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PRESS Passenger Systems Working Group

Battery-Electric and Hydrogen Passenger Rail Equipment Safety

Abstract: This white paper introduces proposed best practices for managing risks from onboard alternative propulsion energy systems utilizing batteries and/or hydrogen on passenger rail equipment.

Keywords: battery-electric, tank (compressed gas), crew, facilities, first responder, fuel cell, hazard, high-pressure piping and equipment, hydrogen, low-pressure piping and equipment, maintenance personnel, mitigation, training, wayside

Summary: As the industry moves toward environmentally-friendly solutions for passenger rail equipment, battery and hydrogen are two common onboard alternative propulsion energy systems being advanced. The hazards and potential mitigations identified in this white paper are specific to such equipment and are intended to guide agencies in performing their project-specific hazard analyses to reduce risk in equipment designs, maintenance and operations.

Foreword

The American Public Transportation Association is a standards development organization in North America. The process of developing standards is managed by the APTA Standards Program's Standards Development Oversight Council (SDOC). These activities are carried out through several standards policy and planning committees that have been established to address specific transportation modes, safety and security requirements, interoperability, and other topics.

APTA used a consensus-based process to develop this document and its continued maintenance, which is detailed in the manual for the APTA Standards Program. This document was drafted in accordance with the approval criteria and editorial policy as described. Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

This document was prepared by the Passenger Systems Working Group's Battery-Electric and Hydrogen Passenger Rail Committee as directed by the Passenger Rail Equipment Safety Standards Policy and Planning Committee.

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Participants

The American Public Transportation Association greatly appreciates the contributions of the **Battery-Electric and Hydrogen Passenger Rail Committee**, which provided the primary effort in the drafting of this document. At the time of publication, the Subject Matter Expert Group included the following members:

Jackson Xue, Ricardo LLC, *Document Lead*
Dave Teumim, Teumim Technical, LLC, *Document Vice Lead*

Rocky Chong, *Televic US Corp*
Richard Drolet, *Alstom*
Brian Ehrhart, *Sandia National Laboratories*
Guillermo Leboriero Enriquez, *Talgo Inc.*
Stephen Jacobs, *WSP USA*
Robert Jones, *Stadler*
Uday Karmarkar, *Wabtec Corp.*
Joseph Kenas, *Alstom*
Yves Laperriere, *Alstom*
Tomoyuki Minami, *JR Central*
Manuel Cabellero Ocaña, *Talgo Inc.*
Frederic Porcher, *Alstom*
Alexander Ross, *Alstom*
Devin Rouse, *DCRail Advisory, LLC*
Gerhard Schmidt, *Siemens Mobility, Inc.*
Amal Tamim, *Mott MacDonald*
Marcin Taraszkiewicz, *HDR*
Steven Von Mach, *Alstom*
Shan Yang, *Alstom*
Chris Zappi, *Wabtec Corp.*

At the time this whitepaper was completed, the **Battery-Electric and Hydrogen Passenger Rail Committee** included the following members:

Jackson Xue, Ricardo LLC, *Document Lead*
Dave Teumim, Teumim Technical, LLC, *Document Vice Lead*

Troy Alvarez, *Hatch*
Graham Beal, *Network Rail Consulting*
Christopher Beringer, *DB ECO*
Anthony Brown, *Southern CA Reg. Rail Auth.*
William Carnegie, *Wabtec Corp.*
Rocky Chong, *Televic US Corp*
Steve Clay, *Federal Railroad Administration*
Bernard Cohen, *ACI Boston*
Joshua Coran, *Talgo*
Sean Cronin, *Metra*
Richard Drolet, *Alstom*
Brian Ehrhart, *Sandia National Laboratories*
Guillermo Leboreiro Enriquez, *Talgo*
Faye Farahmand, *STV, Inc.*
Gavin Fraser, *Jacobs*
Adam Gagne, *Siemens Mobility, Inc.*
Christian Gschnitzer-Baernthaler, *Stadler*
Venu Gupta, *Wabtec Corp.*
Trevor Hartford, *WSP USA*
Lew Hoens, *MTA Metro-North Commuter Railroad*
Chris Homison, *Wabtec Corp.*
Stephen Jacobs, *WSP USA*
Robert Jones, *Stadler*
Uday Karmarkar, *Wabtec Corp.*
Joseph Kenas, *Alstom*
Manjit Khalsa, *Santa Clara Valley Trans. Auth.*
Russell Kubycheck, *Progress Rail*
Chris LaFleur, *Sandia National Laboratories*
Pallavi Lal, *Hatch*
Yves Laperriere, *Alstom*
Victor Lopez, *San Bernardino County Transp. Auth.*
Jason Maher, *Brookville Equipment Corp.*
Francesco Maldari, *MTA Long Island Rail Road*
Liam Martin, *ABB, Inc*
Eloy Martinez, *HNTB*
Jack Martinson, *Stadler*
Joel McNeil, *Brookville Equipment Corp.*
James Michel, *AREMA*
Tomoyuki Minami, *JR Central*
Arash Monsefan, *PGH Wong Engineering, Inc.*

Marc Munger, *Alstom*
Malick Ba Niane, *STV, Inc.*
Max Nitke, *Railroad Development Corp.*
Bill O'Hair, *Valley Link Rail*
Jim Parker, *Raul V. Bravo + Associates, Inc.*
Devon Parsons, *Amtrak*
Rony Philip, *WSP USA*
Frederic Porcher, *Alstom*
Jeffery Pringle, *Raul V. Bravo + Associates, Inc*
Phani Raj, *Federal Railroad Administration*
Joseph Reynolds, *Metro-North Commuter Railroad*
Devin Rouse, *DC Rail Advisory*
Yvon Saint-Pierre, *Alstom*
Brian Schmidt, *San Joaquin Reg. Rail Commission*
Gerhard Schmidt, *Siemens Mobility, Inc.*
Martin Schroeder, *Jacobs*
Melissa Shurland, *Federal Railroad Administration*
Richard Spezzaferri, *WSP USA*
Michelle Stewart, *Southern CA Reg. Rail Auth.*
Laura Sullivan, *VOLPE Center*
Amal Tamim, *Mott MacDonald*
Marcin Taraszkiewicz, *HDR Inc.*
Christine Taute, *Sandia National Laboratories*
Branden Tolle, *STV, Inc.*
Salvatore Trapasso, *MBTA*
Rudy Vazquez, *Amtrak*
Stefan Von-Mach, *Alstom*
David Warner, *STV, Inc.*
Simon Wikstrom, *WSP Sweden*
David Williams, *Stadler*
Derek Wong, *DB ECO*
Shan Yang, *Alstom*
Christopher Zappi, *Wabtec*

At the time this whitepaper was completed, the **PRESS Passenger Systems Working Group** included the following members:

Carlos Perez, Southern California Regional Rail Authority, *Chair*
Yosi Grunberg, WSP Canada, LLC, *Vice Chair*
Marcin Taraszkiewicz, HDR Inc., *Secretary*

Troy Alvarez, *Hatch*
Mark Anderson, *Huber+Suhner, Inc.*
Carl Atencio, *American Rocky Mountaineer*
Andrew Aubert, *TDG International, Inc.*
Charles Barlow, *EverGlow NA Inc.*
Graham Beal, *Network Rail Consulting*
Jeffrey Bennett, *MxV Rail*
Christopher Beringer, *DB ECO*
James Brooks, *Utah Transit Authority*
Anthony Brown, *Southern CA Reg. Rail Auth.*
Bill Bruhn, *Jessip Manufacturing Company*
Paul Callaghan, *Transport Canada*
William Carnegie, *Wabtec Corp.*
Ed Carruthers, SEPTA
Rocky Chong, *Televic US Corp*
Vlad Ciobanu, *Siemens Mobility, Inc.*
Melvin Clark, *Hatch*
Steve Clay, *Federal Railroad Administration*
Bernard Cohen, *ACI Boston*
Joshua Coran, *Talgo*
Sean Cronin, *Metra*
Miles Crumley, *TriMet*
Rahul Dixit, *Hatch*
Richard Drolet, *Alstom*
Sebastian Durzynski, *TDG International Inc.*
Brian Ehrhart, *Sandia National Laboratories*
Guillermo Leboreiro Enriquez, *Talgo*
Phillippe Etchessahar, *Alstom*
Faye Farahmand, *STV, Inc.*
Steve Finegan, *AtkinsRéalis*
Norman Forde, *Mott MacDonald*
Gavin Fraser, *Jacobs*
Tom Freeman, *Intl. Name Plate Supplies Ltd.*
Adam Gagne, *Siemens*
Andre Gagne, *Alstom*
Marc Gagne, *TDG International Inc.*
Jeffrey Gordon, *Federal Railroad Administration*
Lowell Goudge, *Retired*
Christian Gschnitzer-Baernthaler, *Stadler*
Venu Gupta, *Wabtec Corp.*
Nick Harris, *Hatch*
Trevor Hartford, *WSP USA*
Juan Carlos Hernandez, *Mott MacDonald*
Lew Hoens, *MTA Metro-North Commuter Railroad*
Chris Homison, *Wabtec Corp.*
Stephen Jacobs, *WSP USA*

Robert Jones, *Stadler*
Uday Karmarkar, *Wabtec Corp.*
Joseph Kenas, *Alstom*
Manjit Khalsa, *Santa Clara Valley Trans. Auth.*
Christian Knapp, *Denver Transit Operators*
Tammy Krause, *STV, Inc.*
Russell Kubycheck, *Progress Rail*
Chris LaFleur, *Sandia National Laboratories*
Pallavi Lal, *Hatch*
Yves Laperriere, *Alstom*
Peter Lapre, *Federal Railroad Administration*
Victor Lopez, *San Bernardino County Transp. Auth.*
Jason Maher, *Brookville Equipment Corp.*
Francesco Maldari, *MTA Long Island Rail Road*
Liam Martin, *ABB, Inc*
Eloy Martinez, *HNTB*
Jack Martinson, *Stadler*
Joel McNeil, *Brookville Equipment Corp.*
James Michel, *AREMA*
Jonathan Michel, *Fourche Design*
Tomoyuki Minami, *JR Central*
Arash Monsefan, *PGH Wong Engineering, Inc.*
Marc Munger, *Alstom*
Thomas Newey, *Network Rail Consulting*
Malick Ba Niane, *STV, Inc.*
Max Nitke, *Railroad Development Corp.*
Bill O'Hair, *Valley Link Rail*
Jim Parker, *Raul V. Bravo + Associates, Inc.*
Devon Parsons, *Amtrak*
Thomas Peacock, *AtkinsRéalis*
Rony Philip, *WSP USA*
Frederic Porcher, *Alstom*
Jeffery Pringle, *Raul V. Bravo + Associates, Inc*
Phani Raj, *Federal Railroad Administration*
Joseph Reynolds, *Metro-North Commuter Railroad*
Scott Rodda, *Virginkar & Associates, Inc.*
Devin Rouse, *DC Rail Advisory*
Yvon Saint-Pierre, *Alstom*
Mehrdad Samani, Jacobs
Bryan Sawyer, *Utah Transit Authority*
Duane Sayers, *Regional Transportation District*
Brian Schmidt, *San Joaquin Reg. Rail Commission*
Gerhard Schmidt, *Siemens Mobility, Inc*
Martin Schroeder, *Jacobs*
Richard Seaton, *TDG International Inc.*
Kiyotaka Seki, *Railway Technical Research Institute*
Melissa Shurland, *Federal Railroad Administration*
David Skillman, *Amtrak*
Richard Spezzaferri, *WSP USA*
Michelle Stewart, *SCRRA*
Walt Stringer, *Walt Stringer & Associates*
Laura Sullivan, *VOLPE Center*
Lukasz Szmymsiak, *Via Rail Canada, Inc.*
Amal Tamim, *Mott MacDonald*
Christine Taute, *Sandia National Laboratories*
Dave Teumim, *Teumim Technical, LLC*
Branden Tolle, *STV, Inc.*
Salvatore Trapasso, *MBTA*
Rudy Vazquez, *Amtrak*
Stefan Von-Mach, *Alstom*
David Wade, *Intl. Name Plate Supplies, LLC*
Gary Wagner, *Amsted Rail*
David Warner, *STV, Inc.*
Simon Wikstrom, *WSP USA*
David Williams, *Stadler*
Derek Wong, *DB ECO*
Andrew Wood, *AtkinsRéalis*
Jackson Xue, *Ricardo LLC*
Shan Yang, *Alstom*
Christopher Zappi, *Wabtec*

Project team

Nathan Leventon, *American Public Transportation Association*
Bryan Sooter, *American Public Transportation Association*

Introduction

This introduction is not part of APTA PR-PS-WP-007-24, "Battery-Electric and Hydrogen Passenger Rail Safety."

