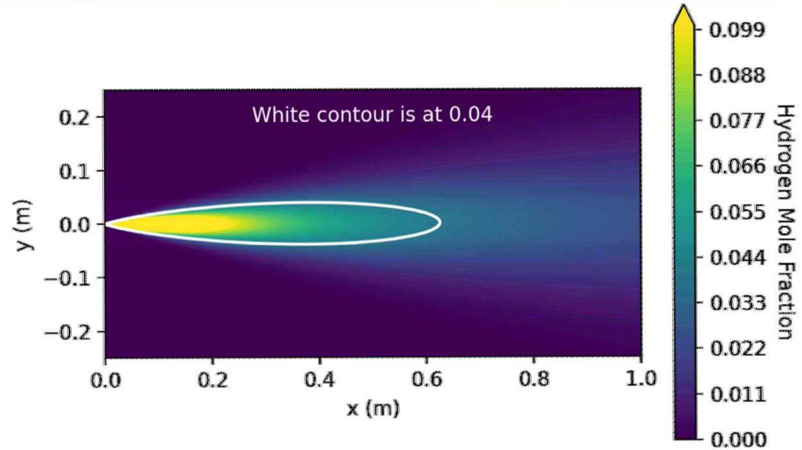
The LH_2 HAZOP identified high-risk scenarios with 2 bounding cases in particular

- Normal flow from trailer vent stack due to venting excess pressure after LH_2 transfer
  - In general, vent stacks on LH_2 systems are unique in that they must be designed for 100% probability of release
  - It might make sense to enable separation of vent stack from bulk LH_2 storage since this could be located away from the storage system and will be at elevation
  - Venting systems refer to CGA G-5.5 (8.3.1.2.2.3)
  - CGA G-5.5 refers back to NFPA 55 for vent location (6.2.8)
  - CGA G-5.5 testing task force looking at thermal radiation from H_2 vent stacks – additional guidance likely to be added to CGA G-5.5
- Loss of containment from pipe leading from tank to vaporizer or vaporizer itself caused by thermal cycles or ice falling from vaporizers
  - In this analysis, we are assuming that a loss of containment does not result in a full bore release
  - Similar to gaseous H_2, the hazard distances do not vary based on volume, but rather pipe size and pressure
  - Safety factor can be added to distance calculation

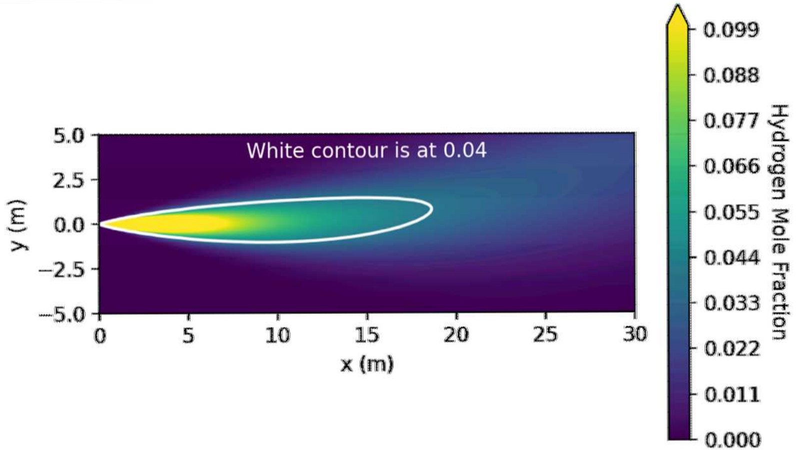
Scenario for Current Calculations

- Same as for Bulk Gaseous Setbacks
  - Does not mean that full quantitative risk assessment has been done for LH_2
  - Does not mean that all LH_2 HAZOP scenarios have been modeled quantitatively
  - Using gaseous scenario and criteria as possible placeholder
- Leak Scenario
  - 1% of flow area
  - Multiple pipe sizes and pressures
- Distance Criteria
  - Group 1: greater of the distances to 8% concentration or 1.577 kW/m^2 heat flux
  - 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 to be determined
  - Current gaseous setbacks use 1.5

