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Liquid Hydrogen Heavy-Duty Vehicle Safety Review and Refueling Facility Design

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ABSTRACT

Liquid hydrogen (LH_2) used as a fuel onboard a heavy-duty vehicle can result in increased storage capacity and faster refueling relative to compressed gas. However, there are concerns about hydrogen losses from boil-off, potential safety issues, gaps in codes and standards for cryogenic hydrogen fuel, and technical challenges with LH_2 systems for widespread transportation applications. A failure modes and effects analysis (FMEA), a safety codes and standards review, and a design review of the onboard liquid hydrogen system for a heavy-duty vehicle identified some of these potential safety issues and gaps in the codes and standards. The FMEA identified some medium and low risk failure points of the conceptual design, and the design review identified how carefully pressure relief needs to be considered for LH_2 systems. In addition, a conceptual design for a LH_2 refueling station was developed. Rough capital costs for the refueling station design were $1 million and the layout occupied approximately 13,000 ft^2. These results can be used to inform future designs and analyses for LH_2 heavy-duty vehicles.

ACKNOWLEDGEMENTS

This work was performed as part of a collaborative, multi-lab project led by Argonne National Laboratory. The authors wish to thank Rajesh Ahluwalia and the team at Argonne National Laboratory for providing the onboard hydrogen system schematics used in the safety review and for the refueling design. The authors also wish to thank Salvador Aceves from Lawrence Livermore National Laboratory and Cassidy Houchins from Strategic Analysis, Inc., as well as the rest of the multi-lab team, for many useful discussions and feedback. The authors also wish to thank Gabriela Bran Anleu from Sandia National Laboratories for making the layout drawings using the SketchUp software, and Benjamin Schroeder from Sandia for providing peer review of this document. Finally, this work was supported by the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE) Hydrogen and Fuel Cell Technologies Office (HFTO) with project management by Zeric Hulvey.

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ACRONYMS AND TERMS

Acronym/Term	Definition
BLEVE	boil liquid expanding vapor explosion
COTS	commercial off the shelf
FMEA	failure mode and effects analysis
GH_2	gaseous hydrogen
HDV	heavy-duty vehicle
LH_2	liquid hydrogen
NFPA	National Fire Protection Association
P&ID	piping and instrumentation diagram
PRD	pressure relief device
PRV	pressure relief valve
SAE	Society of Automotive Engineers

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1. INTRODUCTION

Hydrogen can be liquefied at ambient pressure at very low temperatures. This has a number of potential benefits for use in a heavy-duty vehicle (HDV); the increased density of liquid hydrogen (LH_2) compared to gaseous hydrogen (GH_2) can result in increased storage capacity onboard a vehicle and faster refueling. However, there are concerns about hydrogen losses from boil-off, potential safety issues, gaps in codes and standards, and technical challenges with very low temperature (cryogenic) hydrogen as a fuel for widespread transportation applications.

A multi-laboratory project was undertaken to examine some of these concerns. The goal of this project was to conceptualize a storage system that can be refueled with a low-pressure LH_2 pump at 8-10 kg/min, can maintain hydrogen as liquid in an insulated Type-1 tank, and has a dormancy exceeding the longest duration over which heavy-duty trucks are normally parked continuously without use. The project objectives were to determine the performance (volumetric capacity; gravimetric capacity; insulation and dormancy; liner thickness, compatibility and durability; refueling rate; LH_2 pump requirement; and hydrogen venting loss) and cost of onboard LH_2 storage and its variants.

As part of this project, the team at Sandia National Laboratories conducted a failure modes and effects analysis (FMEA) as well as a safety codes and standards analysis and design review of the onboard LH_2 storage and use system for an HDV. Additionally, the team at Sandia developed a conceptual design for an LH_2 HDV refueling station, to provide a basic high-level feasibility, capital cost, and system layout. These efforts were done to inform future designs and requirements that could apply to LH_2 HDVs. This report describes the results of those efforts at Sandia National Laboratories, while results from other project team members on other portions of the analysis are published elsewhere.

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2. SAFETY ANALYSIS OF HDV ONBOARD LH2 FUEL SYSTEM

A failure modes and effects analysis (FMEA) for an HDV liquid hydrogen fuel system during normal operations was conducted to identify and qualitatively rank failures that could result in a leak or release of either GH_2 or LH_2. Reliability block diagrams were used to define functional groups and specify components' dependencies. These were based on two system diagrams provided by Argonne National Laboratory—one with a pump and one with a pressure build loop rather than a pump to provide the correct flow and pressure of gaseous hydrogen to the HDV fuel cell [1]. An FMEA is a qualitative, inductive process used to identify the effect of component failures on systems and subsystems. In addition to the FMEA, a safety codes and standards review of the HDV LH_2 onboard fuel system was conducted.

2.1. FMEA Methodology

A failure mode defines how a component fails whereas a failure cause describes scenarios describing why a component failed. The primary focus of this FMEA was to identify failure modes, determined by reviewing the block diagrams and considering the individual components. This review specifically looked at credible scenarios and failure modes that could lead to either an unintentional leak or release of gaseous hydrogen or liquid hydrogen. A failure mode can either be an operation, function, or status of a component. A failure effect is a direct consequence of the failure mode. Descriptions for the failure modes and effects are both provided in the full FMEA results. For each unique failure mode and effect, a failure mode identifier was assigned in the worksheet, illustrated in Appendix A.

The team conducting the analysis used a four-bin qualitative scale to characterize the probability of each failure mode, listed in Table 2-1.

Table 2-1. Probability Classes Used in FMEA

Probability Class	Definition
Frequent	Occurs often, continuously experienced
Likely	Occurs several times per year
Occasional	Assumed to occur during the lifetime of the system
Improbable	Assume to not occur during the lifetime of the system

A similar four-bin qualitative scale was used to characterize the overall severity of a failure mode, listed in Table 2-2.

Table 2-2. Severity Classes Used in FMEA

Severity Class	Definition
1	No potential release of LH_2 or GH_2
2	Potential leak or small-scale release of GH_2
3	Potential leak or small-scale release of LH_2
4	Potential for catastrophic release of LH_2 and GH_2

The severity and probability classes were used to create a qualitative risk ranking matrix. The four-by-four matrix, shown in Figure 2-1, lists the severity class on the horizontal axis and probability class on the vertical axis. A risk score of low (L), medium (M), or high (H) is assigned for each component's failure mode based on its probability and severity classification. The color coding was picked for display purposes.

Probability Class					
	Frequent	M	H	H	H
	Likely	L	M	H	H
	Occasional	L	L	M	H
	Improbable	L	L	L	M
		1	2	3	4
		Severity Class			

Figure 2-1. FMEA Risk Ranking Matrix

2.2. System Representative Drawings and Diagrams

The HDV fuel system with the onboard pump being analyzed is represented as a piping and instrumentation diagram (P&ID) in Figure 2-2. Green lines indicate liquid hydrogen entering the tank system from the fuel station, red lines indicate liquid hydrogen leaving the tank system to the vaporizer and eventually to the vehicle's fuel cell stack, and black lines indicate gaseous hydrogen. The system is comprised of three subsystems: the vehicle system, the LH_2 storage system, and the LH_2 distribution system. For this FMEA, it is assumed that a leak in the integrated valve assembly is detected and leads to a system shutdown. Therefore, any leaks within this portion of the system can only result in a severity class of 2 or 3.

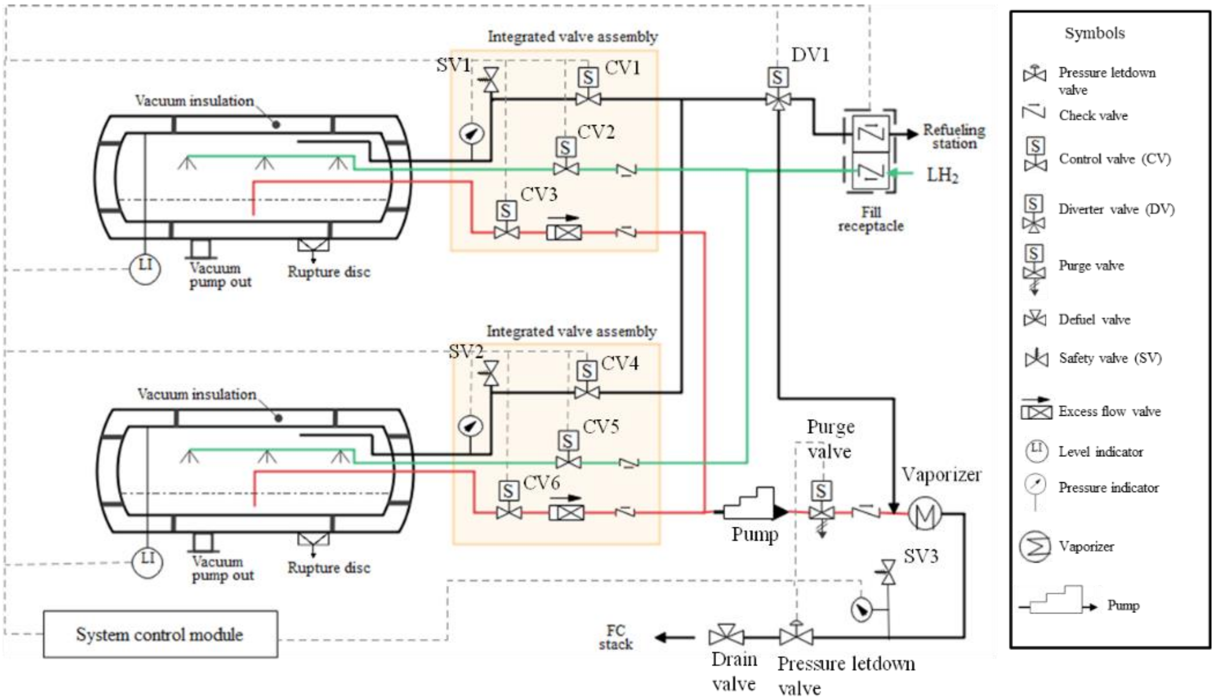

Figure 2-2. P&ID for HDV LH_2 Fuel System with Pump [1]

The system with the pressure build loop is represented in Figure 2-3. Green lines indicate liquid hydrogen entering the tank system from the fuel station, red lines indicate liquid hydrogen leaving the tank system to the vaporizer, purple lines indicate gaseous hydrogen used for the pressure build loop, and black lines indicate gaseous hydrogen. The system is comprised of the same three subsystems: the vehicle system, the LH_2 storage system, and the LH_2 distribution system. It is assumed that leak detection on the integrated valve assembly leads to system shutdown and therefore would not lead to a potentially catastrophic release.