This Whitepaper applies to all:

1. Railroads that operate intercity or commuter passenger train service on the general railroad system of transportation; and
2. Railroads that provide commuter or other short-haul rail passenger train service in a metropolitan or suburban area, including public authorities operating passenger train service.

This Whitepaper may apply to:

1. Rapid transit operations in an urban area that are not connected to the general railroad system of transportation;
2. Tourist, scenic, historic or excursion operations, whether on or off the general railroad system of transportation;
3. Operation of private railcars, including business/office railcars and circus trains; or
4. Railroads that operate only on track inside an installation that is not part of the general railroad system of transportation.

Scope and purpose

This white paper contains current and proposed best practices relative to hazards and mitigations pertaining to battery-electric and hydrogen fuel cell passenger rail equipment with onboard compressed hydrogen storage. The scope of the information is relative to the onboard equipment; however, hazards associated with appropriate key wayside facilities, as they interface with the vehicle (such as battery charging and hydrogen fueling), are also addressed. This document also introduces considerations that will be necessary for first responder, train crew and maintenance personnel training, as well as topics for future research.

This document may be used during the development of project-specific hazard analyses. It is noted, however, that the lists of hazards and potential mitigations are intended as guidance only and by no means intended to be exhaustive. This white paper does not remove the responsibility of the design engineer in determining the appropriate hazards and mitigations through design analyses. A full hazard assessment should take into account the vehicles and the associated infrastructure, systems and interoperability requirements.

This white paper is intended to be applied to the general railroad system under the jurisdiction of the Federal Railroad Administration and/or Transport Canada. However, as much of the technology is mode-agnostic, the information can be used by other transit agencies and public authorities.

Battery-Electric and Hydrogen Passenger Rail Equipment Safety

1. Hazard log considerations

Alternative power sources for North American rail vehicles are currently focused on lithium-ion (Li-ion) battery storage applications, often coupled with range extension using proton exchange membrane fuel cells (PEMFC), compressed hydrogen gas in Type 4 cylindrical pressure vessels, and high-pressure and low-pressure stainless steel piping and equipment.[1] The use of Li-ion batteries and flammable gases such as hydrogen for propulsion are new to the passenger rail sector. This white paper addresses only compressed hydrogen gas and fuel cell systems. However, liquid hydrogen storage systems and/or hydrogen combustion engines may be visited in the future as longer distance ranges for passenger rail are evaluated.

The hazard logs presented in this white paper seek to capture the best practices relative to the design and manufacture of Li-ion battery-electric (referred to in this white paper generically as *battery-electric*) and hydrogen fuel cell-powered (referred to generically as *hydrogen*) passenger rail equipment, along with their direct interfaces to the wayside infrastructure and considerations for operations and maintenance (O&M) personnel, train crew and first responders. The information is not intended to be exhaustive, and there may be additional or nonrelevant hazards and mitigations, depending on the specific project being evaluated.

The intent of this white paper is to ensure adherence to best design practices and consideration of applicable scenarios. Appropriate hazards and associated mitigations should be developed through design analyses at the project stage, and a full hazard assessment should consider the vehicles and the associated infrastructure, systems and interoperability requirements. As part of the assessment, users should parse hazards and mitigations to the appropriate stage of the vehicle life cycle (design, production, maintenance, etc.) in their hazard analyses. Where applicable, hazard and operability studies, layer of protection analyses, and/or failure modes and effects analyses should also be performed on the specific systems.

The hazard assessment should consider use of components and design processes applicable to the railroad environment and installation on a rail vehicle. Depending on the location of the project, local environmental factors (climate, alignment, infrastructure characteristics, etc.) should be accounted for. Furthermore, a study of lessons learned from other transportation modes (e.g., in the automotive, commercial road vehicles, aerospace or marine industries) may be beneficial in addressing hazards specific to battery-electric and

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[1] The hazard list and mitigations in this whitepaper were developed from the perspective of Li-Ion batteries, proton exchange membrane fuel cells, type 4 cylindrical pressure vessels (i.e., fully wrapped containers with nonmetallic liners, similar to those used in automotive standards such as CSA/ANSI HGV 2), and high-pressure and low-pressure stainless steel piping and equipment for passenger rail applications. Although other chemistries, fuel cell types, hydrogen containment systems, and piping and equipment exist and many of these hazards may also apply to them, they'll be addressed in a future update to the whitepaper once they've reached maturity.

hydrogen passenger rail equipment and may help in developing appropriate emergency preparedness procedures and maintenance practices.

Finally, there are parallel developments in the industry relative to standardization of requirements for alternative propulsion rail vehicles, as well as existing standards and regulations that govern other safety aspects of rail vehicle design. The information in this white paper is to be considered supplementary to, and is not intended to replace safety requirements covered by other standards and regulations that pertain to passenger rail equipment.

1.1 Subsystem

The hazard log is organized by subsystem type (e.g., battery, hydrogen), and further broken down into individual components as applicable (e.g., fuel cell, tank (compressed gas)).

All identified hazards are specific to the alternative propulsion sources in consideration and can be applied across different types of passenger rail equipment employing these technologies. These include general hazards; wayside/facilities hazards as they interface with the vehicle (e.g., storage of components that have been removed from the vehicle, charging and fueling hazards, vehicle storage); and considerations for emergency preparedness, inspection and maintenance.

1.2 Hazard

The hazards identified in this document represent those that are specific to onboard battery-electric and hydrogen passenger rail equipment. Wayside hazards that are identified are intended to address the interface to the vehicle directly and are presented at a high level. Additional hazards and mitigations with the static installations will need to be discussed with the appropriate experts and authorities having jurisdiction. This white paper does not detail generic hazards and mitigations (such as those for heavy equipment or sharp edges) that would otherwise be covered by other industry standards and regulations. However, there are several established best practices/mitigations that are recommended to be considered:

- Evaluation of need/feasibility for fire suppression and separation for traction batteries[2]
- Employment of circuit protection from lightning and overload
- Employment of hydrogen detection, ventilation, shutdown and ignition control for mitigation and maintenance/inspection purposes
- Evaluation of the operating environment, along with associated potential hazards (e.g., live wires from overhead contact system, third rail, utility lines)
- Consideration of roof hatches to facilitate emergency roof access/egress (instead of cutting into a structural weak point)
- Calibration of safety-critical components, tools and devices, inclusive of tests to check proper operation
- Use of proper personal protective equipment relevant to the component or system being maintained
- Definition of monitoring devices in the railroad’s inspection, testing, operations, and maintenance plan, inclusive of procedures, frequencies, etc.
- Following of original equipment manufacturer procedures for vehicle and component storage (such as for maintenance and service life considerations), so as to not introduce unintended hazards during use or operation

[2] Depending on the battery chemistry being used, full extinguishment of a battery fire may not be possible, and current practice would be to let the battery burn out. However, it is recommended that feasibility of an onboard fire protection system be evaluated from the perspective of mitigating propagation and providing sufficient time for passengers and crew to evacuate to safety.

- Evaluation of hardware and software safety (including cybersecurity) used in monitoring and controlling the onboard battery and hydrogen systems
- Assessment of onboard systems and components for battery and hydrogen systems in accordance with the "safety-critical" definition per 49 CFR 238.5

1.3 Cause

The causes identified in the hazard logs have been generalized but are unique to the specific subsystem under consideration. These are the events that may lead to a negative safety outcome if left unmitigated. These events include, for example, mechanical penetration or thermal runaway of batteries, and over-temperature and over-pressure of hydrogen storage tanks. There may be additional causes for these alternative propulsion technologies depending on the equipment or components to be installed, hence the full evaluation should be performed during the vehicle design and hazard analysis stages.

1.4 Consequences

The consequences identified represent possible outcomes from the cause and the associated hazard. They have been generalized to indicate the impacts to the onboard equipment, the vehicle in general, the environment, and personnel (e.g., passengers, crew, first responders). The hazards, causes and consequences inform the mitigations to be established that reduce the risks from the hazards and their consequences to an acceptable level.

1.5 Potential mitigations

The potential mitigations identified in this white paper represent current industry best practices in addressing the hazards associated with battery-electric and hydrogen passenger rail equipment. It is not intended that a vehicle meet all the mitigations identified (e.g., a particular selection of battery chemistry may be balanced against use of other mitigation measures). Relevant project-specific mitigations will need to be developed during the design process, and there may be additional mitigations that may be applicable but have not been covered in this white paper. It is incumbent on the design engineer and the railroad's safety committee to identify the appropriate hazards and mitigations that are dependent on the specific needs and environment of the project. Also, in instances where continued or degraded mode operations may be permissible depending on the nature of the failure, the original equipment manufacturer (OEM), the railroad, authorities having jurisdiction, and emergency responders shall jointly coordinate the process to allow the equipment to continue operations until the issue can be addressed. In addition, where applicable, first responder agencies (e.g., local and state fire departments) and authorities having jurisdiction (e.g., FRA) should be engaged early in the project so that appropriate emergency response procedures (e.g., per 49 CFR 239) and system safety cases (e.g., per 49 CFR 270) can be developed.

1.6 Organization of white paper

This white paper introduces hazards and mitigations associated with the onboard traction batteries first, followed by those associated with the onboard hydrogen system. Modern hydrogen passenger rail equipment utilizes traction batteries for motive power, with the onboard fuel cell system serving as a range extender. As such, many of the hazards and mitigations associated with the traction batteries are also applicable for hydrogen passenger rail equipment. Additional hazards and mitigations have been identified for direct interfaces between the wayside and the onboard.

Regarding topics that require a better understanding of potential hazards and mitigations, a section on future research has been developed.

Where applicable, standard references in this document have been dated by the year of reference. The use of future iterations of these referenced standards will be reviewed by the working group and addressed in future updates to this white paper.

2. Hazard log

2.1 Battery

2.1.1 Li-ion traction battery

The hazards and mitigations described in this section are specifically for the family of lithium-ion (Li-ion) traction batteries, as these are employed in current designs of passenger rail equipment. Additional considerations would be necessary for other battery types.

TABLE 1
Battery Hazard Log

Hazard	Cause	Consequences	Potential Mitigations
1. Fire originating from batteries	Overcharging and discharging	Fire source threatening passenger compartment and surrounding equipment	1. Follow OEM procedures for safe design and integration of battery systems into vehicle, operations and maintenance (charging and discharging). 2. Ensure safe monitoring and control of battery cell/module status (voltage, current, temperature) with automatic switch-off of battery when cell/module parameters are out of recommended range.
2. Fire originating from batteries	Mechanical penetration	Fire source threatening passenger compartment and surrounding equipment	1. Use battery box with sufficient resistance to penetration from wayside objects (e.g., ballast, loose track materials, etc.), and/or provide external protections. 2. Locate batteries to mitigate impact from mechanical penetration.
3. Fire originating from batteries	Collision	Fire source threatening passenger compartment and surrounding equipment	1. Design for appropriate collision scenarios specific to the applicable operation, environment and vehicle design. 2. Locate and protect batteries to minimize vulnerability in collision scenarios (e.g., from broken rail or collisions with road vehicles or other railroad equipment).
4. Fire originating from batteries	Thermal runaway	Fire source threatening passenger compartment and surrounding equipment	1. Ensure safe monitoring and control of battery cell/module status (temperature) with automatic switch-off of battery when cell/module parameters are out of recommended range. 2. Utilize passive switch-off as a fail-safe (e.g., breaker, fuse, linear heat detection cable or similar). 3. Consult relevant standards such as IEC 62619:2017 and IEC 62928:2017.
5. Reoccurrence of fire originating from batteries	Stranded energy that may lead to delayed thermal runaway	Fire source threatening passenger compartment and surrounding equipment	1. Follow emergency procedures to isolate a battery that has undergone thermal runaway.