Jets are neutrally buoyant



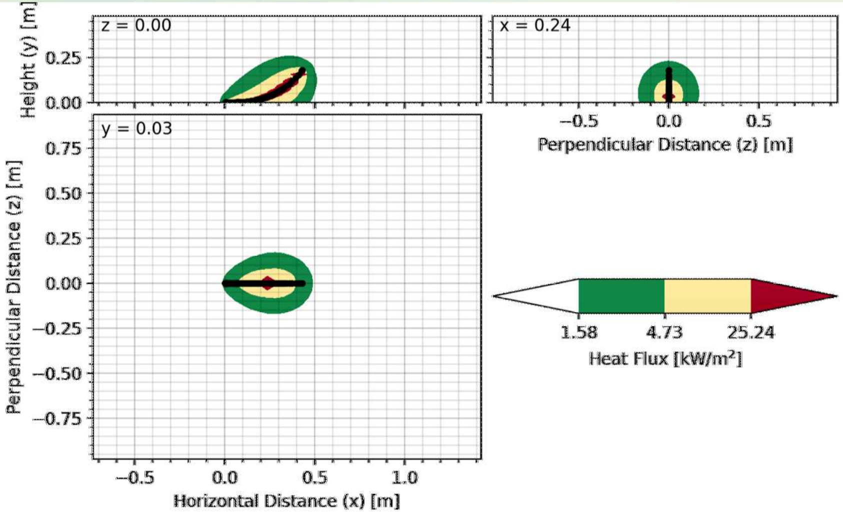
1% area of 0.1” diameter pipe, 100psi, saturated vapor release



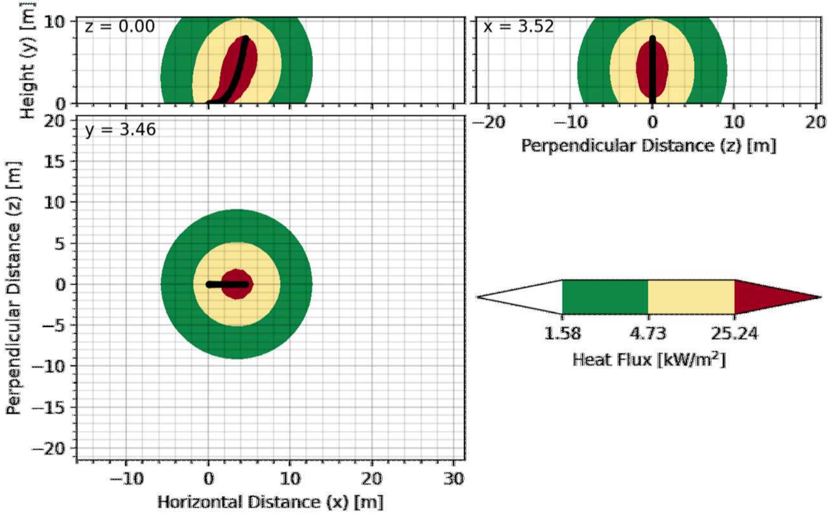
1% area of 3” diameter pipe, 100psi, saturated vapor release

