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Assessment of Potential Failure Modes and Effects for On-Board Components for Hydrogen-Powered Locomotives

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ABSTRACT

Hydrogen fuel sources offer alternatives to conventional fuels in the rail transportation industry. Hydrogen powered locomotive designs utilizing either a fuel cell or an internal combustion engine can make migration to alternative fuels possible for rail transportation. Codes and standards are still in development for rail application of hydrogen and safety risks must be assessed for hydrogen locomotive applications. This report utilizes a failure mode & effects analysis framework to help qualitatively understand possible risks from a hydrogen locomotive system. Findings illustrate how a combination of three mitigations greatly reduces the risks from a hydrogen locomotive system.

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EXECUTIVE SUMMARY

The implementation of hydrogen locomotive technology may offer economic benefits in the transportation sector. However, the technology required to introduce such a locomotive to the rail transport industry has different safety risks than traditional fuels. This report documents hydrogen locomotive safety risks by means of a failure mode effects and analysis (FMEA) framework and looks at four different design concepts based on gaseous (GH_2) or liquid hydrogen (LH_2) fuel, and fuel cell (FC) or internal combustion engine (ICE) engine types. Risks were assigned to each component failure mode in a system based on failure mode likelihood and consequence. These factors allow for a ranking system to qualitatively categorize the system's total risk in 5 categories from lowest to greatest risk: sustainable, marginal, moderate, severe, and critical. To do this, each component failure scenario was reviewed and assigned a frequency/likelihood category based on the likelihood of failure. Then the component failure scenario was assigned an outcome severity category based on how relatively hazardous each scenario could be. All the combinations of likelihood and outcome severity were then combined and assigned to a risk category in a risk matrix. Multiple failure modes for each generic component type for each of the 4 designs were categorized based on their respective risk levels, to identify what components might be expected to be higher-risk and therefore worth additional focus.

Design modification ideas considered for mitigating risk included a shut-off valve, tank damage protection, and first responder access for firefighting. The shut-off valve mitigation stops hydrogen flow to downstream components, which should reduce the potential harm from a leak for those components. The tank protection design modifications, such as tank placement to minimize tank exposure during a collision, reduce the likelihood of a leak from the storage tanks. Finally, the first responder access mitigation allows easier access to hydrogen storage tanks in the event of an accident to ensure uniform abatement of any fires impinging on the tanks. Each of these design modifications may be accomplished in multiple ways, and no quantification of a specific modification was made. Instead, the purpose of this study is to identify potentially high-risk component failures, and how the safety risk for those failures might be addressed.

This study showed a significant decrease in the number of critical and severe risk scenarios as these mitigations were implemented. The shut-off valve mitigation by itself offered the greatest number of reduced risk scenarios, and so may be important to consider for future designs. All mitigations in combination, however, resulted in the greatest risk reduction. In both GH_2 designs, critical risk scenarios fell from 4 down to 1 when implementing a combination of all mitigations, while in both LH_2 designs, critical risk scenarios fell from 13 to 0. This significant drop in high-level risk scenarios illustrates that mitigations and design changes to hydrogen locomotives can reduce risk. However, these systems are not necessarily trivial to implement, and may depend significantly on the specifics of the design under consideration. These qualitative changes in risk scenario rankings can illustrate how changes to a design can improve safety, but the specific implementation and reliability of these preventative and mitigative measures need to be fully considered in future safety assessments.

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ACRONYMS AND TERMS

Acronym/Term	Definition
AAR	Association of American Railroads
BLEVE	boiling liquid expanding vapor explosion
FC	fuel cell
FMEA	failure mode & effects analysis
GH_2	gaseous hydrogen
QRA	quantitative risk assessment
GTI	Gas Technology Institute
ICE	internal combustion engine
LFL	lower flammability limit
LH_2	liquid hydrogen
NG	natural gas
P&ID	piping & instrumentation diagram
PRD	pressure relief device
TPRD	thermally activated pressure relief device

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1. INTRODUCTION

Railroads offer one of the most effective ways to transport freight in an energy efficient way. According to the Association of American Railroads (AAR), freight trains can transport a ton of freight 473 miles on 1 gallon of diesel fuel which is around three to four times more efficient than trucks [1]. This corresponds to a 75% decrease in greenhouse gas emissions [1]. A freight train also differs drastically in scale compared to trucks. A fully loaded freight train could haul the equivalent of several hundred trucks given each rail car can carry about four trucks worth of freight [2]. 83 million additional trucks would be necessary to replace the current freight moved by rail [2]. These metrics exemplify the potentially valuable contribution rail may provide for the future of transportation. As such, its continued success is directly related to the future of fuel sources which may be moving away from diesel. Hydrogen fuel is one such hopeful alternative that would further enable rail transport with lower emission levels. However, the implementation of new technologies often poses different safety risks, and hydrogen locomotives are no exception. The storage of hydrogen fuels differs greatly from traditional diesel fuel given that it must either be pressurized or kept at cryogenic temperatures. Gaseous hydrogen (GH_2) must be stored in high pressure vessels to provide meaningful energy density to power a locomotive. High pressure systems come with a series of hazards related to violent release in the case of a leak or fire. Another option is liquid hydrogen (LH_2) which offers a far greater energy density but requires a cryogenic storage vessel with associated cooling and boil-off expenses and hazards. Secondly, hydrogen fuel systems require different components not commonly used in most rail applications, such as vaporizers for conversion of LH_2 to GH_2 for use in a fuel cell (FC) or internal combustion engines (ICE).

To explore the risk associated with the implementation of a hydrogen locomotive, this work applies a failure mode & effects analysis (FMEA) to hydrogen locomotive designs to identify high risk components. This work then seeks to mitigate risk with design changes that decrease the number of critical and severe risks in the FMEA. These design changes are presented to show how system changes can reduce the likelihood or severity of unintentional hydrogen releases from on-board locomotive components.

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2. METHOD

An FMEA is a structured approach for assessing the failure modes and resulting effects for components comprising a system. Failure modes are ways in which a component could fail, while effects are the consequences of the type of failure. This information can then be used qualitatively to understand the risk posed by individual failure modes or components, identify primary risk drivers for a system and rank them, as well as understand how possible mitigation strategies could be used to reduce the overall system risk. For this work FMEA is applied to preliminary generic hydrogen locomotive designs. The desired outcomes of this FMEA are to provide an initial understanding of the risks associated with each hydrogen locomotive design, make comparisons of risks between designs, identify key component and failure modes driving risk, and explore how different mitigation strategies might be deployed to reduce risk.

2.1. Designs and Components

The first step when developing the FMEA was to identify components comprising the locomotive fueling system based on simplified process schematics provided by Wabtec. It should be noted that these designs are preliminary and generic to these types of systems; future designs might differ from these initial examples, and so the resulting components, connectivity, and failure modes might also differ.

From those designs, 149 different components were identified for 4 different design options. The four design options are related to the state of the stored fuel, either GH_2 or LH_2, and the type of power system, either FC or ICE. Each design has its own subset of components unique to that design. For example, a vaporizer is unique to LH_2 applications. Dividing the analysis into these four designs helps simplify results and offers comparisons between designs. Also, from the piping & instrumentation diagrams (P&IDs) for each component, the following information was gathered: the phase of hydrogen passing through the component during normal operation (gas or liquid), the approximate size of the component (small or large), as well as the approximate pressure and temperature of hydrogen within the component during normal operation. The small or large categorization was selected to differentiate between components that store large amounts of hydrogen (like a storage tank) and those that may have smaller amounts of hydrogen. This additional characterization information informs the potential outcome and its severity if the component were to fail.

The designs are detailed in the following subsections through flowcharts that explain each design. Hydrogen originates at the storage tanks, either gaseous or liquid. The hydrogen then proceeds down the fuel lines through a series of valves that control pressure and allow for refueling. The hydrogen is then delivered to the power generating system, either a FC or ICE. In the following flowcharts, blue shapes represent hydrogen fuel input points to the system. Green shapes are the fuel line system where valves are the primary components. Light yellow shapes are the primary drive systems and ancillary system components.

2.1.1. GH_2/FC Design Flowchart

The GH_2/FC design utilizes gaseous hydrogen storage in high-pressure tanks and a fuel cell to convert the hydrogen into useable electrical energy. This design can be seen in Figure 1.

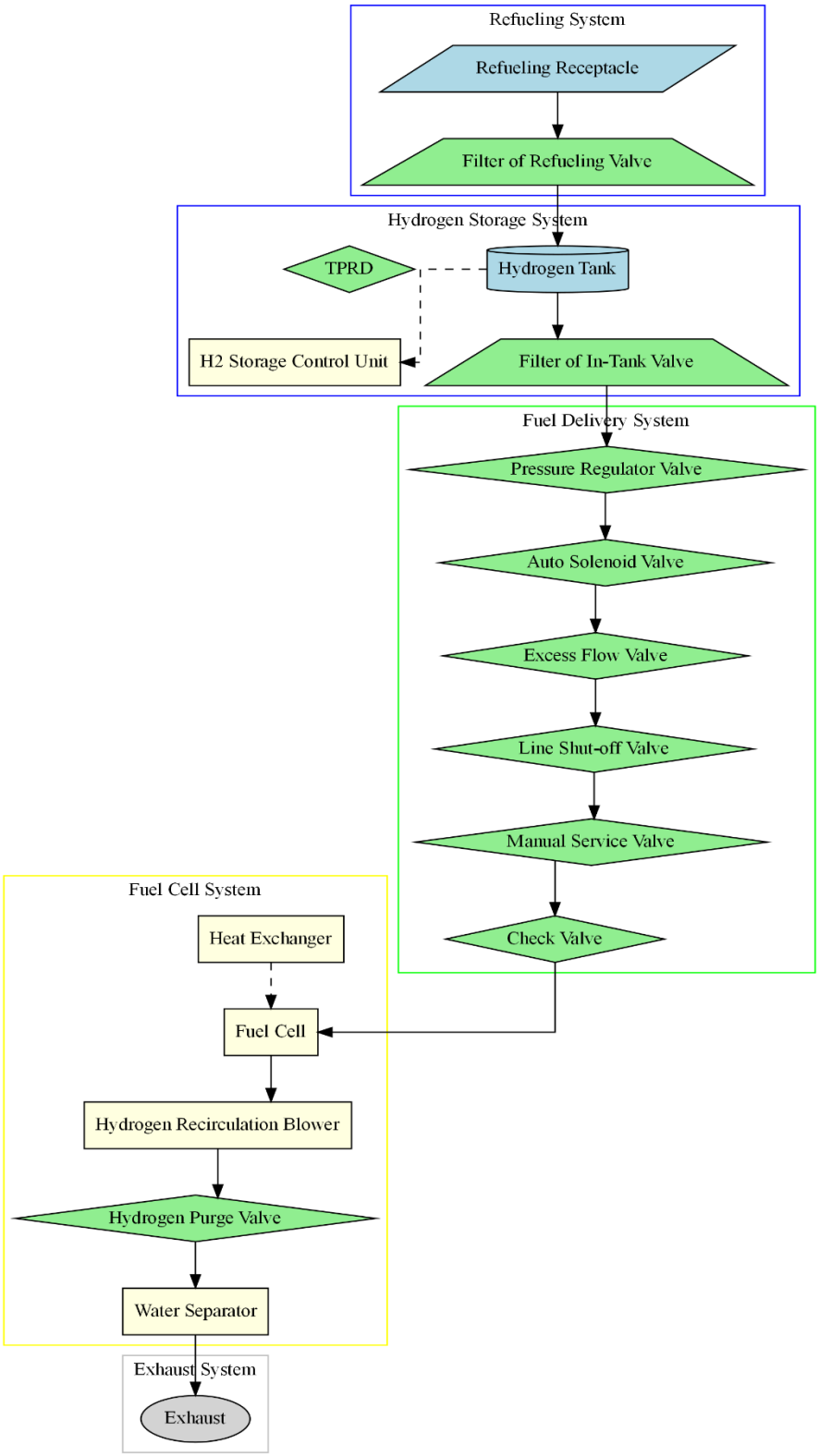


Figure 1: GH_2/FC Design Flowchart

2.1.2. GH_2/ICE Design Flowchart

The GH_2/ICE design utilizes a combustion engine and stored GH_2 to power a locomotive. This design has significant differences from the GH_2/FC design with many of the components studied being unique to ICE application. A flowchart of this design's functionality can be seen in Figure 2.