TABLE 1
Battery Hazard Log

Hazard	Cause	Consequences	Potential Mitigations
6. Fire originating from batteries	Short-circuit	Fire source threatening passenger compartment and surrounding equipment	1. Use short-circuit detection (voltage, current). 2. Use electrical component protective devices (e.g., fuses, overload switches). 3. Secure internal cables and connections. 4. Utilize cabling and component materials compliant with NFPA 130 or equivalent (e.g., EN 45545-2). 5. Ensure safe monitoring and control of battery cell/module status (temperature) with automatic switch-off of battery when cell/module parameters are out of recommended range. 6. Consult relevant standards such as IEC 62619:2017 and IEC 62928:2017.
7. Fire originating from batteries	Lithium plating (decrease of electrode efficiency over battery life)	Fire source threatening passenger compartment and surrounding equipment	1. Limit over-voltages and over-currents. 2. Follow OEM procedures for charging and discharging at low temperatures. 3. Consult relevant standards such as IEC 62619:2017 and IEC 62928:2017.
8. Fire from overheating of battery due to adjacent heat sources or propagation of fire initiated outside of battery enclosure	External fire (e.g., fire on track) affecting batteries	Fire source threatening passenger compartment and surrounding equipment	1. Ensure safe monitoring and control of battery cell/module status (voltage, current, temperature) with automatic switch-off of battery when cell/module parameters are out of recommended range. 2. Perform fire safety analysis and protect from adjacent components (e.g., material selection, protection against flame propagation such as fire barriers). 3. Consult relevant standards such as IEC 62619:2017, IEC 62928:2017, etc.
9. Fire from overheating of battery due to adjacent heat sources or propagation of fire initiated outside of battery enclosure	Fire adjacent to batteries located inside the vehicle	Fire source threatening passenger compartment and surrounding equipment	1. Ensure safe monitoring and control of battery cell/module status (voltage, current, temperature) with automatic switch-off of battery when cell/module parameters are out of recommended range. 2. Perform fire safety analysis and protect from adjacent components (e.g., material selection, protection against flame propagation). 3. Use onboard fire detection system. 4. Design for fire separation/containment (e.g., fire barriers). 5. Consult relevant standards such as IEC 62619:2017, IEC 62928:2017, etc.

TABLE 1

Battery Hazard Log

Hazard	Cause	Consequences	Potential Mitigations
10. Fire from deactivation of battery control systems on the vehicle while in storage	Incorrect maintenance where batteries are stored for an extended period of time at a level of charge higher or lower than prescribed by manufacturer	Fire in vehicle storage area/depot	1. Follow layover instructions recommended by OEM. 2. Train maintenance personnel on proper storage of vehicle as recommended by the OEM.
11. Fire or combustible/toxic gas from unexpected/adverse battery chemical reaction	Internal failure of battery cell	Fire source, toxic gas, smoke threatening passenger compartment and surrounding equipment	1. Ventilate to car exterior (e.g., separate passenger ventilation from battery ventilation). 2. Ensure monitoring and control of battery cell/module status (voltage, current) with automatic switch-off of battery when cell/module parameters are out of recommended range. 3. Use onboard fire detection system for internal batteries. 4. Consult relevant standards such as IEC 62619:2017, IEC 62928:2017, etc.
12. Explosion originating from batteries	• Over-temperature • Overcharge	Damage to surrounding equipment/passenger space, potential fire generation	1. Ensure safe monitoring and control of battery cell/module status (temperature, current) with automatic switch-off of battery when cell/module parameters are out of recommended range. 2. Design against fire propagation within the battery (e.g., IEC 62619:2017).
13. Explosion originating from batteries	Over-pressure	Damage to surrounding equipment/passenger space, potential fire generation	1. Design over-pressure release devices in battery enclosures to vent in a safe manner.
14. Emission of toxic/combustible gases by battery (during a battery fire or overloading of cells)	Failure of other components in the battery	Passenger, personnel or first responder intoxication	1. Vent toxic/combustible gases from battery to a safe location (e.g., away from occupied areas and ignition sources). 2. Safely dilute and disperse toxic gases from battery (e.g., use of proper ventilation to car exterior). 3. Implement a hermetic barrier between traction batteries and passenger area. 4. Avoid encapsulation of battery container within closed compartments. 5. Manage HVAC fresh air in case of fire detection. 6. Develop first responder information and training (inclusive of MSDS/hazard details for battery) that includes fire suppression, containment procedures, electrical safety, etc.

TABLE 1
Battery Hazard Log

Hazard	Cause	Consequences	Potential Mitigations
15. Battery leakage	Mechanical damage of battery box due to external projectiles	Spillage and/or contact with hazardous chemicals	1. Use battery box with sufficient resistance to penetration from wayside objects (e.g., ballast, loose track materials, etc.) and/or provide external protections. 2. Locate batteries to mitigate impact from mechanical penetration.
16. Battery leakage	Mechanical damage of battery due to low mechanical resistance to shocks and vibrations	Spillage and/or contact with hazardous chemicals	1. Design battery in accordance with relevant standards for shocks and vibrations (e.g., compliance with IEC EN 61373 or equivalent). 2. Design battery to resist, without leakage or fire, the load cases adapted from 49 CFR 238.233(a) (i.e., 8g/4g/4g, 250 ms triangular crash pulse) or as otherwise applicable, including evaluation of effects/loads on system due to rollover and derailment.
17. Battery leakage	Mechanical damage of battery box due to internal over-pressure	Spillage and/or contact with hazardous chemicals	1. Design battery box to account for potential over-pressure. 2. Vent over-pressure and toxic/combustible gases from battery to a safe location (e.g., away from occupied areas and ignition sources). 3. Safely dilute and disperse toxic gases from battery (e.g., via proper ventilation to car exterior).
18. Battery leakage	Failure of box to contain battery electrolyte	Spillage and/or contact with hazardous chemicals	1. Utilize liquid-tight battery box to retain potential cell leakage (refer to IEC 62619:2017 and IEC 62928:2017).
19. Cooling system leakage	Mechanical damage of cooling system due to external projectiles	• Spillage and/or contact with hazardous chemicals • Loss of cooling capacity	1. Design cooling system with sufficient resistance to impacts (e.g., ballast, loose track materials), and/or provide external protections. 2. Use industry-evaluated coolant, and analyze for potential risks (e.g., flammability, corrosiveness).
20. Cooling system leakage	Mechanical damage of cooling system due to low mechanical resistance to shocks and vibrations	• Spillage and/or contact with hazardous chemicals • Loss of cooling capacity	1. Design cooling system in accordance with relevant standards for shocks and vibrations (e.g., compliance with IEC EN 61373 or equivalent). 2. Design cooling system to resist, without leakage, the load cases adapted from 49 CFR 238.233(a) (i.e., 8g/4g/4g, 250 ms triangular crash pulse) or as otherwise applicable, including evaluation of effects/loads on system due to rollover and derailment. 3. Use industry-evaluated coolant, and analyze for potential risks (e.g., flammability, corrosiveness).

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Battery Hazard Log

Hazard	Cause	Consequences	Potential Mitigations
21. Cooling system leakage	Mechanical failure of attachments, lines, connections or components	• Spillage and/or contact with hazardous chemicals • Loss of cooling capacity	1. Use fittings, lines and connections suitably tested for railroad environment (temperature, corrosion resistance, pressure cycling, shock and vibration, etc.), and perform tightness tests during production and maintenance. 2. Design cooling system in accordance with relevant standards for shocks and vibrations (e.g., compliance with IEC EN 61373 or equivalent). 3. Design cooling system to resist, without leakage, the load cases adapted from 49 CFR 238.233(a) (i.e., 8g/4g/4g, 250 ms triangular crash pulse) or as otherwise applicable, including evaluation of effects/loads on system due to rollover and derailment. 4. Use industry-evaluated coolant, and analyze for potential risks (e.g., flammability, corrosiveness). 5. Follow OEM maintenance procedures for cooling system.
22. Unintended vehicle stop and complete loss of auxiliary power	Loss of battery traction power in undesired area that causes the vehicle to be unable to move under its own power or power auxiliary hotel systems	• Vehicle located in an inconvenient location; safety concerns for the vehicle passengers or public located along the wayside • Losing auxiliary power to hotel loads; impossibility to continue to operate onboard systems (e.g., HVAC, etc.) • Loss of cooling capability for battery system with potential fire hazard for batteries	1. Send warning alarm in case of minimum capacity from battery system to train crew prior to fault resulting in loss of traction and/or auxiliary power. 2. Ensure sufficient safety margin in battery capacity to manage movement capability in undesired areas and consideration for unintended stops. Consider grade, route length, passenger loading, environmental conditions and charging locations. 3. Ensure sufficient safety margin in battery capacity to allow for auxiliary power systems use until a rescue or evacuation of an immobilized train can occur. Consider grade, route length, passenger loading, environmental conditions and charging locations. 4. Train crew, maintenance personnel and mechanical desk staff on detecting low battery capacity conditions and handling/operation of the equipment in the event of low battery capacity. Identify in railroad's emergency preparedness plan in accordance with 49 CFR 239.101. 5. Eliminate single point failures in traction power design resulting in a simultaneous complete loss of traction and auxiliary power from the battery system. Develop limp-mode procedures to move the vehicle short distances. 6. Develop load shedding profile redirecting auxiliary power to battery cooling system to prevent battery failure leading to other hazards. 7. Develop emergency preparedness procedures.

TABLE 1

Battery Hazard Log

Hazard	Cause	Consequences	Potential Mitigations
23. Unintended vehicle stop of a time duration leading to complete loss of power	Operational issue on the railroad system (e.g., delays)	• Safety concerns for the vehicle passengers or public located along the wayside • Inability to operate onboard systems (HVAC, etc.)	1. Design for appropriate operational plan (e.g., consider onboard battery capacity/wayside charging, battery lifetime, environmental conditions). 2. Implement power source management (e.g., load shedding). 3. Develop operational procedures to move vehicle to appropriate location. 4. Develop emergency preparedness procedures.
24. Fire originating from battery affecting onboard fuel (e.g., diesel in bi-mode traction, or hydrogen in hydrogen vehicles)	Refer to Hazards 1 thru 7 above	Fire source threatening passenger compartment and surrounding equipment	1. Refer to potential mitigations for Hazards 1 thru 7 above. 2. Design for fire separation/containment (e.g., fire barriers). 3. Locate batteries away from fuel source.

2.1.2 Common electric hazards

The hazards and mitigations described in this section address common safety practices for all electric systems including Li-ion traction batteries, but may provide additional insight about the special risks associated with high voltage battery systems in general.

TABLE 2
Common Electric Hazard Log

Hazard	Cause	Consequences	Potential Mitigations
1. Unexpected contact with conductive live parts for traction battery and fuel cell systems	• Default or isolation distance • Cable disconnection • Insufficiency, lack or loss of grounding • Easy access to high-voltage areas by unauthorized people • Insufficient protection against finger intrusion. • Batteries are continuously live • Charging circuit live	Electrical shock to passengers, crew or O&M personnel	1. Manage traction battery interface in the vehicle in a similar fashion as that in an overhead/third rail vehicle. Additionally, batteries shall be treated as continuously live during maintenance. For example, ensure: • Proper electrical isolation for all battery system components • Proper insulation inside electrical boxes that does not inhibit proper ground fault detection or heat dissipation • Proper grounding definition • Torque tightening for electrical connections, including grounding connections • Signage and labels (e.g., 49 CFR 229.85) and/or indicator lights indicating electrical hazard and development of procedures to access high-voltage components • Color-coding of safety-critical components (e.g., AAR M-1004) • Proper securing against passenger access to high-voltage areas • Specification of IP2X rating for areas including high-voltage elements • Presence of external lights (LEDs) indicating the presence of high-voltage energy on battery system inverter; • Presence of bolted covers on electrical enclosures housing permanent high voltage • Proper maintenance procedures and training 2. Ensure that fuel cell system is non-energized prior to performing maintenance work. 3. Follow OEM maintenance procedures and provide associated training for maintenance personnel and operational crews.