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

Flames are quite buoyant



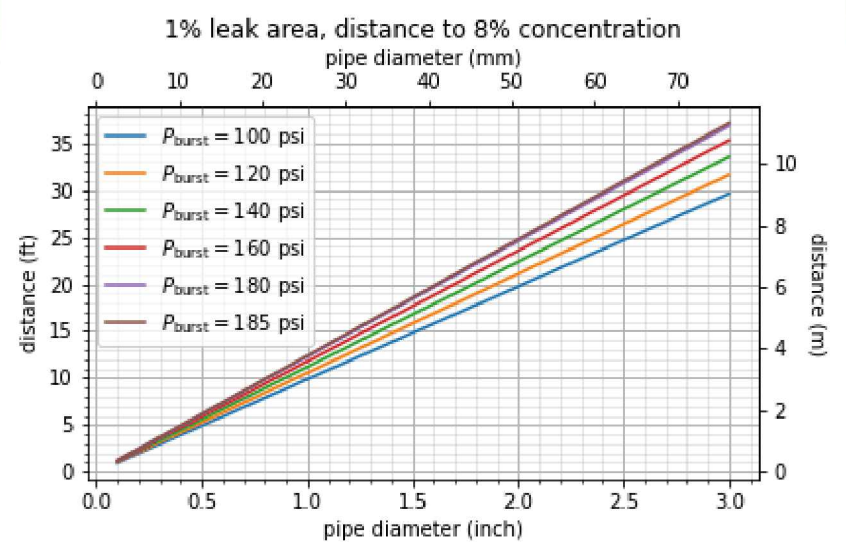
1% area of 0.1" diameter pipe, 185 psi, saturated vapor release

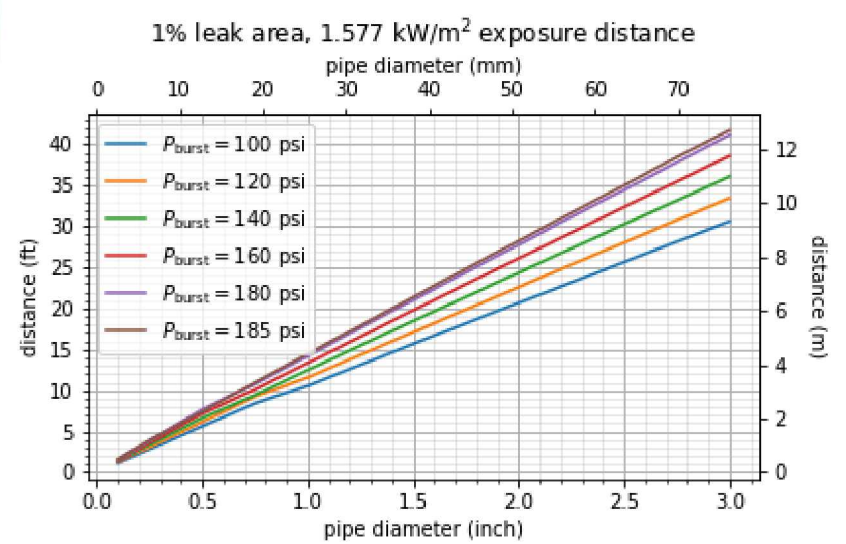


1% area of 3" diameter pipe, 185 psi, saturated vapor release

- Even for the highest momentum release, flames curve significantly upwards due to buoyancy
- Flame length and heat flux values calculated from bird's eye view (xz-plane)

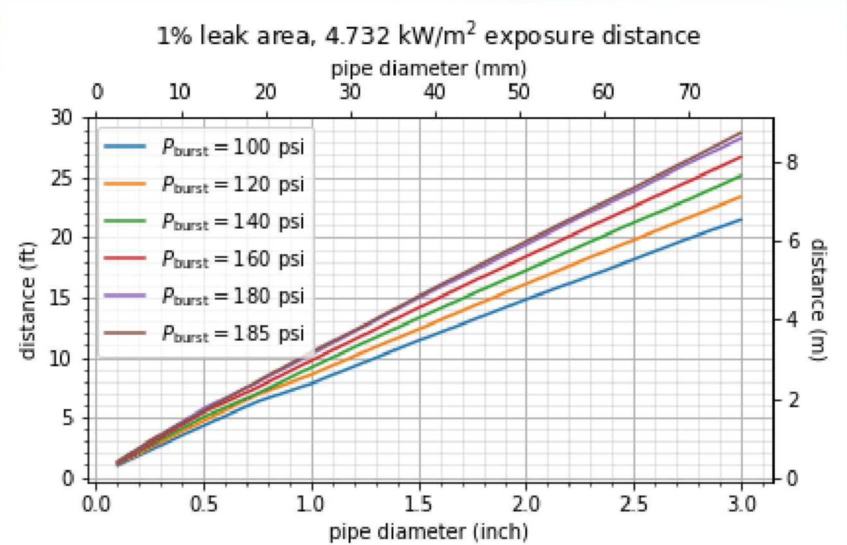
Group 1: greater of 8% concentration or 1.577 kW/m² heat flux