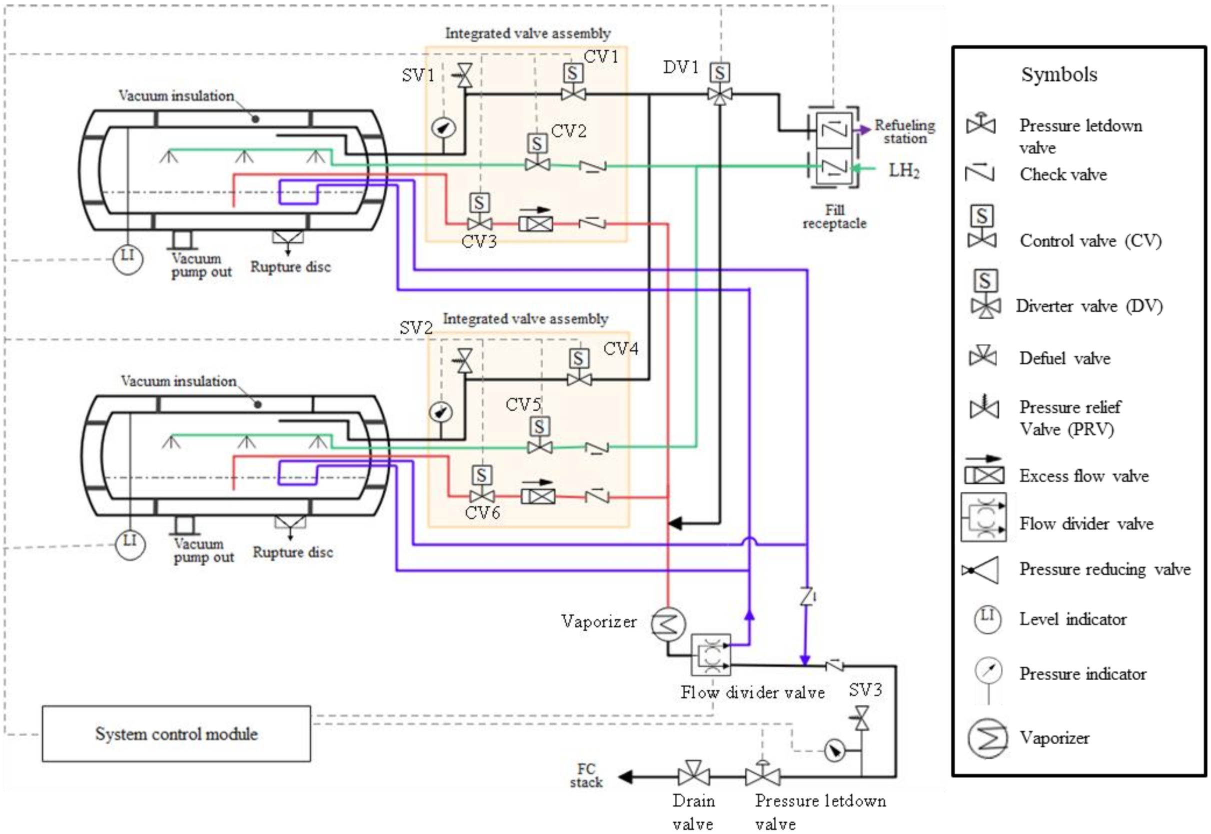

Figure 2-3. P&ID for HDV LH_2 Fuel System with Pressure Build Loop [1]

Reliability block diagrams were created for both the pump and pressure build systems. The reliability block diagrams were used to define the functional groups, assemblies, and independence/dependence of the components within that group. Multiples of ten values were assigned for the functional groups (e.g., LH_2 Storage System, No. 20), assemblies were assigned whole numbers (e.g., Vent System, No. 23), components were given a number with a decimal place (e.g., Valves, No. 23.1), and sub-components were given a second decimal place (e.g., Valve 33.43 as part of the Vaporizer 33.4) to illustrate the how each component aligns to a functional group and system. Figure 2-4 illustrates the reliability block diagram for the fuel system with an onboard pump. Blocks and lines in blue contain LH_2 while green indicates GH_2. Blocks and lines in grey are for vehicle components that do not contain hydrogen; since the focus of this FMEA was the safety of the onboard hydrogen system, these components are included in the diagram for informational purposes only, and not considered further in the FMEA. Similarly, Figure 2-5 is the reliability block diagram for the system with the pressure building system.

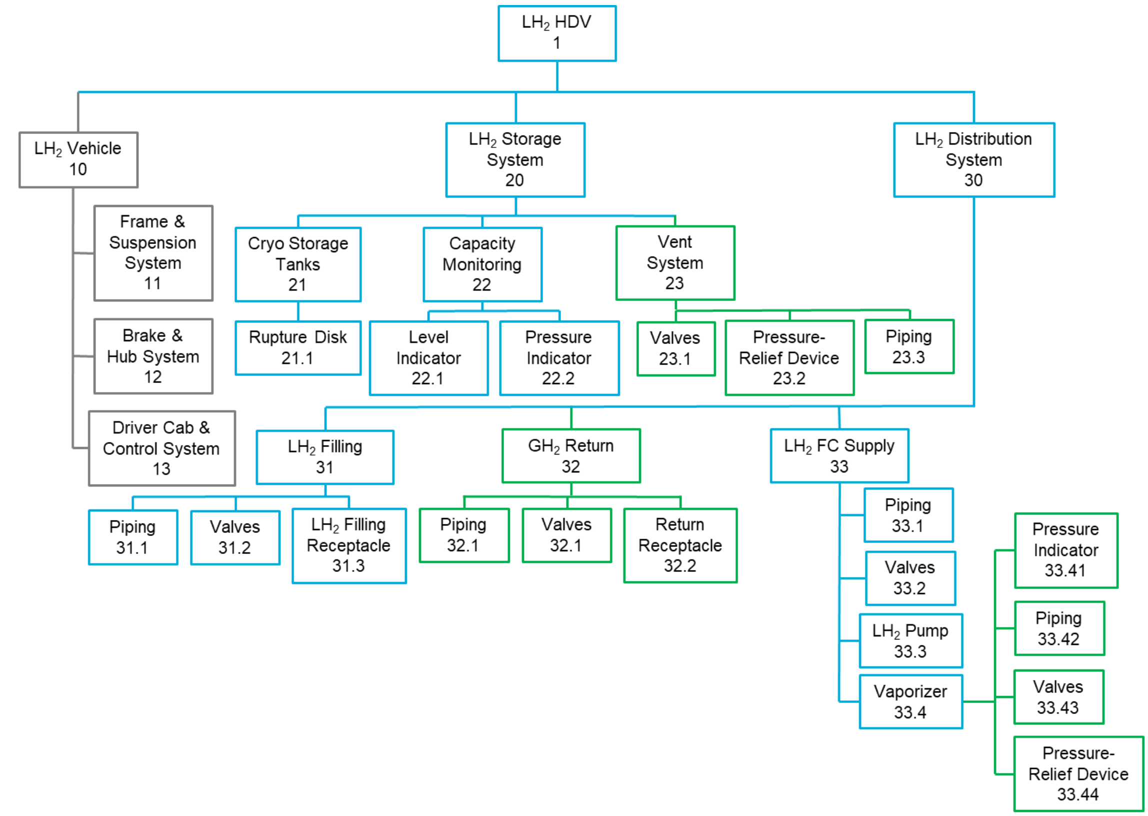

Figure 2-4. Reliability Block Diagram for HDV LH$_2$ Fuel System with Pump

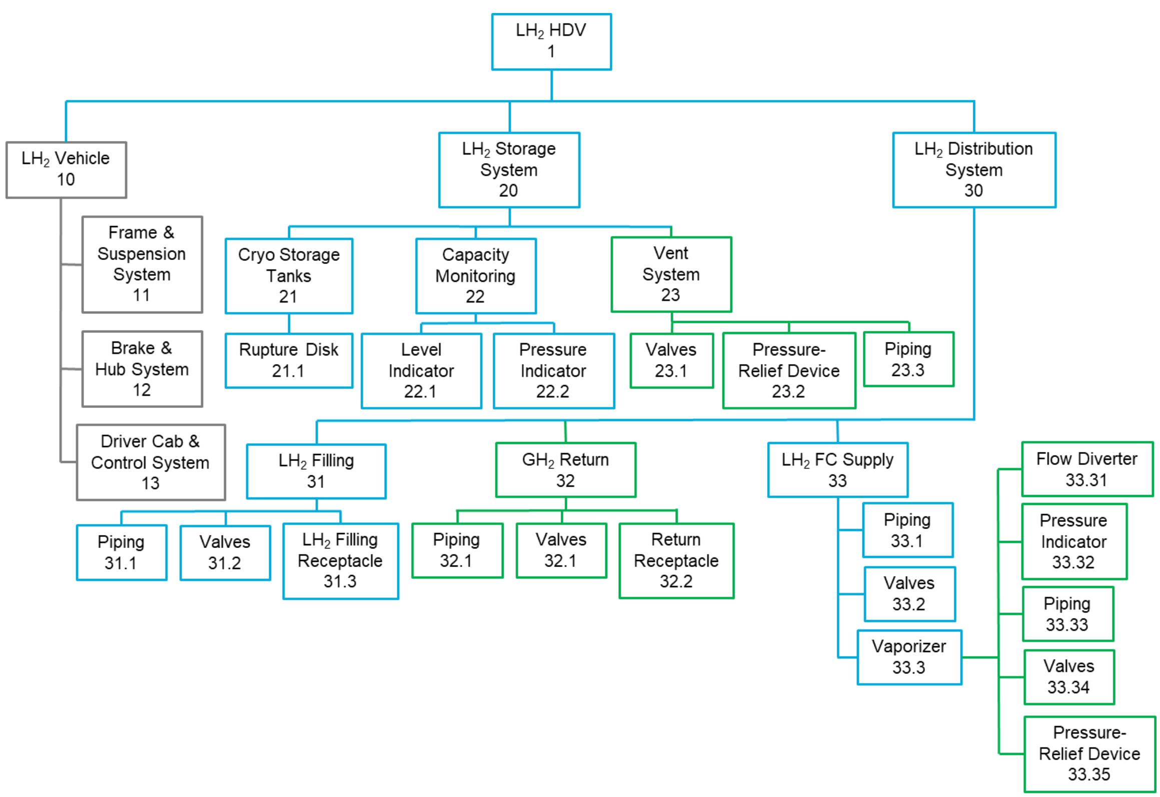

Figure 2-5. Reliability Block Diagram for HDV LH$_2$ Fuel System with Pressure Build Loop

2.3. FMEA Discussion of Key Results

The complete FMEA results are located in Appendix A. The following discussion identifies the failure modes with a medium risk priority. Only low and medium risks were identified; no high risk failures were identified through this FMEA process. A high risk failure would lead to a catastrophic release of LH_2 and GH_2 occasionally, or a frequent unintentional release of GH_2, neither of which were identified. Overall, the two main differences in the number of medium risk failures between the two systems comes from the flow diverter being present in the pressure build loop.

