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RISK SENSITIVITY STUDY AS THE BASIS FOR RISK-INFORMED CONSEQUENCE-BASED SETBACK DISTANCES FOR LIQUID HYDROGEN STORAGE SYSTEMS

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ABSTRACT

A quantitative risk assessment on a representative liquid hydrogen storage system was performed to identify the main drivers of individual risk and provide a technical basis for revised separation distances for bulk liquid hydrogen storage systems in regulations, codes, and standards requirements. The framework in the Hydrogen Plus Other Alternative Fuels Risk Assessment Models (HyRAM+) toolkit was used, and multiple relevant inputs to the risk assessment (e.g., system pipe size, ignition probabilities) were individually varied. For each set of risk assessment inputs, the individual risk as a function of the distance away from the release point was determined, and the risk-based separation distance was determined from an acceptable risk criterion. These risk-based distances were then converted to equivalent leak size using consequence models that would result in the same distance to selected hazard criteria (i.e., extent of flammable cloud, heat flux, and peak overpressure). The leak sizes were normalized to a fraction of the flow area of the source piping. The resulting equivalent fractional hole sizes for each sensitivity case were then used to inform selection of a conservative fractional flow area leak size of 5% that serves as the basis for consequence-based separation distance calculations. This work demonstrates a method for using a quantitative risk assessment sensitivity study to inform the selection of a basis for determining consequence-based separation distances.

1. INTRODUCTION

Hydrogen systems have multiple layers of safety built into the design of the system itself, how the system should be used, and where the system should be located. These requirements generally defined in various regulations, codes, and standards that pertain to different aspects of system design and operation. Setback (or separation) distances define a prescribed distance between a potentially hazardous system and a person, building, material, or other system that may be exposed to that hazard. Risk-informed separation distances are not meant to completely eliminate risk, but rather to limit the risk to an acceptable level; these separation distances alone may not be adequate protection against very unlikely worst-case scenarios. These distances are in addition to the many other necessary safety design features of the system and are meant to reduce the risk associated with a potential release. Setback distances have a direct impact on the siting and location of a system within a facility, and often define where something like a hydrogen system could be located. Therefore, it is critical that the setback distances be based on a solid technical justification so that these requirements promote safety; at the same time, the distances should not be unnecessarily onerous that they exclude hydrogen systems from more sites than necessary.

An overall approach to the basis and justification for updating setback distances for liquid hydrogen in the 2023 edition of the Hydrogen Technologies Code (NFPA 2) [1] was conceptually similar to the approach taken previously in NFPA 2 for bulk gaseous hydrogen setback distances [2]. Similar to the bulk gaseous hydrogen setback distances, a leak size informed by risk assessments was a critical parameter; this leak size served as a proxy for more detailed and variable risk assessments and allowed consequence-based distances to be calculated based on selected physical criteria. Much like the bulk gaseous hydrogen setback distances, the exposures were grouped into exposure groups, and applicable physical harm criteria were chosen for each exposure group. Finally (and again like the bulk gaseous hydrogen setback distances) setback distances were calculated for bulk liquid hydrogen storage systems based on the chosen leak size and the chosen harm criteria for a range of typical pipe sizes and system pressures, rather than the quantity of hydrogen stored.

This work details the risk-informed selection of the fractional leak size that served as the basis for calculating the new setback distances in NFPA 2, but it is important to consider the context of how and why that leak size is used. Additional details on the setback distance calculations, justifications, and mitigations are published elsewhere [3]; these setback distance calculations utilize the leak size basis described in this work. The new setback distances for liquid hydrogen are based on numerical physical models of liquid hydrogen leak consequences. Therefore, a leak size must be determined in order to provide the basis for the leak simulation that will determine the resulting setback distance. There are many potential ways in which such a leak size could be determined; this analysis considers a novel risk-informed equivalent fractional hole size as a basis.

