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Evaluation of Hydrogen Storage Quantity Limits for Safety Requirements

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ABSTRACT

As hydrogen storage facilities increase in size and capacity, it may be necessary to evaluate codes and standards that regulate hydrogen, especially in relation to allowable aggregate quantities. Existing regulations for other substances with comparable hazards such as oxygen, natural gas, and petroleum were reviewed; most fuels do not have aggregate quantity limits despite sometimes having individual tank capacity restrictions or limits for certain non-industrial, indoor, or small-scale applications. This precedent suggests that specifying a hydrogen quantity limit may not be necessary. Several possible methods for identifying an appropriate limit are presented to illustrate different approaches for a limit basis. These methods are based on overall risk, or the specific consequences inflicted by a jet fire or an explosion on people and infrastructure. However, these example metrics tend to require assumptions about potential leak sizes, suggesting that a general aggregate quantity limit would be difficult to justify without more system-specific requirements.

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EXECUTIVE SUMMARY

As advancements in hydrogen storage continue, it is imperative to continue to understand the implications of larger and larger quantities of stored fuel on risk and safety. Namely, this report focuses on the question of whether it is necessary to limit the quantity of aggregate hydrogen storage at individual facilities to ensure safety for operators and people in surrounding areas.

Existing codes and standards for hydrogen as well as substances with analogous flammability concerns such as oxygen and liquid natural gas were reviewed to understand the existing precedent for fuel quantity limits. While the specifics for each standard and substance differ, they can be categorized into three broad bins. First, there are standards with limits for individual containers but no aggregate limits for the entire facility. Second, there are standards with aggregate fuel quantity thresholds above which certain steps such as hazard analysis or mishap reporting are required; these thresholds do not prohibit those larger stored quantities. Third, there are standards such as the 2023 version of the National Fire Protection Association Hydrogen Technologies Code (NFPA 2) that provide an aggregate stored quantity above which they do not apply; however, these standards do not explicitly state that larger stored quantities are not allowed. Most of the reviewed standards did not have aggregate quantity thresholds.

Potential quantitative methods for determining an aggregate stored hydrogen limit are considered. The proposed method for calculating an aggregate storage limit for gaseous hydrogen involves using scaling components of a modularly designed system as a proxy for system size and stored quantity and comparing risk values from different system sizes. Four different example methods are provided for liquid hydrogen systems. The first method involves comparing risk for systems with different tank and leak size combinations, considering the possibility of the leak igniting into either a jet fire or an explosion. The second method uses heat fluxes from a jet fire, along with building damage metrics such as glass breakage and steel structure collapse, to determine acceptable tank sizes based on leak size. The third method uses flame length to demonstrate the reach of a jet fire. The fourth method maps overpressure across distance to quantify infrastructure explosion damage such as storage tank displacement and steel structure collapse, as well as human harm, such as lung hemorrhage probability and immediate blast fatalities. The first three methods use long blowdown and jet fire times to simulate large quantities of leaking hydrogen that, in a worst-case scenario, cannot be stopped. The fourth method simulates an accumulation of a large quantity of leaking hydrogen that explodes all at once. These quantitative methods are provided as examples that can be used by standards committees, authorities having jurisdiction, and hydrogen storage facility designers as ways to consider potential risks of different system configurations.

Most existing standards for hydrogen and other hazardous substances do not limit outdoor stored quantities, and it is not clear if doing so would significantly improve safety. Some of the reviewed documents provided capacity limits for individual containers, while others provided capacity limits for specific applications, such as residential fueling. In addition, indoor storage quantities are generally limited by the maximum allowable quantity (MAQ) or similar limits determined by the building or fire code; if this MAQ is exceeded, the building must be designed to high-hazard specifications and subject to additional requirements. Most of the documents did not provide a rationale for the capacity limits, so it is unclear whether they were informed by risk or another priority. Example quantitative methods all still rely on some sort of consensus on selected harm or risk metrics. In addition, these methods require multiple assumptions about a particular facility, such as an assumed number of components or an assumed leak size, making it difficult to determine a broadly applicable limit that would be appropriate for different facilities.

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ACRONYMS AND TERMS

Acronym/Term	Definition
BST	Baker-Strehlow-Tang
CGA	Compressed Gas Association
CNG	compressed natural gas
LNG	liquefied natural gas
LP-Gas	Liquefied Petroleum Gas
MAQ	maximum allowable quantity
NASA	National Aeronautics and Space Administration
NFPA	National Fire Protection Association
NSS	NASA Safety Standard
scf	standard cubic feet

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1. INTRODUCTION

The anticipated growth in hydrogen storage systems in the coming years may warrant greater storage capacities at individual facilities [1]. When considering failures resulting in leaks or unintentional releases, large systems may have elevated risks compared to systems with smaller stored quantities, since the consequences of failures like total tank ruptures and complete blowdown may have much more catastrophic effects. Currently, the safety of hydrogen system designs is informed by the National Fire Protection Association (NFPA) Hydrogen Technologies Code (NFPA 2), which contains requirements for setback distances between system components and certain exposures [2]. In the previous versions of NFPA 2, those from 2016 [3] and 2020 [4], setback distances were based on pressure and pipe size for gaseous hydrogen, and pressure and stored volume for liquid hydrogen. However, the 2023 release of NFPA 2 transitioned away from using stored quantity for determining liquid system setback distances and instead now uses system pressure and pipe size. Table 8.3.2.3.1.6 in the 2023 Edition of NFPA 2 currently stipulates that the provided setback distances are valid for stored quantities up to 75,000 gallons [2]. Liquid hydrogen storage quantities above this amount are not prohibited by NFPA 2, however it is unclear what the setback distances should be for systems with greater storage quantities. Other regulations, codes, and standards for flammable or hazardous material storage have different requirements for different storage capacity levels, and so it is worth exploring why these levels were chosen.

The objective of this report is to present approaches to determine limits on storage capacity or design sizing in a hydrogen facility that could be incorporated into codes and standards. First, existing codes and standards for hydrogen and other fuels are reviewed for capacity limits and rationale. Second, five metrics relevant to hydrogen storage risk are presented as approaches to determining safe capacity limits.

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2. STORAGE QUANTITY LIMITS IN EXISTING CODES AND STANDARDS

Existing codes and standards for flammable and combustible fuels and chemicals other than hydrogen, especially those that have been more widely used for commercial or public purposes, can provide guidance on hydrogen regulation. The standards listed in Table 2-1 were reviewed to see if the aggregate capacity of hydrogen and non-hydrogen fuels is currently regulated, and, if so, to understand the reasons for capacity limits. Additional details on these documents, including the specific section numbers which describe these limits, are provided in Appendix A.

Table 2-1. Summary of Codes and Standards with Capacity Thresholds.

Document Number	Version	Document Name	Fuel	Phase	Capacity Thresholds	Reference
ANSI/AIAA G-095A-2017	2017	Guide to Safety of Hydrogen and Hydrogen Systems	Hydrogen	Unspecified	Maximum of 150 kg for transportation in cargo aircraft.	[5]
29 CFR 1910.103	2007	Hydrogen	Hydrogen	Unspecified	None found.	[6]
29 CFR 1910.119	2023	Process safety management of highly hazardous chemicals	Hydrogen	Gaseous	Hazard analysis and mishap investigation and reporting required for aggregate capacities over 10,000 lbs.	[7]
40 CFR 68	2024	Chemical Accident Prevention Provisions	Hydrogen	Unspecified	Aggregate capacity maximum of 10,000 lbs.	[8]
CGA H-3	2013	Cryogenic Hydrogen Storage	Hydrogen	Liquid	Per-tank maximum of 25,000 gal.	[9]
CGA H-5	2014	Bulk Hydrogen Supply Systems	Hydrogen	Gaseous	Minimum of 5000 scf.	[10]
NFPA 2	2023	Hydrogen Technologies Code	Hydrogen	Gaseous	MAQ of 1000 scf for unsprinklered indoor control areas with no gas cabinet, gas room, or exhausted enclosure. MAQ of 2000 scf for unsprinklered indoor control areas with gas cabinet, gas room, or exhausted enclosure, and for sprinklered areas with no gas cabinet, gas room, or exhausted enclosure. MAQ of 4000 scf for sprinklered indoor control areas with gas cabinet, gas room, or exhausted enclosure.	[2]
				Liquid	MAQ of 0 gal for unsprinklered indoor control areas with no gas cabinet, gas room, or exhausted enclosure. MAQ of 45 gal for unsprinklered indoor control areas with gas cabinet, gas room, or exhausted enclosure, and for sprinklered areas. Maximum of 75,000 gal of aggregate capacity.	

