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Technical Report

Hydrogen and Battery Locomotive Risk Assessment – Companion Report

Prepared for: Transport Canada
330 Sparks St.
Ottawa, Ontario

Prepared by: S. Girard, M. Hernandez, I. Jimenez

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Prepared by:

Girard, Stephanie
Digitally signed by Girard, Stephanie
DN: cn=Girard, Stephanie, c=CA, o=GC, ou=NRC-CNRC, email=stephanie.girard@cnrc-nrc.gc.ca
Date: 2024.11.27 13:31:02 -05'00'

Stephanie Girard, P. Eng.

Research Officer, Hydrogen Systems Design Engineer

Hernandez, Manuel
Digitally signed by Hernandez, Manuel
DN: cn=Hernandez, Manuel, c=CA, o=GC, ou=NRC-CNRC, email=manuel.hernandez@canada.ca
Date: 2024.11.27 15:17:38 -08'00'

Manuel Hernandez, P. Eng.

Research Council Officer, Energy System Integration, Modelling and Demonstration

Isabella Jimenez
Digitally signed by Isabella Jimenez
Date: 2024.11.27 14:40:47 -05'00'

Isabella Jimenez

Research Officer, Design Engineering

Reviewed by:

PrestonThomas, Jonathan
Digitally signed by PrestonThomas, Jonathan
DN: cn=PrestonThomas, Jonathan, c=CA, o=GC, ou=NRC-CNRC, email=jon.preston-thomas@canada.ca
Date: 2024.11.27 15:03:55 -05'00'

Jon Preston-Thomas, P.Eng.

Principal Engineer, Automotive and Surface Transportation

Approved by:

Poole, Gordon
Digitally signed by Poole, Gordon
DN: cn=Poole, Gordon, c=CA, o=GC, ou=NRC-CNRC, email=gordon.poole@cnrc-nrc.gc.ca
Date: 2024.11.28 09:31:17 -05'00'

Gordon Poole

Director R&D, Transportation Engineering Centre

NRC.CANADA.CA

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Executive Summary

This risk assessment examines and divides a reference hydrogen and battery locomotive into its systems, sub-systems and components to understand, identify, and quantify the individual risks. Examined within are the automatic safety system, the fuel cell system (FCS), the battery system, the control units, the thermal management system, the fuel supply (on-board), and the fuel dispensing system (ground equipment).

The authors identified the risks inherent with this technology by examining modes of operation (such as accelerating, constant speed, coasting, and braking mode), exposure to railway specific stresses (such as shock and vibration profiles), understanding the impacts of different failure events (such as a derailment, collision, etc.), and dissecting all the components in a systematic way, but particularly the fuel cell system and battery, to evaluate their potential for hazards (e.g., hydrogen accumulation risks, and thermal runaway events).

Classified into six principal categories, the risks identified in this risk assessment, ranked by frequency of identification, were:

- Combustible mixture (H_2 in air)
- Thermal runaway (of battery)
- High voltage (>50 V)
- Over-temperature (insufficient cooling)
- Enclosed space (decrease of oxygen in air)
- Environmental exposure (e.g., ice on railroad tracks, coolant spill)

After performing a qualitative risk analysis, three instances were identified as ‘medium’ risk and the remaining instances (498) as ‘low’ risk. The ‘low’ risk items were varied, including often-unignited release of hydrogen (not a hazard when vented in open air), or smoke, fire or battery explosion, which were deemed improbable due to current battery mitigations (e.g., battery management system). The ‘medium’ risks were fire ball and blast wave due to a hydrogen tank rupture after a crash, or due to a failure in the actuation of the thermal pressure relief device (TPRD), or due to H_2 gas venting through the TPRD in an enclosed space (e.g., tunnel).

To further understand the risks in specific rail operation scenarios, the authors suggest building on this risk assessment by doing rail application-specific risk assessments, such as:

- Operating in tunnels,
- Satellite re-fuelling,
- Minor and major maintenance activities,
- On-track breakdowns and repairs,
- Locomotive and tender storage,
- Rail crossings, and
- Terminal layout (goods storage, refuelling infrastructure, maintenance etc.).

Another recommended action is to re-visit this risk assessment periodically and update it. A risk assessment is a dynamic document and should be revised as new field failures occur, new technologies are developed and new operational scenarios are enacted.

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1.0 Introduction

The purpose of this supporting document is to provide guidance to the reader for the interpretation of the "AST-2024-0032 Risk Assessment for Hydrogen and Battery Locomotive", an Excel file that was developed along this written report [1]. These two documents should be read together.

For this phase of the project, the National Research Council of Canada (NRC) was asked by Transport Canada (TC) to produce a standalone, comprehensive report that adapts the work conducted in Phase I on risks and hazards of hydrogen and battery-powered locomotives [2] as well as the regulatory gap analysis [3]. The risk assessment presented here and in the Excel file is a more expanded and in-depth version of the previous works. The reader may refer to [2], and [3], to understand why this risk assessment was important, but very briefly, hydrogen and battery locomotives are novel technologies, with minimal but increasing market adoption. The risks they pose to people, property and environment needed to be examined and understood.

This report documents the methodology for the framework, and the framework itself, as well as the strengths, weaknesses and limitations of this approach. The authors also take the opportunity to make recommendations on future work and ways to improve this framework.

The goal of this project was to educate the audience about the elements of a hydrogen fuel cell or battery powered locomotive that may pose risks, and methods for mitigating these risks. The target reader group is railway companies, government rail safety inspectors and officers (federal and provincial), locomotive designers/integrators, and standards development organizations.

Note that that, in addition to a normal Acronyms and Abbreviations section and a References section, this report includes, after the Conclusions in Section 6.0,

- a List of Codes and Standards section; and
- a Description of Terms section.

The codes and standards are those referenced in AST-2024-0032 [1]. The Description of Terms is a list of terms that are specific to hydrogen or battery risks and hazards, to help orient the reader.

No further references are made to those sections when the codes and standards are described, or when the described terms are used.

2.0 Background

For this work, the authors wanted to focus on the new components in a hydrogen locomotive that were not found in a traditional diesel-electric locomotive design. The authors assumed the diesel-electric locomotive component risks have been studied extensively elsewhere.

The boundary diagrams (Figure 1 in section 2.1, Figure 2 in section 2.2, Figure 3 in section 2.3 and Figure 4 in section 2.4) are provided as a point of reference for the risk assessment. The authors do not presume that they are exhaustive, as each original equipment manufacturer (OEM) will custom design their own system, but the authors do include the major components found in a hydrogen and battery locomotive design. As with all risk assessments, it is a living document that will require continual updates as new technologies emerge and/or new risks are determined.

In-scope for this project was the hydrogen and battery powered locomotive as well as the fuel dispensing system (ground equipment). We assumed that only gaseous hydrogen was used – no liquid hydrogen. Out-of-scope for this risk assessment too were the maintenance facilities.

2.1 Hydrogen and Battery Powered Locomotive

Figure 1 is a boundary diagram for a hydrogen and battery powered locomotive including all the major components as well as the fuel dispensing system. A boundary diagram is an engineering tool which is used to demonstrate the interfaces (e.g., mechanical, electrical, communications, etc.) between different sub-systems in a product. Blue indicates the components included in this risk assessment while green indicates the components which were excluded from this risk assessment, since they were common to a diesel-electric locomotive. “[NRC]” at the end of the figure caption indicates that these figures were developed by the authors.

The connections between the components can be in three ways: mechanical, electrical and/or communication. The basic functional flow is that a power demand is received at the engine control unit (ECU), and then transmitted to the fuel cell control unit (FCU) and battery management system (BMS). Typically, the fuel cell system (FCS) will charge the battery and the battery will drive the traction motors. To turn the FCS on, the battery must send power via the DC-DC converter to start the fuel cell (FC) auxiliary systems (e.g., air compressor, enclosure fan, coolant pump etc.). Once the FCS receives the input power, it will draw in air and fuel to generate power back to the DC-DC converter and either charge the battery or drive the traction motors, in times of high-power demand.

Cooling of the control units is not shown in our boundary diagram specifically but is considered in our risk assessment. Additionally, the automatic safety system is not shown in the boundary diagram since it will depend on the location of the component installations. For example, if the H_2 tank was installed alongside the locomotive instead of inside an enclosed car, the risks associated were different and the safety system would have been considered in a different manner.

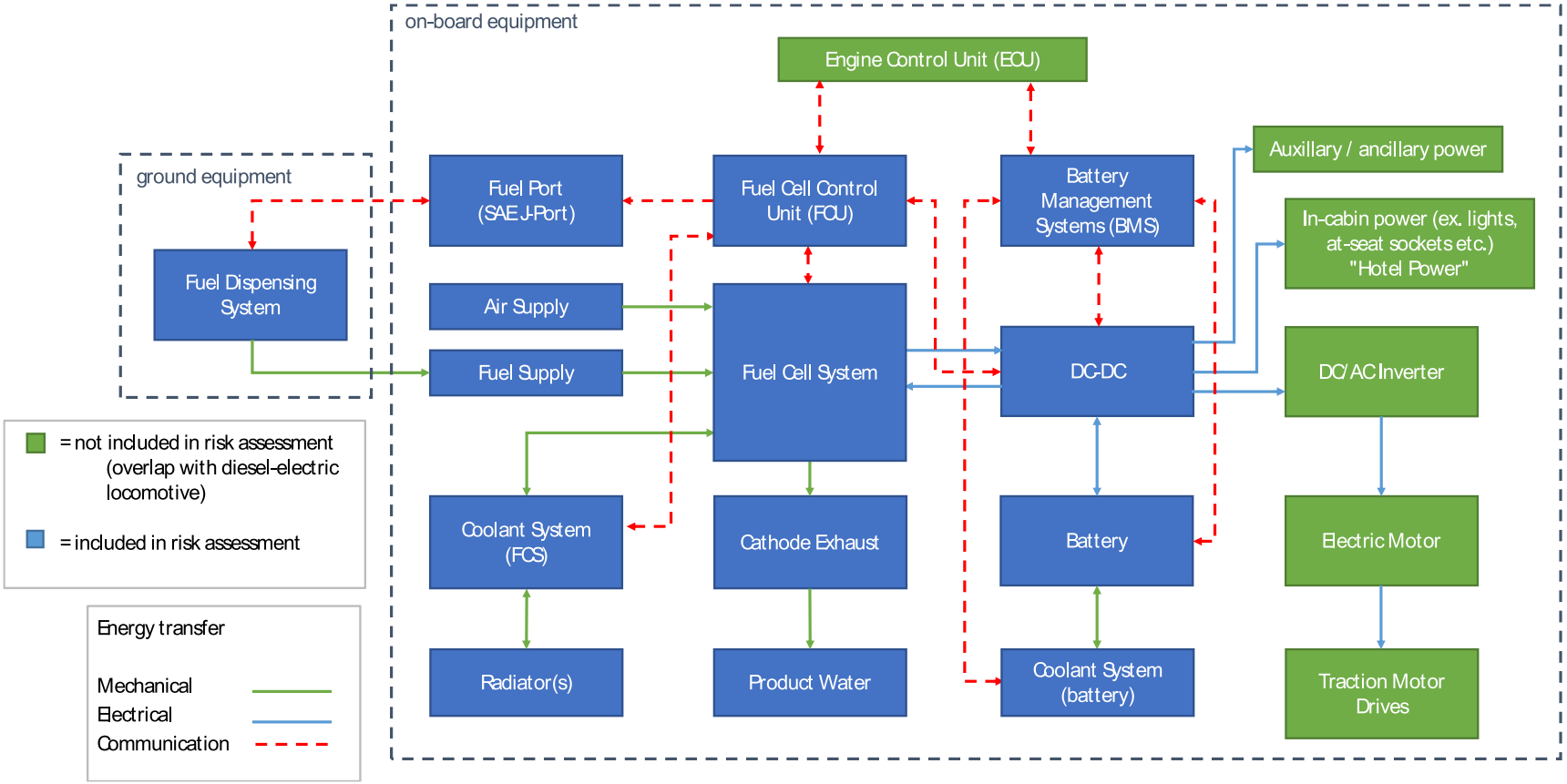

Figure 1: Boundary diagram for a hydrogen and battery powered locomotive [NRC]

2.2 Fuel Cell System

Figure 2 is a boundary diagram for a fuel cell system (FCS). This is a simplified reference design and does not represent any and all FCSs but provides a starting point for examining risks associated with an FCS.

Starting at the fuel supply, at the right of Figure 2, and working in towards the FC module, is an injector or a pressure control valve (PCV) which controls pressure to the fuel (Fx in the figure) inlet port of the fuel cell module. At the outlet of the fuel port of the FC module, there is a vessel to collect product water, with a level switch, and a water drain valve. The water drain valve is opened when the level switch is high and it connects to the cathode exhaust. There is also a nitrogen (N_2) valve at the fuel outlet, which connects to the cathode exhaust; it is opened periodically to remove nitrogen, and allow fresh hydrogen (H_2) to fill the anode circuit. There can also be a hydrogen recirculation blower (HRB) in the anode circuit, typically for operation at idle loads. Lastly, the ejector (part of the injector but separated in our diagram) uses the Venturi effect produced by the injector to circulate flow in the anode circuit.

For the oxidant circuit (Ox in Figure 2), there is first an air compressor and then, typically, a passive humidifier. The product water from the oxidant outlet is used to humidify the dry inlet air via crossover through a porous membrane. There can be additional valves in the oxidant circuit to increase hydrogen protection time but they are not pictured here. Hydrogen protection time refers to the period after shutdown during which hydrogen is maintained in the anode circuit to prevent air from back-flowing from the exhaust and crossing over to the anode. The products, water, nitrogen, some unreacted hydrogen, and oxygen-depleted air, are sent to the cathode exhaust.

For the coolant circuit, the coolant (Cx in Figure 2) is typically a 50/50 water-ethylene glycol (WEG) mixture, specially manufactured for fuel cell systems. There is a pump and then a pressure transducer and thermocouple at inlet and outlet of the module. The inlet temperature and temperature rise from inlet to outlet (often called the dT) must be well controlled for a fuel cell. There can also be a heater in the system for cold starts. The outlet of the coolant circuit goes to radiator fans to reduce the inlet temperature to the desired setpoint. The coolant circuit also provides cooling to the air compressor, and the fuel cell control unit.

There is also a low voltage (LV) (typically 12 V or 24 V) supply to the fuel cell module to power the fuel cell control unit (FCU), any valves, or power to transducers etc. The high voltage (HV) cables (>50 V) connect from the fuel cell module bus bars to the DC-DC converter.

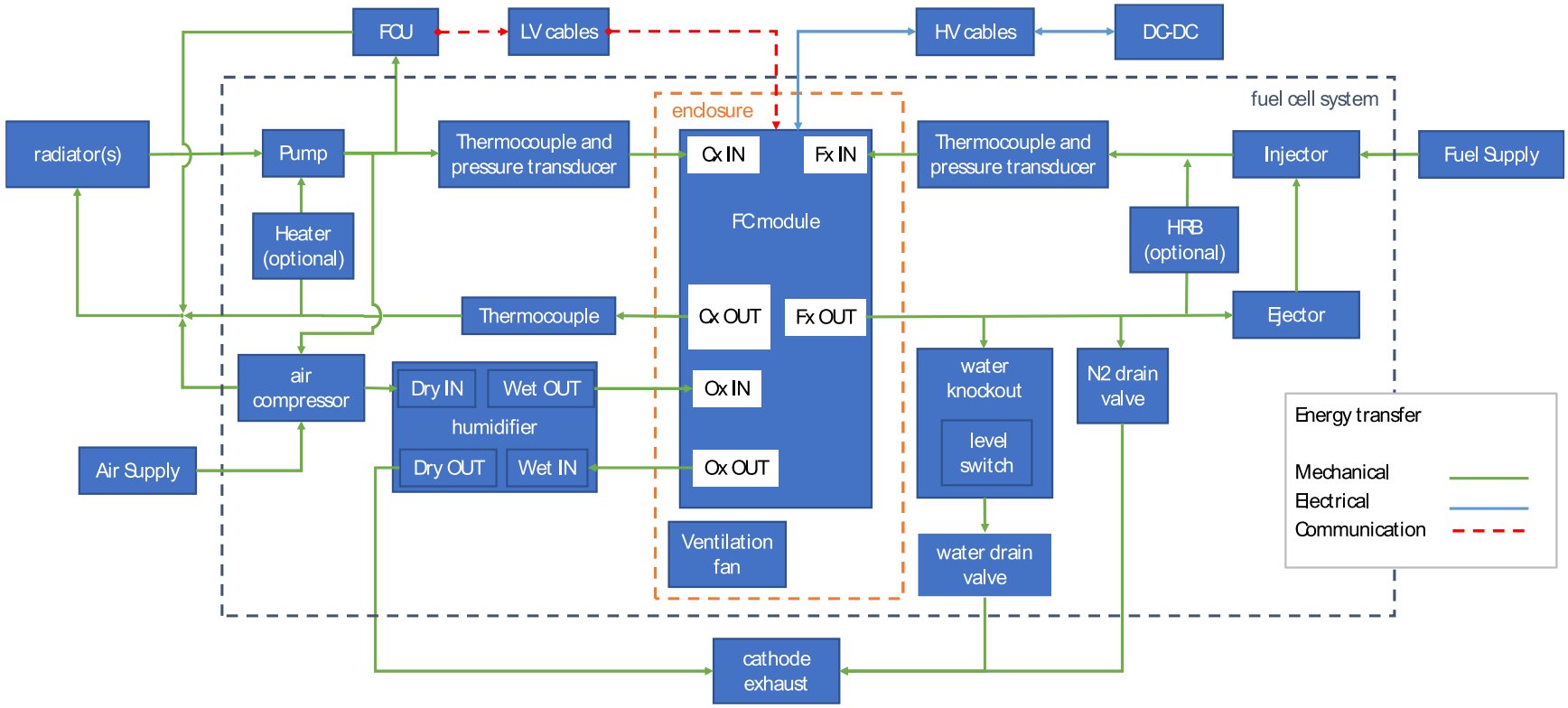

Figure 2: Boundary diagram for a fuel cell system (FCS) [NRC]

2.3 Fuel Supply

Figure 3 is a boundary diagram for a hydrogen fuel supply system. The fuel supply is found on-board a vehicle and connects the fuel dispensing system to the fuel cell system. Starting from left the hydrogen is supplied via the fuel dispensing system followed by a filter assembly, check valve, pressure transducer (PT), thermocouple (T/C) and manual valve. After the manual valve is the hydrogen tank which includes another manual valve and an automatic valve just before it. There is a thermal pressure relief device (TPRD) on the tank itself to protect against the possibility of an adjacent high thermal event. Continuing further right to the fuel cell system there are additional sensors (a PT and T/C again) and valves, including an excess flow valve. An excess flow valve is a mechanical device which shuts off flow when it detects that the flow across is too elevated, for example, in the event of a line rupture. There is also a pressure relief device which connects with a vent line. If pressure in the line is above the pressure relief device limit, it will open and gas will vent through the vent line. The high number of valves here (11 with the TPRD) is for redundancy of the safety system.

2.4 Fuel Dispensing System

The fuel dispensing system is found in the ground equipment at a re-fuelling station, for example. Figure 4 is the boundary diagram for the hydrogen fuel dispensing system. It connects into the fuel supply on-board the vehicle. At the left is the hydrogen low pressure storage device. That is followed by a T/C, PT and a hydrogen compressor. The hydrogen compressor steps up the pressure from somewhere between 20 and 200 bar up to somewhere between 350 and 700 bar. After the compressor we find another T/C and PT, followed by a buffer storage tank. Similar to the case for the fuel supply system, that tank includes a TPRD to guard against the possibility an adjacent high thermal event. Further right towards the dispensing nozzle, there is an excess flow valve followed by a chiller. To fill a vehicle, typically a pressure differential between the dispensing system (higher pressure) and the fuel tank (lower pressure, depressurising phase) is used. Fast filling of hydrogen results in heat generation, which is why the hydrogen gas is pre-cooled down to -40°C before filling.

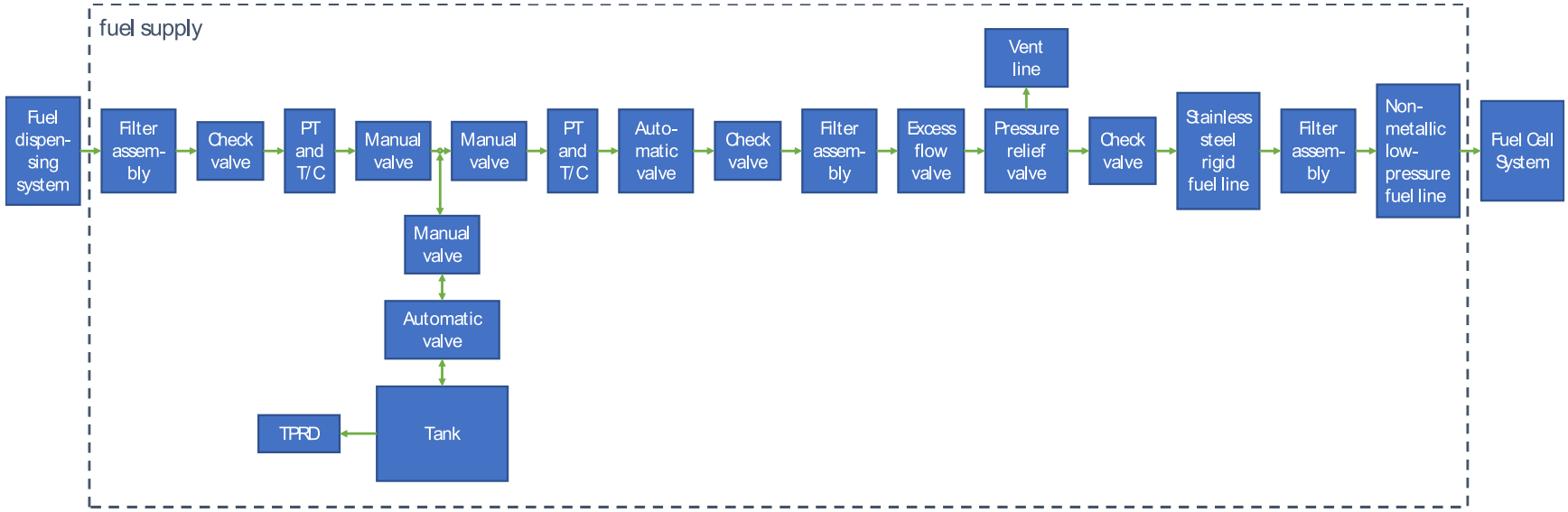

Figure 3: Boundary diagram for a hydrogen fuel supply (on-board). Reproduced from [4]

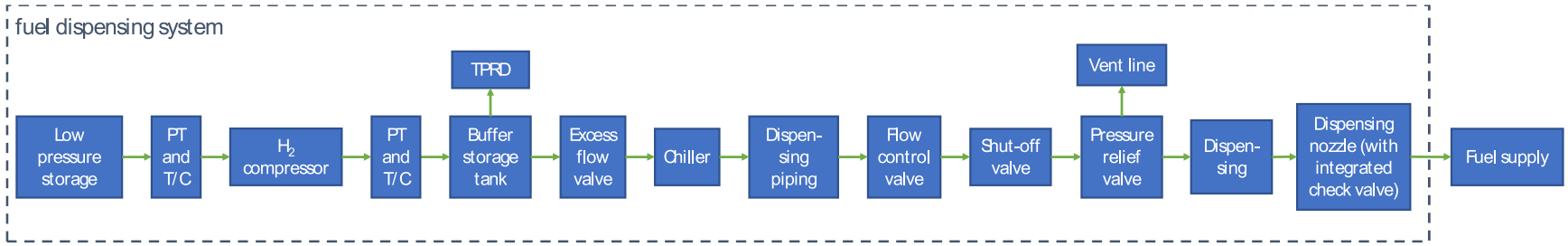

Figure 4: Boundary diagram for a hydrogen fuel dispensing system (ground equipment) [NRC]

3.0 Methodology

A risk assessment is performed in the design-phase of a product development cycle to influence the safe-design of a product. It's a structured method to comprehensively catalogue all potential risks, ensure all codes and standards are met, influence potential mitigations, and ensure adequate verification testing is performed throughout the development process. Furthermore, the output of a risk assessment provides documentation for regulators to ensure adequate due-diligence. While a risk assessment is a critical part of the product development process, regulators should assess it critically under the specific operational circumstances they are aware of, and of the desired outcomes they are aware of, and as part of a set of product documents provided by the OEM.

A hazard is defined as the harm that could be inflicted to a person, property, or the environment because of failure or improper use of a component. Risk is defined as the probability of occurrence times the severity. Probability of occurrence is how frequently an event can happen; severity is how bad could the harm be. Risk can be assigned qualitatively (e.g., low, medium, high) or quantitatively (e.g., $1x10^{-4}$/year), or a combination of the two which would be semi-quantitative.

The risk assessment framework used in this study is based on ISO 12100:2010 Standard - Safety of machinery — General principles for design — Risk assessment and risk reduction [5]. The template used for following this standard was provided by TC.

3.1 Location, System, and Component

Starting at the highest-level, the components from sections 2.1 to 2.4 were categorized into their locations (ground or on-board). The components were then divided into their respective systems (fuel dispensing system, automatic safety, battery, etc.) and finally grouped into component-level elements of the hazard origin. Figure 5 is a graphical illustration of these locations, systems and components (sorted alphabetically).

"Location" and "System" are columns A and B in the "Risk Assessment" worksheet in the Excel spreadsheet [1], and both subsets of a "Source of Potential Harm" group that includes column C – "Hazard Origin (Component)" as well. The latter (column C) includes, for example, the buffer storage tank and chiller for the ground equipment in Figure 5, and the active ventilation and E-stop(s) for the on-board equipment in the same figure. "Components of Associated Hazard Group" is column E in the worksheet.