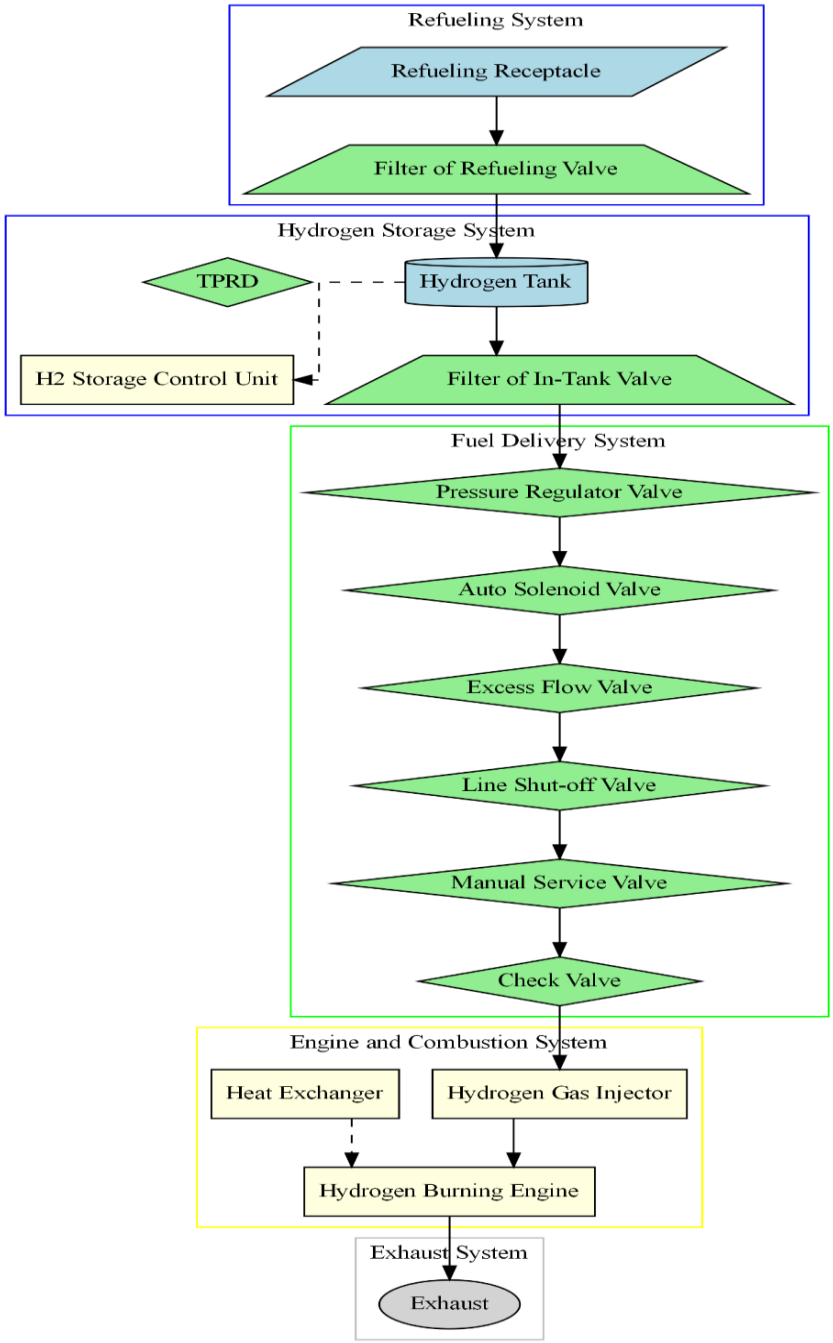


Figure 2: GH_2/ICE Design Flowchart

2.1.3. LH_2/FC Design Flowchart

The LH_2/FC design uses stored LH_2 and a vaporizer to generate gaseous hydrogen used to power a fuel cell. A flowchart of this design is shown below in Figure 3. Cryogenic storage of LH_2 adds some complexity and risk.

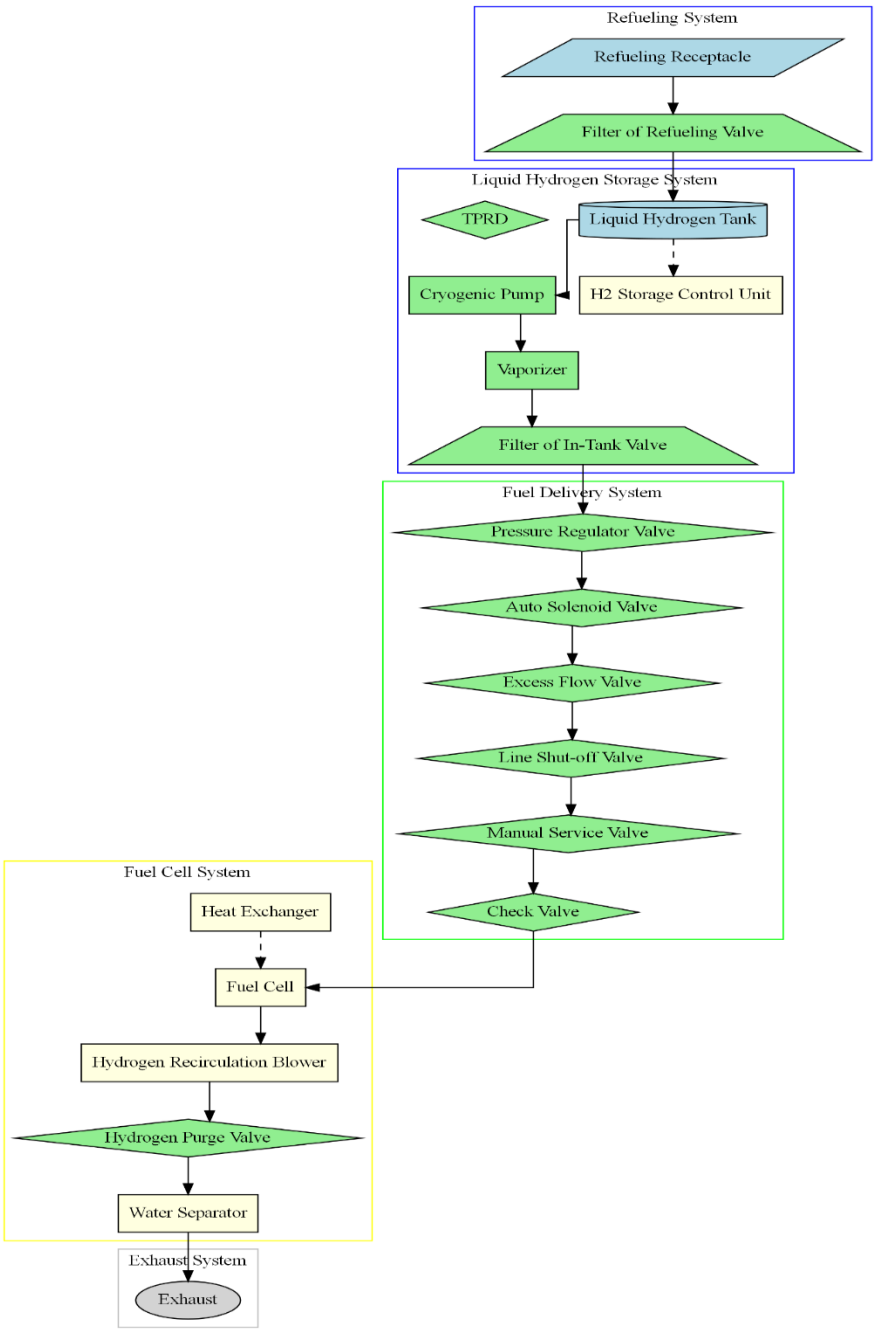


Figure 3: LH_2/FC Design Flowchart

2.1.4. LH_2/ICE Design Flowchart

The LH_2/ICE design utilizes an ICE to power the locomotive after a vaporizer delivers gaseous hydrogen for combustion in the ICE. A flowchart of this design can be seen below in Figure 4.

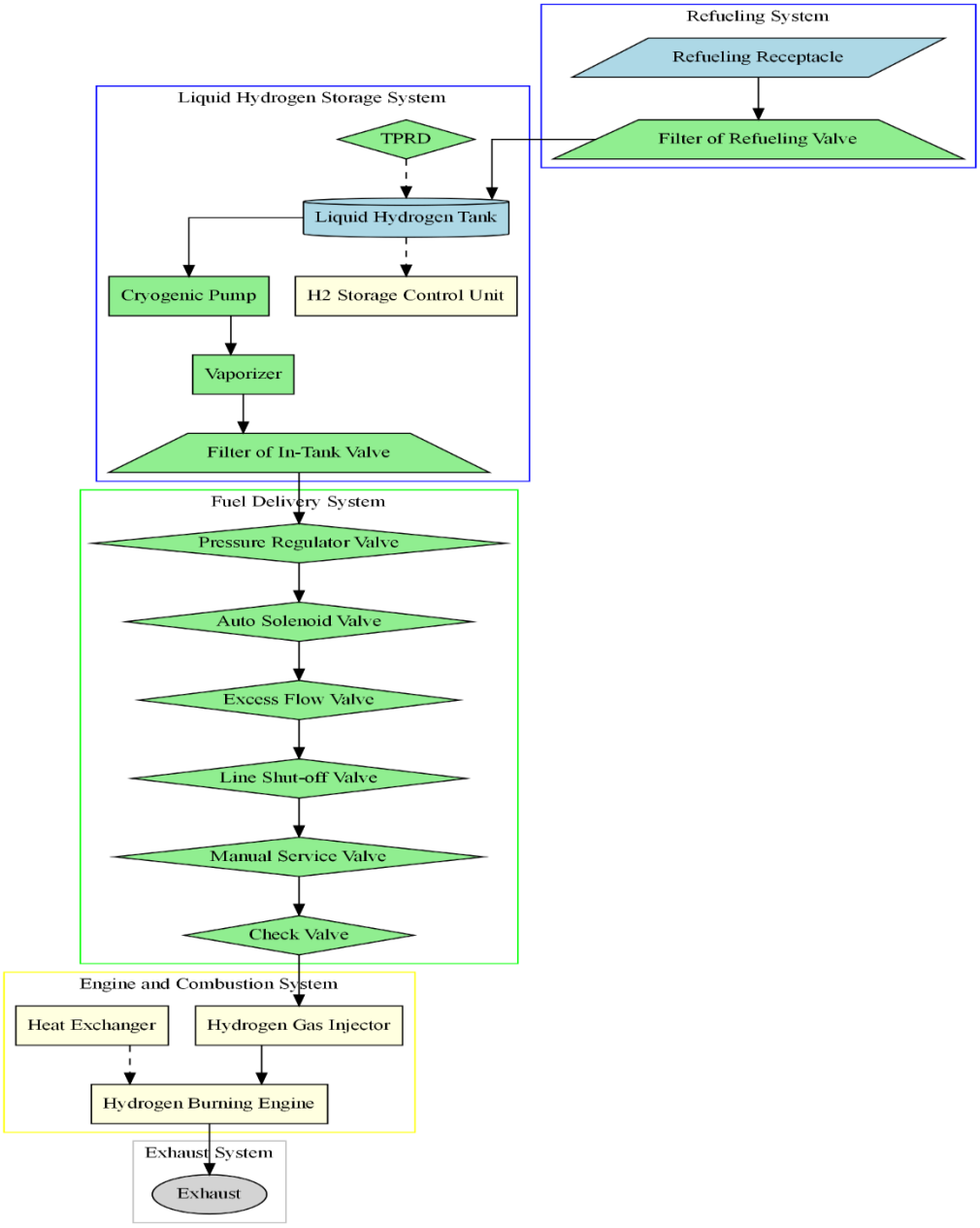


Figure 4: LH_2/ICE Design Flowchart

2.2. Failure Modes and Effects Analysis

Next, potential failure modes were identified for each component. Failure mode selection was based upon previous work in NHTSA DOT HS 811 075 which developed an FMEA for hydrogen fuel cell vehicles, and a quantitative risk assessment (QRA) conducted by the University of Maryland that created a reliability data collection framework for hydrogen fueling station quantitative risk analysis [3] [4]. Qualitative failure rates were taken from the Gas Technology Institute's (GTI) report titled "Consistency Review of Methodologies for Quantitative Risk Assessment" [5] which examined many models and simulations to verify data from sources like NFPA 59A and others. Many failure scenarios were considered such as a leaky valve or catastrophic tank puncture. A list of all failure modes considered is shown below in Table 1.

Table 1. Failure Modes Considered in Locomotive H_2 FMEA Analysis

Failure Modes		
Corrosion fatigue	Fails open	Leak or Rupture
Cracking	Fails or ruptures	Plugging
Creep rupture	Fails to close	Tank leak
Damaged	Fails to function	Tank rupture
Fails	Fails to operate	Thermal fatigue
Fails closed	Leak	

For each failure mode, a potential cause of the failure mode was identified as well as a potential progression of events leading to the failure. For example, a hydrogen fuel line in a gaseous hydrogen system could have a seal degrade leading to the seal failing and hydrogen leaking. This leak could result in a high-pressure hydrogen release that could either immediately ignite causing a jet fire or accumulate and ignite and explode after a delay. Either a fire or explosion could then impact other nearby components leading to subsequent events. The failure mode for this example is a leak, while the cause is an overpressure, degradation, or impact on the seal.