Document Number	Version	Document Name	Fuel	Phase	Capacity Thresholds	Reference
NFPA 30	2024	Flammable and Combustible Liquids Code	Ignitable liquids	Liquid	Maximum of 119 gal per individual drum or container, 660 gal per individual portable tank, and 793 gal per intermediate bulk container. Maximum of 30 gal per control area for Class IA liquids. Maximum of 120 gal per control area for Class IB and IC liquids, for combined Class IA/IB/IC liquids and for Class II liquids. Maximum of 330 gal per control area for Class IIIA liquids. Maximum of 13,200 gal per control area for Class IIIB liquids. Maximum of 1,100 gal for outdoor storage adjacent to a building. Maximum of 100,000 gal for individual Class I, II, or IIIA liquid tanks stored in buildings.	[11]
NFPA 30A	2024	Code for Motor Fuel Dispensing Facilities and Repair Garages	Motor fuels	Liquid	Maximum of 12,000 gal for individual tanks or 15,000 gal for tanks installed in vaults. Maximum of 48,000 gal aggregate capacity. Maximum of 120 gal per indoor tank for each of Class I, II, and IIIA motor fuels, with some exceptions.	[12]
NFPA 51	2023	Standard for the Design and Installation of Oxygen-Fuel Gas Systems for Welding, Cutting, and Allied Processes	Oxygen	Gaseous	Maximum of 120 ft^3 for single cylinder.	[13]
NFPA 52	2023	Vehicular Natural Gas Fuel Systems Code	CNG	Gaseous	Maximum of 9 scf per 1000 ft^3 for indoor residential fueling. Maximum of 750 scf aggregate capacity and 433 scf single storage capacity for outdoor residential fueling.	[14]

Document Number	Version	Document Name	Fuel	Phase	Capacity Thresholds	Reference
					Maximum of 3000 scf aggregate volume for outdoor vehicle fueling appliances.	
NFPA 54	2024	National Fuel Gas Code	Fuel Gas (Natural Gas, LP-Gas)	Gaseous	None found	[15]
NFPA 55	2023	Compressed Gases and Cryogenic Fluids Code	Ethylene Oxide	Gaseous	Maximum of 10,000 gal for indoor storage.	[16]
NFPA 58	2024	Liquefied Petroleum Gas Code	LP-Gas	Gaseous	Maximum of 30,000 gal for dispensing systems. Maximum of 300-gal aggregate capacity for containers supplying fuel to LP-gas-powered vehicle.	[17]
NFPA 59A	2023	Standard for the Production, Storage, and Handling of Liquefied Natural Gas (LNG)	LNG	Liquid	Maximum of 1,056,000 gal of aggregate capacity.	[18]

As discussed in the introduction, the 2023 version of NFPA 2 states that its provided setback distances for liquid hydrogen storage systems are applicable for facilities with aggregate quantities that do not exceed 75,000 gallons [2]. There is no documented reason for this limit in NFPA 2. NFPA 59A (2023), which regulates liquefied natural gas storage, limits aggregate storage to 1,056,000 gallons of water capacity [18]. While a reason for this limit is not provided in the document itself, discussions with the NFPA 59A committee suggest that this limit was based on storage vessel construction and availability rather than consequence or risk.

The OSHA regulation 29 CFR 1910.119 (2023) provides an aggregate gaseous hydrogen quantity of 10,000 lbs. as the limit above which additional requirements such as conducting hazard analyses and reporting mishaps apply; however, this stipulation does not necessarily prohibit systems with aggregate capacities above this limit [7]. The Environmental Protection Agency (EPA) Risk Management Program (RMP) regulation 40 CFR 68 (2024) similarly provides 10,000 lbs. as an allowed threshold quantity of hydrogen, although it does not specify a phase [8].

Fuel quantity or capacity thresholds exist in other standards, but not necessarily in a way that is comparable to the current 75,000-gallon aggregate applicability limit for liquid hydrogen storage in NFPA 2; some of the thresholds are on a per-container basis. For example, CGA H-3 (2013) has a capacity limit of 25,000 gallons per tank for cryogenic hydrogen storage [9]. NFPA 30 (2024) has capacity limits for ignitable liquids in containers of 119 gallons, 660 gallons, and 793 gallons for individual drums, portable tanks, and intermediate bulk containers respectively [11]. NFPA 30 also limits ignitable liquids located outdoors and adjacent to a building to 1,100 gallons of storage. NFPA 30A (2024) limits Class I, II, and IIIA liquids to 100,000 gallons per tank stored in a storage tank building [12]. In addition, NFPA 30A limits storage of Class I, II, and IIIA liquids in buildings to 120 gallons per tank and 240 gallons per container. There are also limits for maximum allowable quantities of fuel by control area rather than overall facility: NFPA 30 (2024) and NFPA 55 (2023) both have these types of regulations for ignitable liquids in containers and cryogenic fluids, respectively [11], [16].

Similarly, there are some limits on gaseous hydrogen storage, but by container or specific applications rather than for an entire facility. NFPA 51 has a volume limit of 120 ft^3 for single cylinders of oxygen and fuel gas. NFPA 52 (2023) has a capacity limit of 750 scf for single containers and an aggregate capacity limit of 3,000 scf for outdoor vehicle fueling appliances [14]. NFPA 52 also specifies limits for residential fueling appliances (9.0 scf per indoor appliance, 750 scf total in the residential fueling appliance, and 433 scf per individual container). NFPA 58 (2024) sets a limit of 30,000 gallons on liquefied petroleum gas dispensing systems and 300 gallons of aggregate water capacity for containers used for motor vehicle fuel supply [17]. NFPA 55 (2023) limits indoor ethylene oxide storage to 10,000 pounds [16]. None of these applications can be easily translated to an industrial-scale, outdoor hydrogen storage. The reasoning for these quantity limits was also not provided in the standards.

Additionally, quantity limits were not found in other reviewed document sections, like CGA H-5 (2014), which did not have a limit for bulk hydrogen supply systems [10]. NFPA 55 (2023) does not have a limit for cryogenic fluids [16]. NFPA 52 (2023) does not have a limit for either LNG or CNG outdoor storage or refueling [14]. NFPA 54 (2024) does not place limits on natural gas, manufactured gas, or vapor-phase LPG (which includes fuels like propane and butane) [15]. The

OSHA regulation 29 CFR 1910.103 (2007) provides required setback distances between hydrogen systems and exposures but also does not limit applicability to certain quantities [6].

Like hydrogen, substances such as oxygen, natural gas, and petroleum products present flammability and combustion risks although the specific properties such as flammability range and ignition probability differ. This review of codes and standards reveals that few existing regulations provide an explicit aggregate facility quantity limit for these other, comparably hazardous compressed gases and cryogenic liquids.

3. POTENTIAL BASES FOR A HYDROGEN QUANTITY LIMIT

Although the discussion in the previous section indicates that it may not be necessary to regulate the aggregate quantity of hydrogen stored in a facility, it may still be helpful to propose potential methods that can be used to determine a limit if needed. The following section provides a proposed method and metric for finding an aggregate gaseous hydrogen capacity limit as well as several methods for determining an aggregate liquid hydrogen capacity limit. Suggestions for quantity limits themselves are not provided in this report, since any authorities having jurisdiction may have different preferences or priorities for safety metrics.