TABLE 2
Common Electric Hazard Log

<table>
<tr><th>Hazard</th><th>Cause</th><th>Consequences</th><th>Potential Mitigations</th></tr>
<tr><td>2. Unexpected contact with conductive live parts</td><td>Default or isolation distance
Cable disconnection
Insufficiency, lack or loss of grounding
Lack of knowledge from first responders
Easy access to high-voltage areas by unqualified people
Insufficient protection against finger intrusion
Stranded energy in battery</td><td>Electrical shock to first responders especially due to unconventional characteristics of alternative energy sources</td><td>1. Respond to traction battery interface in the vehicle in a similar fashion as that in an overhead/third rail vehicle. Batteries shall be treated as continuously live, requiring:
personal protective equipment
signage and labels (e.g., 49 CFR 229.85) and/or indicator lights indicating electrical hazard
development of procedure to access high-voltage components
color-coding of safety-critical components (e.g., AAR M-1004)
first responder information and training (e.g., 49 CFR 239, emergency preparedness plan)
external lights (LEDs) indicating the presence of high-voltage energy on battery system inverter
2. Utilize emergency cutouts to isolate batteries and/or fuel cell system.</td></tr>
<tr><td>3. Unexpected power on collector shoes energizing third rail (applicable for both rail gaps and dead rails)</td><td>No disconnect existing between battery system (and especially its batteries) and the collector shoes
Disconnect exists but not working properly between battery system (and especially its batteries) and the collector shoes</td><td>Electrical shock to maintenance (infrastructure, vehicle) personnel</td><td>1. Utilize dedicated interlock to isolate battery system/high-voltage bus from third rail in nonelectrified territories. Design for redundancy of interlock.

2. Implement special train operation mode and dedicated interlock to isolate battery system/high-voltage bus from third rail when passing rail gaps in electrified territories.

3. Use signage and labels (e.g., 49 CFR 229.85) and/or indicator lights indicating electrical hazard, and develop procedures to access high-voltage components.

4. Use color-coding for safety-critical components (e.g., AAR M-1004).

5. Train O&M personnel in procedures and situational awareness when working near equipment.

6. Implement wayside mitigation (e.g., grounding of third rail).</td></tr>
<tr><td>4. Unexpected power on collector shoes energizing third rail (third rail systems having exposed collector shoes) or pantograph energizing overhead contact system</td><td>No disconnect existing between battery system (and especially its batteries) and the collector shoes or pantograph
Disconnect exists but not working properly between battery system (and especially its batteries) and the collector shoes or pantograph</td><td>Electrical shock to people walking alongside the train

Energy feed back into an isolated overhead contact system</td><td>1. Utilize dedicated interlock to isolate battery system/high-voltage bus from third rail and overhead contact system in nonelectrified territories. Design for redundancy of interlock.

2. Implement special train operation mode and dedicated interlock to isolate battery system/high-voltage bus from third rail when passing rail gaps in electrified territories.

3. Use signage/indicator lights to identify presence of high voltage.

4. Implement wayside mitigation (e.g., grounding of third rail or catenary).

5. Implement dead rail detection.</td></tr>
</table>

2.2 Hydrogen

2.2.1 Proton exchange membrane fuel cell

The hazards and mitigations described in this section are specifically for proton exchange membrane fuel cells (PEMFC), as these are employed in current designs of passenger rail equipment. Additional considerations would be necessary for other fuel cell types.

TABLE 3
Hydrogen Fuel Cell Hazard Log

Hazard	Cause	Consequences	Mitigation Approach
1. Hydrogen leakage with resulting fire and explosion risk	Mechanical failure of fittings, lines, connections or components	• Damage to system, surrounding equipment and passenger space • Potential fire generation • Potential confined hydrogen gas cloud explosion	1. Use hydrogen-rated fittings and connections suitably tested for the railroad environment (temperature, corrosion resistance, pressure cycling, shock and vibration, etc.), following e.g., EC No. 79, HGV 3.1, ISO 1988X. 2. Design fuel cell system in accordance with relevant standards for shocks and vibrations (e.g., compliance with IEC EN 61373 or equivalent). 3. Design fuel cell system to resist, without leakage, the load cases adapted from 49 CFR 238.233(a) (i.e., 8g/4g/4g, 250 ms triangular crash pulse) or as otherwise applicable, including evaluation of effects/loads on system due to rollover and derailment. 4. Upon completion of production/integration, perform manufacturer quality management procedures for sealing validation (no leakage) (e.g., refer to EC No. 79[3] Annex IV, Part 1, or SAE J2578:2023, Section 4.2.4.1. 5. For maintenance, perform quality management procedures and tests for sealing verification (no leakage). 6. Design for pressure tightness (e.g., refer to EN 17127:2020 Annex A, ASME B31.12 Annex). 7. Ensure safe operating conditions by detecting hydrogen leakage (e.g., warning, dilution, passive and active ventilation, or interruption of hydrogen supply).
2. Over-voltage	Over-voltage	• Damage to system, surrounding equipment and passenger space • Potential fire generation	1. Use sensors to protect against fuel cell over-voltage. 2. Respond as recommended by OEM to alarms/events that fuel cell sends to train monitoring system. 3. Ensure that OEM procedures include checking of controls and systems operation in the event of over-voltage. 4. Monitor the isolation resistance of the overall high-voltage system with a device capable of detecting both single and double pole isolation failures.

3. The European Union permitted EC No. 79 to expire in July 2022. However, the regulation still provides for a holistic set of requirements required for type approval of hydrogen-powered motor vehicles. In lieu of a current similar regulation or standard, the mitigations in this white paper reference criteria from EC No. 79 that have been used for European certification.

TABLE 3
Hydrogen Fuel Cell Hazard Log

Hazard	Cause	Consequences	Mitigation Approach
3. High voltage	High voltage	Electrical shock to maintenance (infrastructure, vehicle) personnel	1. Use dedicated interlock to isolate and, as needed, de-energize fuel cell system and cut off fuel supply. 2. Train and qualify O&M personnel per detailed procedures provided by OEM instructions and documentation. 3. Monitor for isolation failure in high-voltage system. 4. Prevent feedback/interference to fuel cell from parallel power systems (e.g., battery charging and regen, third rail/OCS traction). 5. Manage fuel cell electrical system in the vehicle in similar fashion as that in an overhead/third rail vehicle. Additionally, fuel cells shall be treated as live if fuel is present in the system during maintenance. For example: • Use insulation inside electrical boxes that does not inhibit proper ground fault detection or heat dissipation. • Ensure adequate grounding definition. • Torque-tighten electrical connections, including grounding connections. • Utilize signage and labels (e.g., 49 CFR 229.85) and/or indicator lights indicating electrical hazard, and develop procedures to access high-voltage components. • Use color coding for safety-critical components (e.g., AAR M-1004). • Secure against passenger access to high-voltage areas. • Specify IP2X rating for areas including high-voltage elements. • Add external lights (LEDs) indicating the presence of high-voltage energy on fuel cell system components.

TABLE 3

Hydrogen Fuel Cell Hazard Log

Hazard	Cause	Consequences	Mitigation Approach
4. Overheating	• Overloading • Insufficient temperature	• Damage to system, surrounding equipment and passenger space • Potential fire generation	1. For cooling system, use fittings, lines and connections suitably tested for railroad environment (temperature, corrosion resistance, pressure cycling, shock and vibration, etc.) and perform tightness tests during production and maintenance. 2. Ensure safe monitoring and control of fuel cell and cooling system status (temperature). 3. Design cooling system in accordance with relevant standards for shocks and vibrations (e.g., compliance with IEC EN 61373 or equivalent). 4. Design cooling system to resist, without leakage, the load cases adapted from 49 CFR 238.233(a) (i.e., 8g/4g/4g, 250 ms triangular crash pulse) or as otherwise applicable, including evaluation of effects/loads on system due to rollover and derailment. 5. Use industry-evaluated coolant, and analyze for potential risks (e.g., flammability, corrosiveness). 6. Ensure level control of the cooling liquid. 7. Follow OEM maintenance procedures for cooling system (e.g., check refrigerant levels). 8. Separate exhaust to prevent heating of fuel cell components. 9. Ventilate heat from fuel cell external surfaces. 10. Interrupt hydrogen supply to the fuel cell in the event of an incident.
5. Icing of fuel cell system components (e.g., intake, exhaust, piping)	• Insufficient heating • Impedance of airflow into system	• Accumulation of unreacted hydrogen in steam exhaust • Damage to the fuel cell	1. At power system startup, ensure function of heating system for piping and exhaust. 2. Protect drainage for water exhaust and piping for steam exhaust from freezing.
6. Projections of scalding water	Unseparated water and steam exhaust	Injury to maintenance personnel, crew and passengers on stations	1. Separate water and steam flows to avoid projections. 2. Design exhaust to be located away from personnel.
7. Explosion	Fire exposure from external source	• Damage to system, surrounding equipment, passenger space • Potential fire generation	1. Interrupt hydrogen supply to the fuel cell in the event of an incident. 2. Separate external heating sources and/or devices posing fire risk from the fuel cell. 3. Use fire barriers. 4. Evaluate need and feasibility of fire suppression. 5. Ensure safe operating conditions by detecting hydrogen leakage (e.g., warning, dilution, ventilation or interruption of hydrogen supply).

TABLE 3
Hydrogen Fuel Cell Hazard Log

Hazard	Cause	Consequences	Mitigation Approach
8. Explosion	Concentrated hydrogen atmosphere around fuel cell	• Damage to system, surrounding equipment, passenger space • Potential fire generation	1. Isolate fuel cell and high-pressure hydrogen equipment (keep ignition sources away from process lines, especially high-voltage lines). 2. Use electrical connections suitable for a hydrogen environment (ATEX, EC No. 79, etc.). 3. Ensure adequate grounding of metallic parts. 4. Utilize exhaust system to vent residual hydrogen in safe place (e.g., direct the exhaust away from passenger or luggage compartments, and away from brake pads, wheels or other ignition sources). 5. Design for maximum ventilation of compartment.
9. Cooling system hydrogen leakage	Hydrogen gas being present in the cooling system (e.g., plate cracking from over-pressure)	• Damage to surrounding equipment, passenger space • Potential fire generation • Potential confined hydrogen gas cloud explosion	1. Dissipate possible accumulation of hydrogen to a safe location using a cap vent at the top of the system with accompanying hydrogen detector. 2. Ensure safe operating conditions by detecting hydrogen leakage including within system enclosures (e.g., warning, dilution, ventilation or interruption of hydrogen supply). 3. For maintenance, perform quality management procedures and tests for sealing verification (no leakage).
10. Unsafe levels of unreacted hydrogen leakage in exhaust	• Contamination of air • Defective fuel cell • Failure of reactive system	• Resulting fire and explosion • Accumulation of hydrogen in environment	1. Ensure safe operating conditions by detecting hydrogen leakage (e.g., warning, dilution, ventilation or interruption of hydrogen supply). 2. Ensure that the design of the exhaust system is such that any unreacted hydrogen in the steam stream is vented safely. 3. Design for maximum ventilation of compartment.

2.2.2 Type 4 tank (Compressed gas)

The hazards and mitigations described in this section are specifically for Type 4 cylindrical pressure vessels (i.e., fully wrapped tanks with non-metallic liners, similar to those used in automotive standards), as these are employed in current designs of passenger rail equipment. Additional considerations would be necessary for other tank types.