Next, the potential impacts of the component experiencing each failure mode was determined. Impacts considered included fire; a hydrogen leak with the potential of delayed ignition; loss of control of hydrogen flow; system overheating, tank rupture with fire; or no hazard. For the hydrogen line leak example previously mentioned, the potential impacts would include a hydrogen leak, delayed ignition and/or a fire.

2.3. Risk Determination

The assignment of frequency or likelihood of each component-failure mode combination was informed by a previous FMEA for hydrogen vehicles [3]. Frequency or likelihood was discretized into four ranking categories: occasional, probable, frequent; remote; improbable; and eliminated, incredible based on the anticipated frequency of the event as shown in Table 2.

Table 2. Frequency / Likelihood Classes

Frequency / Likelihood	Approximate Frequency Bounds (per year)	Description
Occasional, Probable, Frequent	f > 1E-2	between likely to occur and almost certain to occur repeatedly
Remote	1E-4 < f < 1E-2	unlikely, but possible to occur within the system's lifetime
Improbable	1E-6 < f < 1E-4	unlikely that a failure would occur in the system lifetime
Eliminated, Incredible	f < 1E-6	extremely unlikely to occur

The severity of the potential outcome of a failure mode was then categorized by considering the component size along with the expected hydrogen phase and pressure that would be present. Outcomes of the failure modes were ranked as either low, medium, high, or massive. Table 3 shows the logic applied to assigning outcome to each component-failure mode combination. Due to the extreme nature of a rupture, it is considered in its own outcome class and two large component sizes are presented with different risk levels.

Table 3. Outcome Classes

Component Size	Small or Large	Small or Large	Small	Large	Large
Failure Mode	All	All	All	All Other besides Rupture	Rupture
Pressure (bar)	Low, <8	Medium, 8-20	High, 350-700	High, 350-700	High, 350-700
Rating	Low	Medium	High	High	Massive

Based upon the assigned frequency/likelihood and potential outcome of a component's failure mode, a risk value was determined using the master risk matrix in Figure 5 below. For example, a leak or rupture of a gaseous fuel line connection (a component of small size) operating at high pressure was assigned a remote likelihood and a high outcome, resulting in a risk value of severe. The risk values can be used as a relative measure to make comparisons between the different component-failure mode possibilities for each design and between designs. Risk values were grouped into five categories of severity: sustainable, marginal, moderate, severe, and critical.

		Outcome			
		Low	Medium	High	Massive
Likelihood	Occasional, Probable, Frequent	Moderate	Severe	Critical	Critical
	Remote	Marginal	Moderate	Severe	Critical
	Improbable	Sustainable	Marginal	Moderate	Severe
	Eliminated, Incredible	Sustainable	Sustainable	Marginal	Moderate

Figure 5: Master Risk Matrix

2.4. Mitigations

Three mitigations were considered to reduce risk in the system by focusing on subsystems that offer opportunities for increased safety. The three mitigations are solenoid shut-off valve, tank protections, and first responder access.

2.4.1. Solenoid Shut-Off Valve Mitigation

This mitigation involves using a solenoid actuated shut-off valve in the hydrogen fuel system that shuts off the flow of hydrogen in the event of an anomaly. This valve could be automatic or manual. An automatic shut-off valve could respond to a series of sensors that monitor the system. Such sensors could be hydrogen gas detectors placed in critical leak detection positions. In the case of a manual shut-off, an operator would use sensors and observation to detect an anomaly and shut off gas flow before a more serious issue develops. Example placements of such a shut-off valves can be seen in Figure 6 for a gaseous hydrogen system and a liquid hydrogen system.

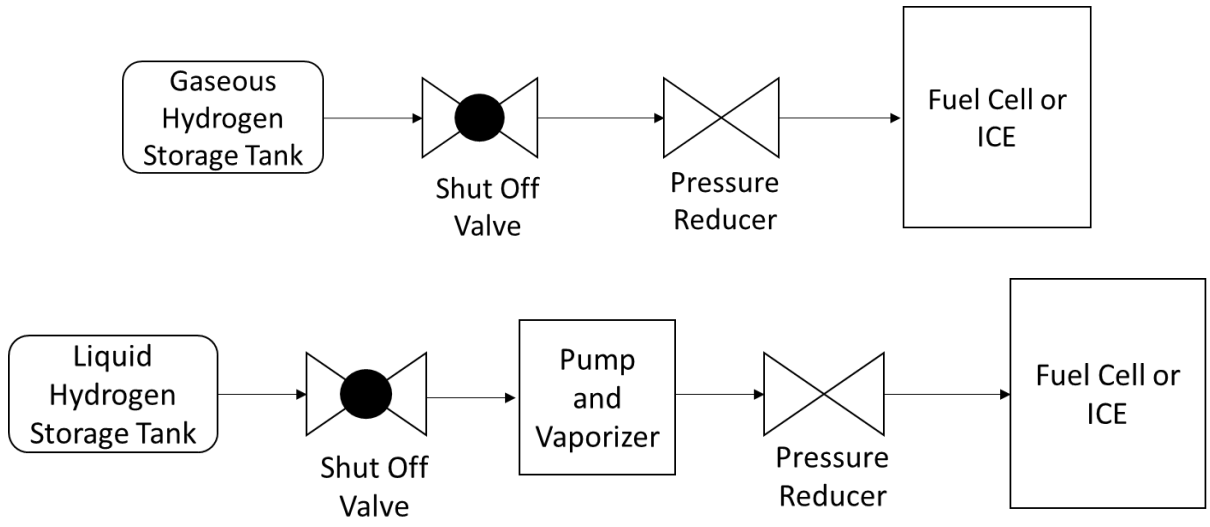


Figure 6: Example placement of shut-off valve in GH_2 system (top) and LH_2 system (bottom)

This mitigation lowers the likelihood of a hazardous outcome (consequence) of all components in the system downstream of the shut-off valve since gas flow would be stopped in time.

2.4.2. Tank Protection Mitigation

The tank protection mitigation focuses on the construction and placement of hydrogen storage tanks to match or exceed requirements listed in 49 CFR 238 (AAR S-5506), 49 CFR 229 (AAR S-580) [6] [7]. This includes increased tank thickness and strategic placement in the interior of the locomotive to avoid common crash vectors. As this is a qualitative study, we will not recommend a specific increase in tank thickness but assume improved tank durability and related components if additional protections are in place. In addition, placement of a tank further away from the tracks and more towards the center or top of the locomotive may provide greater integrity in the case of a collision. This is a broad but potentially very important measure to prevent hydrogen release for rail systems; and as such, a literature review was undertaken on survivability testing requirements for existing hydrogen tanks (Section 2.5).

This mitigation reduces the likelihood of all tank-related components suffering damage. The effect in the FMEA is to reduce the likelihood for all tank-related components by one category. Figure 7: Parts impacted by tank protection mitigation. shows briefly parts impacted by this mitigation. All tank related valves as well as the tank are included. These valves include the thermally activated pressure relief device (TPRD), excess flow valve, filter of in-tank valve, auto-solenoid valve, and bleed valve.

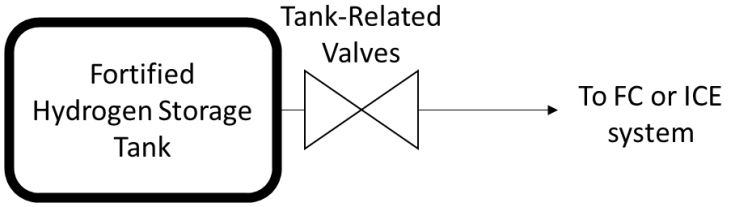


Figure 7: Parts impacted by tank protection mitigation.

2.4.3. First Responder Access Mitigation

First responder access mitigation assumes designs that enable easier access to the hydrogen storage tanks by first responders. By allowing for more direct access to the hydrogen tank storage area, fire suppression and cooling agents can be uniformly distributed over the entire hydrogen storage system. This is critical to avoid non-uniform cooling which could lead to TPRD failures in the case of GH_2 designs where the TPRD is cooled by water while other portions of the tanks remain hot. In this case, the TPRD would not actuate and lead to a violent release of H_2 gas once the pressure inside the tank reached the burst pressure of the tank. For LH_2 designs, non-uniform cooling could lead to a boiling liquid expanding vapor explosion (BLEVE) type event despite application of cooling agents on a portion of the tank. Another consideration for a LH_2 storage system is the application of cooling agents in such a way to avoid sealing any leaks that may have occurred in the event of an accident. Cryogenic LH_2 can freeze water on contact and seal a leak that is safely venting the LH_2 tank, leading to a BLEVE event.

2.5. Fuel Tank Survivability Literature Study

A literature study was undertaken to understand the applicability of existing hydrogen fuel storage tank survivability testing to locomotive systems. Large scale hydrogen vehicles were studied, and results extrapolated for a locomotive application. Beside hydrogen specific applications, some useful knowledge can be gained from examining existing locomotive standards for diesel and natural gas (NG) fuels as was other fuel tank survivability considerations in typical transportation vehicles.

Hydrogen fuel cell electric vehicles (FCEV) are governed by the standard Global Technical Regulations (GTR) 13 which provides performance-based hydrogen vehicle regulations for crashworthiness and fuel tank survivability. Hydrogen fuel tanks that are to be used on passenger vehicles must demonstrate their survivability in a series of rigorous crash test scenarios. Gaseous hydrogen (GH_2) storage system tests are described in chapter 6, while liquid hydrogen storage systems are covered in chapter 7 [8]. Tests for GH_2 systems start with a baseline burst pressure test where the pressure is increased until the tank bursts. Once this is established, tanks are then put through representative (according to local jurisdiction) crash testing. Leak tests are performed afterwards to determine if any hydrogen leaks formed during the crash. Tanks are required to be leak free for 60 minutes post-crash [8]. Tanks undergo a rigorous pressure cycle regime to determine their functionality throughout their life span and overpressure effects which occur during refueling. After a simulated lifecycle, the tanks are again tested at their extremes to determine failure modes. Burst tests and fire tests are performed after an accelerated life test. Fire tests include both localized fires and an engulfing fire which aim to trigger the TPRD. The localized fires test the tank's survivability in the case the TPRD is isolated from the fire. In addition to these tests, the tanks undergo drop, vibration and temperature cycling as well. Individual components on tanks, especially the TPRD, undergo a similar test regimen. Leak, pressure cycling, and accelerated life tests, among others, are performed on components alone before incorporation into a larger storage system assembly. The redundant and cycling tests are designed to ensure storage system survivability in a large passenger vehicle. LH_2 storage systems undergo similar leak and pressure cycling testing. Verification of the pressure relief devices (PRDs) is carried out in a fire scenario in which the PRDs prevent a BLEVE event [8].

As the scale of the hydrogen vehicle is increased to commercial heavy-duty trucks or city buses, the same general type of hydrogen storage tank is used but the number of tanks increases. A typical passenger vehicle FCEV may have only 1 tank while a heavy-duty vehicle may have 4 or more depending on application. Crashworthiness is the same for these two cases, however there is some data to suggest that larger vehicles with several tanks may be more susceptible to tank burst due to overpressure in the case of a fire [9]. This is because the size of the tank compartment inhibits uniform cooling in the case of fire suppression. This can lead to the TPRDs failing to actuate while other parts of the tank heat excessively. Something similar could occur in a large-scale hydrogen locomotive. In this case, proper forethought should be given to the design of larger-scale hydrogen storage to ensure optimal first responder access. This will ensure uniform cooling and effective suppression of any fires while avoiding catastrophic tank ruptures.

49 CFR Part 229 details safety design and crashworthiness requirements for locomotives. Tank protection regulations require main reservoir testing to ensure the integrity of fuel vessels on a locomotive. A pneumatic and hydrostatic pressure test is required to at least 25% the maximum working pressure (MWP). Further overpressure protection is required using a pressure safety valve that reduces pressure whenever 15 lbs/in^2 (103,421 N/m^2) above the MWP is reached [7]. Locomotive fuel tanks are divided into two groups concerning shielding: internal and external. Internal tanks are required to be positioned in a place on the locomotive to reduce risk of puncture and not to leak in the case of an overturned locomotive. In addition, the fuel tank bulkheads and skin must, at a minimum, be equivalent to a 5/16 in (8 mm) thick steel plate with a yield strength of 25,000 lbs/in^2 (172,368,932 N/m^2) as covered in 49 CFR 238.223 [6]. External fuel tanks impact requirements are more detailed and are broken down in Part 238 Appendix D into 4 load cases: minor derailment, jackknifed locomotive, side impact, and penetration resistance. Case 1: minor derailment the end plate of the fuel tank must support loading of one half the weight of the car body at a vertical acceleration of 2 g and not exceed the strength of the material. Space between the rail and the tank should be sufficiently large to prevent impact during derailment [6]. Case 2: jackknifed locomotive the fuel tank must handle loading transversely at the center equivalent to one half the weight of the locomotive at vertical acceleration of 2 g [6]. Case 3: side impact considers impact with an 80,000 lbs (362,874 kg) vehicle hit at the longitudinal center of the fuel tank [6]. Finally, Case 4: penetration resistance requires the end plates of the fuel tank to be equivalent to 5/16 in (8 mm) steel plate with a 25,000 lbs/in^2 (172,368,932 N/m^2) yield strength and the lower third of the end plates to be 3/4 in (19 mm) steel plate equivalent with the same yield strength [6].