3.1. Gaseous Hydrogen

Gaseous hydrogen is generally stored in high-pressure cylinders on the order of 4350 psi (30 MPa) or above, both to sustain a pressure differential between the storage cylinders and the end-use device (such as refueling dispenser systems) and to ensure that sufficient hydrogen is stored for the system to be practical. Many commercially available high-pressure storage systems store gaseous hydrogen modularly, by adding more storage cylinders of some maximum size to a system, rather than increasing the size of the storage cylinders themselves. To see how the risk was affected by gaseous storage quantity, the number of components in our model system was varied by different factors with the assumption that adding storage cylinders would involve adding parallel piping, valves, and instrumentation as well. The component count affects risk because each component has a leak frequency, so scaling the number of components correspondingly scales the number of potential leak points in the system. The default component counts are shown in the table below. These component counts were based on a 100-300 kg/day hydrogen refueling station [19] with the addition of 100 m of piping (i.e., 100 pipe "components").

Table 3-1. Component Counts Used for Example Gaseous Hydrogen System.

Component	Default Number Used
Compressor	2
Vessel	3
Valve	37
Instrument	32
Joint	45
Pipe	100

It should be noted that the risk calculated for this method was not based on actual storage capacity (e.g., the cylinder sizes), and that the sensitivity analysis only depended on the number of components in the system. While this assumption may not be accurate, it follows the current HyRAM+ methodology of evaluating the risk of a steady-state leak, where the component size and the hydrogen temperature and pressure conditions affect the quantified consequence of the leak while the total stored or leaked quantity does not. In other words, the system parameters such as pressure determine the extent of the flammable cloud or jet flame; the storage capacity impacts the duration of that steady state release.

The fuel temperature used was 20°C, the pressure was 15000 psi (103 MPa), and the pipe inner diameter was 6 mm. To scale the size of the system, the component counts were varied by factors of

½, 5, 10, and 50. The quantitative risk assessment (QRA) capabilities in the Hydrogen Plus Other Fuels Risk Assessment Models (HyRAM+) v5.0 [20] were used to compute individual risk from hydrogen system component leaks at different distances and with different component counts. HyRAM+ uses annual component leak frequencies and ignition probabilities in addition to quantified consequences of ignition events (jet fires and overpressure events) to calculate individual risk. The risk metric of interest in this study was the annual frequency of fatality for a person in the gaseous hydrogen facility. These results are plotted in Figure 3-1. The graph shows the risk to an individual in number of fatalities per year, for a person who spends 2000 hours of the year in the facility and is located directly in front of any leak that occurs; the x-axis shows the individual's distance away from the leak. The relative difference for the scaled and default component counts are calculated using the equation in Appendix B and shown in Figure 3-2.

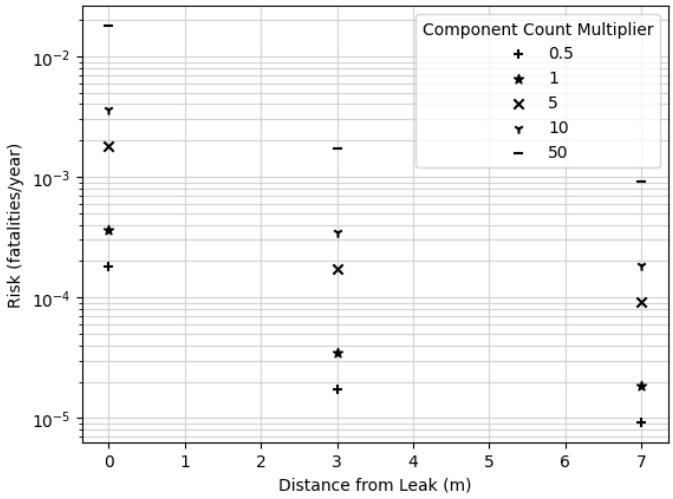


Figure 3-1. Risk over distance using varied component counts.

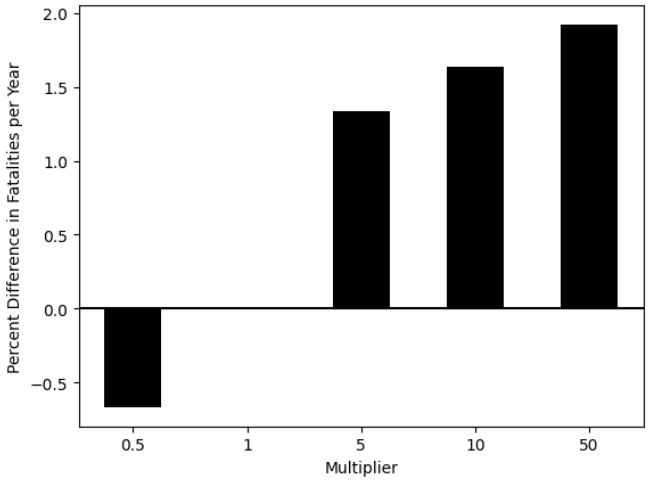


Figure 3-2. Graphed percent differences in risk between scaled and default component counts for a person located three meters in front of the leak.

The percent differences show that scaling the system by component by around 5 times changes the risk by a single order of magnitude. Scaling the system up by component to 50 times changes the risk more, but not much more, than scaling the system 5 times – a component count factor of 50

still increases risk within a single order of magnitude. Scaling the number of components could approximately represent a scaling of the storage capacity; if the same per-tank storage capacity is used, then multiplying the number of storage tanks and other components directly associated with them would multiply the storage capacity accordingly (some components such as compressors may not be scaled up with the number of tanks, but all components have been scaled in this study for simplicity). However, it is also possible to increase or decrease the number of components for the same amount of storage capacity by using larger capacity tanks. This example calculation is meant to show the effect on risk metrics by scaling the number of leak points in a system, which is likely at least somewhat correlated with gaseous hydrogen storage capacity, but it is also likely not a 1:1 correlation.

Risk mitigation measures such as barrier walls and automatic shutoffs could potentially change the effects of scaling seen in Figure 3-2. For example, assuming the presence of a blast/fire wall between the leaking component and the individual could lead to reduction of risk to negligible levels regardless of how many components are in the system.

It should be noted that the leak frequencies used in the results presented here are based on the dataset in HyRAM+ v5.1, and there are still high levels of uncertainty due to lack of empirical hydrogen leak frequency data. More accurate leak frequencies could change these results; however, the impact of uncertainty in the data is not currently accounted for in risk calculations. Additionally, the leak frequencies for components in a particular system could deviate from the leak frequencies in the HyRAM+ dataset if leak prevention measures such as component welding or installation of isolation valves are implemented in the system.

3.2. Liquid Hydrogen

Liquid hydrogen storage requires cryogenic temperatures and can be stored at pressures closer to ambient. These conditions mean that it would make sense to scale up hydrogen storage by tank capacity rather than modularly like gaseous hydrogen. Cryogenic hydrogen is often stored in spheres, which means larger, rather than additional, vessels would be more economical and energy efficient, promoting the lowest possible surface area:volume ratio through which heat can transfer.

The default HyRAM+ QRA and effects are used to calculate the steady state conditions from a leak at the initial (maximum) tank pressure. However, the temporal nature of the consequences from very large-scale storage systems is an important aspect to capture when determining a quantity threshold above which additional considerations should be introduced in QRA methods and regulatory activities. The blowdowns and therefore effects from large-scale systems will last for longer. In addition, larger quantities of leaked or leaking fuel could cause physical outcomes of leaks, such as overpressure events, to be more severe. These two considerations of leak time and leak quantity both contribute to the potential for greater risk to human safety and infrastructure integrity.

A number of different example methodologies are used to illustrate possible approaches to assessing safety risks from various sized tanks and are summarized in

Table 3-2. The hydrogen conditions used for all the examples shown below were 30 K and 145 psi (1 MPa). The first method uses acceptable risk to operators within the vicinity of the storage system as a metric to determine a large-scale threshold based on leak size and tank volume/stored quantity combinations with 2-hour blowdown times. The second and third method use damage to nearby buildings due to heat flux over 30-minutes and 2-hours to characterize the extent and reach of

building damage from a jet flame. The final method uses distances affected by different levels of overpressure as a way to quantify safe quantities of hydrogen for storage; the last method focuses on metrics of building damage and harm to people from overpressure events.