TABLE 4
Tank (Compressed Gas) Hazard Log

Hazard	Cause	Consequences	Potential Mitigations
1. Hydrogen pressure tank system leakage	• Shock/vibration • Derailment • Rollover	• Damage to system, surrounding equipment, passenger space • Potential fire generation	1. Protect with sensors (e.g., shock, hydrogen, etc.), and automatic isolation. 2. Design pressure tank in accordance with relevant standards for shocks and vibrations (e.g., compliance with IEC EN 61373 or equivalent). 3. Design pressure tank to resist, without leakage, the load cases adapted from 49 CFR 238.233(a) (i.e., 8g/4g/4g, 250 ms triangular crash pulse) or as otherwise applicable, including evaluation of effects/loads on system due to rollover and derailment. 4. Follow pressure tank validation requirements identified in, for example, EC No. 79, CSA/ANSI HGV 2, GTR 13, ISO 1988X.
2. Hydrogen pressure tank system leakage	Improper maintenance	• Damage to system, surrounding equipment, passenger space • Potential fire generation	1. Train and qualify O&M personnel per detailed procedures provided by OEM instructions and documentation. 2. For maintenance, perform quality management procedures and periodic tests for sealing verification (no leakage).
3. Hydrogen pressure tank system leakage	Exterior damage	• Damage to system, surrounding equipment, passenger space • Potential fire generation	1. Design hydrogen pressure tank system and/or enclosures with sufficient resistance to penetration from wayside objects (ballast, loose track materials, etc.) and/or provide external protections. 2. Design hydrogen pressure tank with sufficient resistance to burst from ballistics (e.g., CSA/ANSI HGV 2 penetration test) and/or provide external protections. 3. Locate pressure tank to protect against external projections. 4. Locate and protect pressure tank to minimize vulnerability in collision scenarios (e.g., from broken rail or collisions with road vehicles or other railroad equipment). 5. Utilize excess flow device(s) to block excess hydrogen flow in the event of leakage on the line. 6. Ensure safe operating conditions by detecting hydrogen leakage (e.g., warning, dilution, ventilation or interruption of hydrogen supply). 7. Use fittings, piping, bracketry, supporting structure, etc., that allow natural expansion and contraction of the charged/uncharged tank.

TABLE 4
Tank (Compressed Gas) Hazard Log

Hazard	Cause	Consequences	Potential Mitigations
4. Hydrogen pressure tank system leakage	Embrittlement Cyclical fatigue Galvanic corrosion	• Damage to system, surrounding equipment, passenger space • Potential fire generation	1. Follow pressure tank validation requirements identified in, for example, EC No. 79 and CSA/ANSI HGV 2, GTR 13, ISO 1988X. 2. Perform hydrogen compatibility test (e.g., EC No. 79, CSA/ANSI HGV 2). 3. Perform gas cycling test (e.g., EC No. 79, CSA/ANSI HGV 2). 4. Include allowable useful life of tank and tank elements from OEM on maintenance plan, and monitor/record tank cycles through tank life. 5. Monitor over-pressure incidents and effect on fatigue. 6. Ensure adequate grounding of tank metallic and non-metallic parts.
5. Hydrogen pressure tank system leakage	Tank degradation due to temperature and age	• Damage to system, surrounding equipment, passenger space • Potential fire generation	1. Test tank to support a margin of safety above the maximum allowable working pressure (e.g., certification of tank for intended use – e.g., EC No. 79 and CSA/ANSI HGV 2, GTR 13, ISO 1988X). 2. Perform temperature cycle tests during tank certification (e.g., EC No. 79, CSA/ANSI HGV 2). 3. Perform maintenance, inspection and leakage test of tank, fittings and connections. 4. Separate external heating sources and/or devices posing fire risk from the tank. 5. Monitor temperature in tank or tank enclosure. 6. Use proper hydrogen cooling dependent on fueling rate.
6. Hydrogen pressure tank system leakage	External fire	• Damage to system, surrounding equipment, passenger space • Potential fire generation	1. Test tank to support a margin of safety above the maximum allowable working pressure (e.g., certification of tank for intended use – e.g., EC No. 79 and CS/ANSI HGV 2, GTR 13, ISO 1988X). 2. Separate external heating sources and/or devices posing fire risk from the tank.

TABLE 4
Tank (Compressed Gas) Hazard Log

Hazard	Cause	Consequences	Potential Mitigations
7. Hydrogen pressure tank explosion	Exterior damage	• Damage to system, surrounding equipment, passenger space • Potential fire generation	1. Design hydrogen pressure tank system and enclosures with sufficient resistance to penetration from wayside objects (ballast, loose track materials, etc.) and/or provide external protections. 2. Design hydrogen pressure tank with sufficient resistance to burst from ballistics (e.g., CSA/ANSI HGV 2 penetration test) and/or provide external protections. 3. Locate pressure tank to protect against external projections. 4. Locate and protect pressure tank to minimize vulnerability in collision scenarios (e.g., from broken rail or collisions with road vehicles or other railroad equipment).
8. Hydrogen pressure tank explosion	Over-pressure	• Damage to system, surrounding equipment, passenger space • Potential fire generation	1. Test tank to support a margin of safety above the maximum allowable working pressure (e.g., certification of tank for intended use – e.g., EC No. 79 and CSA/ANSI HGV 2, GTR 13, ISO 1988X). 2. Utilize sensors/alarms (onboard and/or external) to monitor the safety of the fueling process (e.g., pressure, temperature, etc.). 3. Follow SAE J2601 series for fueling. 4. Perform maintenance, inspection and leakage test of tank, fittings and connections.
9. Hydrogen pressure tank explosion	Accidental explosive mixture into tank during fueling	• Damage to system, surrounding equipment, passenger space • Potential fire generation	1. Utilize a controlled fueling process (e.g., so as to not introduce air into system). 2. Purge/flush possible oxygen in system utilizing an inert gas. 3. Control quality of hydrogen. 4. Utilize sensors/alarms (onboard and/or external) for monitoring the safety of the fueling process (e.g., pressure, etc.). 5. Utilize trained personnel to perform fueling operations. 6. Ensure use of safe electrical systems in tank such as NEMA 7, NEMA 8 or ATEX-certified equipment.

TABLE 4
Tank (Compressed Gas) Hazard Log

Hazard	Cause	Consequences	Potential Mitigations
10. Hydrogen pressure tank explosion	Fire exposure	• Damage to system, surrounding equipment, passenger space • Potential fire generation	1. Protect tank against bursting (e.g., thermal pressure relief device (TPRD). 2. Separate external heating sources and/or devices posing fire risk from the tank. 3. Use fire barriers.
11. Hydrogen leakage and permeation (weeping)	Vehicle in storage and onboard ventilation systems not active	• Accumulation of hydrogen gas in enclosed area • Fire and explosion	1. Ensure passive movement of air when hydrogen is being stored. 2. Utilize hydrogen gas detection alarm system to initiate dilution of the hydrogen. 3. Use certified tanks that include permeation limits, and control normal leakage at connection points (e.g., EC No. 79 and CS/ANSI HGV 2, GTR 13, ISO 1988X). 4. Separate power sources from tanks.

2.2.3 High-pressure piping and equipment

The hazards and mitigations described in this section are specifically for high pressure stainless steel piping and equipment typically certified for road vehicles (busses, trucks, automobiles), as these are employed in current designs of passenger rail equipment. Additional considerations would be necessary for other types of piping and equipment.

TABLE 5
High-Pressure Piping and Equipment Hazard Log

Hazard	Cause	Consequences	Potential Mitigations
1. High-pressure hydrogen piping and equipment leakage	Embrittlement Cyclical fatigue	• Damage to system, surrounding equipment, passenger space • Potential fire generation (e.g., jet fire)	1. Minimize the number of connections as much as possible. 2. Utilize piping codes (e.g., EC No. 79, ASME B31.12, ASME B31.3). 3. Periodically check hydrogen detection system utilizing proper maintenance procedures and personal protective equipment that avoids electrostatic charges. 4. Perform hydrogen compatibility test (e.g., EC No. 79). 5. Use hydrogen-rated fittings connections, and valves suitably tested for railroad environment (temperature, corrosion resistance, pressure cycling, shock and vibration, etc.), following e.g., EC No. 79, HGV 3.1, ISO 1988X. 6. Design for acceptable gas temperature (e.g., refer to EN 17127:2020 Annex A).

TABLE 5
High-Pressure Piping and Equipment Hazard Log

Hazard	Cause	Consequences	Potential Mitigations
2. High-pressure hydrogen piping and equipment leakage	Shock/vibration	• Damage to system, surrounding equipment, passenger space • Potential fire generation (e.g., jet fire)	1. Design high-pressure piping in accordance with relevant standards for shocks and vibrations (e.g., compliance with IEC EN 61373 or equivalent). 2. Design high-pressure piping and equipment to resist, without leakage, the load cases adapted from 49 CFR 238.233(a) (i.e., 8g/4g/4g, 250 ms triangular crash pulse) or as otherwise applicable, including evaluation of effects/loads on system due to rollover and derailment. 3. Minimize the number of connections as much as possible. 3. Monitor hydrogen gas release. 4. Utilize piping codes (e.g., EC No. 79, ASME B31.12, ASME B31.3). 5. Perform external leakage tests during maintenance.
3. High pressure hydrogen piping and equipment leakage	• Poor fittings/welds • Mechanical failure of fittings, lines, connections or components	• Damage to system, surrounding equipment, passenger space • Potential fire generation (e.g., jet fire)	1. Use qualified/appropriate fittings and connections (with sufficient seal integrity and resisting hydrogen embrittlement), following e.g., EC No. 79, HGV 3.1, ISO 1988X. 2. Perform tightness tests during production and maintenance. 3. Minimize the number of connections as much as possible. 4. Follow OEM maintenance procedures. 5. Utilize piping codes for leak testing, etc. (e.g., EC No. 79, ASME B31.12, ASME B31.3). 6. Ensure quality is maintained for incoming materials and components. 7. Ensure workmanship by use of qualified personnel (e.g., proper training per OEM and railroad instructions, personnel with hydrogen certifications as required follow OSHA 1910.103 for working with hydrogen equipment). 8. Perform intermittent quality testing (e.g., external leakage test).

TABLE 5
High-Pressure Piping and Equipment Hazard Log

Hazard	Cause	Consequences	Potential Mitigations
4. High-pressure hydrogen piping and equipment leakage	Damage from internal or external causes	• Damage to system, surrounding equipment, passenger space • Potential fire generation (e.g., jet fire)	1. Use safe electrical systems for integration into high-pressure piping, such as NEMA 8 or ATEX-certified equipment. 2. Implement a quick-acting hydrogen gas detection system associated with an extraction system for the dilution of the gas and supply cutoff. 3. Implement quick-acting hydrogen flame detection systems in locations of high-pressure piping. 4. Ensure adequate grounding of tank metallic and non-metallic parts. 5. Implement protection against jet fire (e.g., residual gas in pipes after cutoff). 6. Use automatic shut-off valves (excess flow valves) rated for hydrogen to restrict flow in case of pipe rupture.
5. High-pressure hydrogen piping and equipment leakage	Safety management system is disconnected during fueling	• Damage to surrounding equipment, passenger space • Potential fire generation	1. Utilize a controlled fueling process so as to not introduce hydrogen into low-pressure lines without supervision, or to close hydrogen supply ahead of the pressure regulator valve (i.e., prevent the entry of hydrogen into systems downstream of tanks). 2. Ensure that protection systems are active during the fueling process (e.g., hydrogen detection system, monitoring of pressure/temperature inside tank).
6. Leakage in high-pressure hydrogen fueling lines and equipment	• Inappropriate fueling procedures and handling (e.g., over-fueling, excessive flow rate, etc.) • Inadequate safety measures that result in pressure, temperature and flow outside the design ranges due to equipment failure or unexpected behavior (more flow than admissible, line blockage, over-temperature, over-pressure, reverse flow, oxidizers, fuel impurities)	• Damage to system, surrounding equipment, passenger space • Potential fire generation • Explosion	1. Perform hazard and operability study. 2. Control pressure, temperature and flow of the fueling process (emergency stop in case of misfunction). 3. Follow SAE J2601 series for fueling. 4. Implement filters for the proper composition and the entry of dust/water inside the supply line. 5. Avoid reverse flow in the supply line (e.g., check valve). 6. Follow OEM maintenance procedures for fueling.
7. High-pressure hydrogen vent lines collision	Uncontrolled movement of the vent lines during venting	Possible collision with elements of the railway infrastructure	1. Vent lines should be adequately secured to prevent uncontrolled movement during venting or damage during vehicle lifetime.