Tank strength is a critical concern in all scenarios to prevent leaks and increase survivability. Locomotive regulations, due to the potentially large impact forces, aim to ensure tank strength and critical placement to avoid damage. External fuel storage requires additional tank resilience due to its direct exposure to hazards. Internal tanks offer considerable savings in weight while increasing survivability. Similar considerations should be applied to a locomotive with hydrogen fuel tanks. If possible, avoid external placement, especially on the underside nearest the track. Increasing tank thickness allows greater survivability and versatility in placement. A combination of both effective placement and increased tank thickness offers the greatest protection. In some cases, however, external tanks may be required due to the use of the compartment for passengers or cargo. Internal tanks reduce the amount of space available for freight. In addition. a safety concern is presented by leaking tanks that could harm passengers or freight. Finally, accessibility of the tanks for maintenances should be considered. External tanks provide much more accessibility and reduced cost in maintenance.

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3. FMEA RESULTS

The following sections detail the results of the FMEA for each design option. Results are divided into 8 different cases. The definitions of each case are given below:

1. Unmitigated
2. Mitigated with solenoid shut-off
3. Mitigated with tank protection methods
4. Mitigated with first responder access methods
5. Mitigated with both solenoid shut-off and tank protection methods
6. Mitigated with both solenoid shut-off and first responder access methods
7. Mitigated with both tank protection and first responder access methods
8. Mitigated with solenoid shut-off, tank protection and first responder access methods

For each design type, a risk matrix is generated for each of the 8 cases. The matrix will list the number of FMEA scenarios that were categorized into each location in the risk matrix. These results are meant to show the effect of the various mitigations in moving component failure modes (FMEA scenarios) from higher-risk categories to lower-risk categories for the 8 cases described above.

Table 4, Table 5 and Table 6 below detail the results of each mitigation on the outcomes and likelihoods of each component effected by that mitigation. Note that the solenoid shut-off valve mitigation effects the largest number of components of the three mitigation strategies. It will be seen in the follow sections that that is mitigation reduces the number of high risks the most due to the large number of components its effect. It is also worth noting, when examining the results for each design type that the ICE systems are complex as far as number of components. LH_2 systems are also more complex than GH_2 systems. Therefore, these different design types will consider a different total number of risks associated with the number of components. The entire FMEA table, shown in Appendix A, captures the rankings for every component.

Table 4: Solenoid Shut-Off Valve Mitigation Component Impact List

Design Type	Component Name	Pre-Mitigation Outcome	Post-Mitigation Outcome
Gas/Liquid	Check Valve	High	Medium
Liquid	Line Shut-off Valve	High	Medium
Gas/Liquid	Manual Service Valve	High	Medium
Liquid	Pump	High	Medium
Gas/Liquid	Hydrogen Fuel Lines/Connections	Medium	Low
Gas/Liquid	Refueling Receptacle	High	Medium
Gas	Pressure Regulator Valve	High	Medium
Liquid	Vaporizer	High	Medium
Gas/Liquid	Filter of Refueling Valve	High	Medium
Gas/Liquid	Hydrogen Fuel Lines/Connections	High	Medium
Gas/Liquid	Hydrogen Gas Injector	Medium	Low
Gas/Liquid	Pressure Relief Valve (Mid)	Medium	Low
Gas/Liquid	Flat-Plate Collector with Phase Change (FCPC) Heat Exchange	Medium	Low
Gas/Liquid	Manual Defueling Valve	Medium	Low

Table 5: Tank Protection Mitigation Impacted Components

Design Type	Component	Pre-Mitigation Likelihood	Post-Mitigation Likelihood
Gas/Liquid	TPRD	Remote	Improbable
Gas/Liquid	Bleed valve	Remote	Improbable
Gas/Liquid	Filter of in-tank valve	Improbable	Eliminated, Incredible
Gas/Liquid	Excess flow valve	Remote	Improbable
Gas/Liquid	Auto solenoid valve	Improbable	Eliminated, Incredible
Gas/Liquid	Manual service valve	Remote	Improbable
Gas/Liquid	Hydrogen Tank	Remote	Improbable

Table 6: First Responder Access Mitigation Impacted Components

Design Type	Component	Pre-Mitigation outcome	Post-Mitigation outcome
Gas/Liquid	TPRD	High	Medium
Gas/Liquid	Bleed valve	High	Medium
Gas/Liquid	Filter of in-tank valve	High	Medium
Gas/Liquid	Excess flow valve	High	Medium
Gas/Liquid	Auto solenoid valve (controls internal check valve NC)	High	Medium
Gas/Liquid	Manual service valve	High	Medium
Gas/Liquid	Hydrogen Tank	High	Medium

3.1. GH_2/FC Design

The results for the GH_2/FC design for each case are in Figure 8 below where the number of risks in each category is shown in each corresponding cell in the risk matrix. 56 components are considered in this design where each component corresponds to one risk in the matrices below in Figure 8. Each case is displayed individually starting with the unmitigated case (Case #1) in the upper-left down to the fully mitigated case in the lower-right (Case #8).

Case 1 Outcome		Low	Medium	High	Massive
Likelihood	Occasional, Probable, Frequent				
	Remote	9	2	3	
	Improbable	6	11	24	1
	Eliminated, Incredible				

Case 2 Outcome		Low	Medium	High	Massive
Likelihood	Occasional, Probable, Frequent				
	Remote	11		3	
	Improbable	17	10	14	1
	Eliminated, Incredible				

Case 3 Outcome		Low	Medium	High	Massive
Likelihood	Occasional, Probable, Frequent				
	Remote	9	2	1	
	Improbable	6	11	13	
	Eliminated, Incredible			13	1

Case 4 Outcome		Low	Medium	High	Massive
Likelihood	Occasional, Probable, Frequent				
	Remote	9	4	1	
	Improbable	6	24	12	
	Eliminated, Incredible				

Case 5 Outcome		Low	Medium	High	Massive
Likelihood	Occasional, Probable, Frequent				
	Remote	11		1	
	Improbable	17	8	5	
	Eliminated, Incredible		2	11	1

Case 6 Outcome		Low	Medium	High	Massive
Likelihood	Occasional, Probable, Frequent				
	Remote	11	2	1	
	Improbable	20	18	4	
	Eliminated, Incredible				

Case 7 Outcome		Low	Medium	High	Massive
Likelihood	Occasional, Probable, Frequent				
	Remote	9	2	1	
	Improbable	6	13	11	
	Eliminated, Incredible		13	1	

Case 8 Outcome		Low	Medium	High	Massive
Likelihood	Occasional, Probable, Frequent				
	Remote	11		1	
	Improbable	17	10	3	
	Eliminated, Incredible	3	10	1	

Figure 8: GH_2/FC risk count for each case

In the unmitigated scenario (Case #1), the GH_2/FC locomotive design has 4 severe and 26 moderate risks. The primary severe risks are associated with the hydrogen tanks, the TPRD, and the hydrogen fuel lines. The hydrogen tanks pose a significant threat due to the potential for catastrophic failures, such as explosions or long-duration jet flames. The TPRD, a crucial safety valve intended to prevent tank overpressure during a fire, could lead to a tank explosion if it fails to operate as designed. The hydrogen fuel lines, which transport hydrogen throughout the vehicle, are particularly vulnerable due to their exposure and positioning, resulting in a severe risk rating for those scenarios.

Mitigation strategies greatly reduce the number of severe and moderate risks in the GH_2/FC design. The solenoid shut-off valve is highly effective in mitigating risks associated with the hydrogen fuel lines by cutting off the hydrogen supply in the event of a leak, thereby reducing the severity of potential outcomes. Tank protection methods, such as enhanced isolation and increased tank thickness, decrease the likelihood of tank damage by making the tanks more resilient to impacts. First responder access ensures that emergency personnel can quickly and safely address incidents, mitigating the consequences of tank damage. These combined efforts significantly improve the safety profile of the GH_2/FC locomotive by either preventing damage or minimizing its impact.

In the fully mitigated scenario (Case #8), the GH_2/FC design has one severe risk and three moderate risks. The remaining severe risk is linked to the hydrogen fuel lines, particularly the exposed sections before the shut-off valve. Moving the solenoid shut-off valve closer to the storage system could further minimize this risk. The tank and TPRD, initially severe risks, are reduced to moderate due to the combined effects of tank protection and first responder access mitigations. The three moderate risks include components such as the hydrogen fuel lines and other critical parts that, while mitigated, still require more intervention to further reduce their likelihood and impact.

3.2. GH_2/ICE Design

The case-by-case risk matrices for the GH_2/ICE are shown in Figure 9 below, summarizing the results of the application of the mitigations discussed previously. There are 76 components are considered in this design. Each component corresponds to one risk count in the matrices in Figure 9.

Case 1 Outcome		Low	Medium	High	Massive
Likelihood	Occasional, Probable, Frequent				
	Remote	10	2	3	
	Improbable	24	11	24	1
	Eliminated, Incredible				1

Case 2 Outcome		Low	Medium	High	Massive
Likelihood	Occasional, Probable, Frequent				
	Remote	12		3	
	Improbable	35	10	14	1
	Eliminated, Incredible				1

Case 3 Outcome		Low	Medium	High	Massive
Likelihood	Occasional, Probable, Frequent				
	Remote	10	2	1	
	Improbable	24	11	13	
	Eliminated, Incredible			13	2

Case 4 Outcome		Low	Medium	High	Massive
Likelihood	Occasional, Probable, Frequent				
	Remote	10	4	1	
	Improbable	24	24	12	
	Eliminated, Incredible				1

Case 5 Outcome		Low	Medium	High	Massive
Likelihood	Occasional, Probable, Frequent				
	Remote	12		1	
	Improbable	35	8	5	
	Eliminated, Incredible		2	11	2

Case 6 Outcome		Low	Medium	High	Massive
Likelihood	Occasional, Probable, Frequent				
	Remote	12	2	1	
	Improbable	38	18	4	
	Eliminated, Incredible				1

Case 7 Outcome		Low	Medium	High	Massive
Likelihood	Occasional, Probable, Frequent				
	Remote	10	2	1	
	Improbable	24	13	11	
	Eliminated, Incredible		13	1	1

Case 8 Outcome		Low	Medium	High	Massive
Likelihood	Occasional, Probable, Frequent				
	Remote	12		1	
	Improbable	35	10	3	
	Eliminated, Incredible	3	10	1	1

Figure 9:GH_2/ICE risk count for each case

Without mitigation, the GH_2/ICE locomotive design faces four severe risk scenarios: two related to hydrogen tanks, one to the TPRD, and one to the hydrogen fuel lines. These risks are severe due to the potentially high likelihood and potential catastrophic outcomes of failures. The hydrogen tanks, operating under high pressure, are susceptible to damage that could lead to explosions or significant hydrogen release. The TPRD, essential for preventing overpressure, poses a severe risk if it malfunctions. The hydrogen fuel lines, exposed yet essential for transporting hydrogen, present a severe risk due to their vulnerability.

Mitigation strategies substantially reduce the number of severe and moderate risks in the GH_2/ICE design. The solenoid shut-off valve lowers risks associated with the hydrogen fuel lines by cutting off the hydrogen supply in the event of a leak, reducing the severity of potential outcomes. Tank protection methods, such as reinforced casings and strategic placement, can decrease the likelihood of tank damage. First responder access enables more rapid response to a fire scenario and hence may help protect the tank and TPRD. These combined efforts significantly enhance the safety profile of the GH_2/ICE locomotive by either preventing damage or minimizing its impact.

In the fully mitigated scenario, the GH_2/ICE design has one severe risk scenario and three moderate risk scenarios. The remaining severe risk is associated with the hydrogen fuel lines, particularly the sections before the shut-off valve. As mentioned previously, moving the solenoid shut-off valve closer to the storage system could further aid in risk reduction. The tank and TPRD, initially categorized as severe risk scenarios, are reduced to moderate due to the combined effects of tank protection and first responder access mitigations. The three moderate risks include components such as the hydrogen fuel lines and other critical parts that, while mitigated, still require ongoing attention and potential additional strategies to further reduce their likelihood and impact.

3.3. LH_2/FC Design

Figure 10 below shows the case-by-case risk count for the LH_2/FC design. There are 60 components considered in this design. Each component corresponds to one risk count in the matrices in Figure 10.