For the system with the pump, a total of 14 failures modes with medium risk priority were identified and are listed in Table 2-3. There are 3 overall groups these 14 failures modes can fall within: cryogenic tank failures (2 identified), failures of valve/pressure relief device (PRD) (3 identified), and failures involving hardware (9 identified). Failure of the cryogenic tank is improbable but can lead to a large release of both GH_2 and LH_2. Failure of the outer tank could also lead to a boiling liquid expanding vapor explosion (BLEVE) as well as large-scale releases of both GH_2 and LH_2. Valve and pressure-relief failures can lead to both leakage of GH_2 or LH_2. Failure of hardware includes incorrect pressure measurements and pump speeds leading to incorrect operation which might over-pressurize part of the system. Additionally, the vaporizer could develop a leak in one of the coils leading to a release of GH_2 or LH_2.

Table 2-3. Medium Risk Failure Mode Results for LH_2 HDV with Pump

Failure Mode ID	Functional Group	Assembly or Component Level	Component/ Functional Identification	Function	Failure Mode	Failure Effects	Severity Class	Probability Class	Risk Matrix Level
21.02	**20**	**21**	Cryogenic Storage Tank	Stores LH2	Rupture of both inner and outer tank	Rupture of tank and release of LH2	4	Improbable	M
21.04	**20**	**21**			Failure of outer tank due to external fire	Loss of insulation vacuum and rapid heating of LH2, leading to BLEVE or release of LH2 and subsequent ignition	4	Improbable	M
21.1.01	**20**	**21.1**	Rupture Disk	Pressure relief	Fail to open when needed	Excess pressure leading to BLEVE	4	Improbable	M
23.2.02	**20**	**23.2**	Pressure-Relief Device	Vents if pressures exceed thresholds in gas withdrawal system. Enclosed with Integrated Valve Assembly.	Fails close	Excess pressure leads to burst disk opening	3	Occasional	M
31.2.03	**30**	**31.2**	Valves	Check valve to modulate flow from fueling station to cryogenic tank only. Enclosed with Integrated Valve Assembly.	Component leak	Leak of LH2	3	Occasional	M
32.2.03	**30**	**32.2**	Valves	Check valve ensures that flow is always in correct direction. Control valve to modulate return vapor either to fueling station or vaporizer. Enclosed with Integrated Valve Assembly.	Component leak	Leak of GH2	2	Likely	M
33.2.01	**30**	**33.2**	Valves	Excess flow valve ensures there is not too much flow from tank to pump. Check valve ensures that flow is always in correct direction. Control valve modulates LH2 flow from pump to vaporizer.	Component leak	Leak of LH2	3	Occasional	M
33.4.01	**30**	**33.4**	Vaporizer	Converts LH2 to GH2 through heat transfer	Component leak on cold side	Leak of LH2	3	Occasional	M
33.4.02	**30**	**33.4**			Component leak on hot side	Leak of GH2	2	Likely	M
33.41.01	**30**	**33.41**	Pressure Indicator	Measures pressure of GH2 down stream of vaporizer	Reading biased low	Excessive pressure and release of GH2 through the relief valve	2	Likely	M
33.41.03	**30**	**33.41**			Component leak	Leak of GH2	2	Likely	M
33.43.01	**30**	**33.43**	Valves	Pressure let down valve modulates pressure from vaporizer prior to GH2 entering fuel cell. Drain valve	Component leak	Leak of GH2	2	Likely	M

Failure Mode ID	Functional Group	Assembly or Component Level	Component/ Functional Identification	Function	Failure Mode	Failure Effects	Severity Class	Probability Class	Risk Matrix Level
33.43.02	**30**	**33.43**		is used to drain the liquid hydrogen in the storage tank for maintenance or emergency.	Pressure let down is too high	Excessive pressure and release of GH2 through the relief valve	2	Likely	M
33.44.01	**30**	**33.44**	Pressure-Relief Device	Vents if pressures exceed thresholds in gas withdrawal system	Component leak	Leak of GH2	2	Likely	M

For the system with the pressure build loop, a total of 16 failure modes with medium risk priority were identified and are listed in Table 2-4. There are 3 overall groups these 16 failures modes can fall within: cryogenic tank failures (2 identified), failures of valve/PRD (5 identified), and failures involving hardware (9 identified). Failure of the cryogenic tank is improbable but leads to a large release of both GH_2 and LH_2. Valve and pressure-relief failure can lead to both leakage of GH_2 or LH_2. Failure of hardware includes incorrect pressure measurements and flow diversion leading to incorrect operation which might over-pressurize part of the system. Additionally, the vaporizer could develop a leak in one of the coils leading to a release of GH_2 or LH_2.

Table 2-4. Medium Risk Failure Mode Results for LH_2 HDV with Pressure Build Loop

Failure Mode ID	Functional Group	Assembly or Component Level	Component/ Functional Identification	Function	Failure Modes	Failure Effects	Severity Class	Probability Class	Risk Matrix Level
21.02	**20**	**21**	Cryogenic Storage Tank	Stores LH2	Rupture of both inner and outer tank	Rupture of tank and release of LH2	4	Improbable	M
21.04	**20**	**21**			Failure of outer tank due to external fire	Loss of insulation vacuum, rapid heating of LH2, leading to BLEVE or release of LH2 and subsequent ignition	4	Improbable	M
21.1.01	**20**	**21.1**	Rupture Disk	Pressure relief	Fail to open when needed	Excess pressure leading to BLEVE	4	Improbable	M
23.2.02	**20**	**23.2**	Pressure-Relief Device	Vents if pressures exceed thresholds in gas withdrawal system. Enclosed with Integrated Valve Assembly.	Fails close	Excess pressure leads to burst disk opening	3	Occasional	M
31.2.03	**30**	**31.2**	Valves	Check valve to modulate flow from fueling station to cryogenic tank only. Enclosed with Integrated Valve Assembly.	Component leak	Leak of LH2	3	Occasional	M
32.2.03	**30**	**32.2**	Valves	Check valve ensures that flow is always in correct direction. Control valve to modulate return vapor either to fueling station or vaporizer. Enclosed with Integrated Valve Assembly.	Component leak	Leak of GH2	2	Likely	M
33.2.01	**30**	**33.2**	Valves	Excess flow valve ensures there is not too much flow from tank to pump. Check valve ensures that flow is always in correct direction. Control valve modulates LH2 flow from pump to vaporizer.	Component leak	Leak of LH2	3	Occasional	M
33.3.01	**30**	**33.4**	Vaporizer	Converts LH2 to GH2 through heat transfer	Component leak on cold side	Leak of LH2	3	Occasional	M
33.3.02	**30**	**33.4**			Component leak on hot side	Leak of GH2	2	Likely	M
33.31.01	**30**	**33.31**	Flow Diverter	Creates loop to transfer GH2 through cryogenic tank to modulate pressure within tank	Component leak	Leak of GH2	2	Likely	M
33.31.02	**30**	**33.31**			Overpressurizes LH2 tank	Excessive pressure and release of GH2 through relief valve	2	Likely	M
33.32.01	**30**	**33.32**	Pressure Indicator	Measures pressure of GH2 down stream of vaporizer	Reading biased low	Excessive pressure and release of GH2 through relief valve	2	Likely	M
33.32.03	**30**	**33.32**			Component leak	Leak of GH2	2	Likely	M
33.34.01	**30**	**33.34**	Valves	Pressure let down valve modulates pressure from vaporizer prior to GH2 entering fuel cell. Drain valve is used to drain the liquid hydrogen in the storage tank for maintenance or emergency.	Component leak	Leak of GH2	2	Likely	M
33.34.02	**30**	**33.34**			Pressure let down is too high	Excessive pressure and release of GH2 through relief valve	2	Likely	M
33.35.01	**30**	**33.35**	Pressure-Relief Device	Vents if pressures exceed thresholds in gas withdrawal system	Component leak	Leak of GH2	2	Likely	M

2.4. Safety Codes & Standards Review

In addition to the FMEA, a safety codes and standards review was conducted for the LH_2 HDV system. The intent of this review was to determine any safety gaps, missing components, and determine where improvements can be made to the system design. The following three Society of Automotive Engineers (SAE) Standards/Recommended Practices were considered:

- SAE J2343 - Recommended Practices for LNG Powered Heavy-Duty Trucks [2]
- SAE J2578 - Recommended Practice for General Fuel Cell Vehicle Safety - Liquid or Heavy Duty Specific [3]
- SAE J2579 - Standard for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles - Liquid or Heavy Duty Specific [4]

Additionally, National Fire Protection Association (NFPA) 52 - Vehicular Natural Gas Fuel Systems Code 2019 Edition [5], Section 16.4 LNG Engine Fuel Systems was reviewed. While NFPA 52 and SAE J2343 are specific for natural gas systems, some relevant practices were applied to or identified as being applicable to the HDV LH_2 fuel system considered here. For widespread adoption of onboard LH_2 vehicles, similar standards will need to be developed for LH_2. The overall results of the review are listed in Appendix B.

The primary findings from the safety codes and standards review were that any vehicle design will need to ensure that valve and pressure relief configurations are designed to prevent trapping of fuel in various parts of the system. Additionally, spaces where fuel will be trapped such as when fueling is complete must have PRDs (also called pressure relief valves [PRVs]). The results of a design review are visually depicted in Figure 2-6 and Figure 2-7 below. Both the system with the pump and with the pressure build loop were found to have some areas that require PRDs due to the potential for trapped fuel, and a real world system would need to ensure that the integrated valve assembly box has appropriate safeguards against leaks. While adding additional relief valves may introduce additional leak points, these should also help to reduce potential consequences in an accident or fire scenario because there should be less isolated hydrogen fuel remaining in the system pipes.