2. METHODOLOGY

A quantitative risk assessment (QRA) can provide a basis for the determination of setback distances. Separation distances can be risk-based, meaning that they are derived directly from an acceptable level of risk. Separation distances can also be risk-informed, meaning that results utilize insights and justifications from a risk assessment but are not solely based on the results of the risk assessment. In this analysis, a representative example liquid hydrogen storage system was analyzed to develop a risk-informed basis for setback distances. A QRA was performed on the representative system to determine the distance a person would need to be from the system at which a selected individual risk criterion was met. This risk assessment considered multiple leak sizes, the likelihood of each leak size, the likelihood and severity of different consequences of a leak, and the probability of fatality from each consequence. Once this risk-based distance was obtained, an equivalent leak size was calculated based on direct hazard (consequence-based) models that would give the same distance to the hazard criteria as the risk-based distance. A sensitivity study was then performed to vary inputs and assumptions in the risk assessment in order to see how the resulting equivalent leak sizes would vary. Finally, a conservative leak size was selected which was informed by this ensemble of equivalent leak sizes.

2.1. QRA Inputs for Representative Liquid Hydrogen Storage System

While liquid hydrogen storage systems will vary in terms of components used and process flows based on application, the system configuration from the CGA P-28 document [4] was selected as a representative baseline system. From this system, components with which liquid hydrogen interacts were included in the analysis; components that interact with gaseous hydrogen or vacuum were not included. Specific component counts are given in Appendix A. Within the representative system, a single pipe size was assumed with a 4.3 cm (1.7 inch) outer diameter and a 2.5 mm (0.1 inch) wall thickness, resulting in a 3.8 cm (1.5 inch) inner diameter. This pipe size is varied in the analysis as explained below, but in all cases a single pipe size is assumed. This single pipe size is meant to be the maximum pipe size within the storage system; in that sense, this is a conservative assumption, as leaks that originate from smaller pipes that may exist in the system would be limited in their maximum leak size. The fuel within the system was assumed to be pure liquid hydrogen at an absolute pressure of 827 kPa (120 psi) and assumed to be saturated liquid at the leak point. The environment surrounding the system was assumed to be 20°C (68°F) with 90% relative humidity and 101.325 kPa (14.7 psi) absolute pressure (i.e., sea-level). It should be noted that many of these representative base-case inputs are varied in the sensitivity study (see Section 2.4) while others remain constant (see Appendix A for constant inputs).

Leaks are assumed to be horizontal through circular holes with a discharge coefficient of 1. These conditions are used at the leak point itself; no explicit piping effects are considered. This is a conservative assumption, as accounting for piping effects would reduce the pressure and/or density of the hydrogen, leading to a lower release rate. Reduced order physics models are used to model leaks and associated consequences for the hydrogen system. These models simulate steady-state choked flow through the leak orifice and then the unignited plume dispersion without or with ignition leading to overpressure, or ignited jet flame behavior. Although the emptying of a liquid hydrogen system through a leak is a transient process in which the pressure and flow rate decay over time, a steady state flow from the maximum pressure was assumed to be conservative. Version 4.1 of the HyRAM+ software [5] was used to perform the physical leak behavior and risk modeling.

2.2. Risk-Based Distance Calculations

To model risk for a liquid hydrogen storage system, the likelihood of a leak occurring is multiplied by the consequence of the leak and this calculation is repeated for a range of possible leak sizes. The likelihood of a leak is estimated using fault trees with potential leaks coming from different component types. Five leak sizes are considered: 0.01%, 0.1%, 1%, 10%, and 100% of pipe flow area. These fractional leak sizes are applied to the size of the interconnecting piping, meaning that all components result in the same sized leak. The probability of different physical outcomes such as leak detection, no ignition, a jet fire from immediate ignition, or an overpressure from delayed ignition are calculated for different end-states of an event sequence diagram. The physical effects are estimated for a single individual at different horizontal distances away from the leak point (directly in-line with the leak). Fatality probit models for heat flux and overpressure events are then used to determine the spatial distribution of fatality probabilities. Here the consequence of a leak is measured in terms of annual fatalities and risk is shown with a potential loss of life metric. More details on the risk calculations and models used can be found in the HyRAM+ Technical Reference Manual [5].