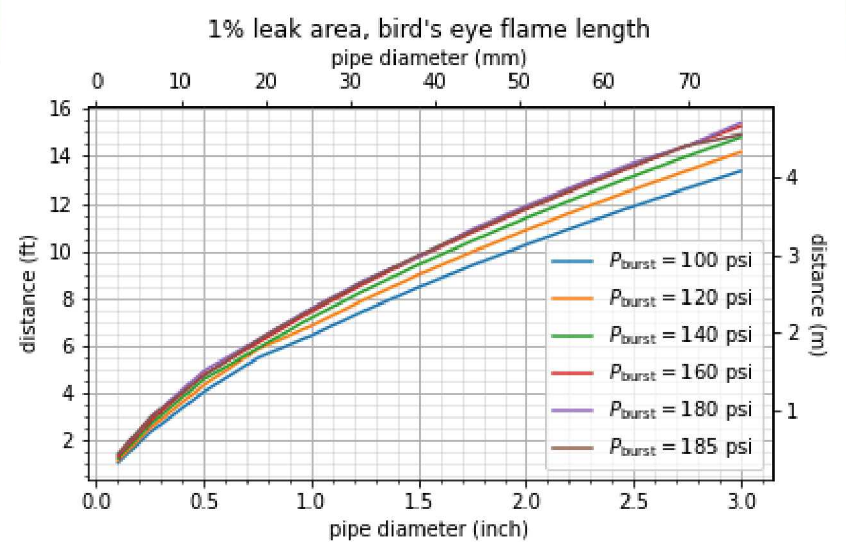
- 1.577 kW/m² exposure slightly greater than 8% concentration
- For characteristic LH_2 pipe with 1.5” ID (maximum line size other than vent stack in CGA P-28), hazard distance is **21 ft (6.5 m)**
- Even with safety factor of 3, this distance is less than current maximum separation distance of 75 ft (23 m)

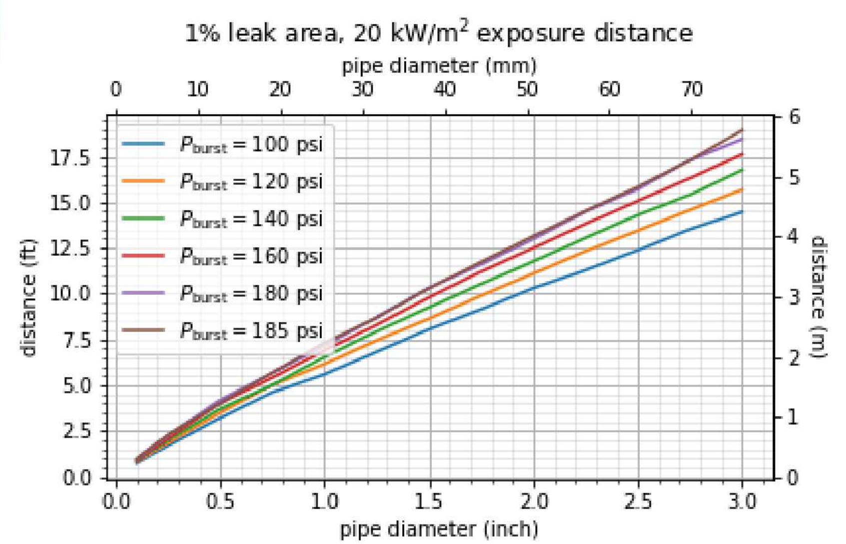
Group 2: distance to a heat flux of 4.732 kW/m²