Table 3-2. Summary of potential liquid hydrogen quantity limit determination methods.

Method	Metric	Failure Mode	Physical Effects	Varied Parameters	Constant Parameters
1	Individual risk	Full-bore leak	Heat flux over 2 hours Overpressure	Leak/tank size combination	Blowdown time (2 hours)
2	Building damage	Full-bore leak	Heat flux over 30 minutes	Leak size, tank size	
3	Building damage	Full-bore leak	Flame length at 2 hours	Leak size, tank size	
4	Hazard distances	Tank rupture	Overpressure	Stored quantity (available flammable mass)	Mach flame speed (5.2)

3.2.1. Method 1: Operator Risk from a Two-Hour Blowdown

For the first method, the range of volumes to test was 100 to 3000 cubic meters, corresponding to a range of 5.6 to around 168 metric tons of hydrogen based on the conditions considered. Each volume was matched with the leak size that would lead to a blowdown time of two hours. The overpressure risk was calculated based on the fuel conditions and was independent of time or fuel quantity, while the risk from heat flux depends on the time that the person is exposed to the jet flame. The person's duration of exposure to the jet fire was assumed to be the entire two-hour period – while this is not a realistic assumption, it would show the worst-case scenario if an individual were unable to evacuate or take mitigative action for the entire blowdown period. The person was also assumed to be directly in front of the leak.

The results are presented in three different ways and described in Figure 3-3.

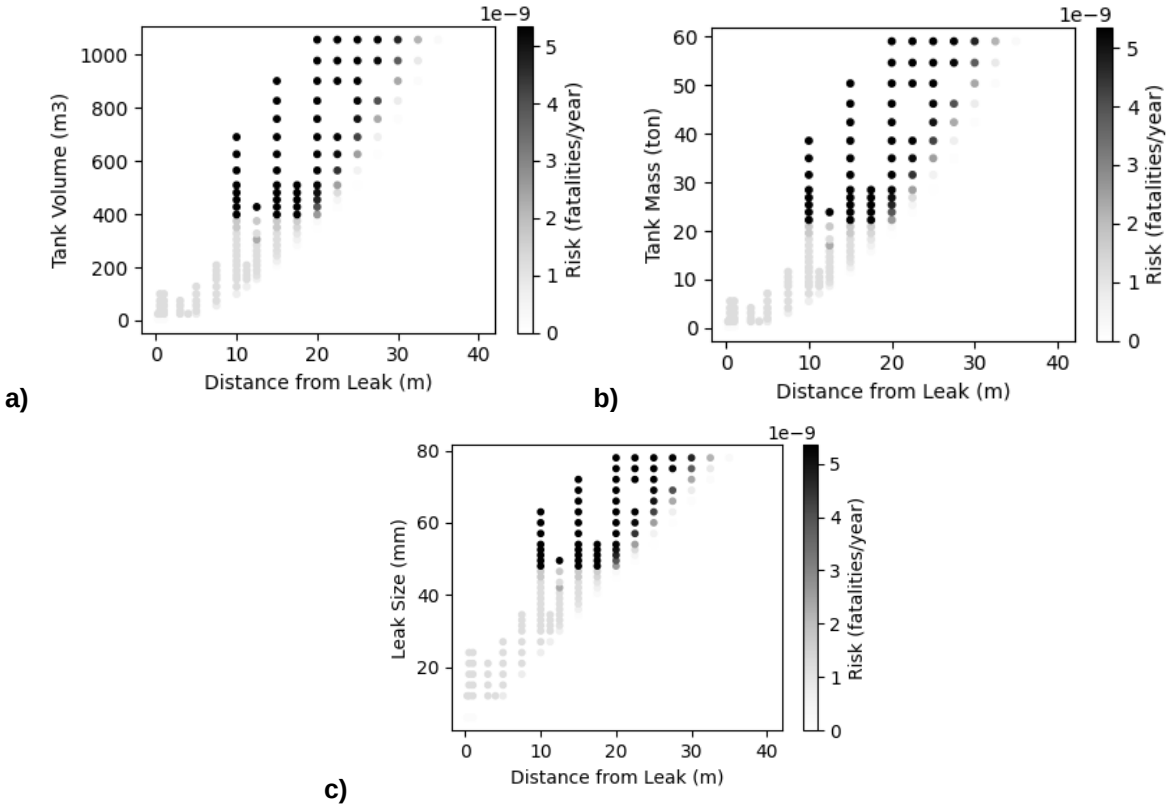


Figure 3-3. Individual risk under example worst-case scenarios, by distance based on a) tank volume, b) mass of stored hydrogen, and c) leak size. Results are determined by HyRAM+ [20].

The graphs and their associated metrics can be used to create quantity thresholds using different perspectives though they describe the same physical systems on the y-axis (each tank volume is associated with a single storage mass and leak size). Figure 3-3(a) frames the risk based on tank volume, which is a useful metric when considering space constraints, while Figure 3-3(b) uses storage capacity mass as the metric of interest, which is an indicator of stored energy capacity. Finally, Figure 3-3(c) shows the risk based on the leak size, which is more related to the desired rate of distribution and flow through the system. One way this approach can be used is by establishing an acceptable level of individual risk to operators within the vicinity of the storage. That threshold can then be used to determine a volume/mass/leak size for a certain fuel pressure and temperature. These types of graphs can also be generated for tank geometries with a different blowdown time, if two hours is determined to not be a suitable characterization.

It should be noted that, for this example, even the highest risk values are on the order of 10^{-9} fatalities per year, which is much lower than the acceptable risk limit of 2×10^{-5} fatalities per year that was used to develop setback distances in NFPA 2 [21], [22]. The risk is limited to this order of magnitude because the default leak frequency for a full-bore leak from a vessel in HyRAM+ is 2.3×10^{-7}/year. Once the leak occurs, there is still a 90% probability of leak detection and isolation and at most a 35% probability of either immediate or delayed ignition (depending on the mass flow rate). These two considerations also contribute to lower the risk in this example scenario.

The difference in risk between a tank blowdown that leads to 5×10^{-9} fatalities per year compared to 1×10^{-9} fatalities per year is likely not enough to drive decision-making or the development of tank

size thresholds. This metric could potentially be used with other fuel conditions and may be useful if it yields more significant risk differences for different tank sizes. Otherwise, this metric may not be as helpful as the other metrics presented in this report for developing hydrogen storage quantity thresholds.

3.2.2. Method 2: Extent of Building Damage from Thirty-Minute Heat Flux

Another possible method of determining large-scale storage quantities that may require additional safety requirements is to use specific physical effects from the release of fuel (such as heat flux and overpressure from jet fires and explosions, respectively) to quantify the amount of damage or affected distances. Harm metrics from these effects should also include harm not only to people but also to infrastructure in the vicinity of an accidental fuel release. This second example approach uses heat flux from a potential jet fire to demonstrate a method of determining large-scale thresholds based on accepted levels of damage to buildings near the stored fuel. LaChance et. al. provides heat flux levels associated with certain types of building damage over a thirty-minute period [23], which are summarized in Table 3-3 below.

Table 3-3. Damage to structures and equipment from thermal radiation, reformatted from [23].

Thermal Radiation Intensity (kW/m^2)	Type of Damage
4	Glass breakage (30 min exposure)
12.5-15	Piloted ignition of wood, melting of plastics (>30 min exposure)
18-20	Cable insulation degrades (>30 min exposure)
10 or 20	Ignition of fuel oil (120 or 40 s, respectively)
25-32	Unpiloted ignition of wood, steel deformation (>30 min exposure)
35-37.5	Process equipment and structural damage (including storage tanks) (>30 min exposure time)
100	Steel structure collapse (>30 min exposure)

For this approach, pipe diameters and stored flammable masses were varied and, unlike in the previous analysis, blowdown time was no longer a constant. The heat flux was calculated at a distance of 10 meters from the leak point at 30 minutes after the leak started. The heat flux from a jet fire is greatest at the onset of the leak and it gradually decreases over time; thus, the points in Figure 3-4 show the minimum heat flux during the 30-minute period.