The system risk was calculated for a single individual at various distances away from the leak point directly in-line with the leak, and the resulting risk was compared to an acceptable level of risk. The risk acceptability criterion used for this analysis was 2×10^{-5} fatalities per year, although this value is varied in the sensitivity study (see Section 2.4). This criterion was originally selected as a risk guideline for a handful of reasons: it was thought to be consistent with risk at existing gasoline stations, was in general agreement with risk criteria being utilized in several countries, represented a low fraction (approximately 5%) of the risk experienced by the public due to all causes, and was roughly equal to the risk imposed by other types of fires [2]. Figure 1 shows the system risk of the representative base case liquid hydrogen storage system as a function of distance. The point at which the risk line intersects with the selected risk criterion line determines the distance away from the system at which that accepted risk level is reached.

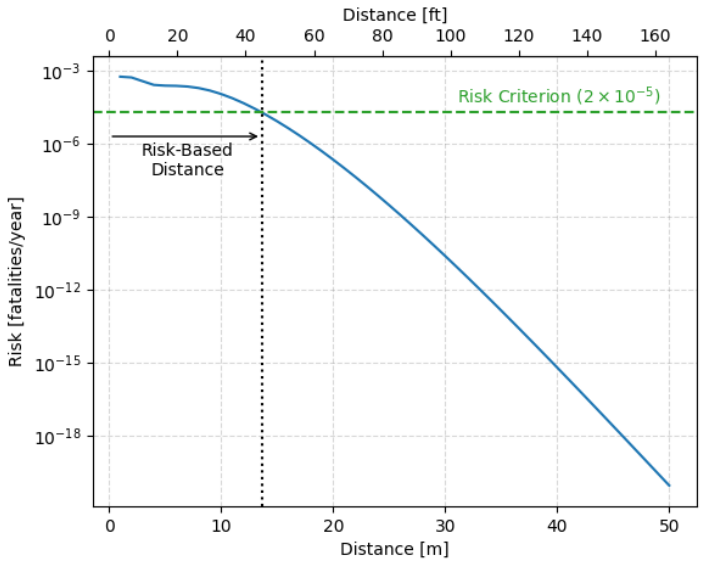

Figure 1. Example risk calculations at various distances away from the leak point for representative liquid hydrogen storage system

2.3. Equivalent Fractional Hole Size Analysis

A risk-based distance alone can be very sensitive to the specifics of the system as well as the uncertainty and variability of model inputs. This can make it difficult to determine a purely risk-based prescriptive general requirement. Instead, the risk-based distances were considered along with the consequence-based models that were used to determine the setback distances to assess what fractional leak size would give the same distances as the risk-based approach. To do this, risk-based distances (as described in Section 2.2) were calculated for a range of pipe sizes, as shown in Figure 2. The range of pipe size is expected to span the variety of liquid hydrogen pipe sizes currently in use. The step-change discontinuity in Figure 2 and subsequent figures is due to the ignition probability value changing with mass flow rate of the leak, as discussed in Appendix A.

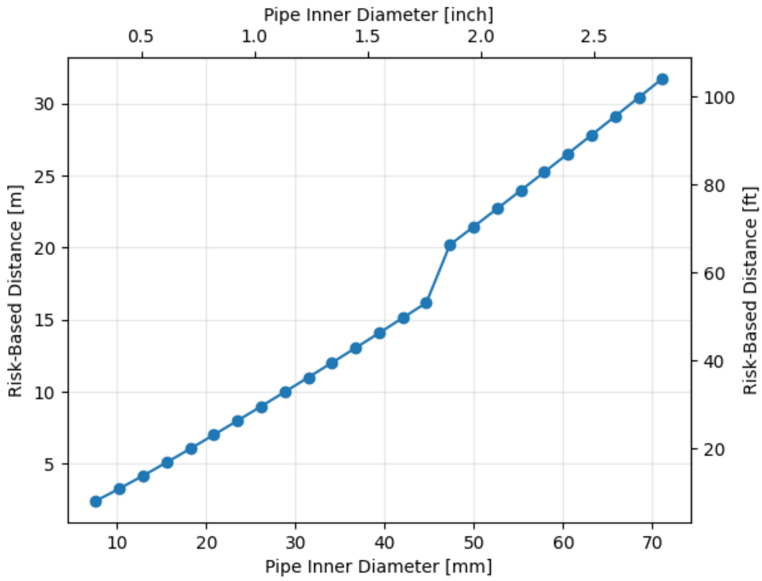

Figure 2. Risk-based distances for a range of pipe sizes when using nominal inputs to the QRA