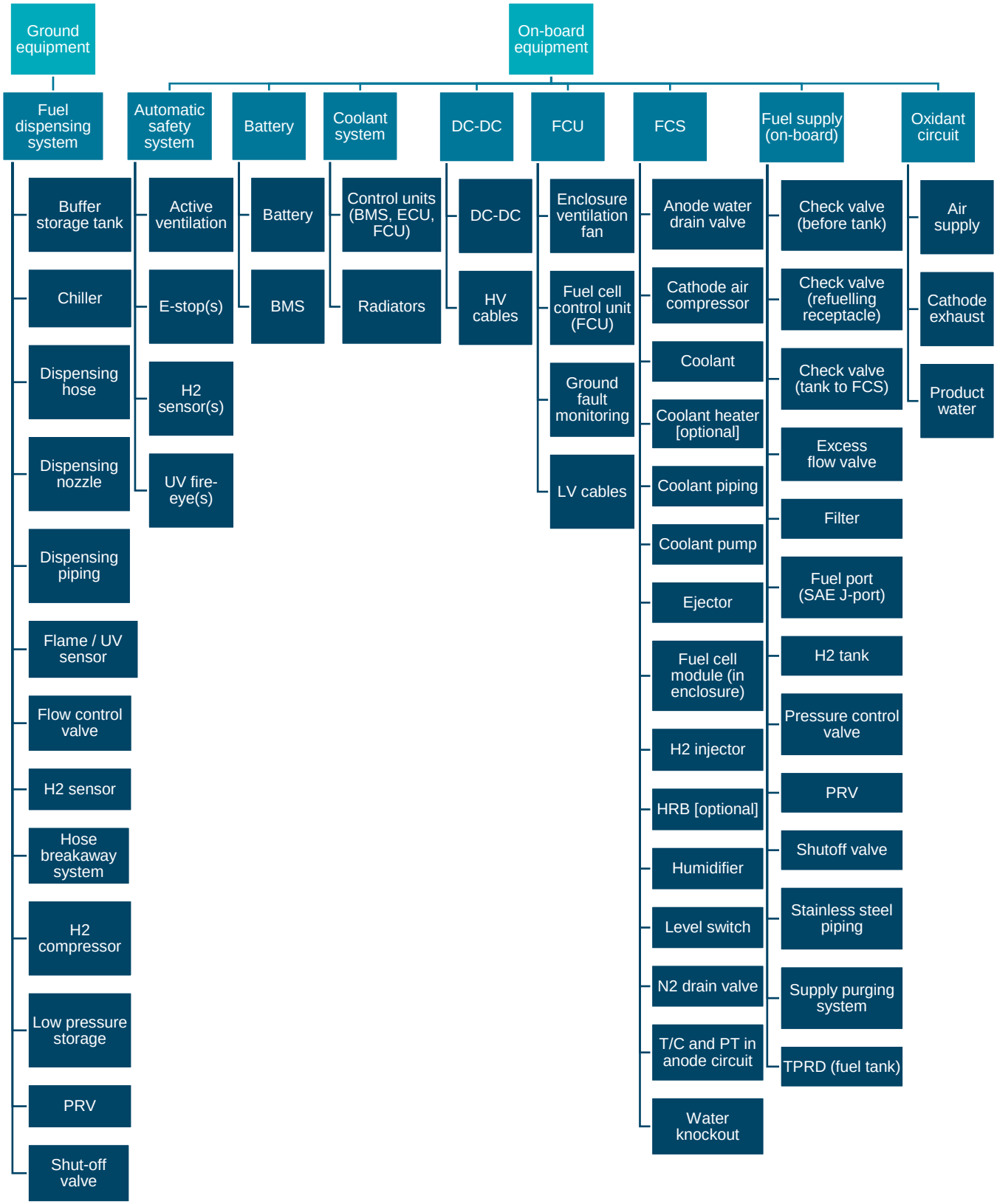

Figure 5: Hydrogen and battery locomotive major systems and components for ground equipment and on-board equipment

3.2 Associated Hazard Group and Component

Figure 6 is the list of hazard groups and their specific components to consider, which were provided by TC to the NRC and come from [5]. The hazard groups were divided into ten major categories:

- Mechanical
- Electrical
- Material / substance
- Ergonomic
- Noise
- Vibration
- Radiation
- Environment
- Thermal
- Combination of risks

“Associated Hazard Group” and “Components of Associated Hazard Group” are columns D and E in the “Risk Assessment” worksheet in the Excel spreadsheet [1], These are both subsections of “Using Table B.1 for Identification of Hazards” in the sheet.

The purpose of providing such a list was to ensure all the various potential risks were considered when performing the risk assessment. While each individual hazard component was considered when examining each hydrogen and battery locomotive system component, identified risks were not associated with each hazard group. Only the hazard groups, for which hazards were identified, pertaining to this risk assessment are shown in a black font in Figure 6; while the remaining hazards, which were not identified in this risk assessment, are in a light-grey font.

The second black element in the mechanical category of Figure 6 is “approach of a moving element to a fixed part”. This is when a system component comes loose and becomes a projectile that could damage a fixed part. An example would be if, in the event of a crash, a part of the locomotive broke off and penetrated the hydrogen storage tank.

Also in the mechanical category, the fourth black element of Figure 6 is “instability”, which refers to the degradation of a part over time through, for instance, deflection, fractures, creep, relaxation, corrosion, or cracking. An example would be a crack in a bipolar plate leading to a fuel or oxidant leak, causing gas in the coolant circuit.

For the third black element in the thermal category of the figure, an example of an “object or material with high or low temperature” was something that could cause a burn or low-temperature burn. In this system, an example would be over-temperature of the FCU which could cause an overload of the FCS, leading to fire or explosion in the cell.

Figure 6: List of associated hazard groups and components.
Light-grey font indicates hazards which were not identified in this risk assessment.

3.3 Risk Scenario Evaluation

When performing the risk scenario evaluation, the authors brainstormed the functions of each component and hypothesized the ways that it could fail, potentially resulting in a hazard. Typically, this involved considering a component failing in three main ways: over-delivering (e.g., power too high), under-delivering (e.g., power too low), and partial delivery (e.g., power intermittent). The purpose of understanding the functions was to help ensure all failures resulting in risks were adequately captured. Evaluating the functions of a component is part of a failure mode effects and analysis (FMEA) assessment, which differs from a risk assessment, in that it feeds into a product development cycle and a verification testing plan. A failure mode may result in a risk but not always. Some failures (for example, power too low) can simply result in a product non-function, which may not be a risk. To brainstorm the potential causes, the authors drew on their knowledge and experience of batteries, hydrogen, fuel cell operation, and refueling as well as their knowledge and understanding of railway operation and the risks and hazards associated with railway operation. The identified hazards were sorted into their associated hazard groups and components.

Once brainstorming was exhausted, the authors cross-referenced the associated hazards and hazard groups already identified against the global list (Figure 6) to further elicit potential hazards and ensure none had been overlooked. If no cause could be hypothesized, this hazard group was left blank and then removed from the workbook.

Focusing solely on the risks, rather than all functions, may be construed as a shortcoming of a risk assessment. Whereas a FMEA considers all functions of each component, and is thus a more complete product analysis; a risk assessment only considers failures which result in a risk. Performing a full FMEA offers the engineer the opportunity for further brainstorming and new risks, not identified in the risk assessment, may be revealed. However, a FMEA is a lengthier process, and if the user is strictly interested in risks, it may be excessive and too time-consuming.

Another drawback of this risk assessment is its broad nature. The authors made best efforts to capture all the risks but not every specific scenario could be considered due to time constraints. In order to employ this risk assessment more effectively, it should be iterated for specific operational scenarios. Some example scenarios that could be evaluated include operation in a tunnel, maintenance in a rail yard, on-track refuelling, on-track breakdowns, etc.

The “Cause” for each risk defined by the authors is shown in column F of the Excel worksheet.[1], and is a subset of a “Scenario” section.

After determining the cause for each component hazard, the “Risk / Effect” (column G in the spreadsheet) from this cause was evaluated, as well as the “Consequence / Result / Impact” (column H) from the risk. Similar to the case where the causes were established in section 3.2, the risk scenarios here were determined through the author’s knowledge and experience of hydrogen and fuel cell systems, and the risks from failures.

3.4 Impact Factor

When evaluating the impact factor of each consequence identified in section 3.3, the authors identified three principal categories: people, property, and the environment (columns I, J and K in the Excel spreadsheet) [1]. The authors stipulated YES/NO if these consequences could impact any or all of these three categories. In this instance, property was defined as the locomotive (hydrogen or battery systems) and/or any property adjacent to the locomotive operation (e.g., tracks, signage, etc.). Identifying which impact factors were affected helped guide the risk analysis for section 3.6.

3.5 Current Controls and Applicable Codes and Standards

For the “current controls, mitigating factors, and others” column (L in the Excel file Risk Assessment worksheet) [1], the authors identified what controls exist in place today to prevent the cause, effect or consequence of these risks. The controls identified there are not requirements but simply these expert-author opinions and, depending on the specific design, different controls can be used.

For the “Code / Standard / Other” column (M in the worksheet), the authors pulled from standards identified in a previous report [6]. The general approach was to refer to the CSA standard first, if available. If the CSA standard did not cover all aspects, then the IEC and/or ISO standard was also referenced. If no CSA standard existed, then the IEC and/or ISO standard is referenced.

3.6 Risk Matrix and Evaluation

The risk matrices below were previously presented in another report [2]. These matrices were developed and prepared by Canadian Nuclear Laboratories (CNL) in conjunction with experts from A.V. Tchouvelev & Associates Inc. (AVT), the Canadian Standards Association (CSA), CNL and the NRC.

Table 1 is the likelihood of the occurrence of the hazard, which is a combination of the risk plus the cause or effect. This means, how likely is this event to happen. We also consider the current mitigations when evaluating the likelihood of occurrence. If the likelihood of cause and effect is high but the current mitigations are adequate, this may result in a low likelihood of occurrence. Each scenario is examined individually. This is important to note because there are many hazards which would be of much higher occurrence or severity were it not for the mitigations already in place.

Table 1: Likelihood of occurrence of risk, and cause or effect

Level	Description	Definition	Frequency
1	IMPROBABLE	possible but may not be heard of or may not be experienced world wide	$x \leq 10^{-3}$ per year
2	REMOTE	unlikely to occur during lifetime/operation of one sub-system	$10^{-3} < x \leq 10^{-2}$ per year
3	OCCASIONAL	likely to occur during lifetime/operation of one sub-system	$10^{-2} < x \leq 10^{-1}$ per year
4	PROBABLE	may occur several times in the sub-system	$10^{-1} < x \leq 1$ per year
5	FREQUENT	will occur frequently at the sub-system	$x > 1$ per year

Table 2 is the severity of the consequence and/or result. This means, if this event happens, how bad will the damage be.

Table 2: Severity of consequence, and/or result

Level	Description	People	Property	Environment
1	NO DAMAGE	No injury, annoyance, disturbance	No material damage	No environmental damage
2	MINOR DAMAGE	Minor injury, annoyance, disturbance	Minor material damage	Minor environmental damage
3	DAMAGE	Medical treatment; lost time injury	Minor structural damage; minor production influence	Local environmental damage of short duration < 1 month
4	MAJOR DAMAGE	Permanent disability Prolonged hospital treatment	Considerable structural damage; production interrupted for weeks	Time for restitution of ecological resource < 2-yrs
5	SEVERE / CATASTROPHIC	One to several fatalities	Loss of station and production interrupted for months	Time for restitution of ecological resource >2-yrs (e.g., recreation areas, ground water)

Table 3 combines the likelihood of occurrence with the severity into a single risk metric: LOW, MEDIUM, or HIGH. Identifying the risks into a single metric allows for simpler identification and sorting for the engineer and helps prioritize which risks should be targeted first to reduce their level (e.g., from HIGH to MEDIUM).

Table 3: Risk matrix

Severity	Occurrence (per year)				
	1-Improbable ($x \leq 10^{-3}$)	2-Remote ($10^{-3} < x \leq 10^{-2}$)	3-Occassional ($10^{-2} < x \leq 10^{-1}$)	4-Probable ($10^{-1} < x \leq 1$)	5-Frequent ($x > 1$)
1-No damage	LOW	LOW	LOW	LOW	LOW
2-Minor damage	LOW	LOW	LOW	LOW	MEDIUM
3-Damage	LOW	LOW	LOW	MEDIUM	HIGH
4-Major damage	LOW	LOW	MEDIUM	HIGH	HIGH
5-Severe / catastrophic	LOW	MEDIUM	HIGH	HIGH	HIGH

4.0 Discussion

In the following sections, the causes, risks and effects, consequences, results, and impacts will be discussed, as well as current controls and applicable codes and standards, and finally, a summary risk analysis.

4.1 Causes

The authors identified 501 risk causes (row 6 to row 506 in the “Risk Assessment” worksheet in the Excel spreadsheet) [1] through this initial risk assessment for the H_2 and battery powered locomotives, fuel cell system, fuel supply and fuel dispensing system (boundary diagrams are in Figure 1 to Figure 4). The authors worked collaboratively to identify as many risks as possible. This document should be revised and edited as new risks are determined or new failure modes are identified.

Each line presents an individually identified risk, although some types of risks were repeated through the course of the document. The risk assessment should be read, understood, and interpreted line by line and component by component. However, the authors were able to identify themes within the associated groups, which came up the most frequently through the risk assessment. In this way, some general conclusions can be presented.

Table 4 provides an accounting of which hazard group and associated components came up and so lets the reader see which came up most often. The focus for the reader should be on the general trends, rather than the exact numbers since it was sometimes possible to categorize risks into multiple categories. For example, mechanical wear could be categorized as mechanical - instability, mechanical - high pressure, environmental - temperature, or others. The authors did their best to evaluate causes in a consistent manner but as this work was undertaken by multiple authors, slight inconsistencies may appear.

Table 4: Risk-cause hazard group (grouped by associated hazard) occurrences

Associated Hazard Group	Components of Associated Hazard Group	Count	Total
Mechanical	approach/departure of a moving element to a fixed part	37	195
Mechanical	high pressure	101	
Mechanical	instability	37	
Mechanical	moving elements	2	
Mechanical	rotating elements	9	
Mechanical	acceleration, deceleration	9	
Electrical	arc	4	115
Electrical	electromagnetic phenomena	3	
Electrical	electrostatic phenomena	3	
Electrical	live parts	4	
Electrical	not enough distance to live parts under high voltage	2	
Electrical	overload	9	
Electrical	disconnection/miswiring/control failure	48	
Electrical	parts that have become live under fault conditions	3	
Electrical	short circuit	39	
Thermal	explosion	2	67
Thermal	flame	33	
Thermal	objects or materials with a high or low temperature	27	
Thermal	radiation from heat sources	5	
Vibration	unbalanced rotating parts	1	26
Vibration	worn parts	25	
Material/substance	combustible	4	62
Material/substance	dust	3	
Material/substance	explosive	1	
Material/substance	flammable	6	
Material/substance	gas	4	
Material/substance	hydrogen material compatibility	44	
Environment	dust and fog	1	34
Environment	moisture	4	
Environment	temperature	26	
Environment	water	1	
Environment	lack of oxygen	2	
Combination of risks	for example, repetitive activity + effort + high environmental temperature	2	2
	TOTAL		**501**

Mechanical had the highest number of associated hazards identified, with 195 in total. Of these, 101 instances were for mechanical - high pressure. This is not unexpected since the hydrogen tank typical pressure is 350 to 700 bara, and the fuel cell system operates nominally at 2 to 3 bara. Next highest were mechanical - instability, and mechanical - approach or departure of a moving element to a fixed part, with 37 instances each. Instability was typically in reference to mechanical wear over time, while approach-departure was due to penetration or crushing from a foreign object. Mechanical - acceleration, deceleration, with 9 instances, was due to response to a mechanical shock force.

Electrical was the second highest number of associated hazards identified with 115 instances. Electrical - disconnection/miswiring/control failure was the highest for electrical, with 48 instances. Control is a critical function for this product since there are at least three different control units: ECU, FCU, and BMS. These units are responsible for ensuring their proper function as well as the function of their sub-components (e.g., battery, FCS, etc.). Electrical - short circuit had 39 instances and is important since there are multiple components that operate with high voltage (>50 V). Electrical - overload, with 9 instances, was generally caused by the FCU or BMS drawing more load than the setpoint.

Thermal had 67 total instances, mostly split between thermal - flame (33 instances), thermal - objects or materials with a high or low temperature (27 instances), and thermal - radiation from heat sources (5 instances). Thermal - flame was caused by other component fires. For example, the battery could have a thermal runaway failure which may cause a fire, which could then propagate to the FCS or fuel tank and cause a secondary failure. The cause for thermal - objects or materials with a high or low temperature was overheating or over-temperature, often due to insufficient cooling. The cause for thermal - radiation from heat sources was the heat load in a tunnel causing the unintended opening of the TPRD valve on the hydrogen tank.

There were 26 instances of risks identified in the vibration group – 25 instances were vibration - worn parts. The hypothesized cause of these was the specific vibration profile of rolling stock.

In material/substance, 62 instances were found. Of these, 44 instances were material/substance - hydrogen material compatibility. H_2 embrittlement is a known failure with prolonged exposure to gaseous hydrogen, but this cause can be greatly reduced with proper material selection.

Within the environment hazard group, 26 of 34 instances were from the environment - temperature category. The causes here could include repeated ambient temperature cycles (sub-zero to above-zero), high or low ambient temperature, or even water condensation or penetration from high humidity operation.

An understanding of which hazard groups and associated component hazard groups come up most often in this hydrogen and battery locomotive risk assessment is helpful in guiding future risk assessments. These identified component and hazard groups provide a good starting point for others who may wish to perform a risk assessment in a similar domain (e.g., hydrogen fuel cell truck or hydrogen locomotive in a specific application). Additionally, if there is a desire to expand the focus for this risk assessment (e.g., break the fuel cell module into its component parts), then examining these component hazard groups first can help perform the risk assessment in a more rapid fashion.

4.2 Risks and Effects

For the report *Hydrogen and Battery-Powered Locomotives – Regulatory Gap Analysis* [3], the risks were categorized by their operational domain as well as risk category. For this risk assessment, the authors took a different approach by categorizing the risks by their "risk type" rather than location. The reason for this characterization is that the same risks (e.g., H_2 leak - small) could be present in multiple operational domains (e.g., FCS, H_2 tank, fuel supply line, etc.). Table 5 is a summarized list of the risks and effects sorted by their risk type. The risks were grouped into six categories, sorted by most frequently to least frequently identified, with the number of risks, n, being identified in each case:

- Combustible mixture (H_2 in air) (n = 306),
- High voltage (>50 V) (n = 123),
- Thermal runaway (n = 32),
- Over-temperature (n = 22),
- Enclosed space (n = 11), and
- Environmental exposure (n = 7).

These six categories are not included in a column of their own in the Excel worksheet, but the result of work by the authors to categorize the risks described in columns F, G and H for each row in this way.

Regarding the "combustible mixture (H_2 in air)" category, it is well known that H_2 has a broad flammability range, from 4% to 75% volume of H_2 in air. We defined this risk type as being a concentration of hydrogen within this range. In this concentration range of H_2 in air, if there is an ignition source present (e.g., flame, spark, static electricity, etc.), the likelihood of a hydrogen fire is frequent (as defined in Table 3 and Table 1). The main mitigations for these risks include, but are not limited to: shutting off the supply of hydrogen in the event of a fire, properly classifying areas where hydrogen is present to ensure the electrical equipment is defined appropriately, adequate grounding, adequate bonding, static electricity prevention [7], and ensuring adequate ventilation is present (e.g., specified amount of air exchanges for the space and quantity of hydrogen). We sorted the size of penetration causing a hydrogen leak into small or large. Small was something like a bolt which backed out from a component inside the locomotive and large was something like a support for the hydrogen tank, which had become disconnected during a crash.

The second risk type identified is "thermal runaway," which could fit under over-temperature, but the authors chose to keep them separate. This risk is related to the battery and occurs when the heating rate exceeds the dissipation rate. The mitigation measures include the battery management system (BMS), strategic placement of the battery, and compartmentalization (which could include pressure differential strategies) to prevent human exposure to fire, smoke, or vented gases, and to stop the fire from spreading to the fuel cell system (FCS) or the hydrogen storage system. Analysis and/or testing should confirm proper battery enclosure and placement with respect to personnel and the fuel cell system.

Table 5: Risks and effects sorted by risk type, with risks shown in order of frequency with the most frequent risk first (abbreviated list)

Risk Type	Risk and Effect
Combustible mixture (H_2 in air), (n = 306)	>4% H2 in air mixture in cathode exhaust accumulation of H2 from small component leaks cell overheating combustible mixture air/H2 into cathode exhaust, in fuel supply line, or released from vent line coolant overheat --> membrane damage --> combustible mix of H2/air creates electrostatic discharge downstream release of H2 into supply line drain valve always OPEN --> combustible mixture air/H2 into cathode exhaust during venting, high pressure hydrogen gas will be released to atmosphere E-stop signal not transmitted to safety system excessive flow, fuel over-pressure, fuel over-temperature, fuel starvation to FC gas in coolant circuit H2 leak – large, H2 leak - small ignition source insufficient air flow and / or pressure to support fuel cell reaction loss of active ventilation in locomotive no hydrogen flow, partial fuel starvation to FC pipe burst potentially explosive mixture released from vent line (enclosed space) rise in H2 concentration not detected rupture spark tank over-fill (leak), TPRD trigger OPEN uncontrolled release of debris into the fuel cell system UV fire not detected
Thermal runaway (of battery), (n = 123)	chemical leak communication loss --> thermal runaway of downstream component(s) damage to BMS, thermal runaway of battery lithium plating over-discharge short circuit, thermal runaway of battery thermal runaway of downstream component(s)
High voltage >50 V, (n = 32)	arc-ing cathode exhaust voltage >50 V damage to HV cable, connection electrical fire, electrocution fuel cell enclosure voltage >50 V unable to monitor isolation FCS and non-live parts (e.g., locomotive) overload, over-temp
Over-temperature, (n = 22)	coolant leak - large coolant over-pressure, over-temperature insufficient cooling of FCS loss of coolant overheating of ECU, FCU, or BMS
Enclosed space, (n = 11)	reduction of oxygen concentration < 19.5% in enclosed space uncontrolled release of H_2 in tank (enclosed space)
Environmental exposure, (n = 7)	coolant leak - small localized ice on railroad tracks

The third risk type is “high voltage, >50 V”. Because the FCS and the battery operate at voltages greater than 50 V and currents above 25 mA, these conditions are considered inherently hazardous. The FCS operates ostensibly at 50A or greater, which could be fatal. The mitigation for this risk is the control units, both BMS and FCU. They continually monitor the ground fault between these high voltages and non-electrically-energized equipment.

The fourth risk type is “over-temperature.” The risk for the FCS and batteries in this category is adequate cooling. Proper control of temperatures in the hydrogen and battery locomotive system is critical for safe functionality, particularly for the FCS (module, and air compressor), the battery, and all the control units (ECU, FCU, BMS). The mitigation for this risk is sufficient temperature monitoring through thermocouples and regulation via the control units.

The “enclosed space” risk can be two-fold. If ventilation in an enclosed space is not adequate, there is the risk of a combustible mixture of H_2 in air (see above) with an increased risk of detonation due to restrictions. The second risk is a reduction in the oxygen concentration in the surrounding environment to below 19.5%, which the Occupational Safety and Health Administration (OSHA) considers to be oxygen-deficient and immediately dangerous to life or health. As fuel cells consume oxygen, they can deplete the oxygen in a space if not adequately ventilated. The mitigation for this risk is ensuring adequate ventilation, and using oxygen sensors to monitor the oxygen concentration.

Within the “environmental exposure” risk type are a coolant leak-small, this is because the typical coolant of an FCS is a mixture of water-ethylene glycol, which can contaminate groundwater or harm plants, if dumped in sufficiently large enough amounts. From an FCS, one of the products is water; when deposited from a downward exhaust pipe and in sub-zero temperature, this may cause the formation of ice on the track rails, which may cause issues with train acceleration or braking.

4.3 Consequences, Results, and Impacts

The resulting consequences from the risks and effects can be categorized by their impact factor. Three impact factors are considered for this work: people, property, and the environment. Consequences that impact people are those that can harm or have an adverse health effect on individuals. Property impacts are those that affect an organization’s equipment, facilities or physical infrastructure (e.g., damage to the locomotive, the rails, the fuel cell system, etc.). Examples of consequences for the environment may include things like pollution, contamination of wastewater, or tunnel cave-ins.

Table 6 lists the consequences, results, and impacts (from column H in the Excel file), sorted by impact factor (columns I, J and K for people, property and environment). The 46 separate consequence/result/impact entries in column H of the Excel file have been combined to create the five groupings, and related impact factors, that are shown in Table 6 of this report. The background colour scheme used for the impact factor columns in Table 6 was also used for all 501 rows of the impact factor entries in the Excel sheet. The majority (257/501 = 51%) of the consequences identified affected both people and property, but not the environment. These were items like fires, jet fires, smoke, reduced

wheel-rail adhesion, and explosions (in the cell). Within-cell explosions are assumed to be damage-limited, so they are not anticipated to have an environmental impact.

Table 6: Consequences, results, and impacts (sorted by impact factor, condensed list)

Consequence/Result/Impact	Impact Factor			Count
	People	Property	Environ-ment	
explosion, fireball and blast wave, potential groundwater contamination	Y	Y	Y	57
explosion (in the cell), fire, inoperable switches, reduced wheel adhesion, jet fire (immediate ignition), smoke	Y	Y	N	257
asphyxiation, electrocution, physical injury, slip hazard, toxic cloud	Y	N	N	42
damage to control unit, fire (in the cell), fuel cell poisoning/fuel starvation/fuel cell damage, over-temperature, low voltage	N	Y	N	35
H_2 pressure too low, non-redundancy in system prevents impact, unignited release	N	N	N	112
TOTAL				**501**

The next highest group (112/501 = 22%) of identified consequences affect neither people, property or the environment. The majority of these were attributed to unignited release of hydrogen. The release of hydrogen into the atmosphere is not a hazard; only with the addition of an ignition source does this become a hazard, which is why the proper electrical rating for equipment in and around hydrogen systems is critical.

Three consequences were identified as impacting people, property and the environment: (1) explosion, (2) fire ball and blast wave, and (3) potential groundwater contamination and these were the contributions to the first grouping. They made up (57/501 =) 11% of the total consequences identified.

In grouping 3 the consequences only impacted people (42/501 = 8%), while in grouping 4 the consequences only impacted property (35/501 = 7%). In the people-only grouping there was asphyxiation, dizziness, fatigue, collapse, electrocution, physical injury, and slip hazard. In the property-only grouping there was damage to equipment, and fire (localized in the cell). A local fire within the cell is not a hazard to a person since the current mitigation strategies would limit damage to the FC module and halt fire propagation.

4.4 Current Controls and Applicable Codes and Standards

In a previous report [6], the applicable codes and standards related to hydrogen and battery technologies were widely enumerated and any gaps were identified. The authors do not seek to duplicate this work. Nevertheless, since the start of Phase I of this work in 2022, the authors have become aware of, or have participated in creating, several rail hydrogen-related standards that have been developed and drafted but not thus far published. Although not yet formally released, these standards are included in this risk

assessment [8-11] and referred to in [1]. Please note that as these are unpublished standards, the numbering and titles are subject to change.

A potential gap identified through this risk assessment is that there does not seem to be a relevant standard in the battery or hydrogen space that specifies a minimum distance between battery, FCS, and hydrogen tank installations, and/or firewall requirements. The risk is that a fire occurring in one of these three components could propagate to another component, and the resulting severity would be catastrophic.

Current mitigations for such an event are modelling, simulation and test verification for design engineers to understand how a fire might propagate within an installation. These measures might result in the strategic placement of the battery, compartmentalization (potentially including pressure differential strategies), implementing a fire barrier between the battery and the fuel cell system (FCS), or maintaining a safety distance between the two. This approach would be tailored to each specific case.

Similarly, it is essential to consider the health and safety effects of human exposure to a battery fire, smoke, and vented gases. Mitigation strategies include the strategic placement of the battery and compartmentalization (possibly involving pressure differential strategies) to prevent this exposure.

Although not addressed by this risk assessment, there is a need for safe distances between hazardous equipment and people for various situations to be addressed by standards or guidelines. There are different layers to this subject. The first, which we have covered in [1] and this companion report, is the high-level or system-level hazard origins, which include items such as, batteries, hydrogen fuel cell systems, high pressure hydrogen storage and high voltage components, etc. The next layer would be examining various operational scenarios, such as normal operation (while parked), normal operation (while driving), normal maintenance and repair and repair during an incident or accident event requiring emergency response. These events include battery thermal runaway, hydrogen leak scenarios (e.g., PRD activation), collisions with cars or truck in crossings, derailment, etc. The third layer includes those affected by the setback distances including the public, maintenance workers and emergency responders.