Case 1 Outcome		Low	Medium	High	Massive
Likelihood	Occasional, Probable, Frequent				
	Remote	9	2	12	
	Improbable	7	11	18	1
	Eliminated, Incredible				

Case 2 Outcome		Low	Medium	High	Massive
Likelihood	Occasional, Probable, Frequent				
	Remote	11	8	4	
	Improbable	18	9	9	1
	Eliminated, Incredible				

Case 3 Outcome		Low	Medium	High	Massive
Likelihood	Occasional, Probable, Frequent				
	Remote	9	2	7	
	Improbable	6	11	13	
	Eliminated, Incredible	1		10	1

Case 4 Outcome		Low	Medium	High	Massive
Likelihood	Occasional, Probable, Frequent				
	Remote	9	7	7	
	Improbable	7	21	9	
	Eliminated, Incredible				

Case 5 Outcome		Low	Medium	High	Massive
Likelihood	Occasional, Probable, Frequent				
	Remote	11	7		
	Improbable	17	9	4	
	Eliminated, Incredible	1	1	9	1

Case 6 Outcome		Low	Medium	High	Massive
Likelihood	Occasional, Probable, Frequent				
	Remote	12	11		
	Improbable	19	17	1	
	Eliminated, Incredible				

Case 7 Outcome		Low	Medium	High	Massive
Likelihood	Occasional, Probable, Frequent				
	Remote	9	2	7	
	Improbable	6	16	8	
	Eliminated, Incredible	1	10	1	

Case 8 Outcome		Low	Medium	High	Massive
Likelihood	Occasional, Probable, Frequent				
	Remote	11	7		
	Improbable	18	12		
	Eliminated, Incredible	2	9	1	

Figure 10: LH_2/FC risk count for each case

In the unmitigated scenario, the LH_2/FC locomotive design faces several severe risks due to the unique challenges of cryogenic hydrogen storage and fuel cell technology. The initial severe risk scenarios include the liquid hydrogen tanks, the TPRD, and the hydrogen fuel lines. The liquid hydrogen tanks are particularly vulnerable due to the extremely low temperatures required to maintain hydrogen in its liquid state, which can lead to material property changes and potential tank rupture. The TPRD, designed to release pressure in the event of an overpressure scenario, poses a severe risk if it fails to operate correctly. The hydrogen fuel lines, responsible for transporting hydrogen from the tanks to the fuel cells, present a severe risk due to their exposure to cryogenic temperatures and high-pressure hydrogen, which can cause leaks or ruptures.

Mitigation strategies significantly reduce the number of severe and moderate risks associated with the LH_2/FC locomotive design. Many of the highest risk components are mitigated effectively by the solenoid shut-off valve, as evidenced by the absence of severe risks when this mitigation is used in combination with at least one other strategy. The solenoid shut-off valve can deactivate several high-risk components, such as the liquid hydrogen pump, before damage occurs, thereby reducing the outcome severity. Other components, like the excess flow valve, line shut-off valve, TPRD, and bleed valve, can be safeguarded by either tank protection methods or first responder access, which reduce the likelihood or outcome category, respectively, by one. Tank protection methods, such as advanced insulation materials and reinforced tank casings, decrease the likelihood of tank damage, by addressing the challenges posed by cryogenic temperatures and their potential impacts. These combined efforts significantly enhance the overall safety profile of the LH_2/FC locomotive by either preventing tank damage or minimizing its impact.

In the fully mitigated case, the LH_2/FC locomotive design has no severe risk scenarios and seven moderate risk scenarios. These moderate risk scenarios involve the pumps, hydrogen fuel lines, line shut-off valve, and a filter for a refueling valve. The shut-off valves, critical components in controlling hydrogen flow, pose a moderate risk scenario if they fail in the open position, potentially leading to significant hydrogen leaks. The engine block presents a moderate risk due to the possibility of fracture during a crash, which could result in the release of a large volume of hydrogen. The lower-pressure hydrogen fuel line, while less critical than the high-pressure lines, still poses a moderate risk due to its potential to leak hydrogen if damaged. These moderate risks underscore the importance of continued vigilance and the potential need for additional mitigation strategies, such as enhanced material selection, redundant safety systems, or advanced monitoring technologies, to further reduce the likelihood and impact of these failure modes.

3.4. LH_2/ICE Design

The risk count for the LH_2/ICE design are shown in Figure 11. There are 80 components considered in this design. Each of these components corresponds to one risk in the matrices in Figure 11.

Case 1 Outcome		Low	Medium	High	Massive
Likelihood	Occasional, Probable, Frequent				
	Remote	10	2	12	
	Improbable	25	11	18	1
	Eliminated, Incredible				1

Case 2 Outcome		Low	Medium	High	Massive
Likelihood	Occasional, Probable, Frequent				
	Remote	12	8	4	
	Improbable	36	9	9	1
	Eliminated, Incredible				1

Case 3 Outcome		Low	Medium	High	Massive
Likelihood	Occasional, Probable, Frequent				
	Remote	10	2	7	
	Improbable	24	11	13	
	Eliminated, Incredible	1		10	2

Case 4 Outcome		Low	Medium	High	Massive
Likelihood	Occasional, Probable, Frequent				
	Remote	10	7	7	
	Improbable	25	21	9	
	Eliminated, Incredible				1

Case 5 Outcome		Low	Medium	High	Massive
Likelihood	Occasional, Probable, Frequent				
	Remote	12	7		
	Improbable	35	9	4	
	Eliminated, Incredible	1	1	9	2

Case 6 Outcome		Low	Medium	High	Massive
Likelihood	Occasional, Probable, Frequent				
	Remote	13	11		
	Improbable	37	17	1	
	Eliminated, Incredible				1

Case 7 Outcome		Low	Medium	High	Massive
Likelihood	Occasional, Probable, Frequent				
	Remote	10	2	7	
	Improbable	24	16	8	
	Eliminated, Incredible	1	10	1	1

Case 8 Outcome		Low	Medium	High	Massive
Likelihood	Occasional, Probable, Frequent				
	Remote	12	7		
	Improbable	36	12		
	Eliminated, Incredible	2	9	1	1

Figure 11: LH_2/ICE risk count for each case

In the unmitigated scenario, the LH_2/ICE locomotive design has 13 severe risk scenarios, primarily associated with the unique challenges of cryogenic hydrogen storage and the internal combustion engine technology. For instance, the cryopump, which is responsible for transferring liquid hydrogen, was assigned a likelihood of remote but an outcome of high due to the potentially large amount of hydrogen that could be released in the event of a failure. Other severe risk scenarios include the liquid hydrogen tanks, the TPRD, and the hydrogen fuel lines. The hydrogen fuel lines, responsible for transporting hydrogen from the tanks to the internal combustion engine, present a severe risk due to their exposure to cryogenic temperatures and high-pressure hydrogen, which can cause leaks or ruptures.

Mitigation strategies can reduce the number of severe and moderate risks associated with the LH_2/ICE locomotive design. The solenoid shut-off valve is particularly effective in mitigating several high-risk components by reducing the outcome severity by one category. For example, the cryopump, which initially had a high outcome due to the potential release of a large amount of hydrogen, is mitigated to a moderate risk when the solenoid shut-off valve is employed. This valve can potentially deactivate the cryopump before a significant release occurs, thereby reducing the overall risk. Other components, such as the excess flow valve, line shut-off valve, TPRD, and bleed valve, are safeguarded by either tank protection methods or first responder access, which reduce the likelihood or outcome category, respectively, by one. Tank protection methods, such as advanced insulation materials and reinforced tank casings, decrease the likelihood of tank damage, by addressing the challenges posed by cryogenic temperatures and potential impacts. These combined efforts significantly enhance the overall safety for LH_2/ICE locomotive by either preventing tank damage or minimizing its impact.

In the fully mitigated scenario, the LH_2/ICE locomotive design has no severe risk scenarios and eight moderate risk scenarios. These moderate risk scenarios involve pumps, hydrogen fuel lines, a filter for a refueling valve, and a line shut-off valve. The shut-off valves, critical components in controlling hydrogen flow, pose a moderate risk if they fail in the open position, potentially leading to significant hydrogen leaks. The engine block again has a moderate risk scenario due to the possibility of fracture during a crash, which could result in the release of a large volume of hydrogen. The lower-pressure hydrogen fuel lines are also a moderate risk due to their potential to leak hydrogen if damaged. These moderate risk scenarios suggest a continued need for additional mitigation or monitoring strategies that will work to make the system safer.

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4. CONCLUSIONS

Hydrogen locomotives are complex systems whose components vary in risk depending on the likelihood of failure and the outcome of such a failure. By applying mitigations in key areas of the design, the total risk can be lowered. Studies of the systems in this work suggested that high risk components included the hydrogen tanks, hydrogen fuel lines, valves, engine block, and pump. Multiple mitigations were considered as ways in which these higher-risk scenarios could be addressed. A solenoid shut-off method cuts off the flow of fuel to several valves, lines, and other components to decrease the severity of a failure in that component. Hydrogen tank protection methods can be deployed to decrease the likelihood of a failure. This could be done by increasing tank thickness or placing the tanks in less vulnerable positions on the locomotive. Finally, first responder access mitigations were considered to reduce the outcome of a tank incident by allowing quick access to key components for cooling or fire suppression. In this analysis, it was shown that the implementation of these mitigations served to move risk scenarios from a higher risk category into a lower risk category. Mitigations applied individually or in combination acted to decrease the number of risks in the high category and help create a less hazardous system. Four design types were considered in this analysis: GH_2/FC, GH_2/ICE, LH_2/FC and LH_2/ICE. While these systems all performed comparably as far as the number of higher-level risks are concerned, the simpler the system, the fewer high-level risks. This tends to favor GH_2 storage and a FC power system design. That said, only the LH_2 designs were able to eliminate all severe risks with the introduction of the three mitigations mentioned. This trade-off will need to be carefully considered and weighed, along with other important criteria, while selecting a hydrogen-powered locomotive design concept.

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APPENDIX A. FMEA FULL RESULTS

Design	Component	State	Size	Pressure (bar)	Temperature (C)	Failure Modes	Cause of Failure	Progression of Failure	Impacts	Case 1 Likelihood	Case 1 Outcome
GH2	Hydrogen Fuel Lines/Connections	Gas	Small	350-700	-45 to 85	Leak or Rupture	Overpressure, degradation, impact	1. Seal or weld degradation 2. Failure of seal or weld causes H2 leak or rupture of line 3. High pressure H2 released 4. Accumulation or immediate ignition of H2 5. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Remote (3)	High (3)
GH2	TPRD	Gas	Small	350-700	108-110	Leak or rupture	Crash or fire failure	1. Internal leak forms within TPRD 2. Pressure within H2 tank increases 3. H2 starts to vent through TPRD 4. Due to leak H2 leaks through TPRD before venting externally 5. Potential for immediate ignition of H2 or accumulation 6. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Remote (3)	High (3)
GH2	Hydrogen Tank	Gas	Large	350-700	-45 to 85	Tank Leak	Degradation of seal(s)	1. Seal or weld degradation 2. Failure of seal or weld causes H2 leak of tank 3. High pressure H2 released 4. Accumulation or immediate ignition of H2 5. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Remote (3)	High (3)
Liquid	Hydrogen Fuel Lines/Connections	Liquid	Small	1.013	-252.87	Leak or rupture	Mechanical, crash, fire	1. Seal or weld degradation 2. Failure of seal or weld causes H2 leak or rupture of the valve 3. Low pressure H2 released 4. Accumulation H2 5. Spark ignites H2 6. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Remote (3)	High (3)
Liquid	Excess Flow Valve	Liquid	Small	1.013	-252.87	Leak or rupture	Mechanical, crash, fire	1. Seal or weld degradation 2. Failure of seal or weld causes H2 leak or rupture of the valve 3. Low pressure H2 released 4. Accumulation H2 5. Spark ignites H2 6. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Remote (3)	High (3)
Liquid	Line Shut-off Valve	Liquid	Small	1.013	-252.87	Leak or rupture	Mechanical, crash, fire	1. Seal or weld degradation 2. Failure of seal or weld causes H2 leak or rupture of the valve 3. Low pressure H2 released 4. Accumulation H2 5. Spark ignites H2 6. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Remote (3)	High (3)
Liquid	Manual Service Valve	Liquid	Small	1.013	-252.87	Leak or rupture	Mechanical, crash, fire	1. Seal or weld degradation 2. Failure of seal or weld causes H2 leak or rupture of the valve 3. Low pressure H2 released 4. Accumulation H2 5. Spark ignites H2 6. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Remote (3)	High (3)