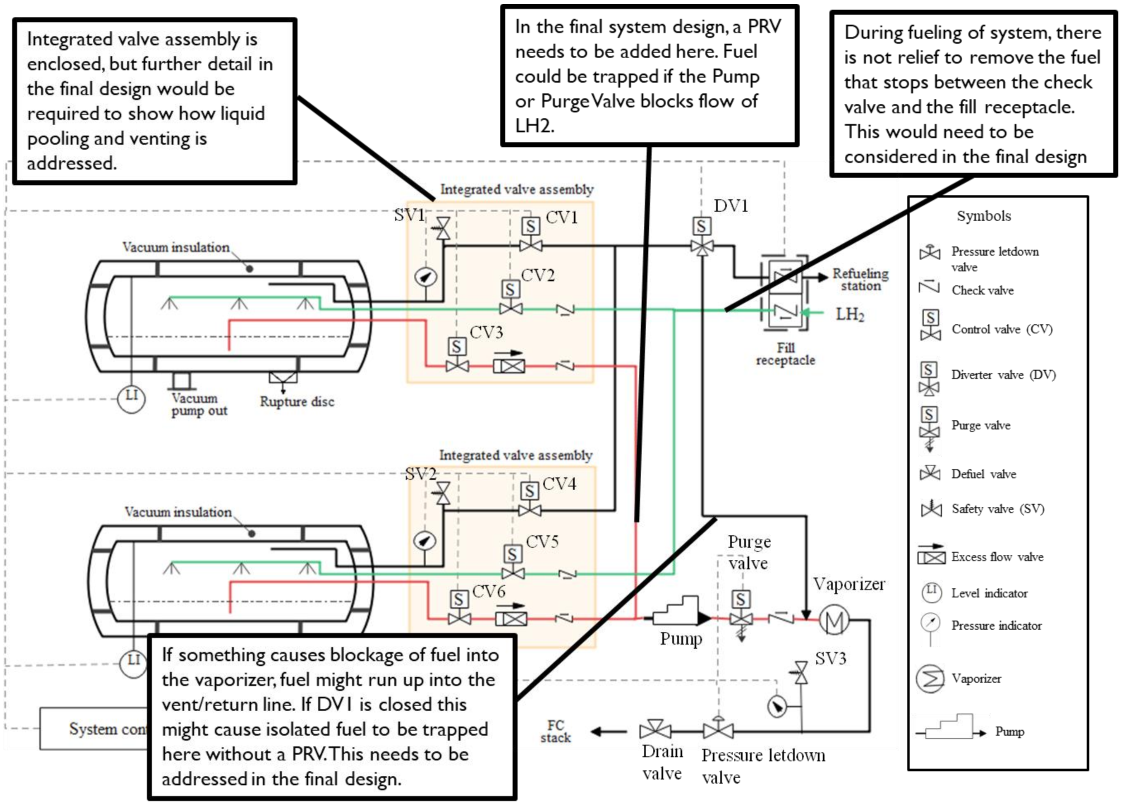

Figure 2-6. LH_2 HDV Fuel System with Pump Safety Review

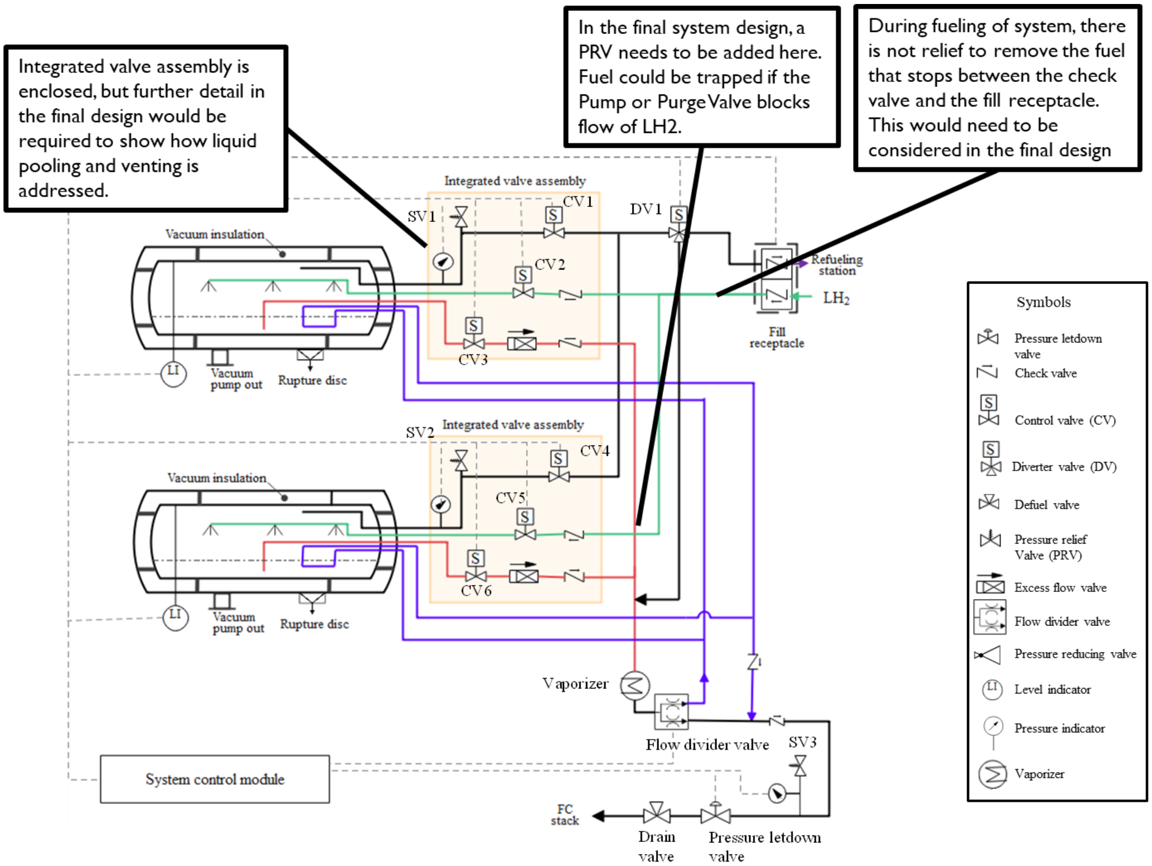

Figure 2-7. LH_2 HDV Fuel System with Pressure Build Loop Safety Review

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3. HDV LH2 REFUELING STATION CONCEPTUAL DESIGN

This section goes over a conceptual refueling station design, including a high-level bill of materials with rough industry costs for applicable commercial off the shelf (COTS) components. There are two ways to transfer LH_2 from the fuel station into the HDV: via pump system or pressure build loop. A basic diagram indicated these options is shown in Figure 3-1.

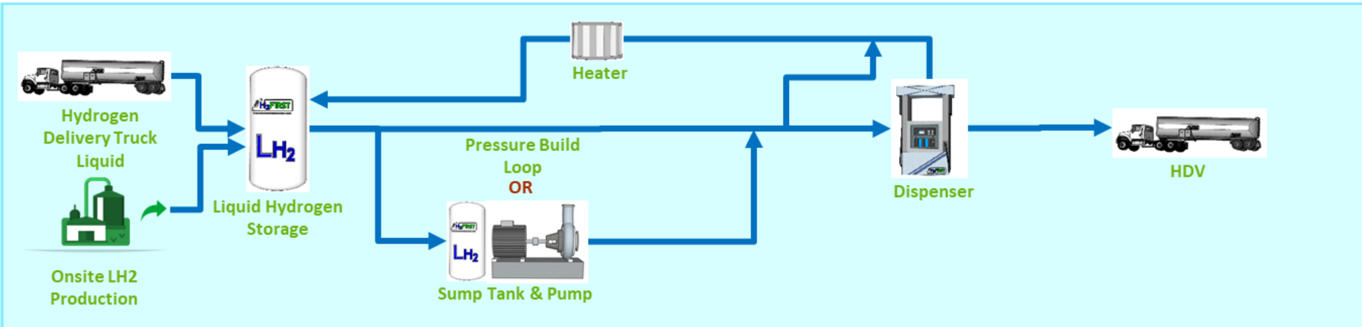

Figure 3-1. HDV LH_2 Fuel Station Basic Diagram

The pressure build loop passes LH_2 through an evaporator/heater and returns to the cryogenic tank as GH_2. This pressurizes the tank, which in turn drives the flow of LH_2 out of the tank. The pressure build loop does have some advantages over the pump system, such as reducing the need for electrical power and moving parts. However, the pressure build loop increases the overall boil-off, using more LH_2 to maintain the correct system pressure. In addition, the system with the pressure build loop operates closer to the relief pressure and could require more venting if the tank is underutilized.

Once the fuel is transported from the cryogenic tank, it must go through a dispenser system to measure and keep track of the flow rate for inventory or sales purposes. The dispenser contains pressure sensors and relief devices to avoid unsafe over-pressurization. The dispenser also has the necessary hoses to connect the supply and potential return lines to the HDV system. The return line is to capture and transport gaseous hydrogen that otherwise would rapidly pressurize inside of the HDV onboard tank when refueling with LH_2.

3.1. Design Inputs

For this study, it is assumed that the mass flow rate is 10 kg/min of LH_2 at a pressure of 8 to 10 bar during the refueling process. Each HDV fueled would require approximately 100 kg of LH_2 which gives a total refueling time of 10 minutes. It is assumed that 10 HDVs will be refueled every day. The daily dispensing output is 1,000 kg.

3.1.1. Bulk Storage

On-site storage is assumed to be 10% above the weekly dispensing capacity. This gives a desired storage capacity of 7,700 kg of LH_2. Assuming a density of 71 kg/m^3, this gives a total volume of 108 m^3 or 108,000 liters. For redundancy purposes (which can add resilience with this rather nascent technology), the storage is divided between two cryogenic storage tanks, with each having 54 m^3 inner storage capacity. Each cylindrical cryogenic tank is assumed to have an overall length (with insulation) of 12.3 meters (40.35 feet) with typical insulation on all sides, with an overall diameter (with insulation) of 4.6 meters (15.1 feet). The industry price per volume ranges from \$3,700 to \$7,000 per m^3 of LH_2 [6]. The cost of each tank was estimated using \$5,000 per m^3 of storage capacity based on industry estimates normalized by volume. Based on this, the total cost per tank is estimated to be $270,000.

3.1.2. Pipe and Valve Sizing

The minimum pipe size and valve diameter is based on the mass flow rate, $\dot{m}$, which is equal to the density, ρ, times the cross-sectional area of the pipe, A_c. Solving for the diameter results in Equation 1:

$$D_{min} = \sqrt{\frac{4\dot{m}}{\pi \rho v_{max}}} \tag{1}$$

The target flow rate is 136 lpm to maintain the 10 kg/min mass flow rate for LH_2 with a density of approximately 55 kg/m^3 at 8 bar. Using a target velocity of 2 m/s for liquid systems [7], gives a minimum inner pipe diameter of 44 mm (1.75 inches).

Using industry estimates, the cost per foot for 2" vacuum jacketed piping is $200. Cryogenic valves were estimated in the design to be $3,300 per valve. The overall quantity valves and piping as well as the system cost for these components is shown in Table 3-1 below.

3.1.1. Cryopump and Sump System

The cryopump supplies the dispenser system with LH_2 from the cryogenic storage. The total flow rate required is 600 kg/hr (10 kg/min). An example cryopump identified has a flow rate of 25,800 kg/hr (430 kg/min). It has a pressure output of at least 10 bar which meets the requirements of 8 to 10 bar into the HDV fuel system. The footprint is 3 ft (0.9 m) long by 3 ft (0.9 m) wide by 6 ft (1.8 m) high. The approximate cost for this cryopump is $250,000 based on industry sources; it should be noted that the example cryopump is significantly oversized for the desired flowrate, making this estimate somewhat conservative.

The cryopump is submerged into cryogenic tank or sump tank so the inlet to the pump is always below the liquid level. LH_2 is always gravity fed into the system rather than pulled in via suction which might cause a phase change from liquid to gas. This could lead to an equipment malfunction [8]. The sump is separate from the cryogenic tank and is assumed to be the same dimensions as the pump: 3 ft (0.9 m) long by 3 ft (0.9 m) wide by 6 ft (1.8 m) high. Based on industry sources, the cost estimate is $150,000. A pressure build loop was not considered for this analysis due to the potential for increased boil-off.

3.1.2. Dispenser

While there was not a commercially available liquid hydrogen dispenser system identified in this work, various components will be described in this section. The two main functions a dispenser must provide are flow control/measurement and connections to the HDV onboard tank system.