As this is a complex subject, there is work required to organize and compile all the information, including the gaps that need to be addressed. Table 7 is an incomplete example draft based on what is discussed above. This subject will require further analysis for completion (the table needs to be refined, completed, and simplified). Also, when this information is completed, the larger setback distance from all the applicable system and sub-system should be selected. Further, as there is no control over the public who may carry cell phones, laptops and other electrical equipment into ordinary locations, the zones (both on the ground, around the train and inside the train), where the public is present, should not be electrical area classified. In other words, during normal operations the train itself should not render the area where it stands and where the public will be expected as electrical area classified.

Table 7: Example incomplete draft setback distances table

System	Sub-system	Operational scenario	Setback distance for			Standard
			Public	Crew, staff, and maintenance workers	First responders	
Ground equipment	Hydrogen storage	Normal – stand-by	TBD	TBD	TBD	e.g., [12, 13] etc.
		Normal – fueling	TBD	TBD	TBD	
		Maintenance and repair	TBD	TBD	TBD	
		Incident e.g., hydrogen leak	TBD	TBD	TBD	
		…	TBD	TBD	TBD	
	Fueling infrastructure	Normal – stand-by	TBD	TBD	TBD	
		Normal – fueling	TBD	TBD	TBD	
		Maintenance and repair	TBD	TBD	TBD	
		Incident e.g., control failure	TBD	TBD	TBD	
		…	TBD	TBD	TBD	
	Battery charging infrastructure	Normal – stand-by	TBD	TBD	TBD	e.g., [14] etc.
		Normal – fueling	TBD	TBD	TBD	
		Maintenance and repair	TBD	TBD	TBD	
		Incident e.g., loss of connectivity	TBD	TBD	TBD	
		…	TBD	TBD	TBD	
Rail equipment	Batteries	Normal - parked	TBD	TBD	TBD	e.g., [15]
		Normal - moving	TBD	TBD	TBD	
		Maintenance and repair	TBD	TBD	TBD	
		Incident e.g., thermal runaway, derailment, collision etc.	TBD	TBD	TBD	
		…	TBD	TBD	TBD	
	FCS	Normal - parked	TBD	TBD	TBD	e.g., [11]
		Normal - moving	TBD	TBD	TBD	
		Maintenance and repair	TBD	TBD	TBD	
		Incident e.g., H_2 leak, derailment, collision etc.	TBD	TBD	TBD	
…	…	…	TBD	TBD	TBD	…

4.5 Risk Analysis

As outlined in section 3.6, the combined occurrence and severity is tabulated to determine if the risk is LOW, MEDIUM, or HIGH. Table 8 summarizes the risk levels identified in this risk assessment. This table makes use of the Excel file data, but is not, itself, included anywhere in the Excel file itself.

The prevailing risk level identified in this work was low with 498 of the total 501 instances. Additionally, of the 501 risks identified, 412 were either improbable occurrence (n = 189) or remote occurrence (n = 223). This is because design engineers of hydrogen or battery technologies currently in service today (e.g., Toyota Mirai, Hyundai Nexo and New Flyer Xcelsior CHARGE FC), working with federal regulatory agencies, have developed a good understanding of the risks and hazards and established adequate mitigations. Some example mitigations include using certified components when working with hydrogen, using compression-type fittings (front and back ferrule) to prevent and reduce H_2 leaks, control units for automatic safety monitoring, active ventilation, electrical area classification, and redundancy in safety, as required. Where gaps may exist is in the novel or emerging application of these technologies (such as heavy-duty trucking, hydrail, tractors, etc.) and in those responsible for the integration work (e.g., fuel cell companies or vehicle OEMs).

Three of the 501 instances were identified as medium risk (shown with a yellow background in the risk level (column R) in the Excel sheet vs. the green used for low risk). Two of these risks were previously identified in [2]: crash-induced damage to the hydrogen tank causing a large H_2 leak, and improper design of the TPRD within the tank causing no TPRD actuation during a localized fire. Both risks are hypothesized to lead to a fireball and blast wave, and hence have the severity of consequence (column P in the Excel file) shown as “severe/catastrophic”.

Some mitigations for crash-induced damage to the H_2 tank include tank mounting that can withstand adequate G-forces experienced by the locomotive and/or tender cars, tank and piping connections that are protected from impact (foreign or internal design component), roll protection, placement away from crushing zones, and performing simulation and crash verification testing.

For the lack of TPRD actuation during a localized fire, some principal mitigations are redundant installations of TPRDs, relief valves routed to a safe location (away from other tanks), verification testing of tank/TPRD location arrangements, and fire detection systems.

Table 8: Combining occurrence and severity for risk analysis evaluation

Occurrence of Hazard (Cause and Effect)	Severity of Consequence and/or Result	Risk Level	Count
Improbable	No Damage	LOW	29
Improbable	Minor Damage	LOW	0
Improbable	Damage	LOW	117
Improbable	Major Damage	LOW	29
Improbable	Severe/Catastrophic	LOW	14
Remote	No Damage	LOW	42
Remote	Minor Damage	LOW	1
Remote	Damage	LOW	142
Remote	Major Damage	LOW	35
Occasional	No Damage	LOW	30
Occasional	Minor Damage	LOW	0
Occasional	Damage	LOW	58
Probable	No Damage	LOW	1
Probable	Minor Damage	LOW	0
Frequent	No Damage	LOW	0
Remote	Severe/Catastrophic	MEDIUM	3
Occasional	Major Damage	MEDIUM	0
Probable	Damage	MEDIUM	0
Frequent	Minor Damage	MEDIUM	0
Occasional	Severe/Catastrophic	HIGH	0
Probable	Major Damage	HIGH	0
Probable	Severe/Catastrophic	HIGH	0
Frequent	Damage	HIGH	0
Frequent	Major Damage	HIGH	0
Frequent	Severe/Catastrophic	HIGH	0
Improbable (n = 189)	No Damage (n = 102)	LOW	498
Remote (n = 223)	Minor Damage (n = 1)	MEDIUM	3
Occasional (n = 88)	Damage (n = 317)	HIGH	0
Probable (n = 1)	Major Damage (n = 64)	**TOTAL**	**501**
Frequent (n = 0)	Severe/Catastrophic (n = 17)		

The third instance (from the Excel sheet) deemed medium risk was H_2 gas venting from the fuel supply system through the vent into an enclosed space. The purpose of the H_2 gas vent line is to provide a safe path to vent H_2 in the event of, for example, an over-pressure event of the fuel supply system. In normal operation, there should be no venting through the H_2 vent line. The consequence of venting H_2 into an enclosed space can be (1) unignited release, (2) jet fire (immediate ignition) or (3) fireball and blast wave. While the risks for the first two are low, the risk for the last is medium because the consequence severity in an enclosed space is catastrophic, as shown in the Excel file. The current mitigations for this risk are to perform a specific risk assessment on operation or storage in an enclosed space, and to perform simulations and verification testing to understand how a large hydrogen release in an enclosed space would propagate.

The count column in Table 8 shows three occurrences that all had a medium risk level, a remote level of occurrence and a severe/catastrophic severity.

Table 8 also shows an additional 14 risks that were identified as having a severe or catastrophic severity of consequence; however, these were deemed low risk since they were all estimated to be improbable due to the current mitigations. One current mitigation is active ventilation, including the use of a sail switch in a normally-closed position. There must be active ventilation in order to start the FCS. Other mitigations may include the use of an oxygen sensor in enclosed areas or on individuals, as the fuel cell system also consumes oxygen and can deplete the oxygen in a space if not properly sourced or ventilated. The consequences identified in these risk cases were (1) asphyxiation and (2) fireball and blast wave.

5.0 Recommendations

As mentioned in this report, a risk assessment is an active document that should be continually updated and iterated. The authors recommend reviewing this risk assessment every two years to evaluate if there have been technology changes, new codes and standards established, or real-world field hazards that need to be captured.

Both a risk assessment and an FMEA are tools in a product development process. While a risk assessment focuses on hazard causes and effects, an FMEA focuses on product failure modes, some of which may result in a hazard but not all. An FMEA also considers detectability—whether a failure can be detected—and proposes verification testing to understand the failure mode and its detection. The choice of tool depends on the information a regulator is interested in. If knowledge about the design verification plan and report (DVP&R) is required to understand if an OEM has adequately verified their design for public release, the FMEA is a good tool to help understand it. Developing an FMEA however is a lengthy process and can sometimes take years to complete comprehensively, whereas a risk assessment can be shorter, depending on the level of detail required.

Due to the broad nature of this first risk assessment on H_2 and battery powered locomotives, a fuel cell system, fuel supply and fuel dispensing systems, it is possible that specific operational scenarios have not been considered in-depth. Further risk assessments should follow from this work for which application-specific hazards are considered. The railway companies and government rail safety inspectors are best positioned to highlight these applications. Some examples that could be studied include:

- Operating in tunnels,
- Satellite re-fuelling,
- Minor and major maintenance activities,
- On-track breakdowns and repairs,
- Locomotive and tender storage,
- Rail crossings, and
- Terminal layout (goods storage, refuelling infrastructure, maintenance etc.).

A gap identified by this risk assessment is that there is currently no standard in Canada that specifies a minimum installation distance between the battery, the FCS, and the hydrogen tank, or a minimum firewall. This is an area that requires further examination and understanding. Additional studies, such as modeling and simulations, and experimental testing, should be undertaken to determine if a standard is required. This would help establish whether a minimum installation distance needs to be set, or if current practices (modeling and verification testing) are sufficient.

6.0 Conclusions

A risk assessment on a reference design of a hydrogen and battery locomotive was performed according to the guidelines set forward in ISO 31000:2018 [16]. The risk assessment is published under AST-2024-0032 in the form of an Excel file. This companion report aids the reader in the interpretation of the risk assessment by providing background, methodology, discussion, and recommendations.

Over the course of the risk assessment, 501 instances of risk were identified. The risks were classified (see Table 4) into their associated hazard groups with many different components identified; in particular:

- Mechanical - high pressure (n = 101),
- Electrical - disconnection, miswiring, or control failure (n = 48),
- Material - hydrogen compatibility (n = 44),
- Electrical - short circuit (n = 39),
- Mechanical - instability (n = 37), and many more.

Identifying the components and their associated hazard group is beneficial for the reader, as it can provide direction and a starting point for future risk assessments of hydrogen or battery projects.

The risks identified in this risk assessment were classified, in Table 5, into six principal categories. Ranked by the highest to lowest number of instances identified, they are:

- Combustible mixture (H_2 in air) (n = 306),
- High voltage (>50 V) (n = 123),
- Thermal runaway (n = 32),
- Over-temperature (n = 22),
- Enclosed space (n = 11), and
- Environmental exposure (n = 7).

A combustible mixture of hydrogen in air was the most prevalent risk identified. The current mitigations for a combustible mixture are to prevent hydrogen leaks (through better design of components), ensure the proper electrical area classification in and around hydrogen, ensure adequate ventilation (sufficient air exchange rate for volume of space and quantity of hydrogen), and to quantify the hydrogen concentration (through hydrogen sensors).

Although a combustible mixture of hydrogen was the most frequently identified risk, the consequence or impact was often an unignited release, which is not hazardous in and of itself. The instances that combined with an ignition source (e.g., static electricity, spark, arc, fire, etc.) were likely to cause a jet fire (immediate ignition of hydrogen at high pressure). Fires were another impact factor that came up repeatedly, caused either by the battery system, the fuel cell system, the fuel supply, or the fuel dispensing system. The severity of a fire or jet-fire includes damage to both people and property.

Table 8 shows that, of the 501 instances of risk identified, 498 were categorized as ‘low’ risk. Additionally, 412 instances were deemed ‘improbable’ or ‘remote’. While these events can occur, the mitigations put in place reduce the likelihood of their occurrence. These mitigations include verification testing, conforming to any and all appropriate standards, automatic shut-off devices, selecting hydrogen-compatible materials, bonding and grounding electrical components (as appropriate), and electrical fault detection, to name a few.

In terms of severity of consequence, 317 instances were identified as potentially causing ‘damage’. In this context, ‘damage’ is a specific term referring to medical treatment for people, local environmental damage, or minor structural damage to property. The potential for damage stems from the inherent risks of a highly flammable gas (hydrogen), high voltage operation (>50 V), thermal runaway of the battery, or enclosed spaces. The potential for damage is reduced by decreasing the size of an event where possible. For example, building a battery with compartment segregation such that a thermal runaway only affects one small area and does not cascade to the entire battery, designing the hydrogen storage into a series of tanks to limit the quantity of hydrogen released from a single tank so that the ventilation rate will never allow the concentration of hydrogen in air to reach above 25% of the lower flammability limit (LFL), or using flow reduction devices to limit the maximum amount of hydrogen that can leak.

A total of 17 instances of risk were identified as severe or catastrophic for severity, but only three were deemed ‘medium’ risk as they had a remote frequency of occurrence (the rest were improbable due to current mitigations). The three identified ‘medium’ risks were:

- Crash damage to the hydrogen storage tank,
- Failure of TPRD actuation during a localized fire, and
- H_2 gas venting through the fuel supply vent line into an enclosed space.

Verification testing and a separate risk assessment should be performed to better understand the risk level of these items individually, and determine if the current mitigations are suitable and the risk level can be lowered.

As new hydrogen and battery locomotive projects are put into service in Canada, follow-on risk assessments should be performed to understand their specific designs and their detailed operational scenarios. These risk assessments might examine specific operational scenarios such as:

- Operating in tunnels,
- Satellite re-fuelling,
- Minor and major maintenance activities,
- On-track breakdowns and repairs,
- Locomotive and tender storage,
- Rail crossings, and
- Terminal layout (goods storage, refuelling infrastructure, maintenance etc.).

List of Codes and Standards

The following is a list of standards referenced in AST-2024-0032 Risk Assessment for Hydrogen and Battery Locomotive (sorted alphabetically):

- AAR S-9401 Railroad Electronics Environmental Requirements Standard. 2009
- ANSI/CSA. America FC 3 Portable Fuel Cell Power Systems. 2004 (R2021).
- ANSI/CSA CHMC 1 Test methods for evaluating material compatibility in compressed hydrogen applications - Metals. 2014 (R2023)
- ANSI/CSA HGV 4.8 Hydrogen gas vehicle fueling station compressor guidelines. 2012 (R2023)
- ASME. B31.12 Hydrogen Piping and Pipelines. 2024.
- ASME. Boiler and Pressure Vessel Code (BPVC). 2023
- CAN/BNQ. 1784-000 (CHIC) Canadian Hydrogen Installation Code. 2022.
- CAN/CSA. C22.2 No. 60947-1 Low-Voltage Switchgear and Controlgear - Part 1: General Rules. 2023 (R2018).
- CAN/CSA. C22.2 No. 61010-1 Safety Requirements for Electrical Equipment for Measurement, Control, and Laboratory Use - Part 1: General Requirements. 2012 (R2022).
- CAN/CSA. E60730-2-6 Automatic Electrical Controls — Part 2-6: Particular Requirements for Automatic Electrical Pressure Sensing Controls Including Mechanical Requirements. 2017 (R2022).
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- CGA. G-5.5 Standard for Hydrogen Vent Systems. 2021.
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Description of Terms

This section includes a list of described terms that are specific to hydrogen or battery risks and hazards, to help orient the reader.

Cause and effect

1. **H_2 leak - small**: hydrogen is leaked through small defects of system components at a relatively low flow rate. Small hydrogen leaks may go undetected; their impact is relatively small.

2. **H_2 leak - large**: hydrogen is released at a relatively high flow rate. It happens under accident conditions and its impact is relatively high.

3. **Tank rupture**: hydrogen storage tank is fully ruptured; the mechanical energy stored in the compressed gas and container materials is uncontrollably released. Its impact is catastrophic.

Potential consequences of hydrogen release or battery thermal runaway

1. **Unignited release**: hydrogen is released from a pressurized system in a jet shape; its concentration decreases along the orientation of the break. No ignition ever happens. There is no safety hazard in open environment or with sufficient vent in closed space.

2. **Jet fire (immediate ignition)**: hydrogen is released and ignited immediately at the break due to self-ignition (depending on the flow rate) or an accidental ignition source; burning continues locally as long as hydrogen is released. The safety concern is the thermal impact from the jet fire.

3. **Smoke**: when a battery fire occurs, smoke is discharged, which can pose a health risk to people such as breathing issues or upper respiratory conditions, like asthma and bronchitis.

4. **Toxic cloud or vapour cloud**: different battery chemistries may emit toxic fumes, for example lithium oxide or lithium hydroxide, from a Lithium battery. These can pose a risk to crew or fire responders. Especially in an enclosed space.

5. **Fire**: for hydrogen, it is released and ignition happens where hydrogen is pre-mixed and accumulated in a confined or partially confined space, but the burning has no significant pressurization. Its impact is mostly the thermal impact from the fire. For a battery fire, they can start quickly, burn hot, and are nearly impossible to extinguish.

6. **Explosion**: for hydrogen, it is released and ignition happens where hydrogen is accumulated and pre-mixed with air in a confined or partially confined space. The flame may initially propagate at a rate less than the speed of sound in the unburnt mixture, referred to as deflagration, but accelerates to

super sonic speed, referred to as detonation, in the presence of obstructions along the path. Its impact is mostly from the pressure wave.

7. **Blast wave**: after a hydrogen tank rupture, the stored mechanical energy is instantly released and the blast wave reflects off the ground and the reflected wave catches up with the head blast wave. The pressure decays rapidly due to spherical expansion. Its impact is strong shockwaves to people and structures.

8. **Fireball**: after the blast wave generation, a fireball is generally formed upon tank rupture. Because of the heat released by combustion and the buoyancy force, the fireball lifts off the ground and establishes a hemispherical cloud. The surrounding air mixes with hydrogen cloud due to intensive convection and diffusion processes and the hydrogen/air mixture in the cloud burns continuously as the remaining fuel mixes with the surrounding air.

9. **Dizziness, fatigue, collapse**: deficient supply of oxygen due to hydrogen or nitrogen displacement of oxygen in air.

10. **Asphyxiation**: prolonged exposure to severely deficient supply of oxygen due to hydrogen or nitrogen displacement of oxygen in air.

Acronyms and abbreviations

Table 9 provides a list of acronyms employed in this report.

Table 9: List of acronyms

Item	Description
BMS	battery management system
Cx	coolant
dT	temperature rise from fuel stack inlet to outlet
ECU	engine control unit
FC	fuel cell
FCS	fuel cell system
FCU	fuel cell control unit
FMEA	failure mode effects analysis
Fx	fuel
H_2	hydrogen
HRB	hydrogen recirculation blower
HV	high voltage
LFL	lower flammability limit
LV	low voltage
N_2	nitrogen
NRC	National Research Council of Canada
Ox	oxidant
PRV	pressure relief valve
PT	pressure transducer
TBD	to be determined
T/C	thermocouple
TPRD	thermal pressure relief device
WEG	water ethylene glycol

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Signatures

Prepared by:

X
Stephanie Girard

Stephanie Girard, P. Eng.

Research Officer, Hydrogen Systems Design Engineer

X
Manuel Hernandez

Manuel Hernandez, P.Eng.
Research Council Officer, Energy System Integration, Modelling and Demonstration

X
Isabella Jimenez

Isabella Jimenez
Junior Engineer, Design Engineering

Reviewed by:

X
Jon Preston-Thomas

Jon Preston-Thomas, P.Eng.

Principal Engineer, Automotive and Surface Transportation

Approved by:

X
Gordon Poole

Gordon Poole

Director R&D, Transportation Engineering Centre

Foreword

This hydrogen and battery locomotive risk assessment should be read and interpreted alongside the following companion

> "AST-2024-0033 Hydrogen and Battery Locomotive Risk Assessment – Companion Report"

All needed references for this Excel file are in the companion report.

Hydrogen and Battery Locomotive Risk Assessment (template provided by TC)

ISO 12100:2010 Standard - Safety of machinery — General principles for design — Risk assessment and risk reduction