Design	Component	State	Size	Pressure (bar)	Temperature (C)	Failure Modes	Cause of Failure	Progression of Failure	Impacts	Case 1 Likelihood	Case 1 Outcome
Liquid	Pump	Liquid	Small	1.013	-252.87	External Leak or Rupture	Damage, degradation	1. Seal or weld degradation 2. Failure of seal or weld causes H2 leak or rupture of the valve 3. Low pressure H2 released 4. Accumulation H2 5. Spark ignites H2 6. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Remote (3)	High (3)
Liquid	Pump	Liquid	Small	1.013	-252.87	Internal Leak or Rupture	Damage, degradation	1. Seal or weld degradation 2. Failure of seal or weld causes H2 leak or rupture of the valve 3. Low pressure H2 released 4. Accumulation H2 5. Spark ignites H2 6. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Remote (3)	High (3)
Liquid	Bleed Valve	Liquid	Small	1.013	-252.87	Leak or rupture	Mechanical, crash, fire	1. Seal or weld degradation 2. Failure of seal or weld causes H2 leak or rupture of the valve 3. Low pressure H2 released 4. Accumulation H2 5. Spark ignites H2 6. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Remote (3)	High (3)
Liquid	PRD	Gas	Small	1.013	-252.87	Leak or rupture	Crash or fire failure	1. Internal leak forms within TPRD 2. Pressure within H2 tank increases 3. H2 starts to vent through TPRD 4. Due to leak H2 leaks through TPRD before venting externally 5. Potential for immediate ignition of H2 or accumulation 6. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Remote (3)	High (3)
Liquid	Hydrogen Fuel Lines/Connections	Liquid	Small	1.013	-252.87	Leak or rupture	Overpressure, degradation, impact	1. Seal or weld degradation 2. Failure of seal or weld causes H2 leak or rupture of line 3. Low pressure H2 released 4. Accumulation H2 5. Spark ignites H2 6. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Remote (3)	High (3)
GH2	Auto Solenoid Valve	Gas	Small	350-700	-45 to 85	Leak or rupture	Electronic failure, damage,	1. Seal or weld degradation 2. Failure of seal or weld causes H2 leak or rupture of the valve 3. High pressure H2 released 4. Accumulation or immediate ignition of H2 5. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	High (3)
GH2	Auto Solenoid Valve	Gas	Small	350-700	-45 to 85	Fails closed	Electronic failure, foreign objects	1. Valve fails closed 2. Upstream components continue to send H2 3. Pressure builds up in within the line 4. Rupture of H2 line due to excess pressure 5. Potential for immediate ignition of H2 6. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	High (3)
GH2	Bleed Valve	Gas	Small	350-700	-45 to 85	Leak or rupture	Mechanical, crash, fire	1. Seal or weld degradation 2. Failure of seal or weld causes H2 leak or rupture of the valve 3. High pressure H2 released 4. Accumulation or immediate ignition of H2 5. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	High (3)

Design	Component	State	Size	Pressure (bar)	Temperature (C)	Failure Modes	Cause of Failure	Progression of Failure	Impacts	Case 1 Likelihood	Case 1 Outcome
GH2	Excess Flow Valve	Gas	Small	350-700	-45 to 85	Leak or rupture	Mechanical, crash, fire	1. Seal or weld degradation 2. Failure of seal or weld causes H2 leak or rupture of the valve 3. High pressure H2 released 4. Accumulation or immediate ignition of H2 5. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	High (3)
GH2	Line Shut-off Valve	Gas	Small	350-700	-45 to 85	Leak or rupture	mechanical, crash, fire	1. Seal or weld degradation 2. Failure of seal or weld causes H2 leak or rupture of the valve 3. High pressure H2 released 4. Accumulation or immediate ignition of H2 5. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	High (3)
GH2	Refueling Receptacle	Gas	Small	350-700	-45 to 85	Fails	Mechanical failure	1. Refueling receptacle fails 2. High pressure H2 is released into the environment 3. High pressure H2 released 4. Accumulation or immediate ignition of H2 5. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	High (3)
GH2	TPRD	Gas	Small	350-700	108-110	Fails to close	Mechanical failure	1. Tank venting required 2. TPRD vents H2 properly 3. TPRD fails to close 4. H2 continues to vent when venting not needed 5. Depending on location of locomotive, H2 could accumulate 6. Delayed ignition can occur 7. Potential impact on nearby structures, damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	High (3)
GH2	TPRD	Gas	Small	350-700	108-110	Fails to operate	Mechanical failure	1. Pressure builds up within H2 tank 2. PRD fails to operate 3. H2 unable to vent 4. H2 leak or release occurs 5. Immediate ignition or H2 accumulation occurs 6. Impacts surrounding components, potential damage, or secondary fire.	Tank rupture with fire/overpressure event	Improbable (2)	High (3)
GH2	Check Valve	Gas	Small	350-700	-45 to 85	Leak or rupture	Mechanical, crash, fire	1. Seal or weld degradation 2. Failure of seal or weld causes H2 leak or rupture of the valve 3. High pressure H2 released 4. Accumulation or immediate ignition of H2 5. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	High (3)
GH2	Pressure Regulator Valve	Gas	Small	from 350-700 to 8-20	-45 to 85	Leak or rupture	Damage, degradation	1. Seal or weld degradation 2. Failure of seal or weld causes H2 leak or rupture of the valve 3. High pressure H2 released 4. Accumulation or immediate ignition of H2 5. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	High (3)
GH2	Pressure Regulator Valve	Gas	Small	from 350-700 to 8-20	-45 to 85	Fails open	Inadequate design, damage	1. Valve fails open 2. H2 continues to flow 3. Pressure regulator unable to properly regulate pressure 4. Low pressure H2 provided downstream	Loss of control of hydrogen flow	Improbable (2)	High (3)

Design	Component	State	Size	Pressure (bar)	Temperature (C)	Failure Modes	Cause of Failure	Progression of Failure	Impacts	Case 1 Likelihood	Case 1 Outcome
GH2	Pressure Regulator Valve	Gas	Small	from 350-700 to 8-20	-45 to 85	Fails closed	Inadequate design, damage	1. Valve fails close 2. Upstream components continue to send H2 3. Pressure builds up in within the line 4. Rupture of H2 line due to excess pressure 5. Potential for immediate ignition of H2 6. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	High (3)
GH2	Auto Solenoid Valve	Gas	Small	350-700	-45 to 85	Fails open	Electronic failure, foreign objects	1. Valve fails open 2. Upstream components continue to send H2 3. Inability to shut-off hydrogen in the case of an emergency or for maintenance	Loss of control of hydrogen flow	Improbable (2)	High (3)
GH2	Bleed Valve	Gas	Small	350-700	-45 to 85	Fails open	Inadequate design, mechanical/electrical failure	1. Valve fails open 2. Upstream components continue to send H2 3. Inability to shut-off hydrogen in the case of an emergency or for maintenance	Loss of control of hydrogen flow	Improbable (2)	High (3)
GH2	Check Valve	Gas	Small	350-700	-45 to 85	Fails open	Inadequate design, mechanical/electrical failure	1. Valve fails open 2. Upstream components continue to send H2 3. Inability to shut-off hydrogen in the case of an emergency or for maintenance	Loss of control of hydrogen flow	Improbable (2)	High (3)
GH2	Excess Flow Valve	Gas	Small	350-700	-45 to 85	Fails open	Inadequate design, mechanical/electrical failure	1. Valve fails open 2. Upstream components continue to send H2 3. Inability to shut-off hydrogen in the case of an emergency or for maintenance	Loss of control of hydrogen flow	Improbable (2)	High (3)
GH2	Line Shut-Off Valve	Gas	Small	350-700	-45 to 85	Fails open	Inadequate design, mechanical/electrical failure	1. Valve fails open 2. Upstream components continue to send H2 3. Inability to shut-off hydrogen in the case of an emergency or for maintenance	Loss of control of hydrogen flow	Improbable (2)	High (3)
GH2	Manual Service Valve	Gas	Small	350-700	-45 to 85	Leak or rupture	mechanical, crash, fire	1. Seal or weld degradation 2. Failure of seal or weld causes H2 leak or rupture of the valve 3. High pressure H2 released 4. Accumulation or immediate ignition of H2 5. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	High (3)
GH2	Manual Service Valve	Gas	Small	350-700	-45 to 85	Fails open	Inadequate design, mechanical/electrical failure	1. Valve fails open 2. Upstream components continue to send H2 3. Inability to shut-off hydrogen in the case of an emergency or for maintenance	Loss of control of hydrogen flow	Improbable (2)	High (3)
Liquid	Vaporizer	Liquid ->Gas	Small	from 1.013 to 8-20	-45 to 85	Leak or Rupture	Damage, degradation	1. Seal or weld degradation 2. Failure of seal or weld causes H2 leak or rupture of the valve 3. Medium pressure H2 released 4. Accumulation or immediate ignition of H2 5. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	High (3)

Design	Component	State	Size	Pressure (bar)	Temperature (C)	Failure Modes	Cause of Failure	Progression of Failure	Impacts	Case 1 Likelihood	Case 1 Outcome
Liquid	Hydrogen Tank	Liquid	Large	1.013	-252.87	Tank Leak	Degradation of seal(s)	1. Seal or weld degradation 2. Failure of seal or weld causes H2 leak of tank 3. High pressure H2 released 4. Accumulation or immediate ignition of H2 5. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	High (3)
Liquid	Auto Solenoid Valve	Gas	Small	1.013	-252.87	Leak or rupture	Electronic failure, damage,	1. Seal or weld degradation 2. Failure of seal or weld causes H2 leak or rupture of the valve 3. Low pressure H2 released 4. Accumulation or immediate ignition of H2 5. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	High (3)
Liquid	Auto Solenoid Valve	Gas	Small	1.013	-252.87	Fails closed	Electronic failure, foreign objects	1. Valve fails closed 2. Upstream components continue to send H2 3. Pressure builds up in within the line 4. Rupture of H2 line due to excess pressure 5. Potential for immediate ignition of H2 6. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	High (3)
Liquid	Filter of In-Tank Valve	Liquid	Small	1.013	-45 to 85	Damaged	Degradation	1. Tank gets damaged over-time 2. Leak pathway forms due to damage, 3. High pressure H2 released 4. Accumulation or immediate ignition of H2 5. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	High (3)
Liquid	Filter of Refueling Valve	Liquid	Small	1.013	-252.87	Damaged	Degradation	1. Filter degrades or is damaged by foreign object 2. Foreign object(s) and low H2 quality enters system 3. Foreign object(s) and low quality H2 can damage, downstream components 4. Over-time this could lead to a H2 fire within the system	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	High (3)
Liquid	Pump	Liquid	Small	1.013	-252.87	Fails to Stop	Inadequate design, mechanical/electrical failure, spurious signal	1. Pump fails to stop 2. Upstream components continue to send H2 3. Inability to shut-off hydrogen in the case of an emergency or for maintenance	Loss of control of hydrogen flow	Improbable (2)	High (3)
Liquid	Refueling Receptacle	Liquid	Small	1.013	-252.87	Fails	Mechanical failure	1. Refueling receptacle fails 2. High pressure H2 is released into the environment 3. High pressure H2 released 4. Accumulation or immediate ignition of H2 5. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	High (3)
Liquid	PRD	Gas	Small	1.013	-252.87	Fails to close	Mechanical failure	1. Tank venting required 2. PRD vents H2 properly 3. PRD fails to close 4. H2 continues to vent when venting not needed 5. Depending on location of locomotive, H2 could accumulate 6. Delayed ignition can occur 7. Potential impact on nearby structures, damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	High (3)

Design	Component	State	Size	Pressure (bar)	Temperature (C)	Failure Modes	Cause of Failure	Progression of Failure	Impacts	Case 1 Likelihood	Case 1 Outcome
Liquid	PRD	Gas	Small	1.013	-252.87	Fails to operate	Mechanical failure	1. Pressure builds up within H2 tank 2. PRD fails to operate 3. H2 unable to vent 4. H2 leak or release occurs 5. Immediate ignition or H2 accumulation occurs 6. Impacts surrounding components, potential damage, or secondary fire.	Tank rupture with fire/overpressure event	Improbable (2)	High (3)
Liquid	Auto Solenoid Valve	Gas	Small	1.013	-252.87	Fails open	Electronic failure, foreign objects	1. Valve fails open 2. Upstream components continue to send H2 3. Inability to shut-off hydrogen in the case of an emergency or for maintenance	Loss of control of hydrogen flow	Improbable (2)	High (3)
Liquid	Check Valve	Liquid	Small	1.013	-252.87	Fails open	Inadequate design, mechanical/electrical failure	1. Valve fails open 2. Upstream components continue to send H2 3. Inability to shut-off hydrogen in the case of an emergency or for maintenance	Loss of control of hydrogen flow	Improbable (2)	High (3)
Liquid	Excess Flow Valve	Liquid	Small	1.013	-252.87	Fails open	Inadequate design, mechanical/electrical failure	1. Valve fails open 2. Upstream components continue to send H2 3. Inability to shut-off hydrogen in the case of an emergency or for maintenance	Loss of control of hydrogen flow	Improbable (2)	High (3)
Liquid	Line Shut-Off Valve	Liquid	Small	1.013	-252.87	Fails open	Inadequate design, mechanical/electrical failure	1. Valve fails open 2. Upstream components continue to send H2 3. Inability to shut-off hydrogen in the case of an emergency or for maintenance	Loss of control of hydrogen flow	Improbable (2)	High (3)
Liquid	Manual Service Valve	Liquid	Small	1.013	-252.87	Fails open	Inadequate design, mechanical/electrical failure	1. Valve fails open 2. Upstream components continue to send H2 3. Inability to shut-off hydrogen in the case of an emergency or for maintenance	Loss of control of hydrogen flow	Improbable (2)	High (3)
Liquid	Bleed Valve	Liquid	Small	1.013	-252.87	Fails open	Inadequate design, mechanical/electrical failure	1. Valve fails open 2. Upstream components continue to send H2 3. Inability to shut-off hydrogen in the case of an emergency or for maintenance	Loss of control of hydrogen flow	Improbable (2)	High (3)
FC	Fuel Cell	Gas	Large	1-2.5	-45 to 85	Fails	Loss of Pressure Differential	1. Loss of pressure differential within fuel cell stack 2. H2 in contact with air and catalyst at cathode 3. H2 fire likely ensues 4. Permanent damage, to fuel cell stack	Fire	Remote (3)	Low (1)
All	Hydrogen Fuel Lines/Connections	Gas	Small	1-2.5	-45 to 85	Leak or Rupture	Overpressure, degradation, impact	1. Seal or weld degradation 2. Failure of seal or weld causes H2 leak or rupture of line 3. Low pressure H2 released 4. Accumulation or immediate ignition of H2 5. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Remote (3)	Low (1)