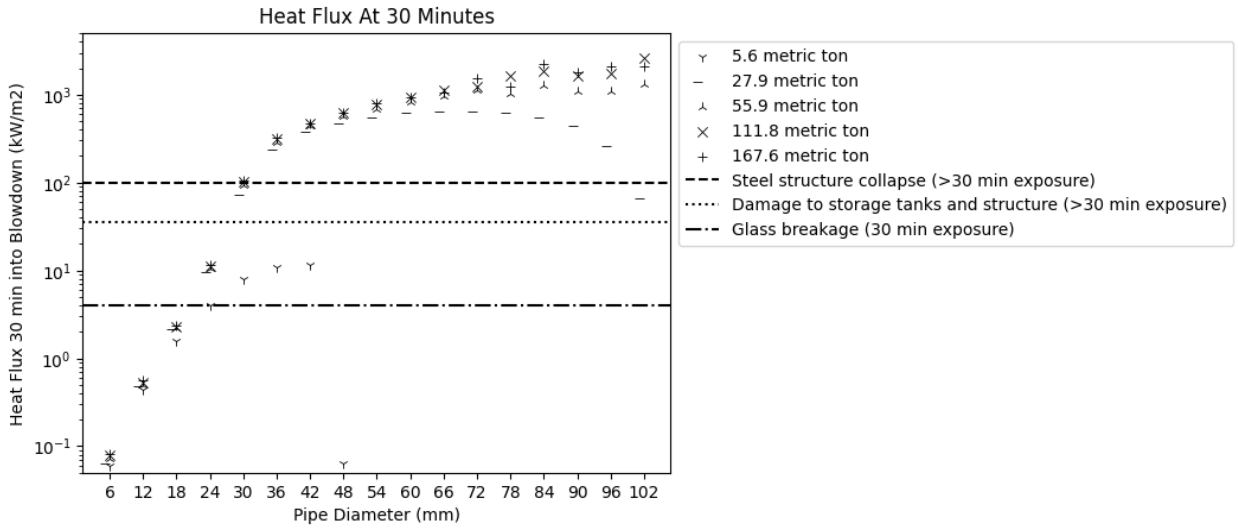


Figure 3-4. Incident heat flux 10 meters in front of a leak 30 minutes after the full-bore leak began.

This method can be used to determine large-scale tank capacities of interest in terms of stored mass/tank volume and leak size depending on storage conditions like temperature and pressure, based on accepted levels of building damage [23] at certain distances from potential leak points. The method can also be used to calculate heat flux harm based on different variables; for example, leak diameter can be held constant while distance can be varied.

3.2.3. Method 3: Affected Distance from Two-Hour Flame

While Method 2 uses the extent of damage based on heat flux intensity as an indicator of harm, Method 3 uses the affected distance from heat flux intensity as an indicator of harm. The flame length two hours after the start of the leak for different leak size/stored quantity combinations is shown in Figure 3-5. This two-hour period is a long blowdown time (like in Method 1), but this analysis can be redone for shorter times. As mentioned in the previous section, the flow rate of a leak and the flame length is greatest at the start of the leak since the pressure in the tank is highest then and decreases as the tank empties. Therefore, the points shown are the minimum flame lengths over the two-hour period, indicating the minimum affected distance.

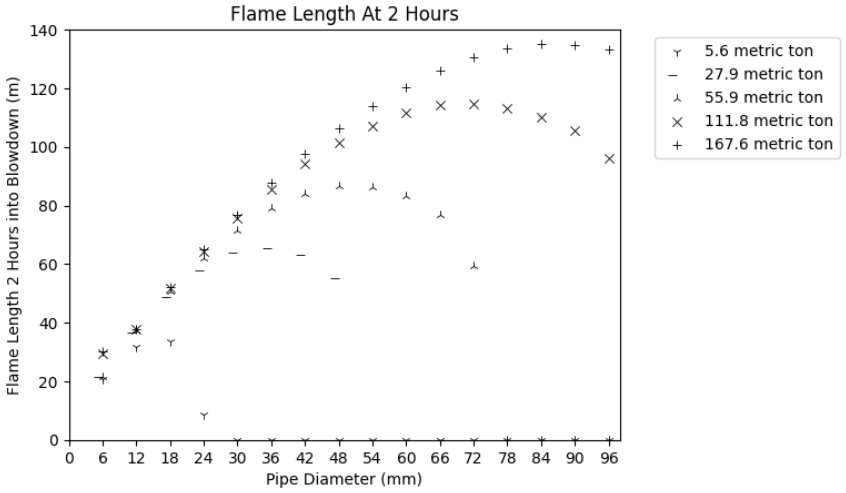


Figure 3-5. Flame length at 2 hours for a full-bore leak from different leak diameters and stored quantity combinations.

This approach could be used to identify appropriate setback distances based on storage conditions, leak size, and stored quantity. Alternatively, it can indicate which stored quantities may require greater regulation or consideration since the harmful condition (flame length) remains present even after such a long period of time.

Another hazard to consider is the maximum flame length that can occur during a leak. The maximum flow rate and associated flame length from the onset of the leak was plotted in Figure 3-6 below based on leak size. The maximum leak flow rate and flame length is dependent on the leak size when the flow is choked, which is the case for all the scenarios in this report since the tank pressures are all significantly above ambient. Since neither the leak size nor the tank pressure depends on the stored quantity of fuel, using the maximum flame length as a metric for determining a large-scale storage threshold would require using leak size as a proxy. For example, a correlation between stored quantity and pipe size may be needed – facilities with higher capacities may be able distribute greater amounts of fuel per day and would therefore need larger pipes. Larger pipes may lead to larger leaks because leaks are assumed to occur at the connections between components, whose sizing may be based on pipe diameter. However, there is no existing fixed correlation between stored quantity and leak size based on either a physical or regulatory rationale. This information, therefore, is more supplementary than directly applicable to large-scale system regulation.

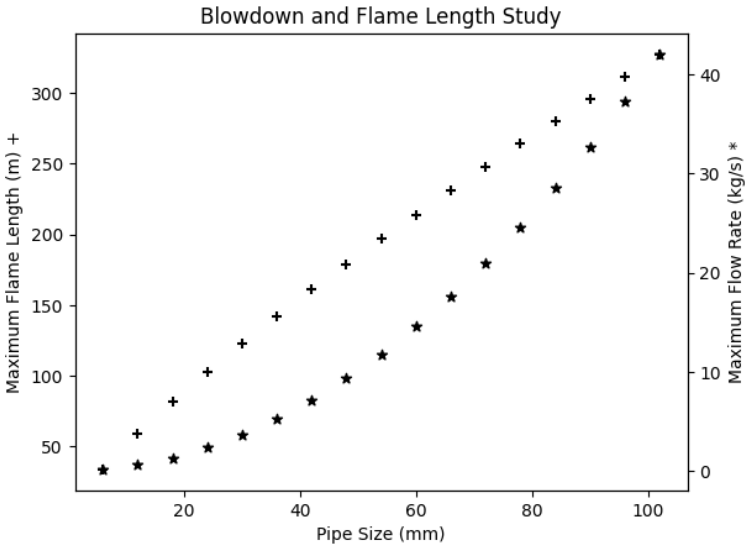


Figure 3-6. Maximum flame length and maximum release rate of fuel from an orifice at the onset of the leak. The left axis corresponds to the '+' markers while the right axis corresponds to the '*' markers. A full-bore leak is assumed.

3.2.4. Method 4: Hazard Distances

A jet fire is a potential physical effect that can occur from the immediate ignition of released fuel; the other harmful potential effect is an explosion, which occurs when released fuel accumulates and ignites after a delay. Therefore, a comprehensive approach to determine additional safety recommendations or regulations for large-scale storage should consider both consequences.