	Source of Potential Harm		Using Table B.1 for identification of Hazards		Scenario			Impact factor				Risk Analysis						Residual Risk						
Location	System	Hazard Origin (Component)	Associated Hazard Group	Components of Associated Hazard Group	Cause	Risk / Effect	Consequence / Result / Impact	People (Y/N)	Property (Y/N)	Environ-ment (Y/N)	Current Controls / Mitigating Factors / Other	Code / Standard / Other (sorted alphabetically)	Probability of Hazard (Cause and Effect)	Level	Severity of Consequence / Result	Level	Risk Level	New Mitigation Measures	Probability of Risk, Cause, and Consequence / Result	Level	Severity of Consequence / Result	Level	Risk Level	Notes
Ground equipment	Fuel dispensing system	Buffer storage tank	Mechanical	approach/departure of a moving element to a fixed part	penetration from foreign object (ex.	H2 leak - small	unignited release	N	N	N	verification testing, automated safety system	CSA/ANSI. HGV 4.9 Hydrogen Fueling Stations. 2020	Remote	1	No Damage	0	Low							
Ground equipment	Fuel dispensing system	Buffer storage tank	Mechanical	approach/departure of a moving element to a fixed part	penetration from foreign object (ex.	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	verification testing, automated safety system	CSA/ANSI. HGV 4.9 Hydrogen Fueling Stations. 2020	Remote	1	Damage	2	Low							
Ground equipment	Fuel dispensing system	Buffer storage tank	Mechanical	high pressure	repeated mechanical cycling	H2 leak - small	unignited release	N	N	N	verification testing, automated safety system	CSA/ANSI. HGV 4.9 Hydrogen Fueling Stations. 2020	Remote	1	No Damage	0	Low							
Ground equipment	Fuel dispensing system	Buffer storage tank	Mechanical	high pressure	repeated mechanical cycling	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	verification testing, automated safety system	CSA/ANSI. HGV 4.9 Hydrogen Fueling Stations. 2020	Remote	1	Damage	2	Low							
Ground equipment	Fuel dispensing system	Buffer storage tank	Mechanical	instability	mechanical damage from wear	H2 leak - small	unignited release	N	N	N	verification testing, automated safety system	CSA/ANSI. HGV 4.9 Hydrogen Fueling Stations. 2020	Remote	1	No Damage	0	Low							
Ground equipment	Fuel dispensing system	Buffer storage tank	Mechanical	instability	mechanical damage from wear	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	verification testing, automated safety system	CSA/ANSI. HGV 4.9 Hydrogen Fueling Stations. 2020	Remote	1	Damage	2	Low							
Ground equipment	Fuel dispensing system	Buffer storage tank	Thermal	flame	adjacent component fire	TPRD trigger OPEN	unignited release	N	N	N	verification testing, automated safety system	CAN/BNQ. 1784-000 (CHIC) Canadian Hydrogen	Remote	1	No Damage	0	Low							
Ground equipment	Fuel dispensing system	Buffer storage tank	Thermal	flame	adjacent component fire	TPRD trigger OPEN	jet fire (immediate ignition)	Y	Y	N	verification testing, automated safety system	CAN/BNQ. 1784-000 (CHIC) Canadian Hydrogen	Remote	1	Damage	2	Low							
Ground equipment	Fuel dispensing system	Buffer storage tank	Material / substance	hydrogen material compatibility	H2 embrittlement	H2 leak - small	unignited release	N	N	N	selecting H2 compatible materials,	CSA/ANSI. HGV 4.9 Hydrogen Fueling Stations. 2020	Improbable	0	No Damage	0	Low							
Ground equipment	Fuel dispensing system	Buffer storage tank	Material / substance	hydrogen material compatibility	H2 embrittlement	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	selecting H2 compatible materials,	CSA/ANSI. HGV 4.9 Hydrogen Fueling Stations. 2020	Improbable	0	Damage	2	Low							
Ground equipment	Fuel dispensing system	Buffer storage tank	Environment	temperature	mechanical wear from repeated	H2 leak - small	unignited release	N	N	N	verification testing, automated safety system	CSA/ANSI. HGV 4.9 Hydrogen Fueling Stations. 2020	Remote	1	No Damage	0	Low							
Ground equipment	Fuel dispensing system	Buffer storage tank	Environment	temperature	mechanical wear from repeated	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	verification testing, automated safety system	CSA/ANSI. HGV 4.9 Hydrogen Fueling Stations. 2020	Remote	1	Damage	2	Low							
Ground equipment	Fuel dispensing system	Chiller	Mechanical	approach/departure of a moving element to a fixed part	penetration from foreign object (ex.	coolant leak - small	slip hazard	Y	N	N	visual inspection, level sensor	CSA/ANSI. HGV 4.1 Hydrogen-Dispensing Systems. 2	Remote	1	Damage	2	Low							
Ground equipment	Fuel dispensing system	Chiller	Mechanical	approach/departure of a moving element to a fixed part	penetration from foreign object (ex.	coolant leak - large	potential groundwater contamination	Y	Y	Y	visual inspection, level sensor	CSA/ANSI. HGV 4.1 Hydrogen-Dispensing Systems. 2	Remote	1	Damage	2	Low							
Ground equipment	Fuel dispensing system	Chiller	Mechanical	instability	part wear over time	coolant leak - small	slip hazard	Y	N	N	visual inspection, level sensor	CSA/ANSI. HGV 4.1 Hydrogen-Dispensing Systems. 2	Remote	1	Damage	2	Low							
Ground equipment	Fuel dispensing system	Chiller	Mechanical	instability	part wear over time	coolant leak - large	potential groundwater contamination	Y	Y	Y	visual inspection, level sensor	CSA/ANSI. HGV 4.1 Hydrogen-Dispensing Systems. 2	Remote	1	Damage	2	Low							
Ground equipment	Fuel dispensing system	Chiller	Environment	temperature	mechanical wear from repeated	coolant leak - small	slip hazard	Y	N	N	visual inspection, level sensor	CSA/ANSI. HGV 4.1 Hydrogen-Dispensing Systems. 2	Remote	1	Damage	2	Low							
Ground equipment	Fuel dispensing system	Chiller	Environment	temperature	mechanical wear from repeated	coolant leak - large	potential groundwater contamination	Y	Y	Y	visual inspection, level sensor	CSA/ANSI. HGV 4.1 Hydrogen-Dispensing Systems. 2	Remote	1	Damage	2	Low							
Ground equipment	Fuel dispensing system	Dispensing hose	Mechanical	approach/departure of a moving element to a fixed part	drive-away while connected with	H2 leak - small	unignited release	N	N	N	1. Breakaway hose coupling device will shut	CSA/ANSI. HGV 4.4 Gaseous Hydrogen — Fuelling S	Remote	1	No Damage	0	Low							
Ground equipment	Fuel dispensing system	Dispensing hose	Mechanical	high pressure	mechanical wear	H2 leak - small	unignited release	N	N	N	1. Qualified hose, pressure tested and	CSA/ANSI. HGV 4.2 Hoses for Dispensing Compress	Occasional	2	No Damage	0	Low							
Ground equipment	Fuel dispensing system	Dispensing hose	Mechanical	high pressure	mechanical wear	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	1. Qualified hose, pressure tested and	CSA/ANSI. HGV 4.2 Hoses for Dispensing Compress	Occasional	2	Damage	2	Low							
Ground equipment	Fuel dispensing system	Dispensing hose	Electrical	electrostatic phenomena	flow rate creating charge	creates electrostatic discharge	fire (localized flame due to leaks)	Y	Y	N	Grounding and bonding in accordance to	CSA. C22.2 No. 0.4 Bonding of Electrical	Occasional	2	Damage	2	Low							
Ground equipment	Fuel dispensing system	Dispensing hose	Material / substance	hydrogen material compatibility	H2 embrittlement	H2 leak - small	unignited release	N	N	N	selecting H2 compatible materials, ANSI/CSA	CSA/ANSI. HGV 4.2 Hoses for Dispensing	Improbable	0	No Damage	0	Low							
Ground equipment	Fuel dispensing system	Dispensing hose	Material / substance	hydrogen material compatibility	H2 embrittlement	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	selecting H2 compatible materials, ANSI/CSA	CSA/ANSI. HGV 4.2 Hoses for Dispensing	Improbable	0	Damage	2	Low							
Ground equipment	Fuel dispensing system	Dispensing nozzle	Mechanical	high pressure	O-ring or nozzle damaged	H2 leak - small	unignited release	N	N	N	1. Nozzle (compliant with SAE J2600 and SAE	CSA/ANSI. HGV 4.1 Hydrogen-Dispensing Systems.	Occasional	2	No Damage	0	Low							
Ground equipment	Fuel dispensing system	Dispensing nozzle	Mechanical	high pressure	O-ring or nozzle damaged	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	1. Nozzle (compliant with SAE J2600 and SAE	CSA/ANSI. HGV 4.1 Hydrogen-Dispensing Systems.	Remote	1	Damage	2	Low							
Ground equipment	Fuel dispensing system	Dispensing nozzle	Electrical	disconnection / miswiring / control failure	loss of communication caused by	tank over-fill (leak)	unignited release	N	N	N	fault detection through FCU, check valve	SAE. J2601 Fueling Protocols for Light Duty Gaseous	Occasional	2	No Damage	0	Low							
Ground equipment	Fuel dispensing system	Dispensing nozzle	Electrical	disconnection / miswiring / control failure	loss of communication caused by	tank over-fill (leak)	jet fire (immediate ignition)	Y	Y	N	fault detection through FCU, check valve	SAE. J2601 Fueling Protocols for Light Duty Gaseous	Occasional	2	Damage	2	Low							
Ground equipment	Fuel dispensing system	Dispensing nozzle	Electrical	disconnection / miswiring / control failure	loss of communication caused by	tank over-fill (leak)	unignited release	N	N	N	fault detection through FCU, check valve	SAE. J2601 Fueling Protocols for Light Duty Gaseous	Occasional	2	No Damage	0	Low							
Ground equipment	Fuel dispensing system	Dispensing nozzle	Electrical	disconnection / miswiring / control failure	loss of communication caused by	tank over-fill (leak)	jet fire (immediate ignition)	Y	Y	N	fault detection through FCU, check valve	SAE. J2601 Fueling Protocols for Light Duty Gaseous	Occasional	2	Damage	2	Low							
Ground equipment	Fuel dispensing system	Dispensing nozzle	Material / substance	hydrogen material compatibility	H2 embrittlement	H2 leak - small	unignited release	N	N	N	selecting H2 compatible materials, ANSI/CSA	CSA/ANSI. HGV 4.1 Hydrogen-Dispensing Systems.	Improbable	0	No Damage	0	Low							
Ground equipment	Fuel dispensing system	Dispensing nozzle	Material / substance	hydrogen material compatibility	H2 embrittlement	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	selecting H2 compatible materials, ANSI/CSA	CSA/ANSI. HGV 4.4 Gaseous Hydrogen — Fuelling	Improbable	0	Damage	2	Low							
Ground equipment	Fuel dispensing system	Dispensing piping	Mechanical	high pressure	leak due to mechanical failure	H2 leak - small	unignited release	N	N	N	1. Adequate components:	ASME. B31.12 Hydrogen Piping and Pipelines.	Remote	1	No Damage	0	Low							
Ground equipment	Fuel dispensing system	Dispensing piping	Mechanical	high pressure	leak due to mechanical failure	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	1. Adequate components:	ASME. B31.12 Hydrogen Piping and Pipelines.	Improbable	0	Damage	2	Low							
Ground equipment	Fuel dispensing system	Dispensing piping	Mechanical	high pressure	leak due to mechanical failure	pipe burst	unignited release	N	N	N	1. Adequate components:	ASME. B31.12 Hydrogen Piping and Pipelines.	Remote	1	No Damage	0	Low							
Ground equipment	Fuel dispensing system	Dispensing piping	Mechanical	high pressure	leak due to mechanical failure	pipe burst	jet fire (immediate ignition)	Y	Y	N	1. Adequate components:	ASME. B31.12 Hydrogen Piping and Pipelines.	Improbable	0	Damage	2	Low							
Ground equipment	Fuel dispensing system	Dispensing piping	Electrical	electrostatic phenomena	flow rate creating charge	creates electrostatic discharge	fire (localized flame due to leaks)	Y	Y	N	Grounding and bonding in accordance to	CSA. C22.2 No. 0.4 Bonding of Electrical	Improbable	0	Damage	2	Low							
Ground equipment	Fuel dispensing system	Dispensing piping	Vibration	worn parts	loosening of joints	H2 leak - small	unignited release	N	N	N	shock and vibration testing, e.g., MIL 810.h	CSA. TS-601 Hydrogen Fuel Cell Power Systems for	Occasional	2	No Damage	0	Low							
Ground equipment	Fuel dispensing system	Dispensing piping	Vibration	worn parts	loosening of joints	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	shock and vibration testing, e.g., MIL 810.h	CSA. TS-601 Hydrogen Fuel Cell Power Systems for	Remote	1	Damage	2	Low							
Ground equipment	Fuel dispensing system	Dispensing piping	Material / substance	hydrogen material compatibility	H2 embrittlement	H2 leak - small	unignited release	N	N	N	selecting H2 compatible materials, ANSI/CSA	CSA/ANSI. HGV 4.1 Hydrogen-Dispensing Systems.	Improbable	0	No Damage	0	Low							
Ground equipment	Fuel dispensing system	Dispensing piping	Material / substance	hydrogen material compatibility	H2 embrittlement	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	selecting H2 compatible materials, ANSI/CSA	CSA/ANSI. HGV 4.1 Hydrogen-Dispensing Systems.	Improbable	0	Damage	2	Low							
Ground equipment	Fuel dispensing system	Flow control valve	Mechanical	high pressure	fails to close due to human error	H2 leak - small	unignited release	N	N	N	Preventive measures:	CSA/ANSI. HGV 4.4 Gaseous Hydrogen — Fuelling	Occasional	2	No Damage	0	Low							
Ground equipment	Fuel dispensing system	Flow control valve	Mechanical	high pressure	fails to close due to human error	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	Preventive measures:	CSA/ANSI. HGV 4.4 Gaseous Hydrogen — Fuelling	Remote	1	Damage	2	Low							
Ground equipment	Fuel dispensing system	Flow control valve	Mechanical	high pressure	fails to close due to mechanical	H2 leak - small	unignited release	N	N	N	Preventive measures:	CSA/ANSI. HGV 4.4 Gaseous Hydrogen — Fuelling	Occasional	2	No Damage	0	Low							
Ground equipment	Fuel dispensing system	Flow control valve	Mechanical	high pressure	fails to close due to mechanical	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	Preventive measures:	CSA/ANSI. HGV 4.4 Gaseous Hydrogen — Fuelling	Remote	1	Damage	2	Low							
Ground equipment	Fuel dispensing system	Flow control valve	Electrical	disconnection / miswiring / control failure	loss of communication caused by	excessive flow	unignited release	N	N	N	automatic emergency shutoff system with	CSA. SPE-1000 Model Code for the Field Evaluation	Occasional	2	No Damage	0	Low							
Ground equipment	Fuel dispensing system	Flow control valve	Electrical	disconnection / miswiring / control failure	loss of communication caused by	excessive flow	jet fire (immediate ignition)	Y	Y	N	automatic emergency shutoff system with	CSA. SPE-1000 Model Code for the Field Evaluation	Occasional	2	Damage	2	Low							
Ground equipment	Fuel dispensing system	Flow control valve	Material / substance	hydrogen material compatibility	H2 embrittlement	H2 leak - small	unignited release	N	N	N	selecting H2 compatible materials, ANSI/CSA	CSA/ANSI. HGV 4.4 Gaseous Hydrogen — Fuelling	Improbable	0	No Damage	0	Low							
Ground equipment	Fuel dispensing system	Flow control valve	Material / substance	hydrogen material compatibility	H2 embrittlement	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	selecting H2 compatible materials, ANSI/CSA	CSA/ANSI. HGV 4.4 Gaseous Hydrogen — Fuelling	Improbable	0	Damage	2	Low							
Ground equipment	Fuel dispensing system	Hydrogen compressor	Mechanical	high pressure	over-pressurization	H2 leak - small	unignited release	N	N	N	material selection, downstream relief valve,	ANSI/CSA HGV 4.8 Hydrogen gas vehicle fueling	Improbable	0	No Damage	0	Low							
Ground equipment	Fuel dispensing system	Hydrogen compressor	Mechanical	high pressure	over-pressurization	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	material selection, downstream relief valve,	ANSI/CSA HGV 4.8 Hydrogen gas vehicle fueling	Improbable	0	Damage	2	Low							
Ground equipment	Fuel dispensing system	Hydrogen compressor	Mechanical	high pressure	over-pressurization	rupture	jet fire (immediate ignition)	Y	Y	N	material selection, downstream relief valve,	ANSI/CSA HGV 4.8 Hydrogen gas vehicle fueling	Improbable	0	Damage	2	Low							
Ground equipment	Fuel dispensing system	Hydrogen compressor	Thermal	objects or materials with a high or low temperature	over-temperature	fuel over-pressure	unignited release	N	N	N	pressure and temperature monitoring,	ANSI/CSA HGV 4.8 Hydrogen gas vehicle fueling	Improbable	0	No Damage	0	Low							
Ground equipment	Fuel dispensing system	Hydrogen compressor	Thermal	objects or materials with a high or low temperature	over-temperature	fuel over-pressure	jet fire (immediate ignition)	Y	Y	N	pressure and temperature monitoring,	ANSI/CSA HGV 4.8 Hydrogen gas vehicle fueling	Improbable	0	Damage	2	Low							
Ground equipment	Fuel dispensing system	Low pressure storage	Mechanical	approach/departure of a moving element to a fixed part	penetration from foreign object (ex.	H2 leak - small	unignited release	N	N	N	verification testing, automated safety system	CSA/ANSI. HGV 4.9 Hydrogen Fueling Stations.	Remote	1	No Damage	0	Low							
Ground equipment	Fuel dispensing system	Low pressure storage	Mechanical	approach/departure of a moving element to a fixed part	penetration from foreign object (ex.	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	verification testing, automated safety system	CSA/ANSI. HGV 4.9 Hydrogen Fueling Stations.	Remote	1	Damage	2	Low							
Ground equipment	Fuel dispensing system	Low pressure storage	Mechanical	instability	mechanical damage from wear	H2 leak - small	unignited release	N	N	N	verification testing, automated safety system	CSA/ANSI. HGV 4.9 Hydrogen Fueling Stations.	Remote	1	No Damage	0	Low							
Ground equipment	Fuel dispensing system	Low pressure storage	Mechanical	instability	mechanical damage from wear	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	verification testing, automated safety system	CSA/ANSI. HGV 4.9 Hydrogen Fueling Stations.	Remote	1	Damage	2	Low							
Ground equipment	Fuel dispensing system	Low pressure storage	Material / substance	hydrogen material compatibility	H2 embrittlement	H2 leak - small	unignited release	N	N	N	selecting H2 compatible materials,	CSA/ANSI. HGV 4.9 Hydrogen Fueling Stations.	Improbable	0	No Damage	0	Low							
Ground equipment	Fuel dispensing system	Low pressure storage	Material / substance	hydrogen material compatibility	H2 embrittlement	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	selecting H2 compatible materials,	CSA/ANSI. HGV 4.9 Hydrogen Fueling Stations.	Improbable	0	Damage	2	Low							
Ground equipment	Fuel dispensing system	Low pressure storage	Environment	temperature	mechanical wear from repeated	H2 leak - small	unignited release	N	N	N	verification testing, automated safety system	CSA/ANSI. HGV 4.9 Hydrogen Fueling Stations.	Remote	1	No Damage	0	Low							
Ground equipment	Fuel dispensing system	Low pressure storage	Environment	temperature	mechanical wear from repeated	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	verification testing, automated safety system	CSA/ANSI. HGV 4.9 Hydrogen Fueling Stations.	Remote	1	Damage	2	Low							
Ground equipment	Fuel dispensing system	PRV for dispensing	Mechanical	high pressure	fails to open at the set pressure	H2 leak - small	unignited release	N	N	N	1. Grounding components to avoid static	CSA/ANSI. HGV 4.4 Gaseous Hydrogen — Fuelling	Remote	1	No Damage	0	Low							
Ground equipment	Fuel dispensing system	PRV for dispensing	Mechanical	high pressure	fails to open at the set pressure	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	1. Grounding components to avoid static	CSA/ANSI. HGV 4.4 Gaseous Hydrogen — Fuelling	Remote	1	Damage	2	Low							
Ground equipment	Fuel dispensing system	PRV for dispensing	Mechanical	high pressure	fails in the open position due to	H2 leak - small	unignited release	N	N	N	1. Automatic emergency shutoff system with	CSA/ANSI. HGV 4.4 Gaseous Hydrogen — Fuelling	Occasional	2	No Damage	0	Low							
Ground equipment	Fuel dispensing system	PRV for dispensing	Mechanical	high pressure	fails in the open position due to	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	1. Automatic emergency shutoff system with	CSA/ANSI. HGV 4.4 Gaseous Hydrogen — Fuelling	Remote	1	Damage	2	Low							
Ground equipment	Fuel dispensing system	PRV for dispensing	Material / substance	hydrogen material compatibility	H2 embrittlement	H2 leak - small	unignited release	N	N	N	selecting H2 compatible materials, ANSI/CSA	CSA/ANSI. HGV 4.4 Gaseous Hydrogen — Fuelling	Improbable	0	No Damage	0	Low							
Ground equipment	Fuel dispensing system	PRV for dispensing	Material / substance	hydrogen material compatibility	H2 embrittlement	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	selecting H2 compatible materials, ANSI/CSA	CSA/ANSI. HGV 4.4 Gaseous Hydrogen — Fuelling	Improbable	0	Damage	2	Low							
Ground equipment	Fuel dispensing system	Shut-off valve for dispensing	Mechanical	high pressure	fails to close due to human error	H2 leak - small	unignited release	N	N	N	Preventive measures:	CSA/ANSI. HGV 4.4 Gaseous Hydrogen — Fuelling	Remote	1	No Damage	0	Low							
Ground equipment	Fuel dispensing system	Shut-off valve for dispensing	Mechanical	high pressure	fails to close due to human error	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	Preventive measures:	CSA/ANSI. HGV 4.4 Gaseous Hydrogen — Fuelling	Remote	1	Damage	2	Low							
Ground equipment	Fuel dispensing system	Shut-off valve for dispensing	Mechanical	high pressure	fails to close due to mechanical	H2 leak - small	unignited release	N	N	N	Preventive measures:	CSA/ANSI. HGV 4.4 Gaseous Hydrogen — Fuelling	Remote	1	No Damage	0	Low							
Ground equipment	Fuel dispensing system	Shut-off valve for dispensing	Mechanical	high pressure	fails to close due to mechanical	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	Preventive measures:	CSA/ANSI. HGV 4.4 Gaseous Hydrogen — Fuelling	Remote	1	Damage	2	Low							
Ground equipment	Fuel dispensing system	Shut-off valve for dispensing	Mechanical	instability	valve stuck in OPEN position	H2 leak - small	unignited release	N	N	N	valve redundancy	CSA/ANSI. HGV 4.4 Gaseous Hydrogen — Fuelling	Occasional	2	No Damage	0	Low							
Ground equipment	Fuel dispensing system	Shut-off valve for dispensing	Mechanical	instability	valve stuck in OPEN position	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	valve redundancy	CSA/ANSI. HGV 4.4 Gaseous Hydrogen — Fuelling	Occasional	2	Damage	2	Low							
Ground equipment	Fuel dispensing system	Shut-off valve for dispensing	Electrical	disconnection / miswiring / control failure	loss of communication caused by	H2 leak - small	unignited release	N	N	N	fault detection, pressure relief valve,	CSA/ANSI. HGV 4.4 Gaseous Hydrogen — Fuelling	Occasional	2	No Damage	0	Low							
Ground equipment	Fuel dispensing system	Shut-off valve for dispensing	Electrical	disconnection / miswiring / control failure	loss of communication caused by	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	fault detection, pressure relief valve,	CSA/ANSI. HGV 4.4 Gaseous Hydrogen — Fuelling	Occasional	2	Damage	2	Low							
Ground equipment	Fuel dispensing system	Shut-off valve for dispensing	Material / substance	hydrogen material compatibility	H2 embrittlement	H2 leak - small	unignited release	N	N	N	selecting H2 compatible materials, ANSI/CSA	CSA/ANSI. HGV 4.4 Gaseous Hydrogen — Fuelling	Improbable	0	No Damage	0	Low							
Ground equipment	Fuel dispensing system	Shut-off valve for dispensing	Material / substance	hydrogen material compatibility	H2 embrittlement	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	selecting H2 compatible materials, ANSI/CSA	CSA/ANSI. HGV 4.4 Gaseous Hydrogen — Fuelling	Improbable	0	Damage	2	Low							
On-board equipment	Automatic safety system	E-stop(s)	Mechanical	moving elements	unable to activate E-stop (ex.	E-stop signal not transmitted to	fire (unable to rapidly halt operation FCS	Y	Y	N	certified parts, secondary safety (ex. other	CAN/BNQ. 1784-000 (CHIC) Canadian Hydrogen	Remote	1	Damage	2	Low							
On-board equipment	Automatic safety system	E-stop(s)	Electrical	disconnection / miswiring / control failure	loss of communication	E-stop signal not transmitted to	fire (unable to rapidly halt operation FCS	Y	Y	N	certified parts, secondary safety (ex. other	CAN/BNQ. 1784-000 (CHIC) Canadian Hydrogen	Occasional	2	Damage	2	Low							
On-board equipment	Automatic safety system	H2 concentration sensor(s)	Material / substance	flammable	improper installation location	rise in H2 concentration not	fire (reach LFL H2 in air with no detection)	Y	Y	N	active ventilation, select proper sensor	CAN/BNQ. 1784-000 (CHIC) Canadian Hydrogen	Remote	1	Damage	2	Low							
On-board equipment	Automatic safety system	H2 concentration sensor(s)	Material / substance	flammable	calibration / drift over time	rise in H2 concentration not	fire (reach LFL H2 in air with no detection)	Y	Y	N	active ventilation, select proper sensor	CAN/BNQ. 1784-000 (CHIC) Canadian Hydrogen	Occasional	2	Damage	2	Low							
On-board equipment	Automatic safety system	Hydrogen flame detector(s)	Material / substance	flammable	improper installation location	UV fire not detected	fire (H2 burns with no shutdown)	Y	Y	N	active ventilation, H2 sensor(s), proper area	CAN/BNQ. 1784-000 (CHIC) Canadian Hydrogen	Remote	1	Damage	2	Low							
On-board equipment	Automatic safety system	Hydrogen flame detector(s)	Material / substance	flammable	physical blockage (ex. temporary	UV fire not detected	fire (H2 burns with no shutdown)	Y	Y	N	active ventilation, H2 sensor(s), proper area	CAN/BNQ. 1784-000 (CHIC) Canadian Hydrogen	Occasional	2	Damage	2	Low							
On-board equipment	Automatic safety system	Ventilation (locomotive)	Mechanical	rotating elements	mechanical wear of fan	loss of active ventilation in	dizziness, fatigue, collapse (H2	Y	N	N	oxygen sensor and notification signal	CAN/BNQ. 1784-000 (CHIC) Canadian Hydrogen	Remote	1	Damage	2	Low							
On-board equipment	Automatic safety system	Ventilation (locomotive)	Mechanical	rotating elements	mechanical wear of fan	loss of active ventilation in	asphyxiation (H2 accumulation in	Y	N	N	oxygen sensor and notification signal	CAN/BNQ. 1784-000 (CHIC) Canadian Hydrogen	Remote	1	Damage	2	Low							
On-board equipment	Automatic safety system	Ventilation (locomotive)	Mechanical	rotating elements	mechanical wear of fan	loss of active ventilation in	jet fire (immediate ignition) (H2	Y	Y	N	FCU, hydrogen % sensor	CAN/BNQ. 1784-000 (CHIC) Canadian Hydrogen	Remote	1	Damage	2	Low							
On-board equipment	Automatic safety system	Ventilation (locomotive)	Electrical	arc	fan electrical arc	spark	jet fire (immediate ignition)	Y	Y	N	Class 1, div 2 rated parts, hydrogen % sensor	IEC. 60079-10-1 Explosive Atmospheres - Part 10-1:	Improbable	0	Damage	2	Low							
On-board equipment	Automatic safety system	Ventilation (tender)	Mechanical	rotating elements	mechanical wear of fan	loss of active ventilation in	dizziness, fatigue, collapse (H2	Y	N	N	oxygen sensor and notification signal	CAN/BNQ. 1784-000 (CHIC) Canadian Hydrogen	Remote	1	Damage	2	Low							
On-board equipment	Automatic safety system	Ventilation (tender)	Mechanical	rotating elements	mechanical wear of fan	loss of active ventilation in	asphyxiation (H2 accumulation in	Y	N	N	oxygen sensor and notification signal	CAN/BNQ. 1784-000 (CHIC) Canadian Hydrogen	Remote	1	Damage	2	Low							
On-board equipment	Automatic safety system	Ventilation (tender)	Mechanical	rotating elements	mechanical wear of fan	loss of active ventilation in	jet fire (immediate ignition) (H2	Y	Y	N	FCU, hydrogen % sensor	CAN/BNQ. 1784-000 (CHIC) Canadian Hydrogen	Remote	1	Damage	2	Low							
On-board equipment	Automatic safety system	Ventilation (tender)	Electrical	arc	fan electrical arc	spark	jet fire (immediate ignition)	Y	Y	N	Class 1, div 2 rated parts, hydrogen % sensor	IEC. 60079-10-1 Explosive Atmospheres - Part 10-1:	Improbable	0	Damage	2	Low							
On-board equipment	Battery	Battery	Mechanical	approach/departure of a moving element to a fixed part	penetration	thermal runaway (battery)	smoke	Y	Y	N	thermocouples, coolant system, BMS, vent	CSA. TS-602 Railway Applications — Rolling Stock	Improbable	0	Damage	2	Low							
On-board equipment	Battery	Battery	Mechanical	approach/departure of a moving element to a fixed part	penetration	thermal runaway (battery)	explosion	Y	Y	Y	thermocouples, coolant system, BMS, vent	CSA. TS-602 Railway Applications — Rolling Stock	Improbable	0	Major Damage	3	Low							
On-board equipment	Battery	Battery	Mechanical	approach/departure of a moving element to a fixed part	penetration	thermal runaway (battery)	fire	Y	Y	N	thermocouples, coolant system, BMS, vent	CSA. TS-602 Railway Applications — Rolling Stock	Improbable	0	Damage	2	Low							
On-board equipment	Battery	Battery	Mechanical	approach/departure of a moving element to a fixed part	crushing	thermal runaway (battery)	smoke	Y	Y	N	thermocouples, coolant system, BMS, vent	CSA. TS-602 Railway Applications — Rolling Stock	Improbable	0	Damage	2	Low							
On-board equipment	Battery	Battery	Mechanical	approach/departure of a moving element to a fixed part	crushing	thermal runaway (battery)	explosion	Y	Y	Y	thermocouples, coolant system, BMS, vent	CSA. TS-602 Railway Applications — Rolling Stock	Improbable	0	Major Damage	3	Low							
On-board equipment	Battery	Battery	Mechanical	approach/departure of a moving element to a fixed part	crushing	thermal runaway (battery)	fire	Y	Y	N	thermocouples, coolant system, BMS, vent	CSA. TS-602 Railway Applications — Rolling Stock	Improbable	0	Damage	2	Low							
On-board equipment	Battery	Battery	Mechanical	acceleration, deceleration	shock (mechanics)	thermal runaway (battery)	smoke	Y	Y	N	verification to appropriate rail shock profile,	CSA. TS-602 Railway Applications — Rolling Stock	Improbable	0	Damage	2	Low							
On-board equipment	Battery	Battery	Mechanical	acceleration, deceleration	shock (mechanics)	thermal runaway (battery)	fire	Y	Y	N	verification to appropriate rail shock profile,	CSA. TS-602 Railway Applications — Rolling Stock	Improbable	0	Damage	2	Low							
On-board equipment	Battery	Battery	Mechanical	acceleration, deceleration	shock (mechanics)	thermal runaway (battery)	explosion	Y	Y	Y	verification to appropriate rail shock profile,	CSA. TS-602 Railway Applications — Rolling Stock	Improbable	0	Major Damage	3	Low							
On-board equipment	Battery	Battery	Electrical	overload	over-discharge	thermal runaway (battery)	smoke	Y	Y	N	thermocouples, coolant system, BMS, vent	CSA. TS-602 Railway Applications — Rolling Stock	Improbable	0	Damage	2	Low							
On-board equipment	Battery	Battery	Electrical	overload	over-discharge	thermal runaway (battery)	fire	Y	Y	N	thermocouples, coolant system, BMS, vent	CSA. TS-602 Railway Applications — Rolling Stock	Improbable	0	Damage	2	Low							
On-board equipment	Battery	Battery	Electrical	overload	over-discharge	thermal runaway (battery)	explosion	Y	Y	Y	thermocouples, coolant system, BMS, vent	CSA. TS-602 Railway Applications — Rolling Stock	Improbable	0	Major Damage	3	Low							
On-board equipment	Battery	Battery	Electrical	disconnection / miswiring / control failure	overcharging	thermal runaway (battery)	smoke	Y	Y	N	thermocouples, coolant system, BMS, vent	CSA. TS-602 Railway Applications — Rolling Stock	Improbable	0	Damage	2	Low							
On-board equipment	Battery	Battery	Electrical	disconnection / miswiring / control failure	overcharging	thermal runaway (battery)	explosion	Y	Y	Y	thermocouples, coolant system, BMS, vent	CSA. TS-602 Railway Applications — Rolling Stock	Improbable	0	Major Damage	3	Low							
On-board equipment	Battery	Battery	Electrical	disconnection / miswiring / control failure	overcharging	thermal runaway (battery)	fire	Y	Y	N	thermocouples, coolant system, BMS, vent	CSA. TS-602 Railway Applications — Rolling Stock	Improbable	0	Damage	2	Low							
On-board equipment	Battery	Battery	Electrical	disconnection / miswiring / control failure	internal manufacturing defects	thermal runaway (battery)	smoke	Y	Y	N	thermocouples, coolant system, BMS, vent	CSA. TS-602 Railway Applications — Rolling Stock	Improbable	0	Damage	2	Low							
On-board equipment	Battery	Battery	Electrical	disconnection / miswiring / control failure	internal manufacturing defects	thermal runaway (battery)	fire	Y	Y	N	thermocouples, coolant system, BMS, vent	CSA. TS-602 Railway Applications — Rolling Stock	Improbable	0	Damage	2	Low							
On-board equipment	Battery	Battery	Electrical	disconnection / miswiring / control failure	internal manufacturing defects	thermal runaway (battery)	explosion	Y	Y	Y	thermocouples, coolant system, BMS, vent	CSA. TS-602 Railway Applications — Rolling Stock	Improbable	0	Major Damage	3	Low							
On-board equipment	Battery	Battery	Electrical	short-circuit	short circuit	thermal runaway (battery)	smoke	Y	Y	N	thermocouples, coolant system, BMS, vent	CSA. TS-602 Railway Applications — Rolling Stock	Remote	1	Damage	2	Low							
On-board equipment	Battery	Battery	Electrical	short-circuit	short circuit	thermal runaway (battery)	explosion	Y	Y	Y	thermocouples, coolant system, BMS, vent	CSA. TS-602 Railway Applications — Rolling Stock	Remote	1	Major Damage	3	Low							
On-board equipment	Battery	Battery	Electrical	short-circuit	short circuit	thermal runaway (battery)	fire	Y	Y	N	thermocouples, coolant system, BMS, vent	CSA. TS-602 Railway Applications — Rolling Stock	Remote	1	Damage	2	Low							
On-board equipment	Battery	Battery	Electrical	short-circuit	low temperature charging	lithium plating	smoke	Y	Y	N	thermocouples, coolant system, BMS, vent	CSA. TS-602 Railway Applications — Rolling Stock	Improbable	0	Damage	2	Low							
On-board equipment	Battery	Battery	Electrical	short-circuit	low temperature charging	lithium plating	fire	Y	Y	N	thermocouples, coolant system, BMS, vent	CSA. TS-602 Railway Applications — Rolling Stock	Improbable	0	Damage	2	Low							
On-board equipment	Battery	Battery	Electrical	short-circuit	low temperature charging	lithium plating	explosion	Y	Y	Y	thermocouples, coolant system, BMS, vent	CSA. TS-602 Railway Applications — Rolling Stock	Improbable	0	Major Damage	3	Low							
On-board equipment	Battery	Battery	Electrical	short-circuit	short circuit	over-discharge	smoke	Y	Y	N	thermocouples, coolant system, BMS, vent	CSA. TS-602 Railway Applications — Rolling Stock	Remote	1	Damage	2	Low							
On-board equipment	Battery	Battery	Electrical	short-circuit	short circuit	over-discharge	fire	Y	Y	N	thermocouples, coolant system, BMS, vent	CSA. TS-602 Railway Applications — Rolling Stock	Remote	1	Damage	2	Low							
On-board equipment	Battery	Battery	Electrical	short-circuit	short circuit	over-discharge	explosion	Y	Y	Y	thermocouples, coolant system, BMS, vent	CSA. TS-602 Railway Applications — Rolling Stock	Remote	1	Major Damage	3	Low							
On-board equipment	Battery	Battery	Thermal	explosion	explosion from the battery	damage to fuel cell system	jet fire (immediate ignition)	Y	Y	N	thermocouples, BMS, FCU, UL 9540A Test	NFPA. 70 National Electrical Code. 2023.	Improbable	0	Damage	2	Low							
On-board equipment	Battery	Battery	Thermal	explosion	explosion from the battery	damage to fuel supply	jet fire (immediate ignition)	Y	Y	N	thermocouples, BMS, FCU, UL 9540A Test	NFPA. 70 National Electrical Code. 2023.	Improbable	0	Damage	2	Low							
On-board equipment	Battery	Battery	Thermal	flame	flame from the battery	damage to fuel cell system	jet fire (immediate ignition)	Y	Y	N	thermocouples, BMS, FCU, UL 9540A Test	NFPA. 70 National Electrical Code. 2023.	Improbable	0	Damage	2	Low							
On-board equipment	Battery	Battery	Thermal	flame	flame from the battery	damage to fuel supply	jet fire (immediate ignition)	Y	Y	N	thermocouples, BMS, FCU, UL 9540A Test	NFPA. 70 National Electrical Code. 2023.	Improbable	0	Damage	2	Low							
On-board equipment	Battery	Battery	Thermal	objects or materials with a high or low temperature	over-heating	thermal runaway (battery)	smoke	Y	Y	N	thermocouples, coolant system, BMS, vent	CSA. TS-602 Railway Applications — Rolling Stock	Remote	1	Damage	2	Low							
On-board equipment	Battery	Battery	Thermal	objects or materials with a high or low temperature	over-heating	thermal runaway (battery)	explosion	Y	Y	Y	thermocouples, coolant system, BMS, vent	CSA. TS-602 Railway Applications — Rolling Stock	Remote	1	Major Damage	3	Low							
On-board equipment	Battery	Battery	Thermal	objects or materials with a high or low temperature	over-heating	thermal runaway (battery)	fire	Y	Y	N	thermocouples, coolant system, BMS, vent	CSA. TS-602 Railway Applications — Rolling Stock	Remote	1	Damage	2	Low							
On-board equipment	Battery	Battery	Thermal	flame	fire from the battery	damage to fuel cell system	jet fire (immediate ignition)	Y	Y	N	thermocouples, BMS, FCU, UL 9540A Test	NFPA. 70 National Electrical Code. 2023.	Improbable	0	Damage	2	Low							
On-board equipment	Battery	Battery	Thermal	flame	fire from the battery	damage to fuel supply	jet fire (immediate ignition)	Y	Y	N	thermocouples, BMS, FCU, UL 9540A Test	NFPA. 70 National Electrical Code. 2023.	Improbable	0	Damage	2	Low							
On-board equipment	Battery	Battery	Thermal	flame	explosion from the battery	damage to fuel cell system	jet fire (immediate ignition)	Y	Y	N	thermocouples, BMS, FCU, UL 9540A Test	NFPA. 70 National Electrical Code. 2023.	Improbable	0	Damage	2	Low							
On-board equipment	Battery	Battery	Thermal	flame	explosion from the battery	damage to fuel supply	jet fire (immediate ignition)	Y	Y	N	thermocouples, BMS, FCU, UL 9540A Test	NFPA. 70 National Electrical Code. 2023.	Improbable	0	Damage	2	Low							
On-board equipment	Battery	Battery	Thermal	objects or materials with a high or low temperature	over-temperature (insufficient	thermal runaway (battery)	smoke	Y	Y	N	thermocouples, coolant system, BMS, vent	CSA. TS-602 Railway Applications — Rolling Stock	Remote	1	Damage	2	Low							