There are a variety of methods to measure the total flow rate to track inventory and point-of-sale metrics. One way is to track the overall tank level. Another way is a flow meter, which can better track individual dispensers. One technology is a turbine flow meter that can measure flow rates for liquid hydrogen between 15 to 225 lpm which meets the 136 lpm target. This meter is reasonably small (less than 1 foot (0.3 m) in any dimension) and is estimated to cost $1,600 (although it would need to be confirmed that this technology meets the accuracy requirements).

Connections from the transfer line to the HDV fuel system can be done a variety of ways. For context, current liquefied natural gas trucks use a hand-held quick-connect/quick-disconnect type connector, but these do not currently exist for liquid hydrogen. These types of connectors are easy and quick to connect and disconnect and can reduce purge requirements compared to other connectors. Commercial feasibility and practicality of these types of connectors for liquid hydrogen would need to be explored further. Cryogenic fluid lines, including those for liquid hydrogen, commonly use bayonet connectors. The minimum inner pipe diameter as described above is 44 mm (1.75 inches). COTS bayonet connectors with an inner diameter of 2" (51 mm) were assumed for this work. The overall outer diameter is approximately 4.3 inches or 108 mm. These were estimated to cost $3,350, and two connectors were assumed, one for the liquid supply line and one for the return line.

Large flexible hose/tubing lines and the connector would constitute a potentially significant amount of weight and bulk that operators would need to handle on a regular basis. This could be mitigated by having moveable support arms or other devices that could support the weight of the transfer line in a way that is maneuverable by an operator.

3.2. Cost Summary

The high-level bill of materials and capital cost estimates for major refueling station system components for a cryopump design are given in Table 3-1. It should be noted that the cost estimate for the crypopump is for a unit that exceeds the needed flowrate, making this estimate somewhat conservative.

Table 3-1. HDV LH2 Fuel Station High-Level Bill of Materials

Component	Description	Specs	Quantity	Cost per Unit ($)	Total Cost ($)
Storage	Cryogenic Storage Tank	54,000 Liter Capacity	2	270,000	540,000
Cryo-Pump	Centrifugal Submerged Cryo-Pump	4 – 6,056 lpm with a wide differential head range	1	250,000	250,000
Pump Sump	Cryo-Tank for Submerged Pump	0.9m x 0.9m x 1.8m- 15,000 Liter Capacity	1	150,000	150,000
Flow Meter	Turbine Flow Meter	1" X 1" with 150 LB RF Flange 15 to 225 LPM	1	1,600	1,600
Dispenser/ Connectors	Bayonet Connector Set	2" Models, cost per pair (male & female)	2	3,250	6,500
Piping	Vacuum Jacketed Cryogenic Piping	2" Inner Diameter (Cost per Foot)	25	200	5,000
Valves	Vacuum Jacketed	2" Vacuum Jacketed	14	3,300	46,200
				Total Cost ($):	999,300

3.3. Piping & Instrumentation Diagram

The P&ID for the liquid hydrogen freight refueling design using a cryopump is given in Figure 3-2:

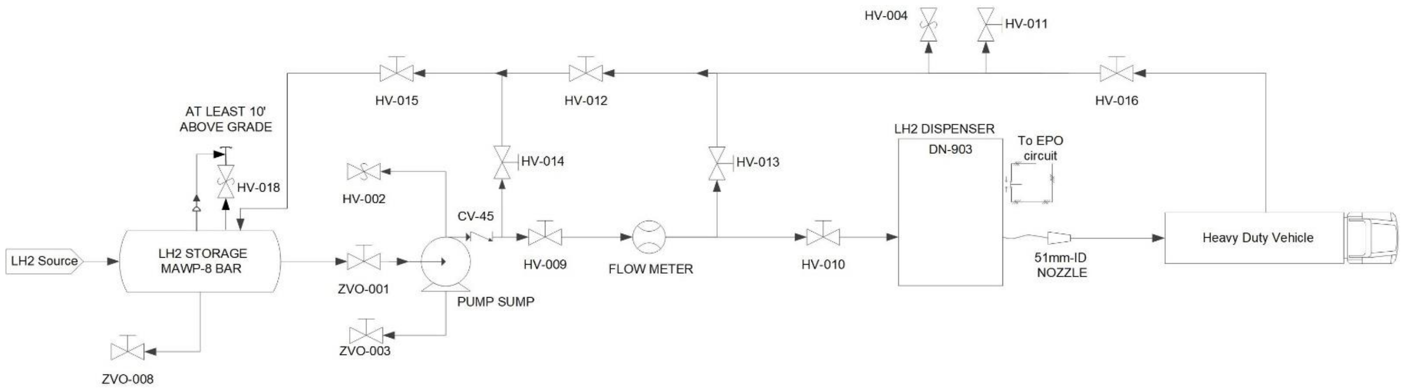

Figure 3-2. HDV LH2 Fuel Station P&ID

3.4. Fuel Station Layout Safety, Codes, & Standards Review

A code compliant layout of the truck refueling facility is shown in Figure 3-3. Shown in the layout are the major components listed above: cryogenic storage tanks surrounded by fire-rated barrier walls on three sides, cryopump, dispenser system under the light blue awning, HDV vehicle being fueled, and a LH_2 delivery truck.

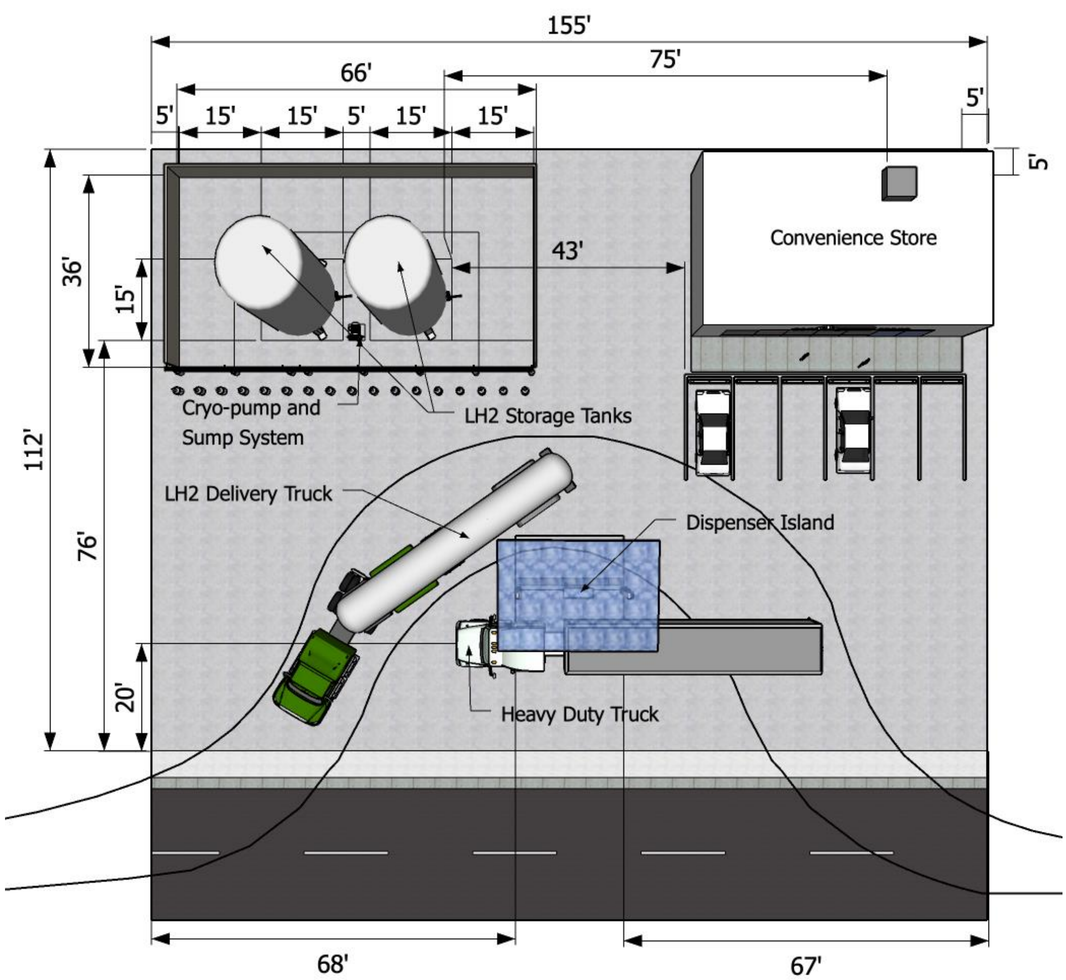

Figure 3-3. HDV LH2 Fuel Station Footprint

In this analysis, NFPA 2 [9] was used to determine the physical layout based on required separation distances. Any design will need to be approved by the local authority having jurisdiction; NFPA 2 is adopted in many jurisdictions. If the prescriptive requirements in NFPA 2 can be met, the path to approval can be simpler than performing rigorous analyses that might otherwise be needed. Based on the location this fuel station is being built, there may be other local regulations to consider (e.g., height restrictions). In this design, the hydrogen system includes the liquid hydrogen storage tanks, cryopumps, and sump tanks. A three-sided fire-rated barrier with a 2-hour fire-rated construction was positioned around the liquid hydrogen system which allows for reduction of setback distances as per Section 8.3.2.3.1.6(A)(2) of NFPA 2. The distance between the fire-rated walls and the liquid hydrogen tanks is required to be at least one diameter of the liquid hydrogen tanks (per Section 8.3.2.3.1.6(A)(2)(c) of NFPA 2). The distance between the liquid hydrogen tanks must be at least 5 ft (1.5 m) per Table 8.3.2.3.1.6(A) in NFPA 2. The fire-rated walls need to be high-enough to interrupt line of sight between the uninsulated portions of the system and the exposure (per Section 8.3.2.3.1.6(A)(2)(a) of NFPA 2); this can be design-specific, but here is assumed to be 10 ft (3 m). The fire-rated barriers need to be at least 5 ft (1.5 m) from the lot lines (property line) and any component in the hydrogen system (per Sections 8.3.2.3.1.6(A)(2)(f) and 8.3.2.3.1.6(A)(2)(g)). The total liquid hydrogen volume in this station is 28,530 gal (108,000 L). There are several relevant setback distances per Table 8.3.2.3.1.6(A) in NFPA 2 (2020 Edition) which include 75 feet from operable openings into a building, air intakes, and public places of assembly, 50 feet from ignition sources, and 25 feet from parked cars. The dispenser is required to be at least 25 ft from lot lines, nearby buildings, and fixed sources of ignition (per Section 11.3.3.1.1 of NFPA 2). Accounting for all of the separation distances and component sizes, a 155 ft (47.2 m) by 112 ft (34.1 m), 12,880 ft^2 rectangular lot would be needed for this station design as shown in Figure 3-3. As the dimensions and layout for tanks changes, as well as the surrounding infrastructure and building(s), this lot size would need to be updated based on NFPA 2 separation distances.