Design	Component	State	Size	Pressure (bar)	Temperature (C)	Failure Modes	Cause of Failure	Progression of Failure	Impacts	Case 1 Likelihood	Case 1 Outcome
FC	Recirculation Blower	Gas	Small	1-2.5	UNK	Fails to function	Mechanical/electrical failure	1. Blower loses power or mechanically fails 2. Fuel cell starts to heat 3. Membrane failure occurs 4. H2 fire occurs	System overheats	Remote (3)	Low (1)
ICE	ICE Fuel Injector(s)	Gas	Small	1.5	40 to 115	Leak or rupture	Abrasion, wear, hydrogen attack	1. Seal or weld degradation 2. Failure of seal or weld causes H2 leak or rupture of the valve 3. Low pressure H2 released 4. Accumulation H2 5. Spark ignites H2 6. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Remote (3)	Low (1)
ICE	Engine Interface	Gas	Small	1.5	40 to 115	Leak or rupture	Abrasion, wear, hydrogen attack	1. Seal or weld degradation 2. Failure of seal or weld causes H2 and Diesel leak 3. H2 and Diesel released 4. Accumulation or immediate ignition of H2 and Diesel 5. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Remote (3)	Low (1)
ICE	Gas Manifold Vent Valve	Gas	Small	1.5	40 to 115	Leak or rupture	mechanical, crash, fire	1. Seal or weld degradation 2. Failure of seal or weld causes H2 leak or rupture of the valve 3. Low pressure H2 released 4. Accumulation or immediate ignition of H2 5. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Remote (3)	Low (1)
ICE	Crankcase Ventilation	Gas	Small	1.5	40 to 115	Pump failure	Design of pump, loss of power	1. Pump fails to circulate water 2. Ventilation water heats up 3. Water starts to evaporate 4. System starts to heat up due to lack of coolant 5. System overheats	System overheats	Remote (3)	Low (1)
GH2	High Pressure Sensor	Gas	N/A	Any	Range	Leak	Electronic failure	1. Sensor leaks 2. H2 is released 3. H2 might be detected 4. System may continue to run 5. Potential delayed ignition of released fire 6. Potential damage, of nearby components and potential secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Remote (3)	Low (1)
Liquid	High Pressure Sensor	Gas	N/A	Any	Range	Leak	Electronic failure	1. Sensor leaks 2. H2 is released 3. H2 might be detected 4. System may continue to run 5. Potential delayed ignition of released fire 6. Potential damage, of nearby components and potential secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Remote (3)	Low (1)
All	Hydrogen Detector Sensor	Gas	N/A	Any	Range	Leak	Electronic failure	1. H2 detector fails 2. H2 leak goes undetected 3. Accumulation or immediate ignition of H2 4. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Remote (3)	Low (1)
All	Mid Pressure Sensor	Gas	N/A	Any	Range	Leak	Electronic failure	1. Sensor leaks 2. H2 is released 3. H2 might be detected 4. System may continue to run	Hydrogen leak, potential delayed ignition and/or fire	Remote (3)	Low (1)

Design	Component	State	Size	Pressure (bar)	Temperature (C)	Failure Modes	Cause of Failure	Progression of Failure	Impacts	Case 1 Likelihood	Case 1 Outcome
								5. Potential delayed ignition of released fire 6. Potential damage, of nearby components and potential secondary fire.			
ICE	Tender Interface	Gas	Small	1.5	40 to 115	Leak or rupture	Abrasion, wear	1. Seal or weld degradation 2. Failure of seal or weld causes H2 leak or rupture of the valve 3. Low pressure H2 released 4. Accumulation H2 5. Spark ignites H2 6. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Remote (3)	Low (1)
FC	Purge Valve	Gas	Small	Ambient	Ambient	Leak or rupture	Inadequate design, damage,	1. Seal or weld degradation 2. Failure of seal or weld causes H2 leak or rupture of the valve 3. Ambient pressure H2 released into the environment.	Hydrogen leak, potential delayed ignition and/or fire	Remote (3)	Low (1)
FC	Purge Valve	Gas	Small	Ambient	Ambient	Fails open	Mechanical/electrical failure	1. Valve fails open 2. Upstream components continue to send H2 3. Inability to shut-off hydrogen in the case of an emergency or for maintenance	Loss of control of hydrogen flow	Remote (3)	Low (1)
FC	Ejector	Gas	Small	1-2.5	UNK	Fails closed	Inadequate design, mechanical failure	1. Valve fails closed 2. Upstream components continue to send H2 3. Pressure builds up in within the line 4. Rupture of H2 line due to excess pressure 5. Potential for immediate ignition of H2 6. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	Low (1)
FC	Ejector	Gas	Small	1-2.5	UNK	Fails open	Inadequate design, damage	1. Ejector fails open 2. Upstream components continue to send H2 3. Inability to shut-off hydrogen in the case of an emergency or for maintenance	Loss of control of hydrogen flow	Improbable (2)	Low (1)
ICE	Engine Head Gasket	Gas	Small	1.5	40 to 115	Gas leakage	Material issue, fatigue	1. Seal or weld degradation 2. Failure of seal or weld causes H2 and Diesel leak 3. H2 and Diesel released 4. Accumulation or immediate ignition of H2 and Diesel 5. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	Low (1)
ICE	Engine Head Gasket	Gas	Small	1.5	40 to 115	Improper diameter	Manufacturing issue	1. Gasket begins to leak H2 and Diesel leak due to improper gasket size 2. H2 and Diesel released 3. Accumulation or immediate ignition of H2 and Diesel 4. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	Low (1)
ICE	Blocking Valve	Gas	Small	1.5	40 to 115	Leak or rupture	mechanical, crash, fire	1. Seal or weld degradation 2. Failure of seal or weld causes H2 leak or rupture of the valve 3. Low pressure H2 released 4. Accumulation H2 5. Spark ignites H2 6. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	Low (1)
ICE	Engine Head Gasket	Gas	Small	1.5	40 to 115	Coolant leakage	Material issue, deformation	1. Coolant begins to leak 2. Ventilation water heats up 3. Water starts to evaporate 4. System starts to heat up due to lack of coolant 5. System overheats	System overheats	Improbable (2)	Low (1)

Design	Component	State	Size	Pressure (bar)	Temperature (C)	Failure Modes	Cause of Failure	Progression of Failure	Impacts	Case 1 Likelihood	Case 1 Outcome
ICE	Engine Interface	Gas	Small	1.5	40 to 115	Communication failure	Software failure	1. Software failure of the engine interface 2. Improper transfer of H2 3. Potential for H2 release 4. Potential for H2 accumulation and delayed ignition 5. Potential damage, to surrounding components, and secondary fires	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	Low (1)
ICE	Exhaust Manifold	Gas	Small	1.5	40 to 115	Crack	Stress	1. Seal or weld degradation 2. Failure of seal or weld causes H2 and Diesel leak or rupture of the valve 3. Low pressure H2 and Diesel released 4. Accumulation H2 and Diesel 5. Spark ignites H2 and Diesel 6. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	Low (1)
ICE	Gas Intake Manifold	Gas	Small	1.5	40 to 115	Crack	Stress	1. Seal or weld degradation 2. Failure of seal or weld causes H2 and Diesel leak or rupture of the valve 3. Low pressure H2 and Diesel released 4. Accumulation H2 and Diesel 5. Spark ignites H2 and Diesel 6. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	Low (1)
GH2	High Pressure Sensor	Gas	N/A	Any	Range	Fails or ruptures	Mechanical or electrical failure	1. Sensor fails or ruptures 2. H2 is released 3. H2 is not detected 4. System continues to run 5. Potential delayed ignition of released fire 6. Potential damage, of nearby components and potential secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	Low (1)
Liquid	High Pressure Sensor	Gas	N/A	Any	Range	Fails or ruptures	Mechanical or electrical failure	1. Sensor fails or ruptures 2. H2 is released 3. H2 is not detected 4. System continues to run 5. Potential delayed ignition of released fire 6. Potential damage, of nearby components and potential secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	Low (1)
All	Hydrogen Detector Sensor	Gas	N/A	Any	Range	Fails or ruptures	Mechanical or electrical failure	1. H2 detector fails 2. H2 leak goes undetected 3. Accumulation or immediate ignition of H2 4. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	Low (1)
ICE	Locomotive Piping	Gas	Small	1.5	40 to 115	Leak or Rupture	Overpressure, degradation, impact	1. Seal or weld degradation 2. Failure of seal or weld causes H2 leak or rupture of the valve 3. Low pressure H2 released 4. Accumulation H2 5. Spark ignites H2 6. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	Low (1)
ICE	Tender Interface	Gas	Small	1.5	40 to 115	Communication failure	Software failure	1. Software failure of the tender interface 2. Improper transfer of H2 3. Potential for H2 release 4. Potential for H2 accumulation and delayed ignition 5. Potential damage, to surrounding components, and secondary fires	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	Low (1)
ICE	Blocking Valve	Gas	Small	1.5	40 to 115	Fails open	Inadequate design,	1. Valve fails open 2. Upstream components continue to send H2	Loss of control of hydrogen flow	Improbable (2)	Low (1)

Design	Component	State	Size	Pressure (bar)	Temperature (C)	Failure Modes	Cause of Failure	Progression of Failure	Impacts	Case 1 Likelihood	Case 1 Outcome
							mechanical/electrical failure	3. Inability to shut-off hydrogen in the case of an emergency or for maintenance			
ICE	Crankcase Ventilation	Gas	Small	1.5	40 to 115	Pump cavitation	Coolant temperature	1. Water temperature increases 2. Pump fails 3. Water starts to evaporate 4. System starts to heat up due to lack of coolant 5. System overheats	System overheats	Improbable (2)	Low (1)
ICE	Gas Manifold Vent Valve	Gas	Small	1.5 bar	40 to 115	Fails open	Inadequate design, mechanical/electrical failure	1. Valve fails open 2. Upstream components continue to send H2 3. Inability to shut-off hydrogen in the case of an emergency or for maintenance	Loss of control of hydrogen flow	Improbable (2)	Low (1)
ICE	Gas Manifold Vent Valve	Gas	Small	1.5 bar	40 to 115	Fails closed	Inadequate design, mechanical/electrical failure	1. Valve fails close 2. Upstream components continue to send H2 3. Pressure builds up in within the line 4. Rupture of H2 line due to excess pressure 5. Potential for immediate ignition of H2 6. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	Low (1)
All	Mid Pressure Sensor	Gas	N/A	Any	Range	Fails or ruptures	Electronic failure	1. Sensor fails or ruptures 2. H2 is released 3. H2 is not detected 4. System continues to run 5. Potential delayed ignition of released fire 6. Potential damage, of nearby components and potential secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	Low (1)
ICE	Crankcase Ventilation	Gas	Small	1.5 bar	40 to 115	Water leakage	Seal or line failure	1. Line forms a crack 2. Water starts to leak out of system 3. Ventilation water heats up 4. Water starts to evaporate 5. System starts to heat up due to lack of coolant 6. System overheats	System overheats	Improbable (2)	Low (1)
ICE	Crankcase Ventilation	Gas	Small	1.5 bar	40 to 115	Thermostat failure	Wax element failure	1. Failure of temperature sensor 2. Ventilation potentially water heats up 3. Water starts to evaporate 4. System starts to heat up due to lack of coolant 5. System overheats	System overheats	Improbable (2)	Low (1)
GH2	Hydrogen Tank	Gas	Large	350-700	-45 to 85	Tank Rupture	Puncture of tank, fire damage,	1. Tank ruptures due to external impact 2. Immediate ignition of all H2 occurs 3. Subsequent fire(s) begin, impacting nearby components	Tank rupture with fire/overpressure event	Improbable (2)	Massive (4)
Liquid	Hydrogen Tank	Liquid	Large	1.013	-252.87	Tank Rupture	Puncture of tank, fire damage,	1. Tank ruptures due to external impact 2. Immediate ignition of all H2 occurs 3. Subsequent fire(s) begin, impacting nearby components	Tank rupture with fire/overpressure event	Improbable (2)	Massive (4)
ICE	Engine Block	Gas	Large	1.5 bar	40 to 115	Fracture	Crash, fire	1. Entire engine block fractures due to extreme event 2. H2 and Diesel ignite immediately 3. Catastrophic fire ensues	Hydrogen leak, potential delayed ignition and/or fire	Eliminated/ Incredible (1)	Massive (4)