Once these risk-based distances were obtained, three consequence models were then used to calculate the equivalent hole size that would result in the same distance as each risk-based distance to the respective consequence metrics being met. The three consequence models utilized were based on different physical effects: hydrogen concentration, heat flux, and peak overpressure. Values for those three metrics are provided in Table 1; the reasons for their selection are published elsewhere [3].

Table 1. Consequence metrics used to calculate equivalent fractional leak size from risk-based distance

Metric	Value
Concentration	8% by volume
Heat Flux	4.732 kW/m^2
Peak Overpressure	6.895 kPa (1 psi)

For each risk-based distance (i.e., each point on the line in Figure 2), the consequence models were used to calculate the equivalent hole size that would result in the same distance to the consequence metric as to the risk-based distance. In order to generalize the values, the flow area for the equivalent hole size was divided by the flow area of the specified system pipe size to determine the equivalent fractional hole size. This resulted in an equivalent fractional hole size for each consequence metric over a range of pipe sizes, as shown by the 3 lines in Figure 3. The equivalent fractional hole size tends to increase with increasing pipe size; this is due to the increasing risk-based distances as shown in Figure 2, although the exact shape of the resulting curves depends on the specific physical effect being modeled.

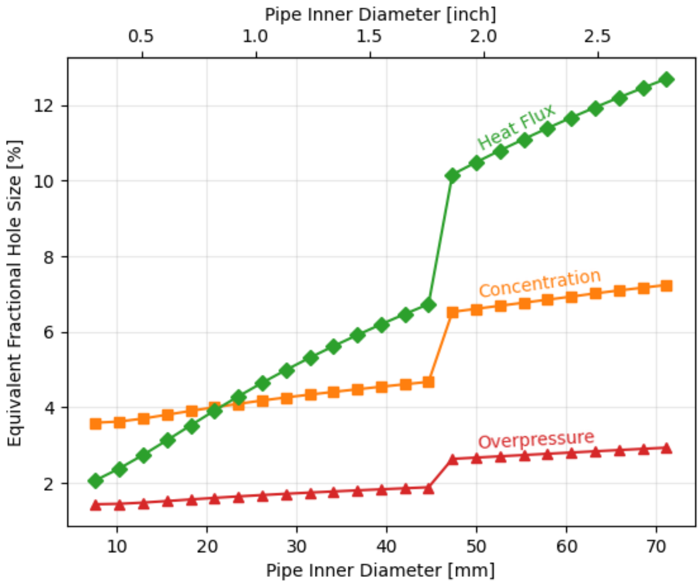

Figure 3. Equivalent fractional hole sizes for each consequence metric for a range of pipe sizes based on nominal inputs to the risk-based distances

The limiting value for each pipe size is the smallest equivalent fractional hole size among the three consequence models. This is because the smallest equivalent fractional hole size would result in a distance equal to the risk-based distance for this set of values (the overpressure curve in Figure 3); the other consequence models, if they used the same fractional hole size, would result in longer distances than the risk-based distance. This minimum value for a range of pipe sizes results in a single functional relationship been equivalent fractional hole size and pipe size for this set of QRA inputs.

Figure 4 shows the resulting minimum curve derived from the three consequence curves in Figure 3. For this particular set of inputs and outputs, the overpressure curve has the minimum equivalent fractional hole size values (see Figure 3), and so the overpressure curve results in the curve shown in Figure 4. However, in other scenarios, other hazards may be dominant, and so the resulting minimum curve maybe based on other hazard curves.