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4. SUMMARY AND CONCLUSIONS

Liquid hydrogen has a number of potential benefits for use in an HDV, including increased storage capacity onboard a vehicle and faster refueling than for compressed gas. However, there are some concerns about hydrogen losses from boil-off, potential safety issues, gaps in codes and standards, and technical challenges in using liquid hydrogen as a fuel for widespread transportation applications. A multi-laboratory project was undertaken to examine some of these concerns.

As part of this project, two safety codes and standards reviews and analyses were conducted for the onboard LH_2 storage and use system for an HDV. A failure modes and effects analysis (FMEA) for an HDV LH_2 fuel system during normal operations identified and enabled qualitative ranking of failures that could result in a leak or release of either GH_2 or LH_2. Only low and medium risks were identified; no high risk failures were identified through this FMEA process. A high risk failure would lead to an occasional (or more frequent) catastrophic release of LH_2 or GH_2, a likely (or more frequent) small-scale release of LH_2, or a frequent unintended release of GH_2, none of which were identified. Valve and pressure-relief failures can lead to leakage of either GH_2 or LH_2. Failure of hardware includes incorrect pressure measurements and pump speeds leading to incorrect operation which might over-pressurize part of the system. Additionally, the vaporizer could develop a leak in one of the coils leading to a release of GH2 or LH_2.

In addition to the FMEA, a safety codes and standards review for the LH_2 HDV system helped to identify potential improvements to the onboard system design. While codes and standards are lacking for LH_2 specifically, the review included LNG standards, and highlighted that any vehicle design will need to ensure that valve and pressure relief configurations are designed to prevent trapping of fuel in various parts of the system. Both the system with the pump and with the pressure build loop were found to have some areas that require PRDs due to the potential for trapped fuel. A more detailed design of the integrated valve assembly box would also be needed to ensure pooling can be avoided and shutdown of the system can be achieved if a leak is detected in the valve assembly box.

Finally, a LH_2 HDV refueling station design was developed in order to provide a basic high-level feasibility, capital cost, and system layout. There are two ways to transfer LH_2 from the fueling station into the HDV: via pump system or pressure build loop. Potential COTS components were identified for each major system component. The main component that was not available COTS was the dispenser and connector; instead, individual components that provide connectivity and flow measurement were identified. However, some of the very large connector components may require additional handling equipment. An overall cost estimate was developed based on unofficial estimates from industry sources; this resulted in an overall capital cost of just under $1 million, about half of which was the storage tank costs. A P&ID of the refueling system was developed for future reference. A physical layout was developed, which includes required separation distances from NFPA 2 (2020 Edition). Accounting for all of the separation distances and component sizes, a 155 ft (47.2 m) by 112 ft (34.1 m), 12,880 ft^2 rectangular lot could accommodate this station design. These results can be used to inform future designs and analyses for LH_2 heavy-duty vehicles.

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REFERENCES

1. R. K. Ahluwalia et al. "Cost Assessment and Evaluation of Liquid Hydrogen Storage for Medium- and Heavy-Duty Applications" in *U.S. Department of Energy Hydrogen Program 2021 Annual Merit Review and Peer Evaluation Meeting*, Project ID ST223, 2021.
2. SAE J2343, Recommended Practice for LNG Medium and Heavy-Duty Powered Vehicles, SAE International, 2018.
3. SAE J2578, Recommended Practice for General Fuel Cell Vehicle Safety, SAA International, 2014.
4. SAE J2579, Standard for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles, SAE International, 2018.
5. NFPA 52, Vehicular Natural Gas Fuel Systems Code, National Fire Protection Association, 2019.
6. C. Houchins, B. James, and Y. Acevedo, "Hydrogen Storage Analysis," in *U.S. Department of Energy Hydrogen Program 2021 Annual Merit Review and Peer Evaluation Meeting*, Project ID ST100, 2021.
7. R. Sinnott, Chemical Engineering Design, 4th ed., Elsevier, 2005.
8. G. Arnold and J. Wolf, "Liquid hydrogen for automotive application next generation fuel for FC and ICE vehicles," *Journal of Cryogenics and Superconductivity Society of Japan,* vol. 40, no. 6, 2005.
9. NFPA 2, Hydrogen Technologies Code, National Fire Protection Association, 2020.

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APPENDIX A. FMEA FULL TABLES

Table A-1. FMEA for LH_2 HDV with Pump

Failure Mode ID	Functional Group	Assembly or Component Level	Component/ Functional Identification	Function	Failure Mode	Failure Effects	Severity Class	Probability Class	Risk Matrix Level	Notes	Number of Devices
10.00	**10**	**10**	LH2 Vehicle	Noted for informational use only; does not contain hydrogen and so not considered in this analysis							
21.01	**20**	**21**	Cryogenic Storage tank	Stores LH2	Outer tank leak/Puncture of outer tank	Loss of insulative capability, leading to boiling of LH2 and release of GH2 through relief valve	2	Occasional	L		2
21.02	**20**	**21**			Rupture of both inner and outer tank	Rupture of tank and release of LH2	4	Improbable	M		
21.03	**20**	**21**			Leak of LH2 into the interstitial space between inner and outer tanks	Loss of insulative capability, leading to boiling of LH2 and release of GH2 through relief valve	2	Occasional	L		
21.04	**20**	**21**			Failure of outer tank due to external fire	Loss of insulation vacuum and rapid heating of LH2, leading to BLEVE or release of LH2 and subsequent ignition	4	Improbable	M		
21.1.01	**20**	**21.1**	Rupture Disk	Pressure Relief	Fail to open when needed	Excess pressure leading to BLEVE	4	Improbable	M		2
21.1.02	**20**	**21.1**			Opens when not needed	Loss of insulative capability, leading to boiling of LH2 and release of GH2 through relief valve	2	Improbable	L	Close to tank outlet and above liquid level.	
22.1.01	**20**	**22.1**	Level Indicator	Measures level of LH2 inside of cryogenic storage tank. Enclosed with Integrated Valve Assembly.	Reading biased low	Overfilling of LH2, leading to release from relief valve	2	Occasional	L	Assume leak detection on Integrated Valve Assembly leads to system shutdown.	2
22.1.02	**20**	**22.1**			Reading biased high	Cryogenic tank runs completely empty	1	Occasional	L	Assume leak detection on Integrated Valve Assembly leads to system shutdown.	
22.1.03	**20**	**22.1**			Outer tank leak	Loss of insulative capability, leading to boiling of LH2 and release of GH2 through relief valve	2	Occasional	L	Assume leak detection on Integrated Valve Assembly leads to system shutdown.	

Failure Mode ID	Functional Group	Assembly or Component Level	Component/ Functional Identification	Function	Failure Mode	Failure Effects	Severity Class	Probability Class	Risk Matrix Level	Notes	Number of Devices
22.1.04	**20**	**22.1**			Leak of LH2 into the interstitial space between inner and outer tanks	Loss of insulative capability, leading to boiling of LH2 and release of GH2 through relief valve	2	Improbable	L	Assume leak detection on Integrated Valve Assembly leads to system shutdown.	
22.2.01	**20**	**22.2**	Pressure Indicator	Measures pressure inside of cryogenic tank. Enclosed with Integrated Valve Assembly.	Component leak	Leak of GH2	2	Occasional	L	Assume leak detection on Integrated Valve Assembly leads to system shutdown.	2
23.1.01	**20**	**23.1**	Valves	Controls inlet and outlet from cryogenic tank. Enclosed with Integrated Valve Assembly.	Component leak	Leak of GH2	2	Occasional	L	Assume leak detection on Integrated Valve Assembly leads to system shutdown.	6
23.2.01	**20**	**23.2**	Pressure-Relief Device	Vents if pressures exceed thresholds in gas withdrawal system. Enclosed with Integrated Valve Assembly.	Fails open	Leak of GH2	2	Improbable	L	Assume leak detection on Integrated Valve Assembly leads to system shutdown.	2
23.2.02	**20**	**23.2**			Fails close	Excess pressure leads to burst disk opening	3	Occasional	M	Assume leak detection on Integrated Valve Assembly leads to system shutdown.	
23.2.03	**20**	**23.2**			Component leak	Leak of GH2	2	Occasional	L	Assume leak detection on Integrated Valve Assembly leads to system shutdown.	
23.3.01	**20**	**23.3**	Piping	Piping up to Return Control Valve. Enclosed with Integrated	Component leak	Leak of LH2	3	Improbable	L	Assume leak detection on Integrated Valve Assembly leads to system shutdown.	2

Failure Mode ID	Functional Group	Assembly or Component Level	Component/ Functional Identification	Function	Failure Mode	Failure Effects	Severity Class	Probability Class	Risk Matrix Level	Notes	Number of Devices
				Valve Assembly.							
31.1.01	**30**	**31.1**	Piping	Transfer path for LH2 to move from fueling station to cryogenic tank	Component leak	Leak of LH2	3	Improbable	L		2
31.2.01	**30**	**31.2**	Valves	Check valve to modulate flow from fueling station to cryogenic tank only. Enclosed with Integrated Valve Assembly.	Fail closed	Unable to refuel system	1	Likely	L	Assume leak detection on Integrated Valve Assembly leads to system shutdown.	2
31.2.02	**30**	**31.2**			Fail open	Overfilling of GH2 leading to release of GH2 through relief valve	2	Occasional	L	Assume leak detection on Integrated Valve Assembly leads to system shutdown.	
31.2.03	**30**	**31.2**			Component leak	Leak of LH2	3	Occasional	M	Assume leak detection on Integrated Valve Assembly leads to system shutdown.	
31.3.01	**30**	**31.3**	LH2 Filling Receptacle	Point for connection between vehicle and fuel station hose for fueling.	Component leak	Leak of LH2	3	Improbable	L		1
32.1.01	**30**	**32.1**	Piping	Transfer path for GH2 to move from return control valve to fueling station or electrolyzer. Enclosed with Integrated Valve Assembly.	Component leak	Leak of GH2	2	Occasional	L	Assume leak detection on Integrated Valve Assembly leads to system shutdown.	2

Failure Mode ID	Functional Group	Assembly or Component Level	Component/ Functional Identification	Function	Failure Mode	Failure Effects	Severity Class	Probability Class	Risk Matrix Level	Notes	Number of Devices
32.2.01	**30**	**32.2**	Valves	Check valve ensures that flow is always in correct direction. Control valve to modulate return vapor either to fueling station or vaporizer. Enclosed with Integrated Valve Assembly.	Fail closed	Overfilling of GH2 leading to release of GH2 through relief valve	2	Occasional	L	Assume leak detection on Integrated Valve Assembly leads to system shutdown.	2
32.2.02	**30**	**32.2**			Fail open	Leak of GH2	2	Improbable	L	Assume leak detection on Integrated Valve Assembly leads to system shutdown.	
32.2.03	**30**	**32.2**			Component leak	Leak of GH2	2	Likely	M	Assume leak detection on Integrated Valve Assembly leads to system shutdown.	
32.3.01	**30**	**32.3**	GH2 Return Receptacle	Point for connection between vehicle and fuel station hose for returning GH2.	Component leak	Leak of GH2	2	Improbable	L		1
33.1.01	**30**	**33.1**	Piping	Transfer path for LH2 to move from cryogenic tank to vaporizer	Component leak	Leak of LH2	3	Improbable	L		1
33.2.01	**30**	**33.2**	Valves	Excess flow valve ensures there is not too much flow from tank to pump. Check valve ensures that flow is always in correct	Component leak	Leak of LH2	3	Occasional	M		8
33.2.02	**30**	**33.2**			Excess flow valve does not allow enough LH2 to vaporizer	Fuel system operates incorrectly	1	Occasional	L		
33.2.03	**30**	**33.2**			Excess flow valve fails open	Leak of LH2	3	Improbable	L		