On-board equipment	Battery	Battery	Thermal	objects or materials with a high or low temperature	over-temperature (insufficient	thermal runaway (battery)	fire	Y	Y	N	thermocouples, coolant system, BMS, vent	CSA. TS-602 Railway Applications — Rolling Stock	Remote	1	Damage	2	Low	
On-board equipment	Battery	Battery	Thermal	objects or materials with a high or low temperature	over-temperature (insufficient	thermal runaway (battery)	explosion	Y	Y	Y	thermocouples, coolant system, BMS, vent	CSA. TS-602 Railway Applications — Rolling Stock	Remote	1	Major Damage	3	Low	
On-board equipment	Battery	Battery	Vibration	worn parts	vibration	thermal runaway (battery)	smoke	Y	Y	N	verification to appropriate rail vibration	CSA. TS-602 Railway Applications — Rolling Stock	Remote	1	Damage	2	Low	
On-board equipment	Battery	Battery	Vibration	worn parts	vibration	thermal runaway (battery)	fire	Y	Y	N	verification to appropriate rail vibration	CSA. TS-602 Railway Applications — Rolling Stock	Remote	1	Damage	2	Low	
On-board equipment	Battery	Battery	Vibration	worn parts	vibration	thermal runaway (battery)	explosion	Y	Y	Y	verification to appropriate rail vibration	CSA. TS-602 Railway Applications — Rolling Stock	Remote	1	Major Damage	3	Low	
On-board equipment	Battery	Battery	Mechanical	approach/departure of a moving element to a fixed part	penetration	chemical leak	fire	Y	Y	N	thermocouples, coolant system, BMS, vent	CSA. TS-602 Railway Applications — Rolling Stock	Improbable	0	Damage	2	Low	
On-board equipment	Battery	Battery	Mechanical	approach/departure of a moving element to a fixed part	penetration	chemical leak	toxic cloud	Y	N	N	thermocouples, coolant system, BMS, vent	CSA. TS-602 Railway Applications — Rolling Stock	Improbable	0	Damage	2	Low	
On-board equipment	Battery	Battery	Mechanical	approach/departure of a moving element to a fixed part	penetration	chemical leak	asphyxiation hazard at the rupture	Y	N	N	thermocouples, coolant system, BMS, vent	CSA. TS-602 Railway Applications — Rolling Stock	Improbable	0	Severe/Catastrophic	4	Low	
On-board equipment	Battery	Battery	Mechanical	approach/departure of a moving element to a fixed part	crushing	chemical leak	fire	Y	Y	N	thermocouples, coolant system, BMS, vent	CSA. TS-602 Railway Applications — Rolling Stock	Improbable	0	Damage	2	Low	
On-board equipment	Battery	Battery	Mechanical	approach/departure of a moving element to a fixed part	crushing	chemical leak	toxic cloud	Y	N	N	thermocouples, coolant system, BMS, vent	CSA. TS-602 Railway Applications — Rolling Stock	Improbable	0	Damage	2	Low	
On-board equipment	Battery	Battery	Mechanical	approach/departure of a moving element to a fixed part	crushing	chemical leak	asphyxiation hazard at the rupture	Y	N	N	thermocouples, coolant system, BMS, vent	CSA. TS-602 Railway Applications — Rolling Stock	Improbable	0	Severe/Catastrophic	4	Low	
On-board equipment	Battery	Battery	Environment	temperature	high-environmental temperature	thermal runaway (battery)	smoke	Y	Y	N	thermocouples, coolant system, BMS, vent	CSA. TS-602 Railway Applications — Rolling Stock	Remote	1	Damage	2	Low	
On-board equipment	Battery	Battery	Environment	temperature	high-environmental temperature	thermal runaway (battery)	fire	Y	Y	N	thermocouples, coolant system, BMS, vent	CSA. TS-602 Railway Applications — Rolling Stock	Remote	1	Damage	2	Low	
On-board equipment	Battery	Battery	Environment	temperature	high-environmental temperature	thermal runaway (battery)	explosion	Y	Y	Y	thermocouples, coolant system, BMS, vent	CSA. TS-602 Railway Applications — Rolling Stock	Remote	1	Major Damage	3	Low	
On-board equipment	Battery	Battery management system (	Mechanical	approach/departure of a moving element to a fixed part	penetration	thermal runaway of downstream	smoke	Y	Y	N	thermocouples, coolant system, vent port	CSA. C22.2 No. 61508-1 Functional Safety of	Improbable	0	Damage	2	Low	
On-board equipment	Battery	Battery management system (	Mechanical	approach/departure of a moving element to a fixed part	penetration	thermal runaway of downstream	fire	Y	Y	N	thermocouples, coolant system, vent port	CSA. C22.2 No. 61508-1 Functional Safety of	Improbable	0	Damage	2	Low	
On-board equipment	Battery	Battery management system (	Mechanical	approach/departure of a moving element to a fixed part	penetration	thermal runaway of downstream	explosion	Y	Y	Y	thermocouples, coolant system, vent port	CSA. C22.2 No. 61508-1 Functional Safety of	Improbable	0	Major Damage	3	Low	
On-board equipment	Battery	Battery management system (	Mechanical	approach/departure of a moving element to a fixed part	crushing	thermal runaway of downstream	smoke	Y	Y	N	thermocouples, coolant system, vent port	CSA. C22.2 No. 61508-1 Functional Safety of	Improbable	0	Damage	2	Low	
On-board equipment	Battery	Battery management system (	Mechanical	approach/departure of a moving element to a fixed part	crushing	thermal runaway of downstream	fire	Y	Y	N	thermocouples, coolant system, vent port	CSA. C22.2 No. 61508-1 Functional Safety of	Improbable	0	Damage	2	Low	
On-board equipment	Battery	Battery management system (	Mechanical	approach/departure of a moving element to a fixed part	crushing	thermal runaway of downstream	explosion	Y	Y	Y	thermocouples, coolant system, vent port	CSA. C22.2 No. 61508-1 Functional Safety of	Improbable	0	Major Damage	3	Low	
On-board equipment	Battery	Battery management system (	Mechanical	acceleration, deceleration	shock (mechanics)	thermal runaway of downstream	smoke	Y	Y	N	verification to appropriate rail shock profile,	AAR S-9401 Railroad Electronics Environmental	Improbable	0	Damage	2	Low	
On-board equipment	Battery	Battery management system (	Mechanical	acceleration, deceleration	shock (mechanics)	thermal runaway of downstream	explosion	Y	Y	Y	verification to appropriate rail shock profile,	AAR S-9401 Railroad Electronics Environmental	Improbable	0	Major Damage	3	Low	
On-board equipment	Battery	Battery management system (	Mechanical	acceleration, deceleration	shock (mechanics)	thermal runaway of downstream	fire	Y	Y	N	verification to appropriate rail shock profile,	AAR S-9401 Railroad Electronics Environmental	Improbable	0	Damage	2	Low	
On-board equipment	Battery	Battery management system (	Electrical	electromagnetic phenomena	EMC	communication loss --> thermal	smoke	Y	Y	N	compliance with functional safety standards,	AAR S-9401 Railroad Electronics Environmental	Improbable	0	Damage	2	Low	
On-board equipment	Battery	Battery management system (	Electrical	electromagnetic phenomena	EMC	communication loss --> thermal	explosion	Y	Y	Y	compliance with functional safety standards,	AAR S-9401 Railroad Electronics Environmental	Improbable	0	Major Damage	3	Low	
On-board equipment	Battery	Battery management system (	Electrical	electromagnetic phenomena	EMC	communication loss --> thermal	fire	Y	Y	N	compliance with functional safety standards,	AAR S-9401 Railroad Electronics Environmental	Improbable	0	Damage	2	Low	
On-board equipment	Battery	Battery management system (	Electrical	overload	overload	thermal runaway (battery)	smoke	Y	Y	N	thermocouples, coolant system, vent port	CSA. C22.2 No. 61508-1 Functional Safety of	Improbable	0	Damage	2	Low	
On-board equipment	Battery	Battery management system (	Electrical	overload	overload	thermal runaway (battery)	fire	Y	Y	N	thermocouples, coolant system, vent port	CSA. C22.2 No. 61508-1 Functional Safety of	Improbable	0	Damage	2	Low	
On-board equipment	Battery	Battery management system (	Electrical	overload	overload	thermal runaway (battery)	explosion	Y	Y	Y	thermocouples, coolant system, vent port	CSA. C22.2 No. 61508-1 Functional Safety of	Improbable	0	Major Damage	3	Low	
On-board equipment	Battery	Battery management system (	Electrical	disconnection / miswiring / control failure	overcharging to downstream	thermal runaway of downstream	smoke	Y	Y	N	thermocouples, coolant system, vent port	CSA. C22.2 No. 61508-1 Functional Safety of	Improbable	0	Damage	2	Low	
On-board equipment	Battery	Battery management system (	Electrical	disconnection / miswiring / control failure	overcharging to downstream	thermal runaway of downstream	explosion	Y	Y	Y	thermocouples, coolant system, vent port	CSA. C22.2 No. 61508-1 Functional Safety of	Improbable	0	Major Damage	3	Low	
On-board equipment	Battery	Battery management system (	Electrical	disconnection / miswiring / control failure	overcharging to downstream	thermal runaway of downstream	fire	Y	Y	N	thermocouples, coolant system, vent port	CSA. C22.2 No. 61508-1 Functional Safety of	Improbable	0	Damage	2	Low	
On-board equipment	Battery	Battery management system (	Electrical	short-circuit	short circuit	thermal runaway of downstream	smoke	Y	Y	N	thermocouples, coolant system, vent port	CSA. C22.2 No. 61508-1 Functional Safety of	Improbable	0	Damage	2	Low	
On-board equipment	Battery	Battery management system (	Electrical	short-circuit	short circuit	thermal runaway of downstream	explosion	Y	Y	Y	thermocouples, coolant system, vent port	CSA. C22.2 No. 61508-1 Functional Safety of	Improbable	0	Major Damage	3	Low	
On-board equipment	Battery	Battery management system (	Electrical	short-circuit	short circuit	thermal runaway of downstream	fire	Y	Y	N	thermocouples, coolant system, vent port	CSA. C22.2 No. 61508-1 Functional Safety of	Improbable	0	Damage	2	Low	
On-board equipment	Battery	Battery management system (	Electrical	short-circuit	hardware failure	short circuit, thermal runaway of	smoke	Y	Y	N	compliance with functional safety standards,	AAR S-9401 Railroad Electronics Environmental	Improbable	0	Damage	2	Low	
On-board equipment	Battery	Battery management system (	Electrical	short-circuit	hardware failure	short circuit, thermal runaway of	explosion	Y	Y	Y	compliance with functional safety standards,	AAR S-9401 Railroad Electronics Environmental	Improbable	0	Major Damage	3	Low	
On-board equipment	Battery	Battery management system (	Electrical	short-circuit	hardware failure	short circuit, thermal runaway of	fire	Y	Y	N	compliance with functional safety standards,	AAR S-9401 Railroad Electronics Environmental	Improbable	0	Damage	2	Low	
On-board equipment	Battery	Battery management system (	Electrical	short-circuit	software failure	short circuit, thermal runaway of	smoke	Y	Y	N	compliance with functional safety standards,	AAR S-9401 Railroad Electronics Environmental	Improbable	0	Damage	2	Low	
On-board equipment	Battery	Battery management system (	Electrical	short-circuit	software failure	short circuit, thermal runaway of	explosion	Y	Y	Y	compliance with functional safety standards,	AAR S-9401 Railroad Electronics Environmental	Improbable	0	Major Damage	3	Low	
On-board equipment	Battery	Battery management system (	Electrical	short-circuit	software failure	short circuit, thermal runaway of	fire	Y	Y	N	compliance with functional safety standards,	AAR S-9401 Railroad Electronics Environmental	Improbable	0	Damage	2	Low	
On-board equipment	Battery	Battery management system (	Thermal	flame	jet fire (immediate ignition) from the	damage to BMS, thermal runaway	smoke	Y	Y	N	thermocouples, coolant system, FCU, BMS,	NFPA. 70 National Electrical Code. 2023.	Improbable	0	Damage	2	Low	
On-board equipment	Battery	Battery management system (	Thermal	flame	jet fire (immediate ignition) from the	damage to BMS, thermal runaway	explosion	Y	Y	Y	thermocouples, coolant system, FCU, BMS,	NFPA. 70 National Electrical Code. 2023.	Improbable	0	Major Damage	3	Low	
On-board equipment	Battery	Battery management system (	Thermal	flame	jet fire (immediate ignition) from the	damage to BMS, thermal runaway	fire	Y	Y	N	thermocouples, coolant system, FCU, BMS,	NFPA. 70 National Electrical Code. 2023.	Improbable	0	Damage	2	Low	
On-board equipment	Battery	Battery management system (	Thermal	flame	jet fire (immediate ignition) from the	damage to BMS, thermal runaway	smoke	Y	Y	N	thermocouples, coolant system, FCU, BMS,	NFPA. 70 National Electrical Code. 2023.	Improbable	0	Damage	2	Low	
On-board equipment	Battery	Battery management system (	Thermal	flame	jet fire (immediate ignition) from the	damage to BMS, thermal runaway	explosion	Y	Y	Y	thermocouples, coolant system, FCU, BMS,	NFPA. 70 National Electrical Code. 2023.	Improbable	0	Major Damage	3	Low	
On-board equipment	Battery	Battery management system (	Thermal	flame	jet fire (immediate ignition) from the	damage to BMS, thermal runaway	fire	Y	Y	N	thermocouples, coolant system, FCU, BMS,	NFPA. 70 National Electrical Code. 2023.	Improbable	0	Damage	2	Low	
On-board equipment	Battery	Battery management system (	Thermal	flame	fire from FCS	damage to BMS, thermal runaway	smoke	Y	Y	N	thermocouples, coolant system, vent port	NFPA. 70 National Electrical Code. 2023.	Improbable	0	Damage	2	Low	
On-board equipment	Battery	Battery management system (	Thermal	flame	fire from FCS	damage to BMS, thermal runaway	fire	Y	Y	N	thermocouples, coolant system, vent port	NFPA. 70 National Electrical Code. 2023.	Improbable	0	Damage	2	Low	
On-board equipment	Battery	Battery management system (	Thermal	flame	fire from FCS	damage to BMS, thermal runaway	explosion	Y	Y	Y	thermocouples, coolant system, vent port	NFPA. 70 National Electrical Code. 2023.	Improbable	0	Major Damage	3	Low	
On-board equipment	Battery	Battery management system (	Thermal	flame	fire from fuel tank	damage to BMS, thermal runaway	smoke	Y	Y	N	thermocouples, coolant system, vent port	NFPA. 70 National Electrical Code. 2023.	Improbable	0	Damage	2	Low	
On-board equipment	Battery	Battery management system (	Thermal	flame	fire from fuel tank	damage to BMS, thermal runaway	fire	Y	Y	N	thermocouples, coolant system, vent port	NFPA. 70 National Electrical Code. 2023.	Improbable	0	Damage	2	Low	
On-board equipment	Battery	Battery management system (	Thermal	flame	fire from fuel tank	damage to BMS, thermal runaway	explosion	Y	Y	Y	thermocouples, coolant system, vent port	NFPA. 70 National Electrical Code. 2023.	Improbable	0	Major Damage	3	Low	
On-board equipment	Battery	Battery management system (	Thermal	objects or materials with a high or low temperature	over-temp	thermal runaway of downstream	smoke	Y	Y	N	thermocouples, coolant system, vent port	CSA. C22.2 No. 61508-1 Functional Safety of	Improbable	0	Damage	2	Low	
On-board equipment	Battery	Battery management system (	Thermal	objects or materials with a high or low temperature	over-temp	thermal runaway of downstream	explosion	Y	Y	Y	thermocouples, coolant system, vent port	CSA. C22.2 No. 61508-1 Functional Safety of	Improbable	0	Major Damage	3	Low	
On-board equipment	Battery	Battery management system (	Thermal	objects or materials with a high or low temperature	over-temp	thermal runaway of downstream	fire	Y	Y	N	thermocouples, coolant system, vent port	CSA. C22.2 No. 61508-1 Functional Safety of	Improbable	0	Damage	2	Low	
On-board equipment	Battery	Battery management system (	Vibration	worn parts	vibration	thermal runaway of downstream	smoke	Y	Y	N	verification to appropriate rail vibration	AAR S-9401 Railroad Electronics Environmental	Improbable	0	Damage	2	Low	
On-board equipment	Battery	Battery management system (	Vibration	worn parts	vibration	thermal runaway of downstream	explosion	Y	Y	Y	verification to appropriate rail vibration	AAR S-9401 Railroad Electronics Environmental	Improbable	0	Major Damage	3	Low	
On-board equipment	Battery	Battery management system (	Vibration	worn parts	vibration	thermal runaway of downstream	fire	Y	Y	N	verification to appropriate rail vibration	AAR S-9401 Railroad Electronics Environmental	Improbable	0	Damage	2	Low	
On-board equipment	Battery	Battery management system (	Environment	moisture	water penetration of BMS	short circuit, thermal runaway of	smoke	Y	Y	N	verification testing to appropriate IP rating,	CSA. C22.2 No. 61508-1 Functional Safety of	Improbable	0	Damage	2	Low	
On-board equipment	Battery	Battery management system (	Environment	moisture	water penetration of BMS	short circuit, thermal runaway of	explosion	Y	Y	Y	verification testing to appropriate IP rating,	CSA. C22.2 No. 61508-1 Functional Safety of	Improbable	0	Major Damage	3	Low	
On-board equipment	Battery	Battery management system (	Environment	moisture	water penetration of BMS	short circuit, thermal runaway of	fire	Y	Y	N	verification testing to appropriate IP rating,	CSA. C22.2 No. 61508-1 Functional Safety of	Improbable	0	Damage	2	Low	
On-board equipment	Battery	Battery management system (	Environment	temperature	water penetration of BMS	short circuit, thermal runaway of	smoke	Y	Y	N	verification testing to appropriate IP rating,	CSA. C22.2 No. 61508-1 Functional Safety of	Improbable	0	Damage	2	Low	
On-board equipment	Battery	Battery management system (	Environment	temperature	water penetration of BMS	short circuit, thermal runaway of	explosion	Y	Y	Y	verification testing to appropriate IP rating,	CSA. C22.2 No. 61508-1 Functional Safety of	Improbable	0	Major Damage	3	Low	
On-board equipment	Battery	Battery management system (	Environment	temperature	water penetration of BMS	short circuit, thermal runaway of	fire	Y	Y	N	verification testing to appropriate IP rating,	CSA. C22.2 No. 61508-1 Functional Safety of	Improbable	0	Damage	2	Low	
On-board equipment	Battery	coolant system (battery)	Thermal	objects or materials with a high or low temperature	over-temperature	thermal runaway (battery)	smoke	Y	Y	N	thermocouples, BMS, vent port location,	CSA. TS-602 Railway Applications — Rolling Stock	Remote	1	Damage	2	Low	
On-board equipment	Battery	coolant system (battery)	Thermal	objects or materials with a high or low temperature	over-temperature	thermal runaway (battery)	fire	Y	Y	N	thermocouples, BMS, vent port location,	CSA. TS-602 Railway Applications — Rolling Stock	Remote	1	Damage	2	Low	
On-board equipment	Battery	coolant system (battery)	Thermal	objects or materials with a high or low temperature	over-temperature	thermal runaway (battery)	explosion	Y	Y	Y	thermocouples, BMS, vent port location,	CSA. TS-602 Railway Applications — Rolling Stock	Remote	1	Major Damage	3	Low	
On-board equipment	Coolant system	Coolant system (control units	Mechanical	instability	coolant pump failure	over-heating of ECU, FCU, or BMS	damage to control unit	N	Y	N	thermocouples on coolant circuit	CSA. TS-601 Hydrogen Fuel Cell Power Systems for	Occasional	2	Damage	2	Low	
On-board equipment	Coolant system	Coolant system (control units	Electrical	disconnection / miswiring / control failure	communication loss	over-heating of ECU, FCU, or BMS	damage to control unit	N	Y	N	communication error checking,	CSA. TS-601 Hydrogen Fuel Cell Power Systems for	Occasional	2	Damage	2	Low	
On-board equipment	Coolant system	Radiator(s)	Mechanical	moving elements	mechanical damage to fan from	insufficient cooling of FCS	fire (membrane failure --> combustible	Y	Y	N	low voltage alarm, outlet temperature alarm	CSA. TS-601 Hydrogen Fuel Cell Power Systems for	Remote	1	Damage	2	Low	
On-board equipment	Coolant system	Radiator(s)	Electrical	disconnection / miswiring / control failure	loss of control	insufficient cooling of FCS	fire (membrane failure --> combustible	Y	Y	N	low voltage alarm, outlet temperature alarm	CSA. TS-601 Hydrogen Fuel Cell Power Systems for	Remote	1	Damage	2	Low	