TABLE 5

High-Pressure Piping and Equipment Hazard Log

Hazard	Cause	Consequences	Potential Mitigations
8. High-pressure hydrogen vent safety lines blocked	Accumulation of impurities, water or condensation on the vent lines	Evacuation of hydrogen to protect a pressure vessel (e.g., during a fire) is not possible	1. Ensure that vent line enclosures, including vent line caps, if used, prevent water ingress due to rain or car wash; maintain functional integrity when exposed to vehicle washing or environmental exposure (e.g., freezing, corrosion); and do not restrict flow when activated. 2. Use applicable codes (e.g., SAE J2578:2023) for vent line design. 3. Use periodic inspection and/or testing to ensure that vent lines are not blocked and are operating correctly.
9. High-pressure hydrogen vent line personal injuries	Discharges in the direction of occupants or people outside the vehicle	Personal injuries in case of gas release	1. The TPRD discharge shall be directed away from: • passengers, crew or bystanders • maintenance personnel • luggage compartments • possible ignition sources • hydrogen storage systems 2. The design and installation should minimize the possibility of external hazards (e.g., projectiles) or train movements resulting from activation of the device. 3. Ensure adequate grounding of metallic and non-metallic parts.
10. High-pressure hydrogen safety vent lines burst	Backpressure or explosion in safety lines	• Damage to environment and infrastructure • Potential fire generation • Explosion • Personal injuries	1. Design pipe and manifold to prevent bursting. 2. Utilize piping codes (e.g., EC No. 79, ASME B31.12, ASME B31.3). 3. Use qualified/appropriate fittings and connections (with sufficient seal integrity and resisting hydrogen embrittlement), following e.g., EC No. 79, HGV 3.1, ISO 1988X.
11. Unintended venting of high-pressure system (tanks, lines)	• TPRD failure • Inappropriate over-pressure protection measures	• Damage to environment and infrastructure • Potential fire generation • Explosion • Personal injuries	1. Follow OEM procedures in maintenance of TPRD over lifetime. 2. Manage over-pressure to standards without use of over-pressure protection devices.
12. Low pressure in vent lines allowing backflow of air	Fire regression in case of external ignition to the tank via open TPRD vent pipe	• Damage to system, surrounding equipment, passenger space • Potential fire generation • Explosion	1. Utilize flame arrestors. 2. Utilize protective vents for dust, water, backflow, etc.

2.2.4 Low-pressure piping and equipment

The hazards and mitigations described in this section are specifically for low pressure stainless steel piping and equipment typically certified for road vehicles (busses, trucks, automobiles), as these are employed in current designs of passenger rail equipment. Additional considerations would be necessary for other types of piping and equipment.

TABLE 6
Low-Pressure Piping and Equipment Hazard Log

Hazard	Cause	Consequences	Potential Mitigations
1. Low-pressure hydrogen piping and equipment leakage	Embrittlement	• Damage to system, surrounding equipment, passenger space • Potential fire generation	1. Minimize the number of connections as much as possible. 2. Utilize piping codes (e.g., EC No. 79, ASME B31.12, ASME B31.3). 3. Periodically check hydrogen detection system utilizing proper maintenance procedures and personal protective equipment that avoids electrostatic charges. 4. Perform hydrogen compatibility test (e.g., EC No. 79). 5. Use hydrogen-rated fittings connections, and valves suitably tested for railroad environment (e.g., temperature, corrosion resistance, pressure cycling, shock and vibration, etc.), following e.g., EC No. 79, HGV 3.1, ISO 1988X. 6. Design for acceptable gas temperature (e.g., refer to EN 17127:2020 Annex A).
2. Low-pressure hydrogen piping and equipment leakage	Shock/vibration	• Damage to system, surrounding equipment, passenger space • Potential fire generation	1. Design low-pressure piping in accordance with relevant standards for shocks and vibrations (e.g., compliance with IEC EN 61373 or equivalent). 2. Design low-pressure piping and equipment to resist, without leakage, the load cases adapted 49 CFR 238.233(a) (i.e., 8g/4g/4g, 250 ms triangular crash pulse) or as otherwise applicable, including evaluation of effects/loads on system due to rollover and derailment. 3. Minimize the number of connections as much as possible. 4. Monitor hydrogen gas release. 5. Utilize piping codes (e.g., EC No. 79, ASME B31.12, B31.3). 6. Perform external leakage tests during maintenance.

TABLE 6
Low-Pressure Piping and Equipment Hazard Log

Hazard	Cause	Consequences	Potential Mitigations
3. Low-pressure hydrogen piping and equipment leakage	• Poor fittings/welds • Mechanical failure of fittings, lines, connections or components	• Damage to system, surrounding equipment, passenger space • Potential fire generation	1. Use qualified/appropriate fittings and connections (with sufficient seal integrity and resisting hydrogen embrittlement) following e.g., EC No. 79, HGV 3.1, ISO 1988X. 2. Perform tightness tests during production and maintenance. 3. Minimize the number of connections as much as possible. 4. Follow OEM maintenance procedures. 5. Utilize piping codes for leak testing, etc. (e.g., EC No. 79, ASME B31.12, ASME B31.3). 6. Ensure that quality is maintained for incoming materials and components. 7. Ensure workmanship by use of qualified personnel (e.g., proper training per OEM and railroad instructions, personnel with hydrogen certifications as required, follow OSHA 1910.103 for working with hydrogen equipment). 8. Perform intermittent quality testing (e.g., external leakage test).
4. Over-pressurization of low-pressure system from high-pressure system	• Inadequate safety measures that may result in pressure, temperature and flow outside the design ranges due to equipment failure or unexpected behavior (more flow than admissible, over-temperature, over-pressure) • Failure of pressure regulator	• Damage to system, surrounding equipment, passenger space • Potential fire generation • Explosion	1. Perform hazard and operability study 2. Implement protection for the pressure regulator failure (e.g., emergency shutoff with a double-block valve). 3. Implement a two-step pressure regulator. 4. Control pressure and temperature downstream from the pressure regulator. 5. Follow OEM maintenance procedures, including purging and inerting. 6. Implement measures to protect low-pressure lines from over-pressure (safety valve, etc.). 7. Inspect and calibrate pressure relief devices periodically to OEM requirements.

TABLE 6
Low-Pressure Piping and Equipment Hazard Log

Hazard	Cause	Consequences	Potential Mitigations
5. Equipment failure of low-pressure system	Operational problems in the low-pressure line (line blockage, over-temperature, over-pressure, oxidizers, fuel impurities)	• Damage to system, surrounding equipment, passenger space • Potential fire generation • Explosion	1. Perform hazard and operability study. 2. Implement protection for the pressure regulator failure (e.g., emergency shutoff with a double-block valve). 3. Implement a two-step pressure regulator. 4. Control pressure and temperature downstream from the pressure regulator. 5. Follow OEM maintenance procedures, including purging and inerting. 6. Implement measures to protect low-pressure lines from over-pressure (safety valve, etc.). 7. Monitor temperature in low-pressure line. 8. Utilize piping codes (e.g., EC No. 79, ASME B31.12, ASME B31.3). 9. Implement filters for the proper composition and the entry of dust/water inside the supply line.
6. Low-pressure hydrogen vent safety lines blocked	Accumulation of impurities, water or condensation on the vent lines	Evacuation of hydrogen to protect the low-pressure lines and equipment is not possible	1. Ensure that vent line enclosures, including vent line caps, if used, prevent water ingress due to rain or car wash; maintain functional integrity when exposed to vehicle washing or environmental exposure (e.g., freezing, corrosion); and do not restrict flow when activated. The vent system must be able to preclude or relieve pressure buildup occurring due to allowable leakage of the safety valve without losing function or integrity. 2. Use applicable codes (e.g., SAE J2578:2023) for vent line design. 3. Use periodic inspection and/or testing to ensure that vent lines are not blocked and are operating correctly.
7. Personal injuries from low-pressure vent lines	Discharges in the direction of occupants or people outside the vehicle	Personal injuries in case of gas release	1. Direct the safety valve discharge away from: • passengers, crew or bystanders • maintenance personnel • luggage compartments • possible ignition sources • hydrogen storage systems 2. Use applicable codes (e.g., SAE J2578:2023) for vent line design. 3. Ensure that the design and installation minimize the possibility of external hazards (e.g., projectiles) resulting from activation of the device. 4. Ensure adequate grounding of metallic and non-metallic parts.

TABLE 6
Low-Pressure Piping and Equipment Hazard Log

Hazard	Cause	Consequences	Potential Mitigations
8. Purge lines blocked; hydrogen or higher pressure remaining in system	• Accumulation of impurities, water or condensation on the purge lines • Defective valve	• Damage to system, surrounding equipment, maintenance facility • Potential fire generation • Explosion • Personal injuries in case of gas release	1. Monitor pressure at multiple locations to ensure that no pressure remains prior to maintenance. 2. Follow OEM maintenance procedures, including purging and inerting. 3. Prevent water ingress, dust and oxidizers (caps, check valves, etc.).
9. Explosive mix in purge vent line; self-ignition	• Air entrapment in purge vent lines • Inadequate venting	• Damage to system, surrounding equipment, maintenance facility • Potential fire generation • Explosion • Personal injuries	1. Monitor pressure at multiple locations to ensure that no pressure remains prior to maintenance. 2. Follow OEM maintenance procedures, including purging and inerting. 3. Prevent water ingress, dust and oxidizers (caps, check valves, etc.).

2.3 Wayside/facilities hazards (interface with vehicle)

2.3.1 Battery storage (outside of vehicle)

TABLE 7
Battery Storage Hazard Log

Hazard	Cause	Consequences	Potential Mitigations
1. Li-ion batteries thermal runaway	• External impact • Overheating • Internal short	Gas leakage or fire	1. Provide ventilation and emergency exhaust. 2. Locate in separate fire compartment from other combustibles and heat exposures. 3. Evaluate need for fire protection systems (e.g., suppression, isolation). 4. Utilize gas and smoke detection, rapid alarm and notification (e.g., infrared, video, aspirating smoke detection). 5. Prepare emergency plan (staff and responders). 6. Prepare emergency procedures to include removing failed batteries to a safe location (e.g., protected location per OEM procedures). 7. Separate storage for used failed batteries from new batteries (e.g., separate from each other, OEM requirements/procedures). 8. Comply with OEM requirements and applicable standards/regulations.

2.3.2 Battery charging hazards

TABLE 8
Battery Charging Hazard Log

Hazard	Cause	Consequences	Potential Mitigations
1. Overheating of wayside power supply and/or grounding circuit, including stationary recharge	• Damaged or insufficient interface between vehicle and wayside charging infrastructure • Insufficient performance of rail/wheel interface • Insufficient performance of vehicle grounding circuit	Damage to vehicle, infrastructure, grounding network, rail and/or wheels	1. Ensure proper contact surface on rails and current collection equipment. 2. Ensure proper contact force of current collection equipment with wayside charging infrastructure. 3. Ensure proper quantity of current collection equipment to interface with wayside charging infrastructure. 4. Verify grounding characteristics. 5. Account for degraded modes (e.g., worn surfaces, trucks cut out).