Failure Mode ID	Functional Group	Assembly or Component Level	Component/ Functional Identification	Function	Failure Mode	Failure Effects	Severity Class	Probability Class	Risk Matrix Level	Notes	Number of Devices
				direction. Control valve modulates LH2 flow from pump to vaporizer.							
33.3.01	**30**	**33.3**	LH2 Pump	Moves LH2 from cryogenic tank to vaporizer	Component leak	Leak of LH2	3	Improbable	L		1
33.3.01	**30**	**33.3**			Operates at higher speed than demand	Excessive pressure and release of GH2 through the relief valve	2	Occasional	L		
33.3.02	**30**	**33.3**			Operates at lower speed than demand	Fuel system operates incorrectly	1	Occasional	L		
33.4.01	**30**	**33.4**	Vaporizer	Converts LH2 to GH2 through heat transfer	Component leak on cold side	Leak of LH2	3	Occasional	M		1
33.4.02	**30**	**33.4**			Component leak on hot side	Leak of GH2	2	Likely	M		
33.41.01	**30**	**33.41**	Pressure Indicator	Measures pressure of GH2 down stream of vaporizer	Reading biased low	Excessive pressure and release of GH2 through the relief valve	2	Likely	M		1
33.41.02	**30**	**33.41**			Reading biased high	Pump speed reduced prematurely	1	Likely	L		
33.41.03	**30**	**33.41**			Component leak	Leak of GH2	2	Likely	M		
33.42.01	**30**	**33.42**	Piping	Transports GH2 from vaporizer to fuel cell	Component leak	Leak of GH2	2	Improbable	L		1
33.43.01	**30**	**33.43**	Valves	Pressure let down valve modulates pressure from vaporizer prior to GH2 entering fuel cell. Drain valve is used to drain the liquid hydrogen in	Component leak	Leak of GH2	2	Likely	M		2
33.43.02	**30**	**33.43**			Pressure let down is too high	Excessive pressure and release of GH2 through the relief valve	2	Likely	M		
33.43.03	**30**	**33.43**			Pressure let down is too low	Fuel system operates incorrectly	1	Likely	L		

Failure Mode ID	Functional Group	Assembly or Component Level	Component/ Functional Identification	Function	Failure Mode	Failure Effects	Severity Class	Probability Class	Risk Matrix Level	Notes	Number of Devices
				the storage tank for maintenance or emergency.							
33.44.01	**30**	**33.44**	Pressure-Relief Device	Vents if pressures exceed thresholds in gas withdrawal system	Component leak	Leak of GH2	2	Likely	M		1
33.44.02	**30**	**33.44**			Fail open	Leak of GH2	2	Occasional	L		
33.44.03	**30**	**33.44**			Fail closed	Buildup GH2 pressure and rupture leading to release of GH2 from system	2	Occasional	L		

Table A-2. FMEA for LH_2 HDV with Pressure Build Loop

Failure Mode ID	Functional Group	Assembly or Component Level	Component/ Functional Identification	Function	Failure Modes	Failure Effects	Severity Class	Probability Class	Risk Matrix Level	Notes	Number of Devices
10.00	**10**	**10**	LH2 Vehicle	Noted for informational use only							1
21.01	**20**	**21**	Cryogenic Storage tank	Stores LH2	Outer tank leak/Puncture of outer tank	Loss of insulative capability, leading to boiling of LH2 and release of GH2 through relief valve	2	Occasional	L		2
21.02	**20**	**21**			Rupture of both inner and outer tank	Rupture of tank and release of LH2	4	Improbable	M		
21.03	**20**	**21**			Leak of LH2 into the interstitial space between inner and outer tanks	Loss of insulative capability, leading to boiling of LH2 and release of GH2 through relief valve	2	Occasional	L		
21.04	**20**	**21**			Failure of outer tank due to external fire	Loss of insulation vacuum and rapid heating of LH2, leading to BLEVE or release of LH2 and subsequent ignition	4	Improbable	M		
21.1.01	**20**	**21.1**	Rupture Disk	Pressure Relief	Fail to open when needed	Excess pressure leading to BLEVE	4	Improbable	M		2
21.1.02	**20**	**21.1**			Opens when not needed	Loss of insulative capability, leading to boiling of LH2 and release of GH2 through relief valve	2	Improbable	L	Close to tank outlet and above liquid level.	
22.1.01	**20**	**22.1**	Level Indicator	Measures level of LH2 inside of cryogenic storage tank. Enclosed with Integrated Valve Assembly.	Reading biased low	Overfilling of LH2, leading to release from relief valve	2	Occasional	L	Assume leak detection on Integrated Valve Assembly leads to system shutdown.	2
22.1.02	**20**	**22.1**			Reading biased high	Cryogenic tank runs completely empty	1	Occasional	L	Assume leak detection on Integrated Valve Assembly leads to system shutdown.	
22.1.03	**20**	**22.1**			Outer tank leak	Loss of insulative capability, leading to boiling of LH2 and release of GH2 through relief valve	2	Occasional	L	Assume leak detection on Integrated Valve Assembly leads to system shutdown.	
22.1.04	**20**	**22.1**			Leak of LH2 into the interstitial space	Loss of insulative capability, leading to boiling of LH2 and release	2	Improbable	L	Assume leak detection on Integrated Valve Assembly leads to system shutdown.	

Failure Mode ID	Functional Group	Assembly or Component Level	Component/ Functional Identification	Function	Failure Modes	Failure Effects	Severity Class	Probability Class	Risk Matrix Level	Notes	Number of Devices
					between inner and outer tanks	of GH2 through relief valve					
22.2.01	**20**	**22.2**	Pressure Indicator	Measures pressure inside of cryogenic tank. Enclosed with Integrated Valve Assembly.	Component leak	Leak of GH2	2	Occasional	L	Assume leak detection on Integrated Valve Assembly leads to system shutdown.	2
23.1.01	**20**	**23.1**	Valves	Controls inlet and outlet from cryogenic tank. Enclosed with Integrated Valve Assembly.	Component leak	Leak of GH2	2	Occasional	L	Assume leak detection on Integrated Valve Assembly leads to system shutdown.	6
23.2.01	**20**	**23.2**	Pressure-Relief Device	Vents if pressures exceed thresholds in gas withdrawal system. Enclosed with Integrated Valve Assembly.	Fails open	Leak of GH2	2	Improbable	L	Assume leak detection on Integrated Valve Assembly leads to system shutdown.	2
23.2.02	**20**	**23.2**			Fails close	Excess pressure leads to burst disk opening	3	Occasional	M	Assume leak detection on Integrated Valve Assembly leads to system shutdown.	
23.2.03	**20**	**23.2**			Component leak	Leak of GH2	2	Occasional	L	Assume leak detection on Integrated Valve Assembly leads to system shutdown.	
23.3.01	**20**	**23.3**	Piping	Piping up to Return Control Valve. Enclosed with Integrated Valve Assembly.	Component leak	Leak of LH2	3	Improbable	L	Assume leak detection on Integrated Valve Assembly leads to system shutdown.	2
31.1.01	**30**	**31.1**	Piping	Transfer path for LH2 to move from fueling	Component leak	Leak of LH2	3	Improbable	L		2

Failure Mode ID	Functional Group	Assembly or Component Level	Component/ Functional Identification	Function	Failure Modes	Failure Effects	Severity Class	Probability Class	Risk Matrix Level	Notes	Number of Devices
				station to cryogenic tank							
31.2.01	**30**	**31.2**	Valves	Check valve to modulate flow from fueling station to cryogenic tank only. Enclosed with Integrated Valve Assembly.	Fail closed	Unable to refuel system	1	Likely	L	Assume leak detection on Integrated Valve Assembly leads to system shutdown.	2
31.2.02	**30**	**31.2**			Fail open	Overfilling of GH2 leading to release of GH2 through relief valve	2	Occasional	L	Assume leak detection on Integrated Valve Assembly leads to system shutdown.	
31.2.03	**30**	**31.2**			Component leak	Leak of LH2	3	Occasional	M	Assume leak detection on Integrated Valve Assembly leads to system shutdown.	
31.3.01	**30**	**31.3**	LH2 Filling Receptacle	Point for connection between vehicle and fuel station hose for fueling.	Component leak	Leak of LH2	3	Improbable	L		1
32.1.01	**30**	**32.1**	Piping	Transfer path for GH2 to move from return control valve to fueling station or electrolyzer. Enclosed with Integrated Valve Assembly.	Component leak	Leak of GH2	2	Occasional	L	Assume leak detection on Integrated Valve Assembly leads to system shutdown.	2
32.2.01	**30**	**32.2**	Valves	Check valve ensures that flow is always in correct direction. Control valve to modulate return vapor either to fueling	Fail closed	Overfilling of GH2 leading to release of GH2 through relief valve	2	Occasional	L	Assume leak detection on Integrated Valve Assembly leads to system shutdown.	2
32.2.02	**30**	**32.2**			Fail open	Leak of GH2	2	Improbable	L	Assume leak detection on Integrated Valve Assembly leads to system shutdown.	
32.2.03	**30**	**32.2**			Component leak	Leak of GH2	2	Likely	M	Assume leak detection on Integrated Valve	

Failure Mode ID	Functional Group	Assembly or Component Level	Component/ Functional Identification	Function	Failure Modes	Failure Effects	Severity Class	Probability Class	Risk Matrix Level	Notes	Number of Devices
				station or vaporizer. Enclosed with Integrated Valve Assembly.						Assembly leads to system shutdown.	
32.3.01	**30**	**32.3**	GH2 Return Receptacle	Point for connection between vehicle and fuel station hose for returning GH2.	Component leak	Leak of GH2	2	Improbable	L		1
33.1.01	**30**	**33.1**	Piping	Transfer path for LH2 to move from cryogenic tank to vaporizer	Component leak	Leak of LH2	3	Improbable	L		1
33.2.01	**30**	**33.2**	Valves	Excess flow valve ensures there is not too much flow from tank to pump. Check valve ensures that flow is always in correct direction. Control valve modulates LH2 flow from pump to vaporizer.	Component leak	Leak of LH2	3	Occasional	M		8
33.2.02	**30**	**33.2**			Excess flow valve does not allow enough LH2 to vaporizer	Fuel system operates incorrectly	1	Occasional	L		
33.2.03	**30**	**33.2**			Excess flow valve fails open	Leak of LH2	3	Improbable	L		
33.3.01	**30**	**33.4**	Vaporizer	Converts LH2 to GH2 through heat transfer	Component leak on cold side	Leak of LH2	3	Occasional	M		1
33.3.02	**30**	**33.4**			Component leak on hot side	Leak of GH2	2	Likely	M		
33.31.01	**30**	**33.31**	Flow Diverter	Creates loop to transfer	Component leak	Leak of GH2	2	Likely	M		1