Design	Component	State	Size	Pressure (bar)	Temperature (C)	Failure Modes	Cause of Failure	Progression of Failure	Impacts	Case 1 Likelihood	Case 1 Outcome
All	Hydrogen Fuel Lines/Connections	Gas	Small	8-20	-45 to 85	Leak or rupture	Overpressure, degradation, impact	1. Seal or weld degradation 2. Failure of seal or weld causes H2 leak or rupture of line 3. Medium pressure H2 released 4. Accumulation or immediate ignition of H2 5. Impacts nearby components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Remote (3)	Medium (2)
All	Hydrogen Gas Injector	Gas	Small	from 8-20 to 1-2.5	-45 to 85	Fails Open	Inadequate design, damage	1. Injector fails open 2. Upstream components continue to send H2 3. Inability to shut-off hydrogen in the case of an emergency or for maintenance	Loss of control of hydrogen flow	Remote (3)	Medium (2)
All	Pressure Relief Valve (Mid)	Gas	Small	8-20	-45 to 85	Leak or rupture	Damage, degradation	1. Seal or weld degradation 2. Failure of seal or weld causes H2 leak or rupture of the valve 3. Medium pressure H2 released 4. Accumulation or immediate ignition of H2 5. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	Medium (2)
All	FCPC Heat Exchanger	Gas	Small	8-20	Range	Thermal fatigue	Thermal cycling	1. Seal or weld degradation 2. Failure of seal or weld causes H2 leak or rupture of line 3. Medium pressure H2 released 4. Accumulation or immediate ignition of H2 5. Impacts nearby components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	Medium (2)
All	FCPC Heat Exchanger	Gas	Small	8-20	Range	Corrosion fatigue	Weld defect, vibration	1. Seal or weld degradation 2. Failure of seal or weld causes H2 leak or rupture of line 3. Medium pressure H2 released 4. Accumulation or immediate ignition of H2 5. Impacts nearby components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	Medium (2)
All	FCPC Heat Exchanger	Gas	Small	8-20	Range	Cracking	High pressure	1. Seal or weld degradation 2. Failure of seal or weld causes H2 leak or rupture of line 3. Medium pressure H2 released 4. Accumulation or immediate ignition of H2 5. Impacts nearby components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	Medium (2)
All	FCPC Heat Exchanger	Gas	Small	8-20	Range	Creep rupture	Formation of deposits	1. Seal or weld degradation 2. Failure of seal or weld causes H2 leak or rupture of line 3. Medium pressure H2 released 4. Accumulation or immediate ignition of H2 5. Impacts nearby components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	Medium (2)
All	Manual Defueling Valve	Gas	Small	8-20	-45 to 85	Leak or rupture	mechanical, crash, fire	1. Seal or weld degradation 2. Failure of seal or weld causes H2 leak or rupture of the valve 3. Medium pressure H2 released 4. Accumulation or immediate ignition of H2 5. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	Medium (2)
All	Manual Defueling Valve	Gas	Small	8-20	-45 to 85	Fails open	Inadequate design, mechanical/electrical failure	1. Valve fails open 2. Upstream components continue to send H2 3. Inability to shut-off hydrogen in the case of an emergency or for maintenance	Loss of control of hydrogen flow	Improbable (2)	Medium (2)

Design	Component	State	Size	Pressure (bar)	Temperature (C)	Failure Modes	Cause of Failure	Progression of Failure	Impacts	Case 1 Likelihood	Case 1 Outcome
All	Pressure Relief Valve (Mid)	Gas	Small	8-20	-45 to 85	Fails open	Inadequate design, damage	1. Valve fails open 2. Upstream components continue to send H2 3. Inability to shut-off hydrogen in the case of an emergency or for maintenance	Loss of control of hydrogen flow	Improbable (2)	Medium (2)
All	Pressure Relief Valve (Mid)	Gas	Small	8-20	-45 to 85	Fails closed	Inadequate design, damage	1. Valve fails close 2. Upstream components continue to send H2 3. Pressure builds up in within the line 4. Rupture of H2 line due to excess pressure 5. Potential for immediate ignition of H2 6. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	Medium (2)
GH2	Auto Solenoid Valve	Gas	Small	350-700	-45 to 85	Plugging	Electronic failure, clogged with foreign objects	1. Foreign object introduced in H2 line 2. Object causes a partial or full block of the valve 3. Pressure builds up in within the line 4. Rupture of H2 line due to excess pressure 5. Potential for immediate ignition of H2 6. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	High (3)
FC	Purge Valve	Gas	Small	Ambient	Ambient	Plugging	Inadequate design, foreign object	1. Foreign object introduced in H2 line 2. Object causes a partial or full block of the valve 3. Pressure builds up in within the line 4. Rupture of H2 line due to excess pressure 5. Potential for immediate ignition of H2 6. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Remote (3)	Low (1)
ICE	ICE Fuel Injector(s)	Gas	Small	1.5	40 to 115	Plugging	Buildup of deposits	1. Foreign object introduced in H2 line 2. Object causes a partial or full block of the valve 3. Pressure builds up in within the line 4. Rupture of H2 line due to excess pressure 5. Potential for immediate ignition of H2 6. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	Low (1)
GH2	Pressure Regulator Valve	Gas	Small	from 350-700 to 8-20	-45 to 85	Plugging	Damage, foreign object	1. Foreign object introduced in H2 line 2. Object causes a partial or full block of the valve 3. Pressure builds up in within the line 4. Rupture of H2 line due to excess pressure 5. Potential for immediate ignition of H2 6. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	High (3)
Liquid	Auto Solenoid Valve	Gas	Small	1.013	-252.87	Plugging	Electronic failure, clogged with foreign objects	1. Foreign object introduced in H2 line 2. Object causes a partial or full block of the valve 3. Pressure builds up in within the line 4. Rupture of H2 line due to excess pressure 5. Potential for immediate ignition of H2 6. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	Low (1)
ICE	Engine Filter	Gas	Small	1.5	40 to 115	Plugging	Poor diesel/hydrogen quality	1. H2 of poor quality enters system 2. Filter begins to plug due to containments 3. Decreased H2 flow occurs within system 4. Low quality H2 can damage, downstream components 5. Over-time this could lead to a H2 fire within the system	Hydrogen leak, potential delayed ignition and/or fire	Remote (3)	Low (1)

Design	Component	State	Size	Pressure (bar)	Temperature (C)	Failure Modes	Cause of Failure	Progression of Failure	Impacts	Case 1 Likelihood	Case 1 Outcome
ICE	Engine Interface	Gas	Small	1.5	40 to 115	Plugging	Inadequate design, foreign object	1. Foreign object introduced in H2 line 2. Object causes a partial or full block of the valve 3. Pressure builds up in within the line 4. Rupture of H2 line due to excess pressure 5. Potential for immediate ignition of H2 6. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	Low (1)
Liquid	Filter of In-Tank Valve	Liquid	Small	1.013	-45 to 85	Plugging	Poor hydrogen quality	1. H2 of poor quality enters system 2. Filter begins to plug due to containments 3. Decreased H2 flow occurs within system 4. Low quality H2 can damage, downstream components 5. Over-time this could lead to a H2 fire within the system	Hydrogen leak, potential delayed ignition and/or fire	Remote (3)	High (3)
GH2	Filter of In-Tank Valve	Gas	Small	350-700	-45 to 85	Plugging	Poor hydrogen quality	1. H2 of poor quality enters system 2. Filter begins to plug due to containments 3. Decreased H2 flow occurs within system 4. Low quality H2 can damage, downstream components 5. Over-time this could lead to a H2 fire within the system	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	High (3)
Liquid	Filter of Refueling Valve	Liquid	Small	1.013	-252.87	Plugging	Poor hydrogen quality	1. H2 of poor quality enters system 2. Filter begins to plug due to containments 3. Decreased H2 flow occurs within system 4. Low quality H2 can damage, downstream components 5. Over-time this could lead to a H2 fire within the system	Hydrogen leak, potential delayed ignition and/or fire	Remote (3)	High (3)
GH2	Filter of Refueling Valve	Gas	Small	350-700	-45 to 85	Plugging	Poor hydrogen quality	1. H2 of poor quality enters system 2. Filter begins to plug due to containments 3. Decreased H2 flow occurs within system 4. Low quality H2 can damage, downstream components 5. Over-time this could lead to a H2 fire within the system	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	High (3)
GH2	Hydrogen Fuel Lines/Connections	Gas	Small	350-700	-45 to 85	Plugging	Inadequate design, foreign object	1. Foreign object introduced in H2 line 2. Object causes a partial or full block of the line 3. Pressure builds up in within the line 4. Rupture of H2 line due to excess pressure 5. Potential for immediate ignition of H2 6. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	High (3)
ICE	Locomotive Piping	Gas	Small	1.5	40 to 115	Plugging	Inadequate design, foreign object	1. Foreign object introduced in H2 line 2. Object causes a partial or full block of the valve 3. Pressure builds up in within the line 4. Rupture of H2 line due to excess pressure 5. Potential for immediate ignition of H2 6. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	Low (1)
All	Pressure Relief Valve (Mid)	Gas	Small	8-20	-45 to 85	Plugging	Damage, foreign object	1. Foreign object introduced in H2 line 2. Object causes a partial or full block of the valve 3. Pressure builds up in within the line 4. Rupture of H2 line due to excess pressure 5. Potential for immediate ignition of H2 6. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	Medium (2)

Design	Component	State	Size	Pressure (bar)	Temperature (C)	Failure Modes	Cause of Failure	Progression of Failure	Impacts	Case 1 Likelihood	Case 1 Outcome
Liquid	Pump	Liquid	Small	1.013	-252.87	Plugging	Inadequate design, foreign object	1. Foreign object introduced in H2 line 2. Object causes a partial or full block of the valve 3. Pressure builds up in within the line 4. Rupture of H2 line due to excess pressure 5. Potential for immediate ignition of H2 6. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Remote (3)	High (3)
ICE	Gas Manifold Vent Valve	Gas	Small	1.5	40 to 115	Plugging	Inadequate design, foreign object	1. Foreign object introduced in H2 line 2. Object causes a partial or full block of the valve 3. Pressure builds up in within the line 4. Rupture of H2 line due to excess pressure 5. Potential for immediate ignition of H2 6. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	Low (1)
Liquid	Hydrogen Fuel Lines/Connections	Liquid	Small	1.013	-252.87	Plugging	Inadequate design, foreign object	1. Foreign object introduced in H2 line 2. Object causes a partial or full block of the line 3. Pressure builds up in within the line 4. Rupture of H2 line due to excess pressure 5. Potential for immediate ignition of H2 6. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	High (3)
All	Hydrogen Fuel Lines/Connections	Gas	Small	8-20	-45 to 85	Plugging	Inadequate design, foreign object	1. Foreign object introduced in H2 line 2. Object causes a partial or full block of the line 3. Pressure builds up in within the line 4. Rupture of H2 line due to excess pressure 5. Potential for immediate ignition of H2 6. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	Medium (2)
All	Hydrogen Fuel Lines/Connections	Gas	Small	1-2.5	-45 to 85	Plugging	Inadequate design, foreign object	1. Foreign object introduced in H2 line 2. Object causes a partial or full block of the line 3. Pressure builds up in within the line 4. Rupture of H2 line due to excess pressure 5. Potential for immediate ignition of H2 6. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	Low (1)
ICE	Tender Interface	Gas	Small	1.5	40 to 115	Plugging	Inadequate design, foreign object	1. Foreign object introduced in H2 line 2. Object causes a partial or full block of the valve 3. Pressure builds up in within the line 4. Rupture of H2 line due to excess pressure 5. Potential for immediate ignition of H2 6. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	Low (1)
Liquid	Vaporizer	Liquid ->Gas	Small	from 1.013 to 8-20	-45 to 85	Plugging	Inadequate design, foreign object	1. Foreign object introduced in H2 line 2. Object causes a partial or full block of the line 3. Pressure builds up in within the line 4. Rupture of H2 line due to excess pressure 5. Potential for immediate ignition of H2 6. Impacts surrounding components, potential damage, or secondary fire.	Hydrogen leak, potential delayed ignition and/or fire	Improbable (2)	High (3)

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