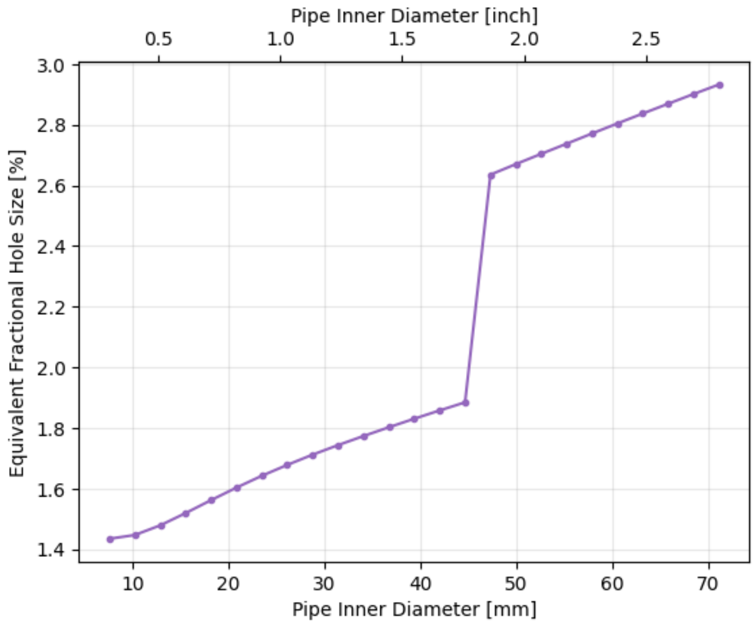

Figure 4. The final equivalent fractional hole size over a range of pipe sizes when using nominal inputs to QRA, based on the minimum equivalent fractional hole size from the three consequence models

2.4. Sensitivity Cases for Risk-Informed Fractional Hole Sizes

In order to account for variability in the risk-based distances due to system variability and analysis assumptions, a sensitivity study was performed. Each varied input was assigned two bounding values that either numerically bound the nominal value or represent alterative options for the assumption. For each of the sensitivity cases below, only one input value was changed at a time while all other values were kept at the nominal values. The varied inputs along with their nominal and alternative values are shown in Table 2. These alternative values characterize some of the extremes of system or model input variability and we wanted to understand the effects of changing a single factor. Combining multiple extreme inputs at a time was thought to be impractical and misleading, although future work could consider combinatorial effects of realistic inputs.

Table 2. Varied inputs for QRA sensitivity cases

Input	Nominal	Alternative Value 1	Alternative Value 2
Detection/Isolation Probability	0.50	0.00	0.95
Fuel Phase	Saturated Liquid	Sub-Cooled Liquid (22.3 K)	Saturated Vapor
Exposure Time (s)	30.0	15.0	60.0
BST Mach Flame Speed	0.35	0.20	5.2
Fuel Pressure (kPa (psi) absolute)	827.4 (120)	413.7 (60)	1289.3 (187)
Ignition Probability Factor	1x	0.5x	2x
Risk Criterion (fatalities/year)	2×10^{-5}	1×10^{-5}	4×10^{-5}
Component Count	69	34	138
Thermal Probit	Eisenberg	Tsao & Perry	TNO
Overpressure Method	BST	TNT	Bauwens/Dorofeev
Relative Humidity (%)	90	1	100
Overpressure Probit	TNO Head	Eisenberg	HSE
Discharge Coefficient	1.0	1.0	0.5

To illustrate the sensitivity of QRA calculations to the parameters included in the sensitivity study, risk-based distances were calculated for each sensitivity case and are shown in Figure 5. Pipe diameter is shown as a parameter in the plot to show the large impact of pipe size (varied from 7.6 mm (0.3 inch) to 71.1 mm (2.8 inch) inner diameter), although pipe size tends to be varied as a parameter in the equivalent fractional hole size plots rather than as a distinct sensitivity case such as those described in Table 2.