This approach maps overpressure over distance for different stored flammable masses, in the event that a large-enough leak occurs for the entire contents of the storage tank to be released nearly simultaneously. This is a conservative calculation as there are likely more in-between cases where only part of the stored fuel is released to the air or only part of the released fuel ends up igniting. Released cryogenic hydrogen can quickly become buoyant, meaning that dispersion and dilution below the flammability range will occur even while a large-scale leak is on-going. When there are larger quantities of flammable mass that undergo delayed ignition, peak overpressures reach farther, and the overpressure drops off over a longer distance from the leak. Thus, infrastructure beyond the facility in addition to infrastructure within the facility may be at risk of being damaged from catastrophic failure events in large-scale hydrogen storage facilities. The affected distances of high levels of overpressure based on this conservative calculation may be a way to compare storage quantities per facility or per tank and can contribute to a development of a threshold for large-scale storage.

The results, using the Baker-Strehlow-Tang (BST) vapor cloud explosion method used from HyRAM+ [20] and a conservative Mach flame speed of 5.2, are shown in Figure 3-7. The graph shows that high overpressures generated from an explosion event blast wave are experienced at distances farther away from the leak origin (where the distance from the leak is 0 m) and from the locations at which the peak overpressure is encountered. For example, immediate blast fatalities would occur in around an 8-meter radius of an overpressure event from a plume with 15 kg of flammable hydrogen, while they might occur in a 35-meter radius of an overpressure event from a plume with 1000 kg of flammable hydrogen.

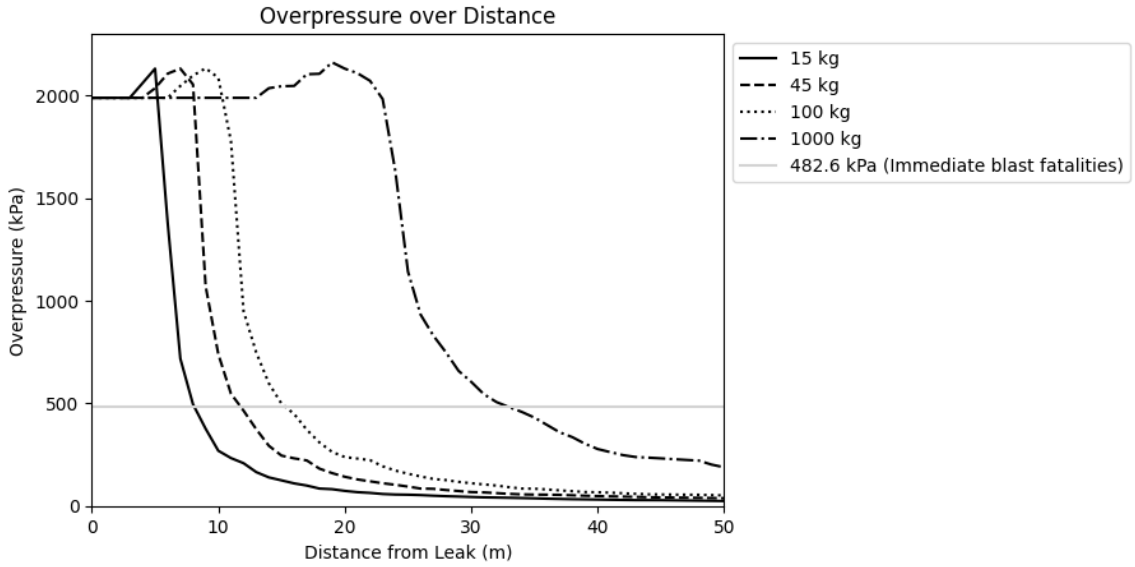


Figure 3-7. Overpressure profile over distance for different stored quantities of hydrogen, in metric tons.

The distances to different levels of harm to buildings from overpressure [23] can also be mapped for the stored quantities of interest, to demonstrate possible criteria that can be used for regulatory recommendations or requirements like setback distances and stored quantity limitations. Figure 3-8 below shows how high overpressures leading to infrastructure harm like storage tank displacement, building destruction, and steel framework collapse occur at much farther distances for larger quantities. The distance from the leak to the overpressure level of interest approximately doubles when the stored quantity increases by a factor of 10; this doubling effect means that the affected distance is more sensitive to stored quantity for lower values of overpressure.

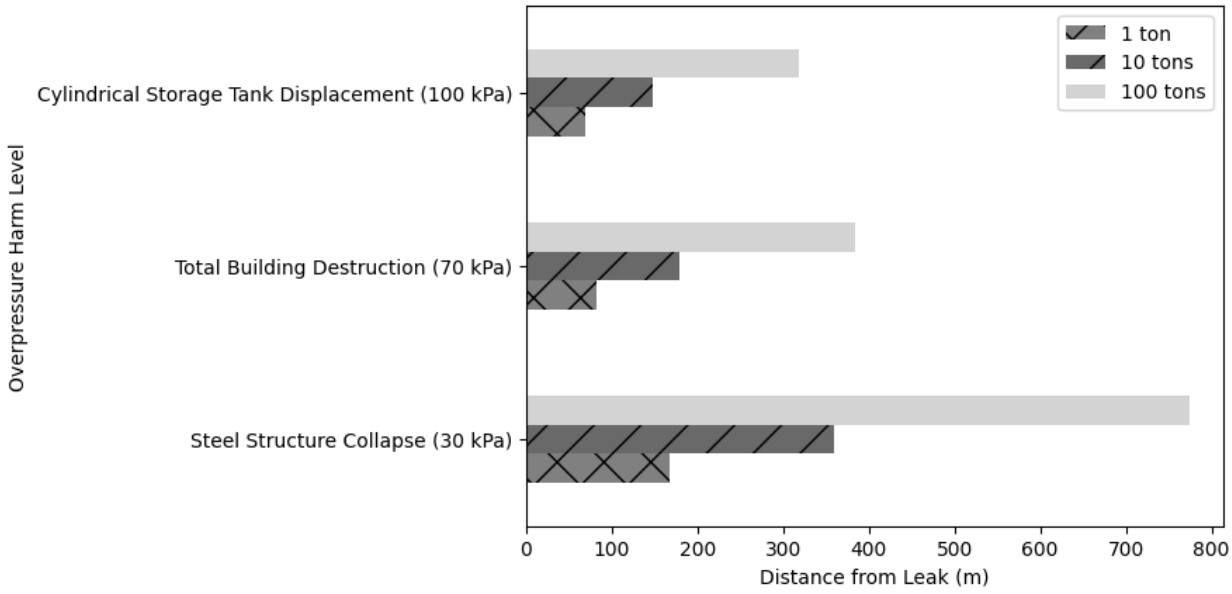


Figure 3-8. Distances to different levels of harm to infrastructure from overpressure. Overpressure levels taken from [23].

Figure 3-8 indicates that harmfully high overpressures to buildings from catastrophic failure of large amounts of stored fuel can reach tens and even hundreds of meters from the source of the released fuel. These overpressures can affect people as well as infrastructure outside of the facility. The distances to overpressures that lead to immediate fatalities, a 90% probability of fatality from lung hemorrhaging, and a 90% probability of eardrum rupture are shown in Figure 3-9. These harm metrics were chosen based on available probit functions for human harm caused by overpressure [21].