On-board equipment	Coolant system	Radiator(s)	Vibration	unbalanced rotating parts	mechanical damage to fan from	insufficient cooling of FCS	fire (membrane failure --> combustible	Y	Y	N	shock and vibration testing, e.g., MIL 810.h	CSA. TS-601 Hydrogen Fuel Cell Power Systems for	Remote	1	Damage	2	Low	
On-board equipment	Coolant system	Radiator(s)	Environment	dust and fog	reduced functionality due to	insufficient cooling of FCS	fire (membrane failure --> combustible	Y	Y	N	correct IP rating	CSA. TS-601 Hydrogen Fuel Cell Power Systems for	Remote	1	Damage	2	Low	
On-board equipment	Coolant system	Radiator(s)	Environment	temperature	high ambient temperature reducing	insufficient cooling of FCS	fire (membrane failure --> combustible	Y	Y	N	low voltage alarm, outlet temperature alarm	CSA. TS-601 Hydrogen Fuel Cell Power Systems for	Occasional	2	Damage	2	Low	
On-board equipment	DC-DC	DC-DC	Mechanical	approach/departure of a moving element to a fixed part	penetration	thermal runaway of downstream	smoke	Y	Y	N	thermocouples, coolant system, BMS, vent	CSA. C22.1 Canadian Electrical Code, Part I (25th	Remote	1	Damage	2	Low	
On-board equipment	DC-DC	DC-DC	Mechanical	approach/departure of a moving element to a fixed part	penetration	thermal runaway of downstream	explosion	Y	Y	Y	thermocouples, coolant system, BMS, vent	CSA. C22.1 Canadian Electrical Code, Part I (25th	Remote	1	Major Damage	3	Low	
On-board equipment	DC-DC	DC-DC	Mechanical	approach/departure of a moving element to a fixed part	penetration	thermal runaway of downstream	fire	Y	Y	N	thermocouples, coolant system, BMS, vent	CSA. C22.1 Canadian Electrical Code, Part I (25th	Remote	1	Damage	2	Low	
On-board equipment	DC-DC	DC-DC	Electrical	disconnection / miswiring / control failure	overcharging to downstream	thermal runaway of downstream	smoke	Y	Y	N	thermocouples, coolant system, BMS, vent	CSA. C22.1 Canadian Electrical Code, Part I (25th	Remote	1	Damage	2	Low	
On-board equipment	DC-DC	DC-DC	Electrical	disconnection / miswiring / control failure	overcharging to downstream	thermal runaway of downstream	explosion	Y	Y	Y	thermocouples, coolant system, BMS, vent	CSA. C22.1 Canadian Electrical Code, Part I (25th	Remote	1	Major Damage	3	Low	
On-board equipment	DC-DC	DC-DC	Electrical	disconnection / miswiring / control failure	overcharging to downstream	thermal runaway of downstream	fire	Y	Y	N	thermocouples, coolant system, BMS, vent	CSA. C22.1 Canadian Electrical Code, Part I (25th	Remote	1	Damage	2	Low	
On-board equipment	DC-DC	DC-DC	Electrical	short-circuit	short circuit	thermal runaway of downstream	smoke	Y	Y	N	thermocouples, coolant system, BMS, vent	CSA. C22.1 Canadian Electrical Code, Part I (25th	Remote	1	Damage	2	Low	
On-board equipment	DC-DC	DC-DC	Electrical	short-circuit	short circuit	thermal runaway of downstream	explosion	Y	Y	Y	thermocouples, coolant system, BMS, vent	CSA. C22.1 Canadian Electrical Code, Part I (25th	Remote	1	Major Damage	3	Low	
On-board equipment	DC-DC	DC-DC	Electrical	short-circuit	short circuit	thermal runaway of downstream	fire	Y	Y	N	thermocouples, coolant system, BMS, vent	CSA. C22.1 Canadian Electrical Code, Part I (25th	Remote	1	Damage	2	Low	
On-board equipment	DC-DC	DC-DC	Thermal	objects or materials with a high or low temperature	over-heating	thermal runaway of downstream	smoke	Y	Y	N	thermocouples, coolant system, BMS, vent	CSA. C22.1 Canadian Electrical Code, Part I (25th	Remote	1	Damage	2	Low	
On-board equipment	DC-DC	DC-DC	Thermal	objects or materials with a high or low temperature	over-heating	thermal runaway of downstream	explosion	Y	Y	Y	thermocouples, coolant system, BMS, vent	CSA. C22.1 Canadian Electrical Code, Part I (25th	Remote	1	Major Damage	3	Low	
On-board equipment	DC-DC	DC-DC	Thermal	objects or materials with a high or low temperature	over-heating	thermal runaway of downstream	fire	Y	Y	N	thermocouples, coolant system, BMS, vent	CSA. C22.1 Canadian Electrical Code, Part I (25th	Remote	1	Damage	2	Low	
On-board equipment	DC-DC	DC-DC	Mechanical	approach/departure of a moving element to a fixed part	crushing	thermal runaway of downstream	smoke	Y	Y	N	thermocouples, coolant system, BMS, vent	CSA. C22.1 Canadian Electrical Code, Part I (25th	Remote	1	Damage	2	Low	
On-board equipment	DC-DC	DC-DC	Mechanical	approach/departure of a moving element to a fixed part	crushing	thermal runaway of downstream	explosion	Y	Y	Y	thermocouples, coolant system, BMS, vent	CSA. C22.1 Canadian Electrical Code, Part I (25th	Remote	1	Major Damage	3	Low	
On-board equipment	DC-DC	DC-DC	Mechanical	approach/departure of a moving element to a fixed part	crushing	thermal runaway of downstream	fire	Y	Y	N	thermocouples, coolant system, BMS, vent	CSA. C22.1 Canadian Electrical Code, Part I (25th	Remote	1	Damage	2	Low	
On-board equipment	DC-DC	HV cabling	Electrical	overload	overload	damage to HV cable --> short-circuit	fire	Y	Y	N	BMS	CSA. C22.1 Canadian Electrical Code, Part I (25th	Remote	1	Damage	2	Low	
On-board equipment	DC-DC	HV cabling	Electrical	parts which have become live under fault conditions	cable insulation breakdown	damage to HV cable --> short-circuit	fire	Y	Y	N	avoid sharp edges where wiring, proper	CSA. C22.1 Canadian Electrical Code, Part I (25th	Remote	1	Damage	2	Low	
On-board equipment	DC-DC	HV cabling	Electrical	parts which have become live under fault conditions	crushing	damage to HV cable --> short-circuit	fire	Y	Y	N	avoid sharp edges where wiring, proper	CSA. C22.1 Canadian Electrical Code, Part I (25th	Remote	1	Damage	2	Low	
On-board equipment	DC-DC	HV cabling	Electrical	short-circuit	short circuit	damage to HV cable --> short-circuit	fire	Y	Y	N	BMS	CSA. C22.1 Canadian Electrical Code, Part I (25th	Remote	1	Damage	2	Low	
On-board equipment	DC-DC	HV cabling	Electrical	short-circuit	improper installation	damage to HV cable --> short-circuit	fire	Y	Y	N	avoid sharp edges where wiring, proper	CSA. C22.1 Canadian Electrical Code, Part I (25th	Remote	1	Damage	2	Low	
On-board equipment	DC-DC	HV cabling	Electrical	short-circuit	wire selection	damage to HV cable --> short-circuit	fire	Y	Y	N	avoid sharp edges where wiring, proper	CSA. C22.1 Canadian Electrical Code, Part I (25th	Remote	1	Damage	2	Low	
On-board equipment	DC-DC	HV cabling	Mechanical	acceleration, deceleration	cable disconnect due to shock and	arc-ing	fire	Y	Y	N	using proper terminal blocks for the	CSA. C22.1 Canadian Electrical Code, Part I (25th	Remote	1	Damage	2	Low	
On-board equipment	Fuel cell control unit (FCU)	Enclosure ventilation van	Mechanical	rotating elements	mechanical fan failure; fan	accumulation of H2 from small	asphyxiation hazard in the enclosure	Y	N	N	1. The ventilation must be proved so that	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Improbable	0	Severe/Catastrophic	4	Low	
On-board equipment	Fuel cell control unit (FCU)	Enclosure ventilation van	Mechanical	rotating elements	mechanical fan failure; fan	accumulation of H2 from small	fire (delayed ignition of accumulated H2)	Y	Y	N	1. The ventilation must be proved so that	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Occasional	2	Damage	2	Low	
On-board equipment	Fuel cell control unit (FCU)	Enclosure ventilation van	Mechanical	rotating elements	mechanical fan failure; fan	accumulation of H2 from small	explosion (delayed ignition of	Y	Y	Y	1. The ventilation must be proved so that	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Remote	1	Major Damage	3	Low	
On-board equipment	Fuel cell control unit (FCU)	Enclosure ventilation van	Electrical	arc	arc-ing, spark from fan	ignition source	fire (delayed ignition of accumulated H2)	Y	Y	N	non arc-ing, non spark-ing fan, properly	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Improbable	0	Damage	2	Low	
On-board equipment	Fuel cell control unit (FCU)	Enclosure ventilation van	Electrical	arc	arc-ing, spark from fan	ignition source	explosion (delayed ignition of	Y	Y	Y	non arc-ing, non spark-ing fan, properly	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Improbable	0	Major Damage	3	Low	
On-board equipment	Fuel cell control unit (FCU)	Enclosure ventilation van	Electrical	disconnection / miswiring / control failure	electrical fan failure; disconnection	accumulation of H2 from small	asphyxiation hazard in the enclosure	Y	N	N	1. The ventilation must be proved so that	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Improbable	0	Severe/Catastrophic	4	Low	Air flow proving system
On-board equipment	Fuel cell control unit (FCU)	Enclosure ventilation van	Electrical	disconnection / miswiring / control failure	electrical fan failure; disconnection	accumulation of H2 from small	fire (delayed ignition of accumulated H2)	Y	Y	N	1. The ventilation must be proved so that	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Occasional	2	Damage	2	Low	
On-board equipment	Fuel cell control unit (FCU)	Enclosure ventilation van	Electrical	disconnection / miswiring / control failure	electrical fan failure; disconnection	accumulation of H2 from small	explosion (delayed ignition of	Y	Y	Y	1. The ventilation must be proved so that	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Remote	1	Major Damage	3	Low	
On-board equipment	Fuel cell control unit (FCU)	Enclosure ventilation van	Electrical	short-circuit	electrical fan failure; fan winding	accumulation of H2 from small	asphyxiation hazard in the enclosure	Y	N	N	1. The ventilation must be proved so that	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Improbable	0	Severe/Catastrophic	4	Low	
On-board equipment	Fuel cell control unit (FCU)	Enclosure ventilation van	Electrical	short-circuit	electrical fan failure; fan winding	accumulation of H2 from small	fire (delayed ignition of accumulated H2)	Y	Y	N	1. The ventilation must be proved so that	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Occasional	2	Damage	2	Low	
On-board equipment	Fuel cell control unit (FCU)	Enclosure ventilation van	Electrical	short-circuit	electrical fan failure; fan winding	accumulation of H2 from small	explosion (delayed ignition of	Y	Y	Y	1. The ventilation must be proved so that	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Remote	1	Major Damage	3	Low	
On-board equipment	Fuel cell control unit (FCU)	Fuel cell control unit (FCU)	Mechanical	instability	malfunction leading to fuel cell	cell overheating	fire (in the cell)	N	Y	N	1. Controls compliant with applicable	CAN/CSA. C22.2 No. 61010-1 Safety Requirements	Remote	1	Damage	2	Low	
On-board equipment	Fuel cell control unit (FCU)	Fuel cell control unit (FCU)	Mechanical	instability	malfunction leading to fuel cell	cell overheating	explosion (in the cell)	Y	Y	N	1. Controls compliant with applicable	CAN/CSA. C22.2 No. 61010-1 Safety Requirements	Remote	1	Major Damage	3	Low	
On-board equipment	Fuel cell control unit (FCU)	Fuel cell control unit (FCU)	Mechanical	instability	malfunction leading to fuel cell	H2 leak - small	fire (in the cell)	N	Y	N	1. Fuel cell safety system will detect low	CAN/CSA. C22.2 No. 61010-1 Safety Requirements	Remote	1	Damage	2	Low	
On-board equipment	Fuel cell control unit (FCU)	Fuel cell control unit (FCU)	Mechanical	instability	malfunction leading to fuel cell	H2 leak - large	explosion (in the cell)	Y	Y	N	1. Fuel cell safety system will detect low	CAN/CSA. C22.2 No. 61010-1 Safety Requirements	Remote	1	Major Damage	3	Low	
On-board equipment	Fuel cell control unit (FCU)	Fuel cell control unit (FCU)	Mechanical	acceleration, deceleration	shock (mechanics)	overload, over-temp	fire (in the cell)	N	Y	N	internal temperature monitoring, compliance	CAN/CSA. C22.2 No. 61010-1 Safety Requirements	Remote	1	Damage	2	Low	
On-board equipment	Fuel cell control unit (FCU)	Fuel cell control unit (FCU)	Mechanical	acceleration, deceleration	shock (mechanics)	overload, over-temp	explosion (in the cell)	Y	Y	N	internal temperature monitoring, compliance	CAN/CSA. C22.2 No. 61010-1 Safety Requirements	Remote	1	Major Damage	3	Low	
On-board equipment	Fuel cell control unit (FCU)	Fuel cell control unit (FCU)	Electrical	short-circuit	software failure	overload, over-temp	fire (in the cell)	N	Y	N	internal temperature monitoring, compliance	CAN/CSA. C22.2 No. 61010-1 Safety Requirements	Remote	1	Damage	2	Low	
On-board equipment	Fuel cell control unit (FCU)	Fuel cell control unit (FCU)	Electrical	short-circuit	software failure	overload, over-temp	explosion (in the cell)	Y	Y	N	internal temperature monitoring, compliance	CAN/CSA. C22.2 No. 61010-1 Safety Requirements	Remote	1	Major Damage	3	Low	
On-board equipment	Fuel cell control unit (FCU)	Fuel cell control unit (FCU)	Electrical	short-circuit	hardware failure	overload, over-temp	fire (in the cell)	N	Y	N	internal temperature monitoring, compliance	CAN/CSA. C22.2 No. 61010-1 Safety Requirements	Remote	1	Damage	2	Low	
On-board equipment	Fuel cell control unit (FCU)	Fuel cell control unit (FCU)	Electrical	short-circuit	hardware failure	overload, over-temp	explosion (in the cell)	Y	Y	N	internal temperature monitoring, compliance	CAN/CSA. C22.2 No. 61010-1 Safety Requirements	Remote	1	Major Damage	3	Low	
On-board equipment	Fuel cell control unit (FCU)	Fuel cell control unit (FCU)	Thermal	objects or materials with a high or low temperature	over-temp	overload	fire (in the cell)	N	Y	N	internal temperature monitoring, compliance	CAN/CSA. C22.2 No. 61010-1 Safety Requirements	Remote	1	Damage	2	Low	
On-board equipment	Fuel cell control unit (FCU)	Fuel cell control unit (FCU)	Thermal	objects or materials with a high or low temperature	over-temp	overload	explosion (in the cell)	Y	Y	N	internal temperature monitoring, compliance	CAN/CSA. C22.2 No. 61010-1 Safety Requirements	Remote	1	Major Damage	3	Low	
On-board equipment	Fuel cell control unit (FCU)	Fuel cell control unit (FCU)	Vibration	worn parts	vibration	overload, over-temp	fire (in the cell)	N	Y	N	internal temperature monitoring, compliance	CAN/CSA. C22.2 No. 61010-1 Safety Requirements	Remote	1	Damage	2	Low	
On-board equipment	Fuel cell control unit (FCU)	Fuel cell control unit (FCU)	Vibration	worn parts	vibration	overload, over-temp	explosion (in the cell)	Y	Y	N	internal temperature monitoring, compliance	CAN/CSA. C22.2 No. 61010-1 Safety Requirements	Remote	1	Major Damage	3	Low	
On-board equipment	Fuel cell control unit (FCU)	Ground fault monitoring	Electrical	disconnection / miswiring / control failure	communication loss	not able to monitor isolation	electrocution, potential cardiac arrest	Y	N	N	FCU	CAN/CSA. C22.2 No. 61010-1 Safety Requirements	Occasional	2	Damage	2	Low	
On-board equipment	Fuel cell system (FCS)	Cathode air supply compresso	Mechanical	high pressure	mechanical failure of the	membrane failure due to high cross-	fire (in the cell)	N	Y	N	1. Compressor pressure relief device	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Remote	1	Damage	2	Low	
On-board equipment	Fuel cell system (FCS)	Cathode air supply compresso	Mechanical	high pressure	mechanical failure of the	membrane failure due to high cross-	explosion (in the cell)	Y	Y	N	1. Compressor pressure relief device	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Remote	1	Major Damage	3	Low	
On-board equipment	Fuel cell system (FCS)	Cathode air supply compresso	Electrical	overload	electrical or control failure	membrane failure due to high cross-	fire (in the cell)	N	Y	N	1. Compressor pressure relief device	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Remote	1	Damage	2	Low	
On-board equipment	Fuel cell system (FCS)	Cathode air supply compresso	Thermal	objects or materials with a high or low temperature	lack of coolant causing low flow, and	unable to support fuel cell reaction	fire	Y	Y	N	monitor air compressor temperature, low	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Remote	1	Damage	2	Low	
On-board equipment	Fuel cell system (FCS)	Cathode air supply compresso	Vibration	worn parts	leak of air causing low flow, and / or	unable to support fuel cell reaction	fire	Y	Y	N	pressure and temperature sensor in cathode	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Occasional	2	Damage	2	Low	
On-board equipment	Fuel cell system (FCS)	Coolant	Electrical	live parts	high coolant conductivity	fuel cell enclosure voltage >50 V	electrocution; potential cardiac arrest	Y	N	N	ground fault detection, regular maintenance	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Occasional	2	Damage	2	Low	
On-board equipment	Fuel cell system (FCS)	Coolant	Electrical	short-circuit	location wrt electrical wiring	coolant leak - small	fire (electrical short)	Y	Y	N	ground fault detection, regular maintenance	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Improbable	0	Damage	2	Low	
On-board equipment	Fuel cell system (FCS)	Coolant heater (optional)	Electrical	short-circuit	short-circuit in coolant heater	electrical fire	jet fire (immediate ignition) [damage to	Y	Y	N	regular maintenance of coolant circuit	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Remote	1	Damage	2	Low	
On-board equipment	Fuel cell system (FCS)	Coolant piping	Mechanical	instability	cooling system line failure, etc.	coolant overheat --> membrane	fire (in the cell)	N	Y	N	1. Fuel cell safety system will detect low	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Remote	1	Damage	2	Low	
On-board equipment	Fuel cell system (FCS)	Coolant piping	Mechanical	instability	cooling system line failure, etc.	coolant overheat --> membrane	explosion (in the cell)	Y	Y	N	1. Fuel cell safety system will detect low	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Remote	1	Major Damage	3	Low	
On-board equipment	Fuel cell system (FCS)	Coolant piping	Mechanical	instability	cooling system line failure, etc.	coolant leak - large	slip hazard	Y	N	N	Regular maintenance on coolant system	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Remote	1	Damage	2	Low	
On-board equipment	Fuel cell system (FCS)	Coolant pump	Mechanical	instability	pump failure	coolant overheat --> membrane	fire (in the cell)	N	Y	N	1. Fuel cell safety system will detect low	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Remote	1	Damage	2	Low	
On-board equipment	Fuel cell system (FCS)	Coolant pump	Mechanical	instability	pump failure	coolant overheat --> membrane	explosion (in the cell)	Y	Y	N	1. Fuel cell safety system will detect low	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Remote	1	Major Damage	3	Low	
On-board equipment	Fuel cell system (FCS)	Coolant pump	Mechanical	instability	pump supply over-pressure	coolant leak - small	fire (in the cell) [lack of Cx to FCS -->	Y	Y	N	coolant pressure transducer, FCU	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Remote	1	Damage	2	Low	
On-board equipment	Fuel cell system (FCS)	Coolant pump	Mechanical	instability	pump supply over-pressure	coolant leak - large	explosion (in the cell) [lack of Cx to FCS -->	Y	Y	N	coolant pressure transducer, FCU	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Remote	1	Major Damage	3	Low	
On-board equipment	Fuel cell system (FCS)	Ejector	Mechanical	high pressure	exposure to high pressure	H2 leak - small	unignited release	N	N	N	ventilation fan, pressure transducer, FCU	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Remote	1	No Damage	0	Low	