2.3.3 Fuel cell storage (removed from vehicle)

TABLE 9
Fuel Cell Storage Hazard Log

Hazard	Cause	Consequences	Potential Mitigations
1. Used fuel cell; leakage of remaining gas within cell	Off-gassing of residual trapped hydrogen	Fire and/or explosion	1. Follow manufacturer procedures to handle fuel cells and purging hydrogen in used fuel cells prior to maintenance and storage. 2. Validate that hydrogen gas has been properly purged prior to storage.

2.3.4 Onboard tank storage (removed from vehicle)

TABLE 10
Onboard Tank Storage Hazard Log

Hazard	Cause	Consequences	Potential Mitigations
1. Used onboard tank storage; leakage of remaining gas within tank	• Off-gassing of residual trapped hydrogen • Permeation	Fire and/or explosion	1. Follow manufacturer procedures to handle onboard tanks and purging hydrogen in used tanks prior to maintenance and storage. Follow manufacturer procedures for maintaining tank pressure with inert gas. 2. Validate that hydrogen gas has been properly purged prior to storage.
2. Used onboard tank storage; leakage inert gas within tank	Failure of valve and/or piping	• Asphyxiation • Personnel injury	1. Prevent concentration and/or include detection of inert gas to prevent asphyxiation hazards. 2. Utilize storage facilities appropriate for storing pressurized gas. 3. Follow appropriate health and safety procedures for handling pressurized inert gases.

2.3.5 Hydrogen fueling hazards

TABLE 11
Hydrogen Fueling Hazard Log

Hazard	Cause	Consequences	Potential Mitigations
1. Over-pressurization of vehicle tanks and connecting fuel lines during fueling	• Error in control system on-line or in-train • Error in monitoring signal • Over-pressure and over-temperature in supply fuel	• Damage or rupture to tank • Hydrogen leakage from pressure tank • Damage to system, surrounding equipment, passenger space • Potential fire generation	1. Refer to NFPA 2: Hydrogen Technologies Code, Chapter 10, GH2 Vehicle Refueling Facilities; EN 17127; etc. 2. Install pressure safety valve on wayside fueling transfer system. 3. Follow OEM procedures and protocols for hydrogen fueling. 4. Utilize sensors/alarms (onboard and/or external) to monitor the safety of the fueling process (e.g., pressure, temperature, etc.). 5. Monitor and record over-pressure and over-temperature incidents and effect on fatigue (e.g., utilizing chart for tanks that identify charge and discharge cycles). 6. Monitor and control pressure and fill rate from wayside (if noncommunication interface is used), or from wayside and vehicle (if communication interface is used).
2. Over-temperature of vehicle tanks during fueling	• High gas temperature entering tank causing overheating • High pressurization/ flow rate entering tank causing overheating	Premature aging of the tank	1. Refer to NFPA 2: Hydrogen Technologies Code, Chapter 10, GH2 Vehicle Refueling Facilities; EN 17127; SAE J2799; etc. 2. Utilize sensors/alarms (onboard and/or external) for monitoring the safety of the fueling process (e.g., temperature, flow rate, etc.). 3. Perform simulations/modeling of fueling process. 4. Monitor and control temperature and fill rate from wayside (if noncommunication interface is used), or from wayside and vehicle (if communication interface is used).
3. Vehicle moves away from fueling dispenser with hose still attached	• Operator error • Failure to properly secure vehicle during fueling	High-flowrate hydrogen release that could cause a fire or explosion	1. Refer to NFPA 2: Hydrogen Technologies Code, Chapter 10, GH2 Vehicle Refueling Facilities; EN 17127; SAE J2799; etc. 2. Install breakaway device on dispenser hose that causes hydrogen gas flow to stop. 3. Follow fueling procedures. 4. Use check valves (wayside nozzle and onboard receptacle). 5. Use proper procedures to secure equipment (e.g., wheel chocks). 6. Use proper communications between wayside and vehicle for fueling process (e.g., SAE J2601). 7. Evaluate need for wayside fire suppression.

TABLE 11
Hydrogen Fueling Hazard Log

Hazard	Cause	Consequences	Potential Mitigations
4. Leak from fueling hose or dispenser	• Damage to fueling hose or dispenser • Error in connecting dispenser hose	High-flowrate hydrogen release that could cause a fire or explosion	1. Refer to NFPA 2: Hydrogen Technologies Code, Chapter 10, GH2 Vehicle Refueling Facilities; EN 17127; SAE J2799; etc. 2. Ensure protections at the supply point in the event of gas presence (detection and cutoff, emergency shutdown of supply of hydrogen, etc.). 3. Use excess flow check valves on the hydrogen supply side. 4. Evaluate need for wayside fire suppression.

2.3.6 Hydrogen system maintenance hazards

TABLE 12
Hydrogen System Maintenance Hazard Log

Hazard	Cause	Consequences	Potential Mitigations
1. Operational risks during maintenance; personal injuries	• Inadequate emptying, inerting of the system • Purging or releasing hydrogen in enclosed spaces	• Hydrogen accumulation • Risk of explosion • High pressure release risk	1. Follow OEM maintenance procedures for purging and inerting system. 2. Utilize gas detection (e.g., portable, facility equipment, etc.) for worker and facility safety. 3. Develop and implement a lock-out/tag-out system for maintenance work. 4. Consider use of tools appropriate for hazardous environment according to area classification (e.g., non-sparking and intrinsically safe). 5. Perform purging or other intentional releases of hydrogen in appropriate environment (outdoors, in ventilated space, etc.).
2. Ignition of hydrogen gas during purging	Static discharge (e.g., lightning) or other sources of ignition	Undetected hydrogen flame	1. Design environment where hydrogen is released to account for detection of hydrogen flame and to prevent fire spread. 2. Consider use of tools appropriate for hazardous environment according to area classification (e.g., non-sparking and intrinsically safe). 3. Plastic or elastomeric materials used in a hazardous location shall be electrically conductive or otherwise designed to avoid static charge buildup.

TABLE 12
Hydrogen System Maintenance Hazard Log

Hazard	Cause	Consequences	Potential Mitigations
3. Gas detection not active during a hazardous release of hydrogen and/or fire	Failure of the gas detection system (i.e., extraction system not activated)	No hydrogen extraction, resulting in gas accumulation	1. Ensure that detected failure of the gas monitoring system activates extraction system, if provided. 2. Perform failure mode and effects analysis. 3. Follow OEM procedures for maintaining extraction system, if provided. 4. Provide appropriate means of fire management (e.g., allowing hydrogen to continuously burn to mitigate an explosion risk). Note: Consider providing additional passive means to support management of failed active safety systems
4. Risks during long-term inactivity with hydrogen inside the installation; personal Injuries	Accumulation of hydrogen derived from the presence of leaks and/or permeation	• Hydrogen accumulation • Risk of explosion	1. Properly design natural ventilation for hydrogen system (e.g., CFD analysis, validation of calculated results) 2. Follow OEM procedures for long-term pressurized storage (e.g., purging and inerting lines, keeping hydrogen in tanks, manual locking of valves) 3. Monitor the presence of gas (explosimeters detection or permanent gas detection system) to detect potential leaks.

2.3.7 Vehicle storage and maintenance facilities for battery-electric and hydrogen

vehicles

TABLE 13
Vehicle Storage and Maintenance Facilities Hazard Log

Hazard	Cause	Consequences	Potential Mitigations
1. Li-ion batteries thermal runaway	• External impact • Overheating • Internal short	Gas leakage or fire	1. Provide ventilation and emergency exhaust. 2. Locate in separate fire compartment from other combustibles and heat exposures. 3. Evaluate need for fire protection systems (e.g., suppression, isolation). 4. Utilize gas and smoke detection, rapid alarm, and notification (e.g., infrared, video, aspirating smoke detection). 5. Prepare emergency plan (staff and responders). 6. Prepare emergency procedures to include removing failed batteries to a safe location (e.g., protected location per OEM procedures). 7. Separate storage for used failed batteries from new batteries (e.g., separate from each other, OEM requirements/procedures). 8. Assess and mitigate hazards for mixed storage for vehicles that utilize different fuels/propulsion means. 9. Evaluate separation or separation barriers for vehicles with respect to operational needs and hazard mitigations. 10. Comply with OEM requirements and applicable standards/regulations.
2. Explosive mixture created in building from leakage from vehicle	• Escaping hydrogen gas leak from inside vehicle • Permeation	Fire or explosion in building once flammable mixture formed	1. Ensure passive and, as needed, active ventilation for escaped hydrogen in and around vehicle and inside facility (e.g., covered/enclosed spaces). 2. Shut down all hydrogen components on vehicle. 3. Investigate keeping hydrogen detectors inside vehicles during storage. 4. Add sensors and local and remote alarms to warn of hydrogen concentrations (e.g., at high points, alcoves, locations of stagnant air pockets). 5. Consider adding hydrogen flame detectors in facility. 6. Assess the need for spark-proofing equipment within facility. 7. Purge and inert gas in the vehicle before long-term storage in facilities. 8. Develop procedures for addressing overhead equipment in maintenance facility.

TABLE 13
Vehicle Storage and Maintenance Facilities Hazard Log

Hazard	Cause	Consequences	Potential Mitigations
3. Explosive mixture created in building from leakage from vehicle	• Failure of the pressure reduction system • Failure of hydrogen tank TPRD on vehicle	Fire or explosion in building once flammable mixture has formed	1. Ensure passive and, as needed, active ventilation for escaped hydrogen in and around vehicle and inside facility (e.g., covered/enclosed spaces). 2. Shut down all hydrogen components on vehicle. 3. Add sensors and local and remote alarms at high points in facility to warn of hydrogen concentrations. 4. Consider adding hydrogen flame detectors in facility. 5. Assess the need for spark-proofing equipment within facility (third rails for cranes, etc.). 6. Evaluate firefighting procedures for fires around hydrogen equipment (e.g., explosive atmosphere). 7. Assess the need/suitability of fire suppression system in the facility. 8. Perform hazard assessment/modeling to understand the dynamics of hydrogen release. 9. Develop procedures for addressing overhead equipment in maintenance facility.
4. Release of high-pressure gas during maintenance	• Unexpected pressure in lines, fittings or vessels • Inadequate purging of pressurized gas before opening to atmosphere • Unintended activation of hydrogen storage system (e.g., opening of tanks due to control issue)	• High-pressure gas release • Injury to workers • Facility damage	1. Purge and inert high-pressure equipment prior to maintenance as recommended by OEM. 2. Lock out high-pressure gas supply during maintenance.
5. Explosive mixture of hydrogen and air within hydrogen equipment	• Lack of positive pressure or vacuum in hydrogen lines • Equipment exposed to air is not inerted before re-pressuring with hydrogen for startup	Flammable atmosphere formed in hydrogen lines, vessels or components	1. Keep all hydrogen containing lines and equipment at a verifiable positive pressure. 2. Use devices (e.g., check valves) to limit introduction of air and maintain positive pressure in line. 3. Use proper purging and inerting before re-pressurization with hydrogen as recommended by OEM.

3. Other best practices

3.1 Battery-electric and hydrogen passenger rail equipment emergency preparedness

Railroads operating trains powered by batteries with or without hydrogen range extension need to tailor their System Safety Plan and Passenger Train Emergency Preparedness Plans to address a number of additional risks, particularly those which are unique to these propulsion systems. For example, hydrogen is both highly flammable and explosive, but unlike methane, does not have an odorizer, has a density significantly less than air and burns without visible light emission. As a result, sensors are needed to detect both hydrogen leaks and fires.

Battery risks include fire, explosion, toxic emission, battery and cooling system leakage, etc. Such events can be caused by external factors such as collision, penetration by projectiles, damage from shocks and vibrations, exposure to external fires, etc., or by internal failures such as overheating, short-circuit, adverse chemical reaction, etc. For hydrogen, the risks include gas leakage, fire, explosion, overheating/freezing equipment, etc. There are also multiple risks associated with the tank and the high- and low-pressure piping and equipment related to leakage, over-pressurization, blocked safety lines, venting, and shock and vibration, etc.

Emergencies can occur onboard trains in service or at maintenance, storage and fueling locations. Preparations which define the appropriate steps in the event of any of these types of emergencies will reduce the probability and severity of risks to train crews, passengers and emergency responders.