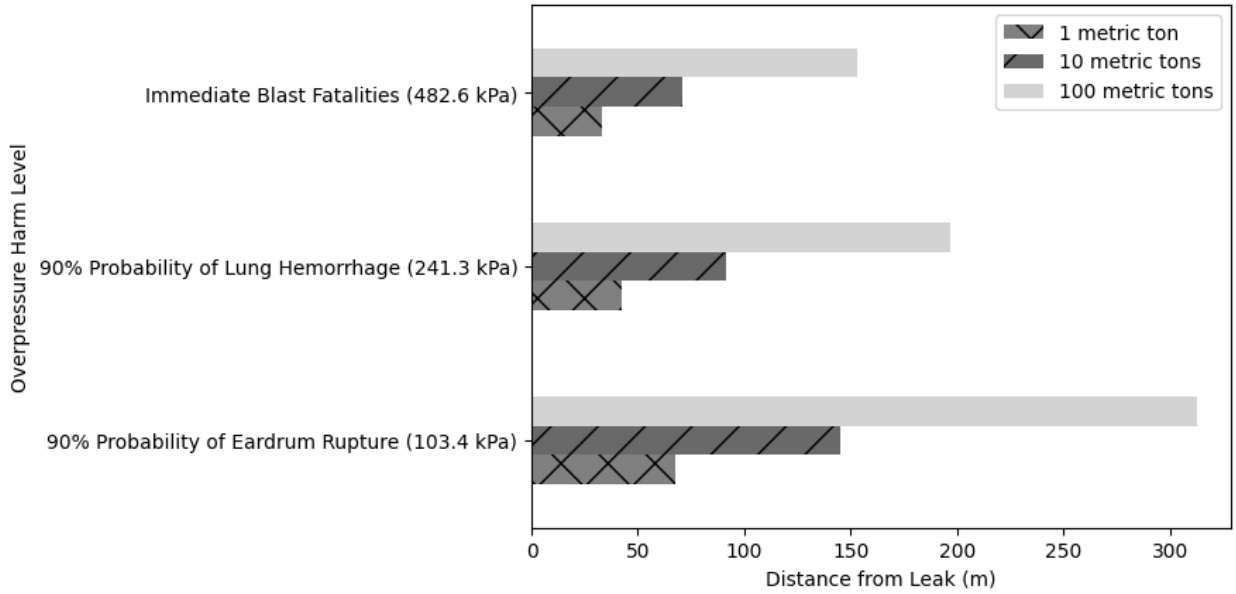


Figure 3-9. Distances to different levels of harm to people from overpressure. Overpressure levels taken from [23].

3.3. Discussion of Quantitative Bases for Hydrogen Quantity Limit

The quantitative methods described in this section illustrate multiple possible ways in which a safety distance could be determined that relates to the stored quantity of hydrogen. However, these examples contain a number of additional assumptions that may not be suitable to use as a basis for safety requirements in codes and standards. Table 3-4 summarizes the various quantitative bases, notes the assumptions made for each, and the potential downside for its utilization as a basis for safety requirements.

Table 3-4. Summary of quantitative basis methodologies, key assumptions, and limitations

Potential Basis	Key Assumption	Potential Downside
Gaseous Hydrogen Increasing Component Counts	Storage capacity scales with number of components	• Not necessarily 1:1 correlation between capacity and system size
Liquid Hydrogen Risk	Risk calculation based on tank volume and leak size that yields 2-hour blowdown	• 2-hour blowdown time is arbitrary • Leak size does not necessarily correlate with tank capacity
Liquid Hydrogen Heat Flux	Heat flux calculated 10 m from leak 30 min after leak start	• 10 m and 30 min are arbitrary • Heat flux from larger flame can be higher at first • Heat flux not only hazard to consider
Liquid Hydrogen Flame Length	Flame length 2 hours after leak start	• 2 hours is arbitrary • Flame length can be much longer at first • Flame length not only hazard to consider
Liquid Hydrogen Overpressure	Overpressure from full storage quantity	• Physically unrealistic for entire stored quantity to contribute to overpressure

It is also important to note that there are significant sources of uncertainty in these quantitative bases in addition to the specific assumptions listed above. The quantitative risk assessment calculations in HyRAM+ utilize leak frequency values that have uncertainty distributions that can span multiple orders of magnitude [20]. There are also many assumptions made for the inputs of these calculations for things like overpressure/blast severity, ignition probability, leak size, and many others, all of which can further contribute to the uncertainty in quantitative results. These quantitative bases are shown here as examples of possible methodologies, and are likely not specific enough to a particular system to be used as-is for safety distance or capacity limit requirements.

4. SUMMARY AND CONCLUSIONS

The potential need for a regulated quantity limit for hydrogen storage systems was evaluated. For example, setback distances between liquid hydrogen storage and different exposures are applicable to up to 75,000 gallons of aggregate capacity in the 2023 version of NFPA 2, but the basis for this limit is unknown. Thus, this document review helped evaluate the need for a capacity limit. This study focused on the storage system for gaseous or liquid hydrogen in particular, and so did not include other aspects of a system more directly related to the production or use of hydrogen, such as electrolyzers or refueling dispensers.

Other codes and standards by NFPA, CGA, and NASA were reviewed to determine if other fuels with flammable hazards such as natural gas, oxygen, and petroleum currently have required quantity limits. Most of the documents included in the review did not mention any aggregate capacity limit for a facility. Some of the documents had capacity limits for individual containers, and some included capacity limits for fuel storage in specific applications, such as residential fueling or indoor storage. Most of the documents did not provide a rationale for the capacity limits, so it is unclear whether they were informed by risk or another priority. There is a lack of precedent for aggregate capacity limits in existing regulations for substances with similar hazards to hydrogen.

The possibility of determining a safety-informed hydrogen capacity limit was investigated for both gaseous and liquid hydrogen. This was done in a variety of ways to illustrate risk scenarios in a large-scale storage system. Since gaseous hydrogen tends to be stored modularly, a potential method for identifying its aggregate capacity limit was to calculate individual risk based on an increased number of components in the system. In this case, the change in the risk increases with the increase in the number of components as potential leak points, not because of the increased stored quantity itself. Each additional component can contribute to the overall system leak likelihood, and different components may leak at different frequencies.

Liquid hydrogen, meanwhile, is more practical to store in larger tanks, so several methods were proposed for determining a liquid hydrogen capacity limit with the consideration of tank stored quantity. The first method uses a metric of individual risk at a certain distance based on tanks with two-hour blowdown times during full-bore leaks. The second method uses a metric of heat flux thirty minutes into a jet fire and at a certain distance away from the leak; it also incorporates varied tank and leak sizes. The thirty-minute timeframe is based on heat flux damage metrics. The third method uses metrics of flame length and leak flow rate two hours into a jet fire. The two-hour timeframe is based on a two-hour fire protection reference point. The last method uses the consequences of an explosion as the basis for a capacity limit, with distances to peak overpressure as the metric of interest. This method uses probits for building damage and harm to people from overpressure.

These high-level methods all show potential ways to set an aggregate capacity limit for hydrogen storage. However, these methods all still rely on some sort of consensus on the selected metrics; for example, acceptable risk metrics must be selected and agreed upon in order to determine a quantity threshold accordingly. In addition, a lot of these methods require multiple assumptions about a particular facility, such as an assumed number of components or leak size. Many of the methods also consider a single point in time (such as 30 minutes or 2 hours into the leak) for the consequence-based calculations. In reality, a large leak from a large-scale storage system is going to be a time-dynamic scenario that can have consequences that can vary widely.

Hydrogen systems in particular may be less sensitive to storage capacity because spilled fuel outdoors dissipates over time, making it difficult to describe a realistic scenario in which the full quantity of fuel contributes to a hazardous scenario. Many current risk assessment methodologies make a conservative assumption of a steady-state leak into open air, and significant additional limiting assumptions would be needed to claim that additional storage capacity would necessarily increase risk. Since these steady-state models do rely on leak size, the collection of more information about how often differently sized leaks occur could help develop a basis for more realistic leak sizes and inform a potential storage capacity limit or threshold above which additional safety measures are applicable.

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APPENDIX A. QUANTITY LIMITS IN EXISTING CODES AND STANDARDS

Table A-1. Gaseous Fuel Limits.