Failure Mode ID	Functional Group	Assembly or Component Level	Component/ Functional Identification	Function	Failure Modes	Failure Effects	Severity Class	Probability Class	Risk Matrix Level	Notes	Number of Devices
33.31.02	**30**	**33.31**		GH2 through cryogenic tank to modulate pressure within tank	Overpressurizes LH2 tank	Excessive pressure and release of GH2 through the relief valve	2	Likely	M		
33.32.01	**30**	**33.32**	Pressure Indicator	Measures pressure of GH2 down stream of vaporizer	Reading biased low	Excessive pressure and release of GH2 through the relief valve	2	Likely	M		1
33.32.02	**30**	**33.32**			Reading biased high	Pump speed reduced prematurely	1	Likely	L		
33.32.03	**30**	**33.32**			Component leak	Leak of GH2	2	Likely	M		
33.33.01	**30**	**33.33**	Piping	Transports GH2 from vaporizer to fuel cell	Component leak	Leak of GH2	2	Improbable	L		1
33.34.01	**30**	**33.34**	Valves	Pressure let down valve modulates pressure from vaporizer prior to GH2 entering fuel cell. Drain valve is used to drain the liquid hydrogen in the storage tank for maintenance or emergency.	Component leak	Leak of GH2	2	Likely	M		2
33.34.02	**30**	**33.34**			Pressure let down is too high	Excessive pressure and release of GH2 through the relief valve	2	Likely	M		
33.34.03	**30**	**33.34**			Pressure let down is too low	Fuel system operates incorrectly	1	Likely	L		
33.35.01	**30**	**33.35**	Pressure-Relief Device	Vents if pressures exceed thresholds in gas withdrawal system	Component leak	Leak of GH2	2	Likely	M		1
33.35.02	**30**	**33.35**			Fail open	Leak of GH2	2	Occasional	L		
33.35.03	**30**	**33.35**			Fail closed	Buildup GH2 pressure and rupture leading to release of GH2 from system	2	Occasional	L		

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APPENDIX B. SAFETY CODES AND STANDARDS REVIEW

Table B-1. LH_2 HDV Fuel System Safety Codes and Standards Review

Component	NFPA 52 Requirements	Potential Design Gap
Valving	16.4.3.5.3 Valves 16.4.3.5.3.1 A positive shutoff valve shall be installed in the fuel supply line. 16.4.3.5.3.2 The shutoff valve shall close automatically and prevent the flow of fuel to the engine when the ignition switch is off or in the accessory position and when the engine is not running and the ignition switch is on. 16.4.3.5.3.3 Where multiple fuel systems or containers are installed on a vehicle, automatic valves shall be provided to shut off the container that is not being utilized. 16.4.3.5.3.4 The vehicular fueling system shall be equipped with a backflow check valve to prevent the return flow of LNG from the container(s) to the filling connection. 16.4.3.5.3.5 The check valve in 16.4.3.5.3.4 shall be permitted to be integral to another component in the system, such as the vehicular fueling connector.	A positive shutoff valve should be on fuel supply and interlocked to FC controls and normally closed.
Pressure Relief Device	16.4.3.1.1.13 A secondary PRD, designed to prevent rupture of the fuel supply container upon failure of the primary PRD, shall not be required to be piped away from the fuel supply container.	There is not a secondary PRD included on the fuel supply container. While there is one on the inlet supply line, it is contained in the integrated valve assembly. This may not be ideal and should be evaluated closer in the final system design.
PRV between potentially isolated fuel	16.4.3.4.6 A PRV shall be installed in each section of piping or tubing in which LNG can be isolated between shutoff valves so as to relieve the trapped fuel pressure to a safe atmosphere.	Ensure that valving does not contain trapped fuel and if it does ensure a PRV is located where it can relieve that fuel pressure
Component	**SAE J2343 Requirements**	**Potential Design Gap**
Overfilling and Relief Device	4.2.1.8 Container Overfilling/Shutoff: LNG tanks shall be equipped with a device, or devices, that prevent overfilling. The outer vessel shall be provided with an overpressure safety device to vent the annular insulation space in the event of a vacuum loss.	The outer vessel must be equipped with an overpressure safety device to vent the annular insulation in the event of a vacuum loss.

Component	NFPA 52 Requirements	Potential Design Gap
Shutoff Valve	4.2.1.8.1 Container Shutoff Devices: Each container shall be equipped with accessible shutoff devices that allow for its complete isolation from the rest of the engine fuel supply system. Container shutoff devices shall be labeled as to their function (decals or stencils shall be acceptable) and shall be appropriately labeled "LIQUID SHUTOFF" for liquid supply and "VAPOR SHUTOFF" for vapor supplies. Manual devices shall also be labeled with the direction of closure (decals or stencils shall be acceptable). Normally closed automatic shutoff devices that are held open by electric current, pneumatic or hydraulic pressure, or a combination thereof, or manually operated shutoff devices shall be permitted to be used to meet this requirement. An automatic shutoff valve used in lieu of a manual shutoff valve shall be marked with the words "AUTOMATIC SHUTOFF VALVE."	Container must be able to be shutoff/isolated from the rest of the fuel system.
Pressure Relief Devices	4.2.2 Pressure Relief Devices: Containers shall be equipped with pressure relief devices or pressure control devices required by the code under which the containers were designed and fabricated. Rupture discs shall not be used except on the outer vessel. Each relief valve shall be labeled with the manufacturer's name, part number, and set pressure. Each relief valve shall have separate inlet connections which communicate directly with the vapor space of the tank. Each relief device shall have a separate outlet. The primary pressure relief valve shall be piped to a vent stack which extends above the vehicle. The vent stack shall be suitable for LNG service. Primary and secondary relief valve outlets shall be protected from fouling by dirt, debris, snow, ice, and/or water. The vent stack shall be sized to prevent flow restriction due to pressure drop. Gas exiting the vent stack or secondary relief valve shall not impinge on enclosed areas, other vehicles, engine intakes, or engine exhausts. In the case of dual tanks, the primary relief valve outlet piping for each tank may be manifolded to a common outlet stack. All safety relief devices on vehicular fuel containers that discharge to the atmosphere shall vent outside of the vehicle. All discharge lines and outlets shall be installed as follows: 1. Pressure relief discharge lines shall be suitable for the maximum pressure and temperature of the discharged fluid. 2. Discharge lines and adapters shall be sized, located, and secured so as to permit the required relief discharge capacity and to minimize the possibility of physical damage. 3. A means shall be provided (e.g., loose-fitting caps) to minimize the possibility of the entrance of water or dirt into either the relief device or its discharge line and to drain any water that accumulates in the discharge line. The means of protection shall remain in place except when the relief device operates. In this event, the means of protection shall permit the relief device to operate at required capacity. 4. The outlet of the discharge line shall be fitted with a device or configured to prevent the formation or accumulation of any ice that could prevent the relief device from operating at required capacity. 5. The relief valve discharge from fuel containers on vehicles shall be directed upward or shall not impinge directly on the vehicular fuel container(s), the exhaust system, or any other part of the vehicle, and shall not be directed into the interior of the vehicle.	Pressure relief device must be installed in piping sections that can be isolated where fuel can vent to atmosphere.

Component	NFPA 52 Requirements	Potential Design Gap
	6. The discharge line from pressure relief devices on all buses shall be located at the rear of the vehicle, directed upward, and extended to the top of the vehicle roof. 7. Secondary relief devices designed to prevent rupture of the container upon failure of the primary relief device shall not be required to be piped away from the tank Pressure relief devices shall be so designed that the possibility of tampering is minimized. Externally set or adjusted devices shall be provided with a means of sealing the adjustment A pressure relief valve shall be installed in each section of piping or tubing in which LNG can be isolated between shutoff devices so as to relieve the pressure that can develop from trapped fuel to a safe atmosphere. The pressure relief valve shall not have a setting greater than the maximum allowable working pressure of the line or devices it protects.	
Enclosures	4.2.9 Connection and Manifold Enclosures All non-electrical connections and manifolds for the fuel tank shall be protected from mechanical damage by means of a suitable connection enclosure. Enclosure shall be adequately vented and designed to prevent pooling of any liquids. Each non-electrical component within the connection enclosure shall be adequately labeled as to its function.	No details on whether or not enclosure is vented and prevents pooling of liquids.
Component	**SAE J2578 Requirements**	**Potential Design Gap**
Fail-safe of fluid control system	4.1.1.4 Fail-Safe Design The vehicle design should consider fail-safe design of electrical and hazardous fluid system controls. Automatic electrical disconnects should open and fuel shutoffs should close when deactivated. By so doing, any interruption of this control signal will cause isolation of electrical or fuel sources. Vehicle operational safety should consider loss of vehicle power due to an automatic shutdown that may in itself lead to a hazardous operating condition. A staged warning and shutdown process or some other alternative means should be provided to mitigate the posed hazard, particularly, if the vehicle is moving. When faults that pose potential hazards are detected, specific actions to be taken are defined in 4.6. Guidance can be found in ISO 6469-2 - Electric road vehicles - Safety specifications. Part 2: Functional safety means and protection against failures.	System should shut-off in a fail-safe condition using electronic signals to isolate fuel sources. The system is recommended to have a staged approach such that a hazardous condition does not occur while the vehicle is moving.
Component	**SAE J2579 Requirements**	**Potential Design Gap**

Component	NFPA 52 Requirements	Potential Design Gap
Manual Valving	4.1.1.3 Manual Fuel Shut Off Manual shut off functionality shall be provided on the storage systems for vehicle maintenance. This function may be met by manual over-ride of automatic shut off valves or use of manual shut off valves. See Appendix E for guidance.	Manual shutoff valve should be provided for use during maintenance. This can be met by manual over-ride of automatic valves or an additional manual shutoff valve.
Pressure Relief Valves	5.1.4 Over-Pressure Protection PRVs shall be used to provide over-pressure protection of the system that stores the liquefied hydrogen. It is the nature of cryogenic fluids to evaporate and have the vapors accumulate in the container. Unless a PRV is present, pressures due to evaporation can exceed 100 MPa (14 500 psi). Consequently, all assemblies where liquid can conceivably be trapped without release should be equipped with a PRV. Additionally, the possibility that contaminants in the liquefied hydrogen could freeze and block flow outlets should be considered as part of the design and, if necessary, redundant PRVs (from separate points of the system) should be used to ensure that boil-off can be vented and does not cause an over-pressure. The vacuum jacket surrounding the liquefied hydrogen storage vessel shall also be protected by a PRV. PRVs shall be sized and selected in accordance with CGA S-1.1 or comparable standard. See also 4.1.1.5 and Appendices A and E for guidance.	PRVs should be added including redundant PRVs to ensure that isolated fuel even due to frozen H2 blocking sections of the system cannot cause an over-pressure.

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