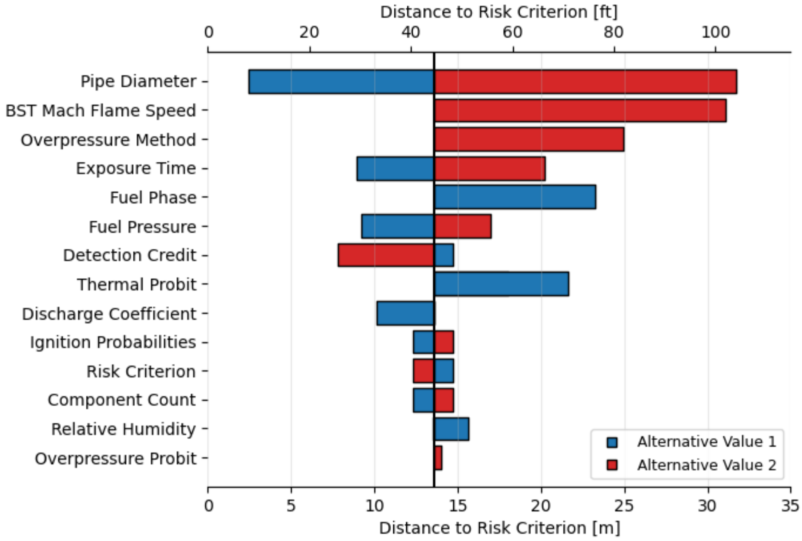

Figure 5. Tornado plot showing the effect of sensitivity cases on risk-based distances

Figure 5 shows that risk-based distances are highly sensitive to pipe diameter due to this determining the mass flow rate of a leak. Both the higher BST Mach Flame speed and Bauwens/Dorofeev overpressure model assume detonation, resulting in large increases to the risk-based distance. Changing the exposure time directly changes the thermal dose (and therefore fatality probability) calculated for heat fluxes from a jet fire. Changing the fuel phase to a sub-cooled liquid can increase the leak source density and mass flow rate which directly affects hazards.

For each of the sensitivity cases described in Table 2 and shown in Figure 5, the same process of determining equivalent fractional hole sizes for risk-based distances for different pipe sizes was performed (as described in Section 2.3). This results in a collection of equivalent fractional hole size values, which can all be compared and considered as a group.

3. RESULTS

The sensitivity study resulted in a group of multiple equivalent fractional hole size values, as shown in Figure 6. For each sensitivity case, one QRA input was varied resulting in a separate equivalent fractional hole size curve.

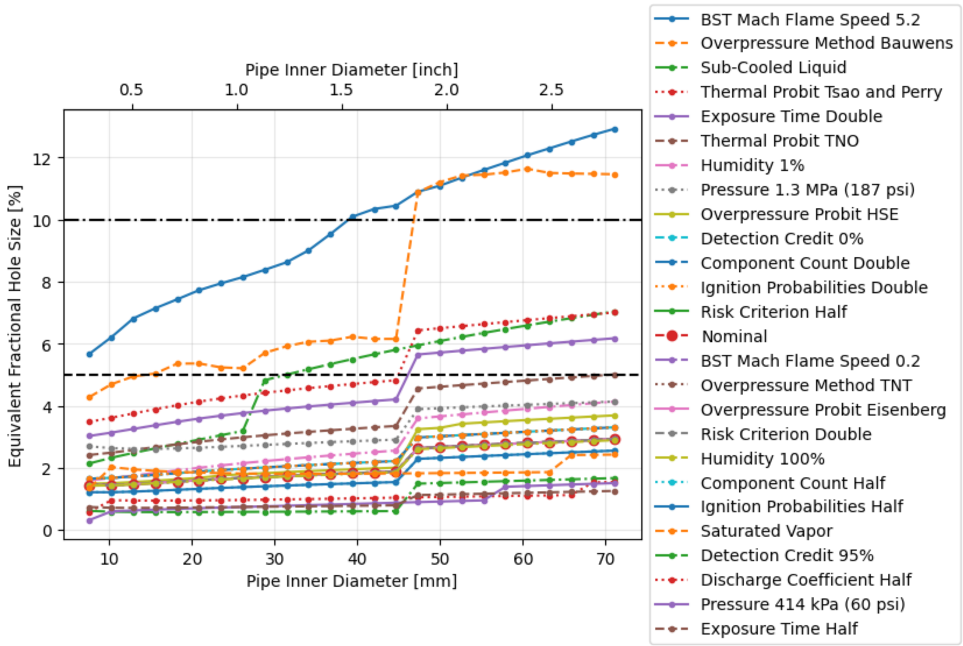

Figure 6. Equivalent fractional hole sizes for different sensitivity cases, each as a function of pipe diameter, with 5% and 10% equivalent fractional hole size marked for clarify