Fuel	Document Number	Aggregate Capacity Limit	Reference Section	Notes
Hydrogen	NFPA 2	None	Chapter 7 (Gaseous Hydrogen)	
	NFPA 55	None	Chapter 10 (Gas Hydrogen Systems)	This chapter is being removed in the next version of the document and hydrogen will be exclusively handled by NFPA 2.
	CGA H-5	None	Scope	Applies to systems with over 5000 scf of hydrogen; taken from the 2014 version
Oxygen	NFPA 51	120 ft^3 for a single cylinder of oxygen 120 ft^3 for a single cylinder of fuel gas	Section 1.1.5 (Scope)	
CNG	NFPA 52	None	Chapter 9 (Outdoor Storage), Chapter 11 (CNG Fueling)	
		9.0 scf per residential fueling appliance (indoor) 750 scf total in the residential fueling appliance (433 scf per single container)	Chapter 12 (Residential Fueling Appliances)	Not for industrial applications; limits are also by appliance rather than aggregate capacity in an entire facility
		3000 scf aggregate volume 750 scf single container capacity	Section 13.1.14.2 (Vehicle Fueling Appliances Installed Outdoors)	

Fuel	Document Number	Aggregate Capacity Limit	Reference Section	Notes
Natural Gas	NFPA 54	None		
Manufactured Gas		None		
Vapor-phase LPG (propane, butane) and LP-Gas-air mixtures		None		
LP-Gas	NFPA 58	30,000 gal (dispensing systems)	Section 5.2.1.9 in Chapter 5 (LP-Gas Equipment and Appliances)	
		300 gal (aggregate water capacity of containers supplying fuel to LP-gas-powered vehicle)	Section 12.3.2.3 in Chapter 12 (Motor Vehicles Intended for On-Road Use or Designed to Transport Passengers and Are Fueled by LP-Gas)	
Compressed Gases	NFPA 55	None	Chapter 7 (Compressed Gases)	
Carbon Dioxide		None	Section 13.4 (Insulated Liquid Carbon Dioxide Systems)	
Ethylene Oxide		10,000 lb (indoors)	Section 14.3 (Storage of Ethylene Oxide)	No capacity limit provided for outdoor storage
Acetylene		None	Chapter 15 (Acetylene Cylinder Charging Plants)	
Nitrous Oxide		None	Chapter 16 (Liquid Nitrous Oxide Systems)	
Flammable, inert, oxidizing, pyrophoric, unstable (reactive), corrosive, highly toxic, and toxic gases		MAQs set by control area	Table 6.3.1.1 (Maximum Allowable Quantity (MAQ) of Hazardous Materials per Control Area)	MAQ by control area doesn't necessarily mean that is the size limit for the system as a whole

Table A-2. Liquid Fuel Limits.

Fuel	Document Number	Aggregate Capacity Limit	Reference Section	Notes
Hydrogen	NFPA 2	75,000 gal	Table 8.3.2.3.1.6(a) (Minimum Distance from Outdoor Bulk Liquefied Hydrogen (LH_2) Systems to Exposures, Up to 75,000 gal (280,000 L) – Typical Inner Diameter *(d)* 1.5 in. (38.1 mm) in Chapter 8 (Liquid Hydrogen)	Based on size of tanks that can/have been built
	NFPA 55	283,906 L	Table 11.3.2.2 (Minimum Distance from Outdoor Bulk Liquefied Hydrogen Systems to Exposures) in Chapter 11 (Bulk Liquefied Hydrogen Systems)	
	CGA H-3	25,000 gal per tank	Scope	Taken from the 2013 version; no aggregate capacity
	CGA H-5	None	Scope	Applies to supply systems with over 39.7 gal of H_2, taken from the 2014 version
Ignitable (Flammable or Combustible) Liquids in Containers	NFPA 30	119 gal (individual capacity for drums or containers) 660 gal (individual capacity for portable tanks) 793 gal (intermediate bulk containers) Aggregate quantities of fuels are limited by control area, not by overall facility (See Table 9.6.1)	Section 9.1 (Storage of Ignitable Liquids in Containers – General Requirements Scope), Section 10.1 (Storage of Ignitable Liquids in Containers – Mercantile Occupancies Scope), Section 11.1 (Storage of Ignitable Liquids in Containers – Industrial Occupancies Scope), Section 12.1 (Storage of Ignitable Liquids in Containers – Storage Occupancies Scope), Section 13.1 (Storage of Ignitable Liquids in Containers – Detached, Unprotected Buildings Scope), Section 14.1 (Hazardous Materials Storage	There are additional requirements provided for tanks that have capacities above the ones listed (Section 21.1, Storage of Ignitable Liquids in Tanks – Requirements for All Storage Tanks Scope) – so these aren't aggregate capacity requirements nor a hard limit on individual tank capacity requirements

Fuel	Document Number	Aggregate Capacity Limit	Reference Section	Notes
			Lockers Scope), Section 15.1 (Outdoor Storage Scope)	
		1100 gal (outdoor storage adjacent to a building)	Section 15.4 (Outdoor Storage Adjacent to a Building)	
		None	Table 22.4.1.1(b) (Reference Table for Use with Tables 22.4.1.1(a), 22.4.1.3, and 22.4.1.5)	Provides setback distances for tank capacity ranges; the largest range is 3,000,001 gal or more
Class IIIB Stable Fluids		None	Table 22.4.1.5 (Location of Aboveground Storage Tanks Storing Class IIIB Liquids [FP ≥ 200°F (93°C)	Provides setback distances for tank capacity ranges; the largest range is 100,001 gal or more
Class I, Class II, and Class IIIA liquids		100,000 gal (individual tank limit for tanks stored in storage tank buildings)	Section 24.4.3	
Cryogenic Fluids	NFPA 55	None	Chapter 8 (Cryogenic Fluids)	
LNG	NFPA 59A	1,056,000 gal water capacity	Section 17.1.2 (Requirements for Stationary Applications for Small Scale LNG Facilities)	Based on size of tanks that can/have been built
	NFPA 52	None	Chapter 9 (Outdoor Storage) and Chapter 14 (LNG Fueling)	
Class I liquid motor fuels	NFPA 30A	120 gal	Section 4.3.9.1.1 (Storage of Liquids Inside Buildings – Class I, II, and IIIA Liquids in	

Fuel	Document Number	Aggregate Capacity Limit	Reference Section	Notes
			Tanks Not Exceeding 454 L (120 gal) Capacity and in Containers)	
Class II and Class IIIA liquid motor fuels		120 gal (tank) 240 gal (containers)	Section 4.3.9.1.2 (Storage of Liquids Inside Buildings – Class I, II, and IIIA Liquids in Tanks Not Exceeding 454 L (120 gal) Capacity and in Containers)	Aggregate quantities inside buildings where Class I liquids are also stored; 240 gal limit for Class II liquids inside buildings where there are no Class I liquids stored
Carbon Dioxide	NFPA 55	None	Section 13.3 (Insulated Carbon Dioxide Compressed Gas Systems)	
Cryogenic fluids, liquefied flammable, inert, oxidizing, pyrophoric, unstable (reactive), corrosive, highly toxic, and toxic gases		MAQs set by control area	Table 6.3.1.1 (Maximum Allowable Quantity (MAQ) of Hazardous Materials per Control Area)	MAQ by control area doesn't necessarily mean that is the size limit for the system as a whole

Table A-3. Limits for Unspecified or Any Fuel Phase.

Fuel	Document Number	Aggregate Capacity Limit	Reference Section	Notes
Hydrogen	29 CFR 1910.103	None	Section 1910.103(a)(2)	
	29 CFR 1910.119	10,000 lb	Section 1910.119(a)(1)(ii)	Above this threshold, a hazard analysis and mishap investigation and reporting are required
	40 CFR 68	10,000	Table 3 (List of Regulated Flammable Substances and Threshold Quantities for Accidental Release Prevention) to 68.130	

Fuel	Document Number	Aggregate Capacity Limit	Reference Section	Notes
	ANSI/AIAA G-095A	None		Section 14 (Transport Information) sets a quantity limit of 150 kg of hydrogen for transportation in cargo aircraft
Oxygen	NFPA 55	None	Chapter 9 (Bulk Oxygen Systems)	

APPENDIX B. SUPPLEMENTARY MATERIAL FOR DETERMINING QUANTITY LIMITS

The percent difference for each component count scaling factor is shown in Figure 3-2. These percent differences were calculated using:

$$Percent\ Difference = \frac{Risk_{scaled} - Risk_{default}}{\left(\frac{Risk_{scaled} + Risk_{default}}{2}\right)} \quad \text{(Equation B-1)}$$

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