- For characteristic LH2 pipe with 1.5" ID (maximum line size other than vent stack in CGA P-28), hazard distance is **15 ft (4.6 m)**
- Safety factor will increase this distance
- Currently two Group 2 separation distances of 75 ft [23 m](public assembly) and 25 ft [7.6 m] (parked cars)

Group 3: distance to visible flame length or heat flux of 20 kW/m²





- Flame length longer for small diameter pipes, 20 kW/m² for larger pipes
- For characteristic LH_2 pipe with 1.5" ID (maximum line size other than vent stack in CGA P-28), hazard distance is **10 ft (3 m)**
- Even without safety factor, larger than smallest distance in 8.3.2.3.1.6(A) of 5 ft [1.5m]
- Fire barrier walls used for further reductions

The idea: use these calculations for values in an updated LH_2 exposure distance table with additional analysis to justify and/or modify later

Big changes:

- Exposure distances no longer related to storage volume
- Exposures grouped in similar manner to GH_2 table
- Additional language around vent stack separation from bulk storage

Next steps for this approach:

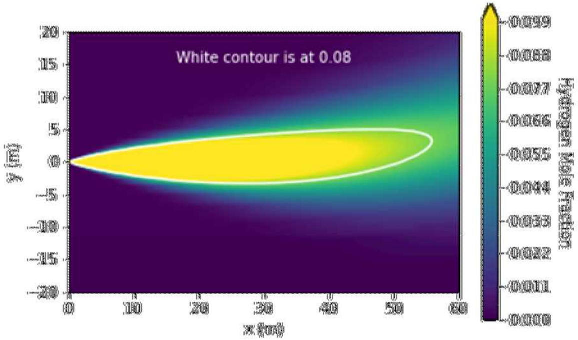
- Regroup and relate exposures to hazards
- Determine safety factor

Subsequent work

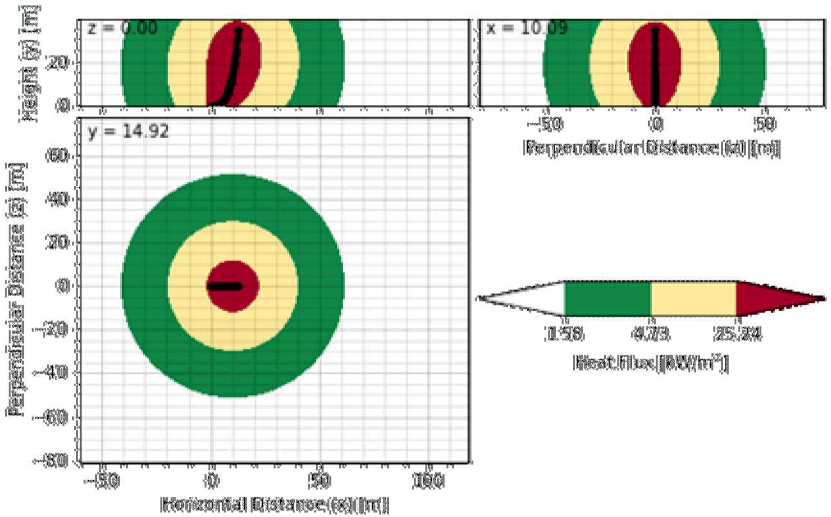
- Use leak frequency and QRA to justify (or update) 1% leak area assumption
- Publish justification of this approach
- Additional validation of model for larger leak sizes
- Assist with guidance around vent stacks (either CGA G-5.5 or NFPA 2)

Discussion?
Questions?

Exposure distances for full bore releases, without accounting for pooling, are large



100% area of 1.5” diameter pipe, 185 psi, saturated vapor release



100% area of 1.5” diameter pipe, 185 psi, saturated vapor release

Distances before safety factor:

- Group 1: 200 ft [61 m]
- Group 2: 130 ft [40 m]
- Group 3: 77 ft [23 m]