Of the 26 cases included in the sensitivity study, 21 had values that were all below a value of 5% equivalent fractional hole size, even for the largest inner pipe diameter studied. All 5 of the sensitivity cases that had any values above 5% equivalent fractional hole size were already highlighted as being parameters to which the QRA calculations are highly sensitive in the risk-based distance tornado plot (see Figure 5). The 2 cases that had any values that exceeded a 10% equivalent fractional hole size both assumed overpressure models with detonation, which is believed to be unrealistic for the unconfined outdoor release: the BST model with a 5.2 Mach flame speed and the Bauwens/Dorofeev model. For example, Jallais et al. did not observe detonations in their unconfined overpressure outdoor release experiments [6].

The other 3 cases that exceeded 5% hole size (but not 10% hole size) were all considered to use unrealistically conservative assumptions: the leak coming from a sub-cooled liquid source; doubling the exposure time, which doubles the heat flux thermal dose; and using the Tsao and Perry thermal probit model that includes infrared effects. A leak of a sub-cooled liquid would increase the density of the leak flow, potentially leading to more severe consequences. However, this modeling defines the source conditions of the liquid hydrogen at the leak point, not necessarily in the bulk storage. Recent experiments with liquid hydrogen showed difficulty in getting hydrogen to exit an orifice in a liquid state, even though this was the intention of the experimental efforts and the liquid in the storage tank was sub-cooled [7, 8]. Therefore, because of the warming that can occur between the bulk source of hydrogen and a potential leak point, it is assumed that the leak through an orifice of a sub-cooled liquid is unrealistic.

The exposure time input value affects the thermal dose and therefore the thermal harm probability of fatality in the risk assessment. The default value in HyRAM+ was previously 60 seconds [5], but after reviewing the literature basis for this value, 30 seconds was selected as the nominal value for this analysis. Exposure time should reflect the amount of time it takes an individual to move a sufficient distance away from the flame such that they are no longer being harmed, which will be person dependent. Multiple sources suggested that a 30 second exposure time is an appropriate (or even conservative) estimate for this thermal dose and harm calculation [9, 10].

Finally, the Tsao & Perry thermal harm probit includes effects from infrared radiation from nuclear explosions [2, 5, 11]. By contrast, the Eisenberg thermal probit (used as the nominal selection) only considers ultraviolet radiation from explosions. Including infrared effects may be unrealistic for hydrogen fires, which do not radiate as much as hydrocarbon fires due to the relative lack of carbon in the flame [11]. Conversely, the other thermal probit sensitivity case used the TNO probit, which is based on the Tsao & Perry model but modified to account for clothing [5, 11]. Therefore, the use of the Tsao & Perry probit, which overpredicts the effects of radiation from hydrogen fires while also not accounting for clothing, is assumed to be unrealistic for this analysis.

Alternate values for the sensitivity cases were chosen to be bounding, and so some of the inputs chosen were intentionally conservative. For the reasons discussed above, all cases that had any values above a 5% equivalent fractional hole size are considered to be overly conservative. Most of the cases had equivalent fractional hole sizes that for all pipe sizes considered fall below the 5% value. As a result, a 5% fraction hole size was selected as a conservative but not unrealistic risk-informed basis for the setback distance source leak size. It should be noted that none of the scenario lines in Figure 6 line up exactly with the constant 5% equivalent fractional hole size value; this means that no single particular scenario exactly describes the selected 5% equivalent fractional hole size value. Instead, the 5% value was chosen because it was a conservative choice (i.e., the value was greater than most of the scenario values calculated) while not being unrealistic.