On-board equipment	Fuel cell system (FCS)	Ejector	Mechanical	high pressure	exposure to high pressure	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	ventilation fan, pressure transducer, FCU	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Remote	1	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Ejector	Mechanical	instability	mechanical wear	H2 leak - small	unignited release	N	N	N	ventilation fan, pressure transducer, FCU	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Remote	1	No Damage	0	Low
On-board equipment	Fuel cell system (FCS)	Ejector	Mechanical	instability	mechanical wear	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	ventilation fan, pressure transducer, FCU	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Remote	1	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Ejector	Material / substance	hydrogen material compatibility	H2 embrittlement	H2 leak - small	unignited release	N	N	N	ventilation fan, pressure transducer, FCU	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Improbable	0	No Damage	0	Low
On-board equipment	Fuel cell system (FCS)	Ejector	Material / substance	hydrogen material compatibility	H2 embrittlement	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	ventilation fan, pressure transducer, FCU	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Improbable	0	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Mechanical	approach/departure of a moving element to a fixed part	impact damage	H2 leak - small	unignited release	N	N	N	1. enclosure ventilation fan	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Occasional	2	No Damage	0	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Mechanical	approach/departure of a moving element to a fixed part	impact damage	H2 leak - large	asphyxiation hazard at the rupture	Y	N	N	1. enclosure ventilation fan	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Improbable	0	Severe/Catastrophic	4	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Mechanical	approach/departure of a moving element to a fixed part	impact damage	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	1. enclosure ventilation fan	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Occasional	2	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Mechanical	approach/departure of a moving element to a fixed part	impact damage	H2 leak - large	fire (delayed ignition of accumulated H2)	Y	Y	N	1. enclosure ventilation fan	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Remote	1	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Mechanical	approach/departure of a moving element to a fixed part	impact damage	H2 leak - large	explosion (delayed ignition of	Y	Y	Y	1. enclosure ventilation fan	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Remote	1	Major Damage	3	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Mechanical	high pressure	mechanical failure	H2 leak - small	unignited release	N	N	N	1. enclosure ventilation fan	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Remote	1	No Damage	0	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Mechanical	high pressure	mechanical failure	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	1. enclosure ventilation fan	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Remote	1	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Mechanical	high pressure	mechanical failure	H2 leak - large	fire (delayed ignition of accumulated H2)	Y	Y	N	1. enclosure ventilation fan	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Remote	1	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Mechanical	instability	plate crack --> fuel or oxidant leak to	gas in coolant circuit	damage to coolant pump	N	Y	N	pressure transducer on coolant circuit	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Occasional	2	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Mechanical	instability	plate crack --> fuel to external	H2 leak - small	unignited release	N	N	N	ventilation, automatic safety system, fuel	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Occasional	2	No Damage	0	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Mechanical	instability	plate crack --> fuel to external	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	ventilation, automatic safety system, fuel	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Occasional	2	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Mechanical	instability	plate crack --> oxidant to external	unable to support fuel cell reaction	fire	Y	Y	N	pressure transducer, stack voltage sensor	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Occasional	2	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Mechanical	instability	plate crack --> coolant to external	loss of coolant	damage to coolant pump	N	Y	N	pressure transducer on coolant circuit	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Occasional	2	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Electrical	live parts	coolant conductivity too high	fuel cell enclosure voltage >50 V	electrocution; potential cardiac arrest	Y	N	N	active monitoring coolant conductivity,	CSA. C22.1 Canadian Electrical Code, Part I (25th	Occasional	2	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Electrical	not enough distance to live parts under high voltage	insufficient air gaps during design	fuel cell enclosure voltage >50 V	electrocution; potential cardiac arrest	Y	N	N	ground fault detection	CSA. C22.1 Canadian Electrical Code, Part I (25th	Remote	1	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Electrical	not enough distance to live parts under high voltage	damage to components reducing air	fuel cell enclosure voltage >50 V	electrocution; potential cardiac arrest	Y	N	N	ground fault detection	CSA. C22.1 Canadian Electrical Code, Part I (25th	Remote	1	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Electrical	overload	current draw too high	damage to high voltage cable	fire	Y	Y	N	FCU control of load draw	CSA. C22.1 Canadian Electrical Code, Part I (25th	Improbable	0	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Electrical	disconnection / miswiring / control failure	HV cable +/- swapped, HV cable	damage to high voltage cable	fire	Y	Y	N	FCU control of load	CSA. C22.1 Canadian Electrical Code, Part I (25th	Improbable	0	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Electrical	short-circuit	penetration damage to HV cables	fuel cell enclosure voltage >50 V	electrocution; potential cardiac arrest	Y	N	N	ground fault detection	CSA. C22.1 Canadian Electrical Code, Part I (25th	Remote	1	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Electrical	short-circuit	penetration damage to HV cables	damage to high voltage cable	fire	Y	Y	N	ground fault detection	CSA. C22.1 Canadian Electrical Code, Part I (25th	Remote	1	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Thermal	flame	fire in fuel cell module	thermal runaway (battery)	smoke	Y	Y	N	FCU, BMS	NFPA. 70 National Electrical Code. 2023.	Improbable	0	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Thermal	flame	fire in fuel cell module	thermal runaway (battery)	fire (electrical)	Y	Y	N	FCU, BMS	NFPA. 70 National Electrical Code. 2023.	Improbable	0	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Thermal	flame	fire in fuel cell module	thermal runaway (battery)	explosion	Y	Y	Y	FCU, BMS	NFPA. 70 National Electrical Code. 2023.	Improbable	0	Major Damage	3	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Thermal	flame	jet fire, in fuel cell module,	thermal runaway (battery)	smoke	Y	Y	N	FCU, BMS	NFPA. 70 National Electrical Code. 2023.	Improbable	0	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Thermal	flame	jet fire, in fuel cell module,	thermal runaway (battery)	fire (electrical)	Y	Y	N	FCU, BMS	NFPA. 70 National Electrical Code. 2023.	Improbable	0	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Thermal	flame	jet fire, in fuel cell module,	thermal runaway (battery)	explosion	Y	Y	Y	FCU, BMS	NFPA. 70 National Electrical Code. 2023.	Improbable	0	Major Damage	3	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Thermal	flame	fire in fuel cell module	damage to fuel supply	unignited release	N	N	N	FCU	NFPA. 70 National Electrical Code. 2023.	Improbable	0	No Damage	0	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Thermal	flame	fire in fuel cell module	damage to fuel supply	jet fire (immediate ignition)	Y	Y	N	FCU	NFPA. 70 National Electrical Code. 2023.	Improbable	0	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Thermal	flame	jet fire, in fuel cell module,	damage to fuel supply	jet fire (immediate ignition)	Y	Y	N	FCU, TPRD	NFPA. 70 National Electrical Code. 2023.	Improbable	0	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Thermal	objects or materials with a high or low temperature	loss of coolant	membrane failure causing	fire	Y	Y	N	temperature and pressure sensor on coolant	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Occasional	2	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Thermal	objects or materials with a high or low temperature	loss of coolant causing over-temp of	thermal runaway (battery)	smoke	Y	Y	N	temperature and pressure sensor on coolant	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Occasional	2	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Thermal	objects or materials with a high or low temperature	loss of coolant causing over-temp of	thermal runaway (battery)	fire (electrical)	Y	Y	N	temperature and pressure sensor on coolant	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Occasional	2	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Thermal	objects or materials with a high or low temperature	loss of coolant causing over-temp of	thermal runaway (battery)	explosion	Y	Y	Y	temperature and pressure sensor on coolant	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Remote	1	Major Damage	3	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Vibration	worn parts	loosening of fitting due to shock and	H2 leak - small	unignited release	N	N	N	shock and vibration testing, e.g., MIL 810.h	AAR S-9401 Railroad Electronics Environmental	Occasional	2	No Damage	0	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Vibration	worn parts	disconnected fitting due to shock	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	shock and vibration testing, e.g., MIL 810.h	AAR S-9401 Railroad Electronics Environmental	Occasional	2	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Vibration	worn parts	broken component due to shock	H2 leak - small	unignited release	N	N	N	shock and vibration testing, e.g., MIL 810.h	AAR S-9401 Railroad Electronics Environmental	Occasional	2	No Damage	0	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Vibration	worn parts	broken component due to shock	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	shock and vibration testing, e.g., MIL 810.h	AAR S-9401 Railroad Electronics Environmental	Occasional	2	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Vibration	worn parts	loss in stack compression due to	H2 leak - small	unignited release	N	N	N	shock and vibration testing, e.g., MIL 810.h	AAR S-9401 Railroad Electronics Environmental	Occasional	2	No Damage	0	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Vibration	worn parts	loss in stack compression due to	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	shock and vibration testing, e.g., MIL 810.h	AAR S-9401 Railroad Electronics Environmental	Occasional	2	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Vibration	worn parts	plate crack --> fuel or oxidant leak to	gas in coolant circuit	damage to coolant pump	N	Y	N	shock and vibration testing, e.g., MIL 810.h	AAR S-9401 Railroad Electronics Environmental	Occasional	2	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Vibration	worn parts	plate crack --> fuel to external	H2 leak - small	unignited release	N	N	N	shock and vibration testing, e.g., MIL 810.h	AAR S-9401 Railroad Electronics Environmental	Occasional	2	No Damage	0	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Vibration	worn parts	plate crack --> fuel to external	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	shock and vibration testing, e.g., MIL 810.h	AAR S-9401 Railroad Electronics Environmental	Occasional	2	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Vibration	worn parts	plate crack --> oxidant to external	unable to support fuel cell reaction	fire	Y	Y	N	shock and vibration testing, e.g., MIL 810.h	AAR S-9401 Railroad Electronics Environmental	Occasional	2	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Vibration	worn parts	plate crack --> coolant to external	loss of coolant	damage to coolant pump	N	Y	N	shock and vibration testing, e.g., MIL 810.h	AAR S-9401 Railroad Electronics Environmental	Occasional	2	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Material / substance	flammable	fuel cell membrane break	H2 leak - small	fire (in the cell)	N	Y	N	low stack voltage alarm, FCU	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Remote	1	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Material / substance	flammable	fuel cell membrane break	H2 leak - large	explosion (in the cell)	Y	Y	N	low stack voltage alarm, FCU	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Remote	1	Major Damage	3	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Material / substance	hydrogen material compatibility	H2 embrittlement	H2 leak - small	unignited release	N	N	N	selecting H2 compatible materials	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Improbable	0	No Damage	0	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Material / substance	hydrogen material compatibility	H2 embrittlement	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	selecting H2 compatible materials	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Improbable	0	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Environment	moisture	accumulated moisture on	fuel cell enclosure voltage >50 V	electrocution; potential cardiac arrest	Y	N	N	ground fault detection, verification testing to	CSA. C22.1 Canadian Electrical Code, Part I (25th	Improbable	0	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Environment	temperature	cell or vessel rupture due to freeze-	H2 leak - small	unignited release	N	N	N	1. enclosure ventilation fan	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Remote	1	No Damage	0	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Environment	temperature	cell or vessel rupture due to freeze-	H2 leak - large	asphyxiation hazard at the rupture	Y	N	N	1. enclosure ventilation fan	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Improbable	0	Severe/Catastrophic	4	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Environment	temperature	cell or vessel rupture due to freeze-	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	1. enclosure ventilation fan	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Remote	1	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Environment	temperature	cell or vessel rupture due to freeze-	H2 leak - small	fire (delayed ignition of accumulated H2)	Y	Y	N	1. enclosure ventilation fan	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Remote	1	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Environment	temperature	cell or vessel rupture due to freeze-	H2 leak - large	explosion (delayed ignition of	Y	Y	Y	1. enclosure ventilation fan	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Remote	1	Major Damage	3	Low
On-board equipment	Fuel cell system (FCS)	Fuel cell module (inside an en	Environment	water	accumulated moisture on	fuel cell enclosure voltage >50 V	electrocution; potential cardiac arrest	Y	N	N	ground fault detection, verification testing to	CSA. C22.1 Canadian Electrical Code, Part I (25th	Improbable	0	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	H2 injector	Mechanical	high pressure	exposure to high pressure	H2 leak - small	unignited release	N	N	N	ventilation fan, pressure decay rate	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Improbable	0	No Damage	0	Low
On-board equipment	Fuel cell system (FCS)	H2 injector	Mechanical	high pressure	exposure to high pressure	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	ventilation fan, pressure decay rate	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Improbable	0	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	H2 injector	Mechanical	instability	mechanical wear	H2 leak - small	unignited release	N	N	N	ventilation fan, pressure decay rate	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Remote	1	No Damage	0	Low
On-board equipment	Fuel cell system (FCS)	H2 injector	Mechanical	instability	mechanical wear	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	ventilation fan, pressure decay rate	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Remote	1	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	H2 injector	Material / substance	hydrogen material compatibility	H2 embrittlement	H2 leak - small	unignited release	N	N	N	ventilation fan, pressure decay rate	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Improbable	0	No Damage	0	Low
On-board equipment	Fuel cell system (FCS)	H2 injector	Material / substance	hydrogen material compatibility	H2 embrittlement	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	ventilation fan, pressure decay rate	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Improbable	0	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Hydrogen recirculation blower	Mechanical	high pressure	exposure to high pressure	H2 leak - small	unignited release	N	N	N	ventilation fan, pressure decay rate	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Improbable	0	No Damage	0	Low
On-board equipment	Fuel cell system (FCS)	Hydrogen recirculation blower	Mechanical	high pressure	exposure to high pressure	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	ventilation fan, pressure decay rate	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Improbable	0	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Hydrogen recirculation blower	Mechanical	instability	mechanical wear	H2 leak - small	unignited release	N	N	N	ventilation fan, pressure decay rate	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Occasional	2	No Damage	0	Low
On-board equipment	Fuel cell system (FCS)	Hydrogen recirculation blower	Mechanical	instability	mechanical wear	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	ventilation fan, pressure decay rate	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Occasional	2	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Hydrogen recirculation blower	Material / substance	hydrogen material compatibility	H2 embrittlement	H2 leak - small	unignited release	N	N	N	ventilation fan, pressure decay rate	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Improbable	0	No Damage	0	Low
On-board equipment	Fuel cell system (FCS)	Hydrogen recirculation blower	Material / substance	hydrogen material compatibility	H2 embrittlement	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	ventilation fan, pressure decay rate	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Improbable	0	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Level switch	Electrical	disconnection / miswiring / control failure	level switch remains HIGH	drain valve always OPEN -->	unignited release	N	N	N	periodic maintenance of drain valve, monitor	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Occasional	2	No Damage	0	Low
On-board equipment	Fuel cell system (FCS)	Level switch	Electrical	disconnection / miswiring / control failure	level switch remains HIGH	drain valve always OPEN -->	jet fire (immediate ignition)	Y	Y	N	periodic maintenance of drain valve, monitor	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Occasional	2	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Level switch	Material / substance	dust	level switch remains HIGH	drain valve always OPEN -->	unignited release	N	N	N	periodic maintenance of drain valve, monitor	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Occasional	2	No Damage	0	Low
On-board equipment	Fuel cell system (FCS)	Level switch	Material / substance	dust	level switch remains HIGH	drain valve always OPEN -->	jet fire (immediate ignition)	Y	Y	N	periodic maintenance of drain valve, monitor	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Occasional	2	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	N2 drain valve	Electrical	disconnection / miswiring / control failure	N2 valve remains OPEN	combustible mixture air/H2 into	unignited release	N	N	N	periodic maintenance of valve, monitor fuel	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Occasional	2	No Damage	0	Low
On-board equipment	Fuel cell system (FCS)	N2 drain valve	Electrical	disconnection / miswiring / control failure	N2 valve remains OPEN	combustible mixture air/H2 into	jet fire (immediate ignition)	Y	Y	N	periodic maintenance of valve, monitor fuel	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Occasional	2	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Pump	Electrical	disconnection / miswiring / control failure	loss of communicaton due to low	insufficient cooling of FCS	fire (membrane failure --> combustible	Y	Y	N	stack low voltage alarm, outlet temperature	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Occasional	2	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Pump	Electrical	disconnection / miswiring / control failure	loss of communication due to	insufficient cooling of FCS	fire (membrane failure --> combustible	Y	Y	N	stack low voltage alarm, outlet temperature	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Occasional	2	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Thermocouple and pressure t	Mechanical	instability	mechanical wear	fuel over-pressure	jet fire (immediate ignition) [leak - large]	Y	Y	N	FCU, ventilation fan, stack low voltage alarm	ANSI/CSA. America FC 3 Portable Fuel Cell Power Sy	Remote	1	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Thermocouple and pressure t	Mechanical	instability	mechanical wear	fuel over-temperature	fire (in the cell)	N	Y	N	FCU, stack low voltage alarm	ANSI/CSA. America FC 3 Portable Fuel Cell Power Sy	Remote	1	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Thermocouple and pressure t	Electrical	disconnection / miswiring / control failure	communication loss	fuel over-pressure	jet fire (immediate ignition) [leak - large]	Y	Y	N	FCU, ventilation fan, stack low voltage alarm	ANSI/CSA. America FC 3 Portable Fuel Cell Power Sy	Occasional	2	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Thermocouple and pressure t	Electrical	disconnection / miswiring / control failure	communication loss	fuel over-temperature	fire (in the cell)	N	Y	N	FCU, stack low voltage alarm	ANSI/CSA. America FC 3 Portable Fuel Cell Power Sy	Occasional	2	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Thermocouple and pressure t	Environment	temperature	mechanical wear from repeated	fuel over-pressure	jet fire (immediate ignition) [leak - large]	Y	Y	N	FCU, ventilation fan, stack low voltage alarm	ANSI/CSA. America FC 3 Portable Fuel Cell Power Sy	Remote	1	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Thermocouple and pressure t	Environment	temperature	mechanical wear from repeated	fuel over-temperature	fire (in the cell)	N	Y	N	FCU, stack low voltage alarm	ANSI/CSA. America FC 3 Portable Fuel Cell Power Sy	Remote	1	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Thermocouple and pressure t	Mechanical	instability	mechanical wear	coolant over-pressure	slip hazard (leak - large)	Y	N	N	FCU, regular scheduled maintenance	ANSI/CSA. America FC 3 Portable Fuel Cell Power Sy	Remote	1	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Thermocouple and pressure t	Mechanical	instability	mechanical wear	coolant over-temperature	fire (in the cell)	N	Y	N	FCU, stack low voltage alarm, regular	ANSI/CSA. America FC 3 Portable Fuel Cell Power Sy	Remote	1	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Thermocouple and pressure t	Electrical	disconnection / miswiring / control failure	communication loss	coolant over-pressure	slip hazard (leak - large)	Y	N	N	FCU, regular scheduled maintenance	ANSI/CSA. America FC 3 Portable Fuel Cell Power Sy	Occasional	2	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Thermocouple and pressure t	Electrical	disconnection / miswiring / control failure	communication loss	coolant over-temperature	fire (in the cell)	N	Y	N	FCU, stack low voltage alarm, regular	ANSI/CSA. America FC 3 Portable Fuel Cell Power Sy	Occasional	2	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Thermocouple and pressure t	Environment	temperature	mechanical wear from repeated	coolant over-pressure	slip hazard (leak - large)	Y	N	N	FCU, regular scheduled maintenance	ANSI/CSA. America FC 3 Portable Fuel Cell Power Sy	Remote	1	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	Thermocouple and pressure t	Environment	temperature	mechanical wear from repeated	coolant over-temperature	fire (in the cell)	N	Y	N	FCU, stack low voltage alarm, regular	ANSI/CSA. America FC 3 Portable Fuel Cell Power Sy	Remote	1	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	water drain valve	Mechanical	high pressure	mechanical or control failure	H2 leak - small	fire (in the cell)	N	Y	N	1. Purge valves are vented to a safe location	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Remote	1	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	water drain valve	Mechanical	high pressure	mechanical or control failure	H2 leak - large	explosion (in the cell)	Y	Y	N	1. Purge valves are vented to a safe location	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Remote	1	Major Damage	3	Low
On-board equipment	Fuel cell system (FCS)	water drain valve	Electrical	disconnection / miswiring / control failure	electrical failure de-energizing the	H2 leak - small	fire (in the cell)	N	Y	N	1. Purge valves are vented to a safe location	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Remote	1	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	water drain valve	Electrical	disconnection / miswiring / control failure	electrical failure de-energizing the	H2 leak - large	explosion (in the cell)	Y	Y	N	1. Purge valves are vented to a safe location	CSA. C22.2 No. 62282-2 Fuel Cell Technologies —	Remote	1	Major Damage	3	Low
On-board equipment	Fuel cell system (FCS)	water knockout	Mechanical	instability	mechanical wear	H2 leak - small	unignited release	N	N	N	using certified receptacles	ANSI/CSA. America FC 3 Portable Fuel Cell Power Sy	Remote	1	No Damage	0	Low
On-board equipment	Fuel cell system (FCS)	water knockout	Mechanical	instability	mechanical wear	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	using certified receptacles	ANSI/CSA. America FC 3 Portable Fuel Cell Power Sy	Remote	1	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	water knockout	Material / substance	hydrogen material compatibility	H2 embrittlement	H2 leak - small	unignited release	N	N	N	using certified receptacles	ANSI/CSA. America FC 3 Portable Fuel Cell Power Sy	Improbable	0	No Damage	0	Low
On-board equipment	Fuel cell system (FCS)	water knockout	Material / substance	hydrogen material compatibility	H2 embrittlement	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	using certified receptacles	ANSI/CSA. America FC 3 Portable Fuel Cell Power Sy	Improbable	0	Damage	2	Low
On-board equipment	Fuel cell system (FCS)	water knockout	Environment	temperature	mechanical wear from repeated	H2 leak - small	unignited release	N	N	N	using certified receptacles	ANSI/CSA. America FC 3 Portable Fuel Cell Power Sy	Remote	1	No Damage	0	Low
On-board equipment	Fuel cell system (FCS)	water knockout	Environment	temperature	mechanical wear from repeated	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	using certified receptacles	ANSI/CSA. America FC 3 Portable Fuel Cell Power Sy	Remote	1	Damage	2	Low
On-board equipment	Fuel supply	Check valve from storage tank	Mechanical	high pressure	fail to seal properly in the closed	H2 leak - small	unignited release	N	N	N	Redundancy. The receptacle has an	CSA/ANSI. HGV 3.1 Fuel System Components for	Remote	1	No Damage	0	Low
On-board equipment	Fuel supply	Check valve from storage tank	Mechanical	high pressure	fail to seal properly in the closed	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	Redundancy. The receptacle has an	CSA/ANSI. HGV 3.1 Fuel System Components for	Remote	1	Damage	2	Low
On-board equipment	Fuel supply	Check valve from storage tank	Mechanical	high pressure	stuck open with debris	H2 leak - small	unignited release	N	N	N	Redundancy. The receptacle has an	CSA/ANSI. HGV 3.1 Fuel System Components for	Remote	1	No Damage	0	Low
On-board equipment	Fuel supply	Check valve from storage tank	Mechanical	high pressure	stuck open with debris	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	Redundancy. The receptacle has an	CSA/ANSI. HGV 3.1 Fuel System Components for	Remote	1	Damage	2	Low
On-board equipment	Fuel supply	Check valve from storage tank	Mechanical	high pressure	excessively high or variable pressure	H2 leak - small	unignited release	N	N	N	Redundancy. The receptacle has an	CSA/ANSI. HGV 3.1 Fuel System Components for	Remote	1	No Damage	0	Low
On-board equipment	Fuel supply	Check valve from storage tank	Mechanical	high pressure	excessively high or variable pressure	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	Redundancy. The receptacle has an	CSA/ANSI. HGV 3.1 Fuel System Components for	Remote	1	Damage	2	Low
On-board equipment	Fuel supply	Check valve from storage tank	Mechanical	high pressure	external release	H2 leak - small	unignited release	N	N	N	Using certified check valves: Compliance with	CSA/ANSI. HGV 3.1 Fuel System Components for	Remote	1	No Damage	0	Low
On-board equipment	Fuel supply	Check valve from storage tank	Mechanical	high pressure	external release	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	Using certified check valves: Compliance with	CSA/ANSI. HGV 3.1 Fuel System Components for	Remote	1	Damage	2	Low
On-board equipment	Fuel supply	Check valve from storage tank	Mechanical	high pressure	failure to open	no hydrogen flow	H2 pressure too low	N	N	N	Using certified check valves: Compliance with	CSA/ANSI. HGV 3.1 Fuel System Components for	Remote	1	Damage	2	Low
On-board equipment	Fuel supply	Check valve from storage tank	Material / substance	hydrogen material compatibility	H2 embrittlement	H2 leak - small	unignited release	N	N	N	selecting H2 compatible materials	ANSI/CSA CHMC 1 Test methods for evaluating mat	Improbable	0	No Damage	0	Low
On-board equipment	Fuel supply	Check valve from storage tank	Material / substance	hydrogen material compatibility	H2 embrittlement	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	selecting H2 compatible materials	ANSI/CSA CHMC 1 Test methods for evaluating mat	Improbable	0	Damage	2	Low
On-board equipment	Fuel supply	Check valve in the hydrogen	Mechanical	high pressure	fail to seal properly in the closed	H2 leak - small	unignited release	N	N	N	Redundancy. The receptacle has an	CSA/ANSI. HGV 3.1 Fuel System Components for	Remote	1	No Damage	0	Low
On-board equipment	Fuel supply	Check valve in the hydrogen	Mechanical	high pressure	fail to seal properly in the closed	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	Redundancy. The receptacle has an	CSA/ANSI. HGV 3.1 Fuel System Components for	Remote	1	Damage	2	Low
On-board equipment	Fuel supply	Check valve in the hydrogen	Mechanical	high pressure	stuck open with debris	H2 leak - small	unignited release	N	N	N	Redundancy. The receptacle has an	CSA/ANSI. HGV 3.1 Fuel System Components for	Remote	1	No Damage	0	Low
On-board equipment	Fuel supply	Check valve in the hydrogen	Mechanical	high pressure	stuck open with debris	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	Redundancy. The receptacle has an	CSA/ANSI. HGV 3.1 Fuel System Components for	Remote	1	Damage	2	Low
On-board equipment	Fuel supply	Check valve in the hydrogen	Mechanical	high pressure	excessively high or variable pressure	H2 leak - small	unignited release	N	N	N	Redundancy. The receptacle has an	CSA/ANSI. HGV 3.1 Fuel System Components for	Remote	1	No Damage	0	Low
On-board equipment	Fuel supply	Check valve in the hydrogen	Mechanical	high pressure	excessively high or variable pressure	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	Redundancy. The receptacle has an	CSA/ANSI. HGV 3.1 Fuel System Components for	Remote	1	Damage	2	Low
On-board equipment	Fuel supply	Check valve in the hydrogen	Mechanical	high pressure	external release	H2 leak - small	unignited release	N	N	N	Using certified check valves: Compliance with	CSA/ANSI. HGV 3.1 Fuel System Components for	Remote	1	No Damage	0	Low
On-board equipment	Fuel supply	Check valve in the hydrogen	Mechanical	high pressure	external release	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	Using certified check valves: Compliance with	CSA/ANSI. HGV 3.1 Fuel System Components for	Remote	1	Damage	2	Low
On-board equipment	Fuel supply	Check valve in the hydrogen	Mechanical	high pressure	failure to open	no hydrogen flow	H2 pressure too low	N	N	N	Using certified check valves: Compliance with	CSA/ANSI. HGV 3.1 Fuel System Components for	Remote	1	Damage	2	Low
On-board equipment	Fuel supply	Check valve in the hydrogen	Material / substance	hydrogen material compatibility	H2 embrittlement	H2 leak - small	unignited release	N	N	N	selecting H2 compatible materials	ANSI/CSA CHMC 1 Test methods for evaluating mat	Improbable	0	No Damage	0	Low
On-board equipment	Fuel supply	Check valve in the hydrogen	Material / substance	hydrogen material compatibility	H2 embrittlement	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	selecting H2 compatible materials	ANSI/CSA CHMC 1 Test methods for evaluating mat	Improbable	0	Damage	2	Low
On-board equipment	Fuel supply	Check valve in the hydrogen	Combination of risks	for example, repetitive activity + effort + high environmental temperature	mechanical failure of check valve +	air can go into a tank with hydrogen	explosion	Y	Y	Y	Using certified check valves	CSA/ANSI. HGV 3.1 Fuel System Components for	Improbable	0	Damage	2	Low
On-board equipment	Fuel supply	Excess flow valve	Mechanical	high pressure	fail to fully stop the flow during a	release of hydrogen to the	unignited release	N	N	N	Compliance with the CSA/ANSI HGV 3.1	CSA/ANSI. HGV 3.1 Fuel System Components for	Occasional	2	No Damage	0	Low
On-board equipment	Fuel supply	Excess flow valve	Mechanical	high pressure	fail to fully stop the flow during a	release of hydrogen to the	jet fire (immediate ignition)	Y	Y	N	Compliance with the CSA/ANSI HGV 3.1	CSA/ANSI. HGV 3.1 Fuel System Components for	Occasional	2	Damage	2	Low
On-board equipment	Fuel supply	Excess flow valve	Mechanical	high pressure	activates during normal operation	no hydrogen flow	H2 pressure too low	N	N	N	Compliance with the CSA/ANSI HGV 3.1	CSA/ANSI. HGV 3.1 Fuel System Components for	Improbable	0	Damage	2	Low
On-board equipment	Fuel supply	Excess flow valve	Mechanical	high pressure	fails to activate during a high flow	release of hydrogen to the	unignited release	N	N	N	Compliance with the CSA/ANSI HGV 3.1	CSA/ANSI. HGV 3.1 Fuel System Components for	Improbable	0	No Damage	0	Low
On-board equipment	Fuel supply	Excess flow valve	Mechanical	high pressure	fails to activate during a high flow	release of hydrogen to the	jet fire (immediate ignition)	Y	Y	N	Compliance with the CSA/ANSI HGV 3.1	CSA/ANSI. HGV 3.1 Fuel System Components for	Improbable	0	Damage	2	Low
On-board equipment	Fuel supply	Excess flow valve	Mechanical	high pressure	valve does not reset itself	no hydrogen flow	H2 pressure too low	N	N	N	Compliance with the CSA/ANSI HGV 3.1	CSA/ANSI. HGV 3.1 Fuel System Components for	Improbable	0	Damage	2	Low
On-board equipment	Fuel supply	Excess flow valve	Material / substance	hydrogen material compatibility	H2 embrittlement	H2 leak - small	unignited release	N	N	N	selecting H2 compatible materials	ANSI/CSA CHMC 1 Test methods for evaluating mat	Improbable	0	No Damage	0	Low
On-board equipment	Fuel supply	Excess flow valve	Material / substance	hydrogen material compatibility	H2 embrittlement	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	selecting H2 compatible materials	ANSI/CSA CHMC 1 Test methods for evaluating mat	Improbable	0	Damage	2	Low
On-board equipment	Fuel supply	Filter	Mechanical	high pressure	blocked filter	no hydrogen flow	H2 pressure too low	N	N	N	Add a low pressure sensor upstream from	CSA/ANSI. HGV 3.1 Fuel System Components for	Remote	1	Damage	2	Low
On-board equipment	Fuel supply	Filter	Mechanical	high pressure	external release	H2 leak - small	unignited release	N	N	N	Ventilation	CSA/ANSI. HGV 3.1 Fuel System Components for	Occasional	2	No Damage	0	Low
On-board equipment	Fuel supply	Filter	Mechanical	high pressure	external release	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	Ventilation	CSA/ANSI. HGV 3.1 Fuel System Components for	Occasional	2	Damage	2	Low
On-board equipment	Fuel supply	Filter	Mechanical	high pressure	release of debris in the fuel line	H2 leak - small	unignited release	N	N	N	Ventilation	CSA/ANSI. HGV 3.1 Fuel System Components for	Remote	1	No Damage	0	Low
On-board equipment	Fuel supply	Filter	Mechanical	high pressure	release of debris in the fuel line	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	Ventilation	CSA/ANSI. HGV 3.1 Fuel System Components for	Remote	1	Damage	2	Low
On-board equipment	Fuel supply	Filter	Mechanical	high pressure	release of debris in the fuel line	uncontrolled release of debris into	fuel cell poisoning / fuel starvation / fuel	N	Y	N	Ventilation	CSA/ANSI. HGV 3.1 Fuel System Components for	Remote	1	Damage	2	Low