4. CONCLUSIONS

A risk analysis for a representative liquid hydrogen storage system was used to determine the distance at which a specified risk criteria was met. Equivalent leak hole sizes were then calculated for concentration, heat-flux, and maximum overpressure consequence models based on meeting specified consequence criteria at the same distance as the risk-based distance. Equivalent fractional hole size values were calculated using those equivalent leak sizes for a range of pipe sizes and then normalizing by the pipe flow area. A sensitivity study was then used to quantify the impact of assumptions and input variability in the risk assessment and resulted in an ensemble of equivalent fractional hole size values. This sensitivity study resulted in the selection of a 5% fractional hole size based on pipe inner flow area as being a conservative, but not unrealistic, basis for liquid hydrogen storage system setback distances. This basis was used (as described elsewhere [3]) to calculate the consequence-based setback distances for bulk liquid hydrogen storage in the recent 2023 edition of NFPA 2 [1].

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APPENDIX A. QUANTITATIVE RISK ASSESSMENT DETAILED INPUTS

The baseline liquid hydrogen storage system included the components listed in Table 3.

Table 3. Part counts of representative liquid hydrogen storage system

Component	Count
Compressors	1
Filters	2
Flanges	8
Instruments	3
Pipes (1 m)	10
Valves	44
Vessels	1

Table 4 shows the parameter values that remained fixed throughout the analyses. Values for component leak frequency were also kept constant throughout the sensitivity cases. The values used were the default liquid hydrogen leak frequency inputs in HyRAM+ version 4.1 [5] for all components, except for compressor (meant to simulate a pump), instrument, and filter; for these components, the default gaseous hydrogen leak frequency inputs were used. It should be noted that these leak frequency parameters are highly uncertain. Because the total system leak frequency for each leak size is a sum of all component leak frequencies weighted by the number of components in the system, the sensitivity cases which doubled or halved the component counts also effectively doubled or halved the leak frequency values. So, while not included as a separate sensitivity case, the variability of these parameters was considered.

Table 4. Constant parameters in the QRA analysis sensitivity cases

Parameter	Value
Ambient temperature	20°C (68°F)

Ambient pressure (absolute)	101.325 kPa (14.7 psi)
Notional nozzle model	Yüceil/Ötügen
Exclusion radius	0.01 m
Dispenser failure probability	0.0 (not used)

Discontinuities can be seen in many of the figures in Section 2.2 through Section 3. These discontinuities are due to the ignition probabilities in HyRAM+ [5]. Ignition probabilities are specified based on mass flow rate and change value at specified mass flow rate thresholds. Figure 7 demonstrates how the mass flow rate increases with pipe inner diameter, but when the flow passes a mass flow rate threshold, a step-change in the ignition probability occurs. The discontinuities in ignition probabilities are propagated through the risk assessment, resulting in discontinuities in the calculated risk-based distances and ultimately the equivalent fractional hole size curves.

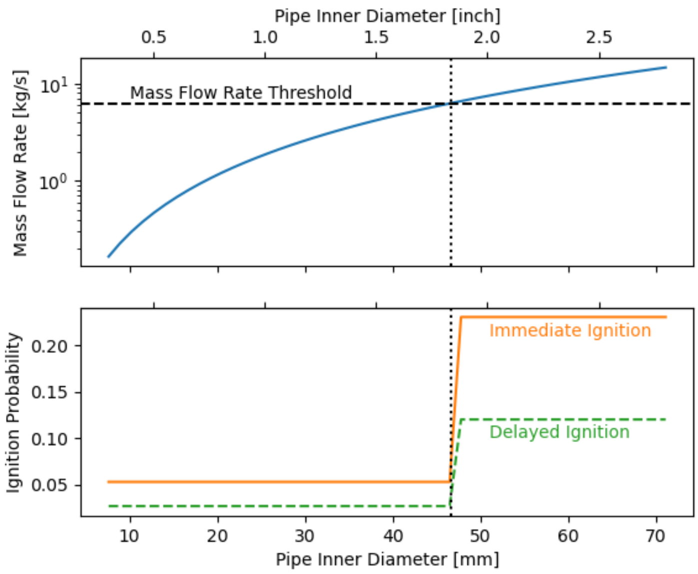

Figure 7. Mass flow rate of the leak affecting the ignition probability values (ignition probabilities only shown for 10% leak size)