On-board equipment	Fuel supply	Fuel port (SAE J-port)	Electrical	disconnection / miswiring / control failure	over-fill of fuel tank	H2 leak - large	unignited release	N	N	N	FCU	SAE. J2799 Hydrogen Surface Vehicle to Station	Remote	1	No Damage	0	Low	
On-board equipment	Fuel supply	Fuel port (SAE J-port)	Electrical	disconnection / miswiring / control failure	valve staying in closed position	fuel over-pressure	unignited release	N	N	N	FCU, pressure relief valve	SAE. J2799 Hydrogen Surface Vehicle to Station	Occasional	2	No Damage	0	Low	
On-board equipment	Fuel supply	Fuel port (SAE J-port)	Electrical	disconnection / miswiring / control failure	valve staying in closed position	fuel over-pressure	jet fire (immediate ignition)	Y	Y	N	FCU, pressure relief valve	SAE. J2799 Hydrogen Surface Vehicle to Station	Occasional	2	Damage	2	Low	
On-board equipment	Fuel supply	Fuel port (SAE J-port)	Electrical	disconnection / miswiring / control failure	incorrect pre-purge of fuel	combustible mixture in fuel supply	jet fire (immediate ignition)	Y	Y	N	FCU	SAE. J2799 Hydrogen Surface Vehicle to Station	Improbable	0	Damage	2	Low	
On-board equipment	Fuel supply	hydrogen tank	Mechanical	approach/departure of a moving element to a fixed part	crash induced damage or	H2 leak - large	fire ball and blast wave	Y	Y	Y	1. Tank mounting can withstand adequate Gg-	CSA. B51 Boiler, Pressure Vessel, and Pressure	Remote	1	Severe/Catastrophic	4	Medium	
On-board equipment	Fuel supply	hydrogen tank	Mechanical	high pressure	Mechanical failure	H2 leak - small	unignited release	N	N	N	1. No ignition sources.	CSA. B51 Boiler, Pressure Vessel, and Pressure	Occasional	2	No Damage	0	Low	
On-board equipment	Fuel supply	hydrogen tank	Mechanical	high pressure	Mechanical failure	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	1. No ignition sources.	CSA. B51 Boiler, Pressure Vessel, and Pressure	Remote	1	Damage	2	Low	
On-board equipment	Fuel supply	hydrogen tank	Material / substance	hydrogen material compatibility	H2 embrittlement	H2 leak - small	unignited release	N	N	N	selecting H2 compatible materials, H2 sensor,	CSA. TS-601 Hydrogen Fuel Cell Power Systems for	Improbable	0	No Damage	0	Low	
On-board equipment	Fuel supply	hydrogen tank	Material / substance	hydrogen material compatibility	H2 embrittlement	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	selecting H2 compatible materials, H2 sensor,	CSA. TS-601 Hydrogen Fuel Cell Power Systems for	Improbable	0	Damage	2	Low	
On-board equipment	Fuel supply	Integrated check valve within	Mechanical	high pressure	fail to seal properly in the closed	H2 leak - small	unignited release	N	N	N	Using certified check valves: Compliance with	CSA/ANSI. HGV 3.1 Fuel System Components for	Remote	1	No Damage	0	Low	1
On-board equipment	Fuel supply	Integrated check valve within	Mechanical	high pressure	fail to seal properly in the closed	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	Using certified check valves: Compliance with	CSA/ANSI. HGV 3.1 Fuel System Components for	Remote	1	Damage	2	Low	1
On-board equipment	Fuel supply	Integrated check valve within	Mechanical	high pressure	excessively high or variable pressure	H2 leak - small	unignited release	N	N	N	Using certified check valves: Compliance with	CSA/ANSI. HGV 3.1 Fuel System Components for	Remote	1	No Damage	0	Low	1
On-board equipment	Fuel supply	Integrated check valve within	Mechanical	high pressure	excessively high or variable pressure	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	Using certified check valves: Compliance with	CSA/ANSI. HGV 3.1 Fuel System Components for	Remote	1	Damage	2	Low	1
On-board equipment	Fuel supply	Integrated check valve within	Mechanical	high pressure	external release	H2 leak - small	unignited release	N	N	N	Using certified check valves: Compliance with	CSA/ANSI. HGV 3.1 Fuel System Components for	Remote	1	No Damage	0	Low	1
On-board equipment	Fuel supply	Integrated check valve within	Mechanical	high pressure	external release	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	Using certified check valves: Compliance with	CSA/ANSI. HGV 3.1 Fuel System Components for	Remote	1	Damage	2	Low	1
On-board equipment	Fuel supply	Integrated check valve within	Mechanical	high pressure	failure to open	no hydrogen flow	H2 pressure too low	N	N	N	Using certified check valves: Compliance with	CSA/ANSI. HGV 3.1 Fuel System Components for	Remote	1	Damage	2	Low	
On-board equipment	Fuel supply	Integrated check valve within	Combination of risks	for example, repetitive activity + effort + high environmental temperature	mechanical failure of check valve in	air can go into a tank with hydrogen	explosion	Y	Y	Y	Using certified check valves	CSA/ANSI. HGV 3.1 Fuel System Components for	Improbable	0	Damage	2	Low	
On-board equipment	Fuel supply	Main shutoff valve for onboar	Mechanical	high pressure	shutoff valve component damage	H2 leak - small	unignited release	N	N	N	1. Two valves in series for redundancy.	CSA. C22.2 No. 139 Electrically Operated Valves.	Remote	1	No Damage	0	Low	
On-board equipment	Fuel supply	Main shutoff valve for onboar	Mechanical	high pressure	shutoff valve component damage	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	1. Two valves in series for redundancy.	CSA. C22.2 No. 139 Electrically Operated Valves.	Remote	1	Damage	2	Low	
On-board equipment	Fuel supply	Main shutoff valve for onboar	Mechanical	high pressure	fail to close leaving the system	H2 leak - small	unignited release	N	N	N	1. Two valves in series for redundancy.	CSA. C22.2 No. 139 Electrically Operated Valves.	Remote	1	No Damage	0	Low	
On-board equipment	Fuel supply	Main shutoff valve for onboar	Mechanical	high pressure	fail to close leaving the system	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	1. Two valves in series for redundancy.	CSA. C22.2 No. 139 Electrically Operated Valves.	Remote	1	Damage	2	Low	
On-board equipment	Fuel supply	Main shutoff valve for onboar	Electrical	disconnection / miswiring / control failure	valve closes or fails to open stopping	fuel starvation to FC	over-temp and low voltage	N	Y	N	min. stack voltage alarm, FCU	CSA. C22.2 No. 61508-1 Functional Safety of	Occasional	2	Damage	2	Low	
On-board equipment	Fuel supply	Main shutoff valve for onboar	Electrical	disconnection / miswiring / control failure	valve closes or fails to open stopping	fuel starvation to FC	fire (in the cell) [over-temp, fuel cell	N	Y	N	min. stack voltage alarm, FCU	CSA. C22.2 No. 61508-1 Functional Safety of	Occasional	2	Damage	2	Low	
On-board equipment	Fuel supply	Main shutoff valve for onboar	Electrical	parts which have become live under fault conditions	environmental damage to wiring	electrocution (12 or 24 V)	physical injury (contact burn to skin)	Y	N	N	continual fault detection, grounding of non-fc	CSA. C22.2 No. 61508-1 Functional Safety of	Remote	1	Minor damage	1	Low	
On-board equipment	Fuel supply	Main shutoff valve for onboar	Electrical	short-circuit	valve fail open	downstream release of H2 into	none - redundancy in system prevents	N	N	N	redundant valves in system design	CSA. C22.2 No. 61508-1 Functional Safety of	Occasional	2	No Damage	0	Low	
On-board equipment	Fuel supply	Main shutoff valve for onboar	Electrical	short-circuit	valve fail closed	fuel starvation to FC	damage to FC	N	Y	N	low voltage detection and shutdown by FCU,	CSA. C22.2 No. 61508-1 Functional Safety of	Occasional	2	Damage	2	Low	
On-board equipment	Fuel supply	Main shutoff valve for onboar	Electrical	short-circuit	valve fail partial open	downstream release of H2 into	none - redundancy in system prevents	N	N	N	redundant valves in system design	CSA. C22.2 No. 61508-1 Functional Safety of	Occasional	2	No Damage	0	Low	
On-board equipment	Fuel supply	Main shutoff valve for onboar	Electrical	short-circuit	valve fail partial closed	partial fuel starvation to FC	damage to FC	N	Y	N	low voltage detection and shutdown by FCU,	CSA. C22.2 No. 61508-1 Functional Safety of	Occasional	2	Damage	2	Low	
On-board equipment	Fuel supply	Main shutoff valve for onboar	Material / substance	hydrogen material compatibility	shutoff valve component damage	H2 leak - small	unignited release	N	N	N	1. Two valves in series for redundancy.	ANSI/CSA CHMC 1 Test methods for evaluating	Improbable	0	No Damage	0	Low	
On-board equipment	Fuel supply	Main shutoff valve for onboar	Material / substance	hydrogen material compatibility	shutoff valve component damage	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	1. Two valves in series for redundancy.	ANSI/CSA CHMC 1 Test methods for evaluating	Remote	1	Damage	2	Low	
On-board equipment	Fuel supply	Main shutoff valve for onboar	Material / substance	hydrogen material compatibility	component damage from hydrogen	H2 leak - small	unignited release	N	N	N	1. Two valves in series for redundancy.	ANSI/CSA CHMC 1 Test methods for evaluating	Improbable	0	No Damage	0	Low	
On-board equipment	Fuel supply	Main shutoff valve for onboar	Material / substance	hydrogen material compatibility	component damage from hydrogen	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	1. Two valves in series for redundancy.	ANSI/CSA CHMC 1 Test methods for evaluating	Remote	1	Damage	2	Low	
On-board equipment	Fuel supply	Onboard hydrogen supply pur	Mechanical	high pressure	mechanical or control failure	H2 leak - small	fire (in the cell)	N	Y	N	1. Controls compliant with applicable	CAN/CSA. C22.2 No. 61010-1 Safety Requirements	Remote	1	Damage	2	Low	
On-board equipment	Fuel supply	Onboard hydrogen supply pur	Mechanical	high pressure	mechanical or control failure	H2 leak - large	explosion (in the cell)	Y	Y	N	1. Controls compliant with applicable	CAN/CSA. C22.2 No. 61010-1 Safety Requirements	Remote	1	Major Damage	3	Low	
On-board equipment	Fuel supply	Onboard hydrogen supply pur	Electrical	disconnection / miswiring / control failure	electrical failure de-energizing the	H2 leak - small	fire (in the cell)	N	Y	N	1. Controls compliant with applicable	CAN/CSA. C22.2 No. 61010-1 Safety Requirements	Remote	1	Damage	2	Low	
On-board equipment	Fuel supply	Onboard hydrogen supply pur	Electrical	disconnection / miswiring / control failure	electrical failure de-energizing the	H2 leak - large	explosion (in the cell)	Y	Y	N	1. Controls compliant with applicable	CAN/CSA. C22.2 No. 61010-1 Safety Requirements	Remote	1	Major Damage	3	Low	
On-board equipment	Fuel supply	Pressure regulator for onboar	Mechanical	high pressure	miss-adjustment	H2 leak - small	unignited release	N	N	N	1. TPRD are vented to an open air high safe	CGA. G-5.5 Standard for Hydrogen Vent Systems.	Occasional	2	No Damage	0	Low	
On-board equipment	Fuel supply	Pressure regulator for onboar	Mechanical	high pressure	miss-adjustment	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	1. TPRD are vented to an open air high safe	CGA. G-5.5 Standard for Hydrogen Vent Systems.	Occasional	2	Damage	2	Low	
On-board equipment	Fuel supply	Pressure regulator for onboar	Mechanical	high pressure	malfunction	H2 leak - small	unignited release	N	N	N	1. TPRD are vented to an open air high safe	CGA. G-5.5 Standard for Hydrogen Vent Systems.	Occasional	2	No Damage	0	Low	
On-board equipment	Fuel supply	Pressure regulator for onboar	Mechanical	high pressure	malfunction	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	1. TPRD are vented to an open air high safe	CGA. G-5.5 Standard for Hydrogen Vent Systems.	Occasional	2	Damage	2	Low	
On-board equipment	Fuel supply	Pressure regulator for onboar	Mechanical	high pressure	Mechanical failure	H2 leak - small	unignited release	N	N	N	1. Active proved ventilation.	CSA/ANSI. FC 1 CSA C22.2 No. 62282-3-100 Fuel	Occasional	2	No Damage	0	Low	
On-board equipment	Fuel supply	Pressure regulator for onboar	Mechanical	high pressure	Mechanical failure	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	1. Active proved ventilation.	CSA/ANSI. FC 1 CSA C22.2 No. 62282-3-100 Fuel	Remote	1	Damage	2	Low	
On-board equipment	Fuel supply	Pressure regulator for onboar	Material / substance	hydrogen material compatibility	H2 embrittlement	H2 leak - small	unignited release	N	N	N	selecting H2 compatible materials	ANSI/CSA CHMC 1 Test methods for evaluating mat	Improbable	0	No Damage	0	Low	
On-board equipment	Fuel supply	Pressure regulator for onboar	Material / substance	hydrogen material compatibility	H2 embrittlement	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	selecting H2 compatible materials	ANSI/CSA CHMC 1 Test methods for evaluating mat	Improbable	0	Damage	2	Low	
On-board equipment	Fuel supply	PRV for onboard hydrogen su	Mechanical	high pressure	during an overpressure scenario,	H2 leak - small	unignited release	N	N	N	1. Active proved ventilation.	CSA/ANSI. FC 1 CSA C22.2 No. 62282-3-100 Fuel	Remote	1	No Damage	0	Low	
On-board equipment	Fuel supply	PRV for onboard hydrogen su	Mechanical	high pressure	during an overpressure scenario,	H2 leak - large	asphyxiation hazard at the rupture	Y	N	N	1. Active proved ventilation.	CSA/ANSI. FC 1 CSA C22.2 No. 62282-3-100 Fuel	Improbable	0	Severe/Catastrophic	4	Low	
On-board equipment	Fuel supply	PRV for onboard hydrogen su	Mechanical	high pressure	during an overpressure scenario,	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	1. Active proved ventilation.	CSA/ANSI. FC 1 CSA C22.2 No. 62282-3-100 Fuel	Remote	1	Damage	2	Low	
On-board equipment	Fuel supply	PRV for onboard hydrogen su	Mechanical	high pressure	during an overpressure scenario,	H2 leak - large	fire (delayed ignition of accumulated H2)	Y	Y	N	1. Active proved ventilation.	CSA/ANSI. FC 1 CSA C22.2 No. 62282-3-100 Fuel	Remote	1	Damage	2	Low	
On-board equipment	Fuel supply	PRV for onboard hydrogen su	Mechanical	high pressure	during an overpressure scenario,	H2 leak - large	explosion (delayed ignition of	Y	Y	Y	1. Active proved ventilation.	CSA/ANSI. FC 1 CSA C22.2 No. 62282-3-100 Fuel	Improbable	0	Major Damage	3	Low	
On-board equipment	Fuel supply	PRV for onboard hydrogen su	Mechanical	high pressure	fails open due to mechanical failure	H2 leak - small	unignited release	N	N	N	1. PRV are vented to an open air high safe	CGA. G-5.5 Standard for Hydrogen Vent Systems.	Occasional	2	No Damage	0	Low	
On-board equipment	Fuel supply	PRV for onboard hydrogen su	Mechanical	high pressure	fails open due to mechanical failure	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	1. PRV are vented to an open air high safe	CGA. G-5.5 Standard for Hydrogen Vent Systems.	Remote	1	Damage	2	Low	
On-board equipment	Fuel supply	PRV for onboard hydrogen su	Material / substance	hydrogen material compatibility	H2 embrittlement	H2 leak - small	unignited release	N	N	N	selecting H2 compatible materials	ANSI/CSA CHMC 1 Test methods for evaluating mat	Improbable	0	No Damage	0	Low	
On-board equipment	Fuel supply	PRV for onboard hydrogen su	Material / substance	hydrogen material compatibility	H2 embrittlement	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	selecting H2 compatible materials	ANSI/CSA CHMC 1 Test methods for evaluating mat	Improbable	0	Damage	2	Low	
On-board equipment	Fuel supply	Stainless steel hydrogen lines	Mechanical	high pressure	inadequate design and	pipe burst	unignited release	N	N	N	Canadian Registration Number as per CSA	ASME. B31.12 Hydrogen Piping and Pipelines.	Remote	1	No Damage	0	Low	
On-board equipment	Fuel supply	Stainless steel hydrogen lines	Mechanical	high pressure	inadequate design and	pipe burst	jet fire (immediate ignition)	Y	Y	N	Canadian Registration Number as per CSA	ASME. B31.12 Hydrogen Piping and Pipelines.	Improbable	0	Damage	2	Low	
On-board equipment	Fuel supply	Stainless steel hydrogen lines	Electrical	electrostatic phenomena	flow rate creating charge	creates electrostatic discharge	fire (localized flame due to leaks)	Y	Y	N	Grounding and bonding in accordance to	CSA. C22.2 No. 0.4 Bonding of Electrical	Occasional	2	Damage	2	Low	
On-board equipment	Fuel supply	Stainless steel hydrogen lines	Vibration	worn parts	loosening of joints	H2 leak - small	unignited release	N	N	N	shock and vibration testing, e.g., MIL 810.h	CSA. TS-601 Hydrogen Fuel Cell Power Systems for	Occasional	2	No Damage	0	Low	
On-board equipment	Fuel supply	Stainless steel hydrogen lines	Vibration	worn parts	loosening of joints	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	shock and vibration testing, e.g., MIL 810.h	CSA. TS-601 Hydrogen Fuel Cell Power Systems for	Remote	1	Damage	2	Low	
On-board equipment	Fuel supply	TPRD protecting the onboard	Mechanical	high pressure	open due to mechanical failure	H2 leak - small	unignited release	N	N	N	1. TPRD are vented to an open air high safe	CSA/ANSI. HPRD 1 Thermally Activated Pressure	Remote	1	No Damage	0	Low	
On-board equipment	Fuel supply	TPRD protecting the onboard	Mechanical	high pressure	open due to mechanical failure	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	1. TPRD are vented to an open air high safe	CSA/ANSI. HPRD 1 Thermally Activated Pressure	Remote	1	Damage	2	Low	
On-board equipment	Fuel supply	TPRD protecting the onboard	Thermal	flame	open in case of fire	H2 leak - small	unignited release	N	N	N	Preventive measures: 1. TPRD are vented to	CSA. TS-601 Hydrogen Fuel Cell Power Systems for	Remote	1	No Damage	0	Low	
On-board equipment	Fuel supply	TPRD protecting the onboard	Thermal	flame	open in case of fire	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	Preventive measures: 1. TPRD are vented to	CSA. TS-601 Hydrogen Fuel Cell Power Systems for	Remote	1	Damage	2	Low	
On-board equipment	Fuel supply	TPRD protecting the onboard	Thermal	flame	fail to open in case of fire due to	H2 leak - large	fire ball and blast wave	Y	Y	Y	Preventive measures: 1. Two TPRDs per tank.	CSA/ANSI. HPRD 1 Thermally Activated Pressure	Improbable	0	Severe/Catastrophic	4	Low	
On-board equipment	Fuel supply	TPRD protecting the onboard	Thermal	flame	inadequate tank/TPRD arrangement	H2 leak - large	fire ball and blast wave	Y	Y	Y	Preventive measures: 1. Two TPRDs per tank	CSA. B51 Boiler, Pressure Vessel, and Pressure	Remote	1	Severe/Catastrophic	4	Medium	
On-board equipment	Fuel supply	TPRD protecting the onboard	Thermal	objects or materials with a high or low temperature	open in case of overheating	H2 leak - small	unignited release	N	N	N	Preventive measures: 1. TPRD are vented to	CSA. B51 Boiler, Pressure Vessel, and Pressure	Remote	1	No Damage	0	Low	
On-board equipment	Fuel supply	TPRD protecting the onboard	Thermal	objects or materials with a high or low temperature	open in case of overheating	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	Preventive measures: 1. TPRD are vented to	CSA. B51 Boiler, Pressure Vessel, and Pressure	Remote	1	Damage	2	Low	
On-board equipment	Fuel supply	TPRD protecting the onboard	Thermal	objects or materials with a high or low temperature	fail to open in case of overheating	H2 leak - large	fire ball and blast wave	Y	Y	Y	Preventive measures: 1. Two TPRDs per tank.	CSA/ANSI. HPRD 1 Thermally Activated Pressure	Improbable	0	Severe/Catastrophic	4	Low	
On-board equipment	Fuel supply	TPRD protecting the onboard	Thermal	radiation from heat sources	open due to heat load in tunnel	uncontrolled release of H2 in tank	unignited release	N	N	N	verification testing	CSA. TS-601 Hydrogen Fuel Cell Power Systems for	Improbable	0	No Damage	0	Low	
On-board equipment	Fuel supply	TPRD protecting the onboard	Thermal	radiation from heat sources	open due to heat load in tunnel	uncontrolled release of H2 in tank	jet fire (immediate ignition)	Y	Y	N	verification testing	CSA. TS-601 Hydrogen Fuel Cell Power Systems for	Improbable	0	Damage	2	Low	
On-board equipment	Fuel supply	TPRD protecting the onboard	Thermal	radiation from heat sources	open due to heat load in tunnel	uncontrolled release of H2 in tank	explosion (delayed ignition of	Y	Y	Y	verification testing	CSA. TS-601 Hydrogen Fuel Cell Power Systems for	Improbable	0	Major Damage	3	Low	
On-board equipment	Fuel supply	TPRD protecting the onboard	Thermal	radiation from heat sources	open due to heat load in tunnel	uncontrolled release of H2 in tank	dizziness, fatigue, collapse	Y	N	N	verification testing	CSA. TS-601 Hydrogen Fuel Cell Power Systems for	Improbable	0	Damage	2	Low	
On-board equipment	Fuel supply	TPRD protecting the onboard	Thermal	radiation from heat sources	open due to heat load in tunnel	uncontrolled release of H2 in tank	asphyxiation	Y	N	N	verification testing	CSA. TS-601 Hydrogen Fuel Cell Power Systems for	Improbable	0	Severe/Catastrophic	4	Low	
On-board equipment	Fuel supply	TPRD protecting the onboard	Material / substance	hydrogen material compatibility	H2 embrittlement	H2 leak - small	unignited release	N	N	N	selecting H2 compatible materials, ANSI/CSA	CSA/ANSI. HPRD 1 Thermally Activated Pressure	Improbable	0	No Damage	0	Low	
On-board equipment	Fuel supply	TPRD protecting the onboard	Material / substance	hydrogen material compatibility	H2 embrittlement	H2 leak - large	jet fire (immediate ignition)	Y	Y	N	selecting H2 compatible materials, ANSI/CSA	CSA/ANSI. HPRD 1 Thermally Activated Pressure	Improbable	0	Damage	2	Low	
On-board equipment	Fuel supply	Vent line	Mechanical	high pressure	selection of vent location	during venting, high pressure	physical injury	Y	N	N	verification testing	CGA. G-5.5 Standard for Hydrogen Vent Systems.	Improbable	0	Damage	2	Low	
On-board equipment	Fuel supply	Vent line	Material / substance	combustible	H2 gas venting (normal function)	combustible mixture released from	unignited release	N	N	N	verification testing	CGA. G-5.5 Standard for Hydrogen Vent Systems.	Remote	1	No Damage	0	Low	
On-board equipment	Fuel supply	Vent line	Material / substance	combustible	H2 gas venting (normal function)	combustible mixture released from	jet fire (immediate ignition)	Y	Y	N	verification testing	CGA. G-5.5 Standard for Hydrogen Vent Systems.	Remote	1	Damage	2	Low	
On-board equipment	Fuel supply	Vent line	Material / substance	explosive	H2 gas venting (normal function)	potentially explosive mixture	fire ball and blast wave	Y	Y	Y	verification testing, separate risk assessment	CGA. G-5.5 Standard for Hydrogen Vent Systems.	Remote	1	Severe/Catastrophic	4	Medium	
On-board equipment	Fuel supply	Vent line	Environment	lack of oxygen	H2 gas venting in enclosed space	reduction of O2 centration < 20.9%	dizziness, fatigue, collapse	Y	N	N	verification testing, separate risk assessment	CGA. G-5.5 Standard for Hydrogen Vent Systems.	Remote	1	Damage	2	Low	
On-board equipment	Fuel supply	Vent line	Environment	lack of oxygen	H2 gas venting in enclosed space	reduction of O2 centration < 20.9%	asphyxiation	Y	N	N	verification testing, separate risk assessment	ANSI/CSA. America FC 3 Portable Fuel Cell Power Sy	Improbable	0	Severe/Catastrophic	4	Low	
On-board equipment	Oxidant circuit	Air filter	Vibration	worn parts	air supply to FCS blocked due to	insufficient air flow and / or	fire (in the cell) [overheating in cell]	N	Y	N	FCU, pressure transducer	ANSI/CSA. America FC 3 Portable Fuel Cell Power Sy	Improbable	0	Damage	2	Low	
On-board equipment	Oxidant circuit	Air filter	Material / substance	dust	air supply to FCS blocked due to	insufficient air flow and / or	fire (in the cell) [overheating in cell]	N	Y	N	FCU, pressure transducer, maintenance	CSA. C22.2 No. 0.4 Bonding of Electrical Equipment.	Improbable	0	Damage	2	Low	
On-board equipment	Oxidant circuit	Cathode exhaust	Electrical	live parts	coolant conductivity too high	cathode exhaust voltage >50 V	electrocution; potential cardiac arrest	Y	N	N	FCU, ground fault detection, isolation	CSA. C22.2 No. 0.4 Bonding of Electrical Equipment.	Occasional	2	Damage	2	Low	
On-board equipment	Oxidant circuit	Cathode exhaust	Electrical	live parts	insufficient air gaps during design	cathode exhaust voltage >50 V	electrocution; potential cardiac arrest	Y	N	N	FCU, ground fault detection, isolation	CSA. C22.2 No. 0.4 Bonding of Electrical Equipment.	Remote	1	Damage	2	Low	
On-board equipment	Oxidant circuit	Cathode exhaust	Material / substance	combustible	venting of un-reacted hydrogen into	>4% H2 in air mixture in cathode	unignited release	N	N	N	H2 concentration in cathode exhaust	CSA/ANSI. FC 1 CSA C22.2 No. 62282-3-100 Fuel	Probable	3	No Damage	0	Low	
On-board equipment	Oxidant circuit	Cathode exhaust	Material / substance	combustible	venting of un-reacted hydrogen into	>4% H2 in air mixture in cathode	jet fire (immediate ignition)	Y	Y	N	H2 concentration in cathode exhaust, H2	CSA/ANSI. FC 1 CSA C22.2 No. 62282-3-100 Fuel	Remote	1	Damage	2	Low	
On-board equipment	Oxidant circuit	Cathode exhaust	Material / substance	gas	venting of nitrogen (from	reduction of O2 centration < 20.9%	dizziness, fatigue, collapse	Y	N	N	Ventilation system, oxygen monitor	CSA/ANSI. FC 1 CSA C22.2 No. 62282-3-100 Fuel	Improbable	0	Damage	2	Low	
On-board equipment	Oxidant circuit	Cathode exhaust	Material / substance	gas	venting of nitrogen (from	reduction of O2 centration < 20.9%	asphyxiation	Y	N	N	Ventilation system, oxygen monitor	CSA/ANSI. FC 1 CSA C22.2 No. 62282-3-100 Fuel	Improbable	0	Severe/Catastrophic	4	Low	
On-board equipment	Oxidant circuit	Cathode exhaust	Material / substance	gas	venting of un-reacted hydrogen into	reduction of O2 centration < 20.9%	dizziness, fatigue, collapse	Y	N	N	Ventilation system, oxygen monitor	CSA/ANSI. FC 1 CSA C22.2 No. 62282-3-100 Fuel	Improbable	0	Damage	2	Low	
On-board equipment	Oxidant circuit	Cathode exhaust	Material / substance	gas	venting of un-reacted hydrogen into	reduction of O2 centration < 20.9%	asphyxiation	Y	N	N	Ventilation system, oxygen monitor	CSA/ANSI. FC 1 CSA C22.2 No. 62282-3-100 Fuel	Improbable	0	Severe/Catastrophic	4	Low	
On-board equipment	Oxidant circuit	Product water	Environment	temperature	disposal of product water generated	localized ice on railroad tracks	slip hazard	Y	N	N	proper storage and containment of product	CSA. TS-601 Hydrogen Fuel Cell Power Systems for I	Improbable	0	Damage	2	Low	
On-board equipment	Oxidant circuit	Product water	Environment	temperature	disposal of product water generated	localized ice on railroad tracks	inoperable switches, reduce wheel rail	Y	Y	N	proper storage and containment of product	CSA. TS-601 Hydrogen Fuel Cell Power Systems for I	Remote	1	Major Damage	3	Low	