Appropriate emergency preparation entails an awareness of hydrogen and battery characteristics and risks and modification of existing action plans; procedures; inventory of tools, devices and equipment; and employee and first-responder training.

For example, some unique challenges include the following:

- How to respond to a fire or explosion due to gas leak, fuel leak or battery short-circuit inside a vehicle, building or tunnel
- How to respond to emission of toxic gases
- How to safely dilute and disperse toxic gases from a battery
- How to control pressure, temperature and flow of the hydrogen fueling process (emergency stop in case of disfunction)
- How to train engineer and crew on handling/operation of the equipment in the event of low battery capacity

Some industry best practices may differ from typical emergency responses. For example, one recommended practice is not attempting to extinguish a battery fire, or a leaking hydrogen gas fire. First responders may need to equip themselves with specialized tools such as thermal imaging equipment (to improve the visibility of hydrogen flames) and non-sparking tools. Laser thermometers can also be used to safely identify high- or low-temperature items. Continuous gas monitoring to display gas concentrations in the atmosphere, such as oxygen and hydrogen. Additional considerations would need to be made depending on the specific situation/scenario. It is recommended that firefighting procedures for such fires follow the latest NFPA guidelines.

The following lists emergency response policies and procedures that may need to be amended:

- Initial assessment of the emergency
- Communication by onboard train crews, control center staff, on-scene personnel and others
- Passenger notifications
- First responder engagement, plan distribution, training, simulations
- Operations protocols
- Inventory of onboard emergency equipment
- Employee training and qualification (including instruction on location and function of onboard emergency equipment)

- Special circumstances such as tunnels and joint or parallel operations with other transportation modes
- Operational tests and inspections, including recordkeeping
- Passenger safety awareness information
- Procedures for passengers with disabilities
- Train evacuation guidelines
- Procedures to address onboard traction equipment, including the battery and connected equipment
- Procedures to address sudden release of high-pressure hydrogen from activated (emergency) or failed (random non-emergency) TPRD

Railroads are encouraged to have conversations with the original passenger equipment manufacturers, as well as with other agencies that may have procured similar passenger equipment to leverage lessons learned. During the development of the passenger equipment, railroads should provide guidance to the OEMs on those characteristics that are consistent with traditional operating equipment. Training of first responders on the unique properties and risks of battery-electric and hydrogen fuel cell technologies will be imperative. It would therefore be recommended for railroads to solicit feedback from first responders in developing response plans and training requirements, including periodic drills to replicate actual emergencies. Furthermore, railroads may also benefit from conferring with other modes (e.g., buses, ferries) using alternative power sources to understand how those agencies have prepared for similar emergencies.

More information regarding federally mandated safety practices can be found in the U.S. Code of Federal Regulations (49 CFR parts 239 and 270).

3.2 Battery-electric and hydrogen passenger rail equipment inspection and maintenance

Railroads operating trains powered by batteries with or without hydrogen range extension may take on new inspection, maintenance and testing responsibilities unique to those propulsion systems. As a result, they may need to modify their facilities, revise their rolling stock maintenance plans, and update their safety and training plans. These efforts protect the health and welfare of maintenance employees and ensure the safety and good working order of the propulsion systems.

Monitoring tests and procedures associated with proper maintenance of zero-emission systems include: battery cell/module status; hydrogen leakage/accumulation detection; static discharge detection; control of high-pressure gas; inerting of the system; isolation failure in high-voltage systems, fuel cell cooling system status; safety line and purge vent line pressure; hydrogen compatibility of metallic components; gas cycling; tank fittings and connections; controlled fueling; etc..

Railroads will likely need to purchase and maintain new monitoring/diagnostic instrumentation, as well as specialized tools and equipment. Protocols for separating the specialized tools and equipment (e.g., spark-proof tools) from those that are used to maintain conventional components and systems may need to be developed.

Detailed training and maintenance manuals with highlights on the novel and unique aspects of the propulsion and energy storage systems, are especially important for such passenger equipment.

Implementation of alternative propulsion technologies will likely require the following changes in maintenance and upkeep:

- maintenance facility layouts and equipment
- preventive and corrective maintenance programs, procedures and forms
- maintenance manuals, including drawings, photographs, safety precautions and handling procedures

- safety protocols and job safety briefings
- tools and parts inventory
- testing, inspection procedures, and documentation
- cleaning protocols

Railroads may also need to reprogram asset management systems for alternative propulsion systems to ensure proper maintenance implementation, documentation, tracking and controls.

Training maintenance employees on alternative propulsion systems would be critical. Rolling stock maintenance training programs may need to be updated, including curriculum, classroom and OJT courses, proficiency reviews, recurrent recertification training, training materials, competency testing, training for revised procedures and training records.

The midlife overhaul text in fleet management plans may also need to be updated.

Finally, railroads should also review complementary plans that may also need to be revised, including configuration control; quality assurance/quality control, and occupational and system safety, among other topics.

4. Recommended topics for future research

The following topics are recommended for future research and development efforts that would advance the state of the art. These are concrete R&D issues that could be answered by development/testing programs at reasonable cost by FRA, the Transportation Research Board, or other government agencies.

4.1 Hydrogen safety related

- Tests to evaluate life cycle safety requirements for hydrogen tanks used in railroad applications, including pressure cycling of the tanks and development of possible destructive test requirements.
- Evaluation of the performance of onboard hydrogen systems in abnormal conditions (e.g., crashes and collisions).
- Lab or field evaluation of new nondestructive examination methods to monitor degradation/failure of the liner/carbon fiber overlay of hydrogen tanks. Note that many of the NDE techniques that can be applied to metal tanks cannot be used with composite tanks.
- Field testing of rail equipment to review system performance through all seasons/environmental conditions.
- Paper studies to provide guidance to the car builders and equipment suppliers developing new products. The R&D work might include literature search, expert opinions from other industries and transportation modes, review of accident reports and application of calculations or simulation programs on passenger rail equipment. An example of this is to review the benefits and hazards of TPRDs, pressure regulators, safety valves, hydrogen vent systems, and other safety equipment in direct contact with hydrogen gas.

  NOTE: TPRDs offer protective pressure release when a hydrogen tank is exposed to high temperatures; however, there are other risks that will need to be addressed for their safe application in transportation. These include inadvertent activation (random, non-emergency failure) and failed function (insufficient pressure release in an emergency). Additional concerns include jet fire hazards at TPRD vents, and potential ineffectiveness from localized impingement fire that is not close enough for TPRD activation.

- Research available technologies for a fire suppression system for onboard hydrogen systems.

- In general, the safety questions for passenger rail are common for all surface transportation modes using hydrogen (trucks, cars, freight rail, etc.), thus a joint effort from all applicable transportation modes (including industry and government agencies) should be consolidated to handle programs of this magnitude. For example, such a project could analyze the multimodal problem of how to manage hydrogen discharge and fires in tunnels.

4.2 Battery related

- Evaluate current testing programs for Li-ion batteries to assist in developing U.S. rail industry criteria for these systems.
- Evaluation of the performance of onboard battery systems in abnormal conditions (e.g., crashes and collisions).
- Field testing of rail equipment to review system performance through all seasons/environmental conditions.
- Develop common emergency response procedures for rail operators and first responders to help manage incidents involving thermal runaway and other failures in Li-ion batteries.
- Develop and conduct testing to define requirements for fire enclosures as a means of protection from fires in Li-ion battery power systems. This includes reviewing testing already conducted by others (e.g., Federal Aviation Administration, U.S. Navy).
- Research available fire suppression technologies for Li-ion battery systems.
- Evaluate electromagnetic fields generated from recharging Li-ion battery systems and their effects on passengers and crew onboard or adjacent to the vehicle.

5. List of referenced standards and regulations

AAR M-1004 – Interoperable Fuel Tenders for Locomotives

While this standard pertains to fuel tenders for locomotives, it is referenced in this white paper for the color-coding of safety-critical components.

ASME B31.3 – Process Piping

This standard specifies engineering requirements deemed necessary for safe design and construction of pressure piping.

ASME B31.12 – Hydrogen Piping and Pipelines

This standard contains requirements for piping in gaseous and liquid hydrogen service and pipelines in gaseous hydrogen service.

CFR – United States Code of Federal Regulations

The CFRs contain regulations governing the design and safety of passenger rail equipment.

CSA/ANSI HGV 2 – Compressed Hydrogen Gas Vehicle Fuel Containers

This document contains requirements for the material, design, manufacture, marking, and testing of serially produced, refillable Type HGV 2 containers intended only for the storage of compressed hydrogen gas for on-road vehicle operation.

CSA/ANSI HGV 3.1 – Fuel Cell Components for Compressed Hydrogen Gas Powered Vehicles

This document contains requirements for newly produced compressed hydrogen gas fuel system components.

EC No. 79 – Regulation (EC) No 79/2009 of the European Parliament and of the Council of 14 January 2009 on Type-Approval of Hydrogen-Powered Motor Vehicles, and Amending Directive 2007/46/EC; and Commission Regulation (EU) No 406/2010 of 26 April 2010 Implementing Regulation (EC) No

79/2009 of the European Parliament and of the Council on Type Approval of Hydrogen-Powered Motor Vehicles

This regulation establishes requirements for the type-approval of motor vehicles with regard to hydrogen propulsion and for the type-approval of hydrogen components and hydrogen systems. This regulation also establishes requirements for the installation of such components and systems.

EN 17127 – Outdoor Hydrogen Refuelling Points Dispensing Gaseous Hydrogen and Incorporating Filling Protocols

This standard defines the minimum requirements to ensure the interoperability of hydrogen refueling points, including refueling protocols that dispense gaseous hydrogen to road vehicles that comply with legislation applicable to such vehicles.

EN 45545-2 – Railway Applications – Fire Protection on Railway Vehicles – Part 2: Requirements for Fire Behaviour of Materials and Components

This standard specifies the reaction to fire performance requirements for materials and products used on railway vehicles.

GTR 13 – Global Technical Regulation on Hydrogen and Fuel Cell Vehicles

This global technical regulation established by the United Nations is intended to ensure that hydrogen-fueled vehicles attains or exceeds equivalent levels of safety when compared to conventional gasoline-fueled vehicles.

IEC 61373 – Railway Applications – Rolling Stock Equipment – Shock and Vibration Tests

This standard covers the requirements for random vibration and shock testing of pneumatic, electrical and electronic equipment/components to be fitted onto railway vehicles.

IEC 62619 – Secondary Cells and Batteries Containing Alkaline or Other Non-Acid Electrolytes – Safety Requirements for Secondary Lithium Cells and Batteries, for Use in Industrial Applications

This standard specifies requirements and tests for the safe operation of secondary lithium cells and batteries used in industrial applications, including stationary applications.

IEC 62928 – Railway Applications – Rolling Stock – Onboard Lithium-Ion Traction Batteries

This standard applies to onboard Li-ion traction batteries for railway applications. This document specifies the design, operation parameters, safety recommendations, data exchange, routine and type tests, as well as marking and designation.

ISO 1988X Series – Gaseous Hydrogen

This series of ISO standards identify requirements pertaining to gaseous hydrogen and their design and use for land vehicles.

NFPA 2 – Hydrogen Technologies Code

This standard provides fundamental safeguards for the generation, installation, storage, piping, use and handling of hydrogen in compressed gas form or cryogenic liquid form.

NFPA 130 – Standard for Fixed Guideway Transit and Passenger Rail Systems

This standard specifies fire protection and life safety requirements for underground, surface and elevated fixed guideway transit and passenger rail systems.

SAE J2574 – Fuel Cell Vehicle Terminology

This standard contains definitions for hydrogen fuel cell powered vehicle terminology.

SAE J2578 – Recommended Practice for General Fuel Cell Vehicle Safety

This recommended practice identifies and defines requirements relating to the safe integration of the fuel cell system, the hydrogen fuel storage and handling systems, and high-voltage electrical systems into the overall fuel cell vehicle.

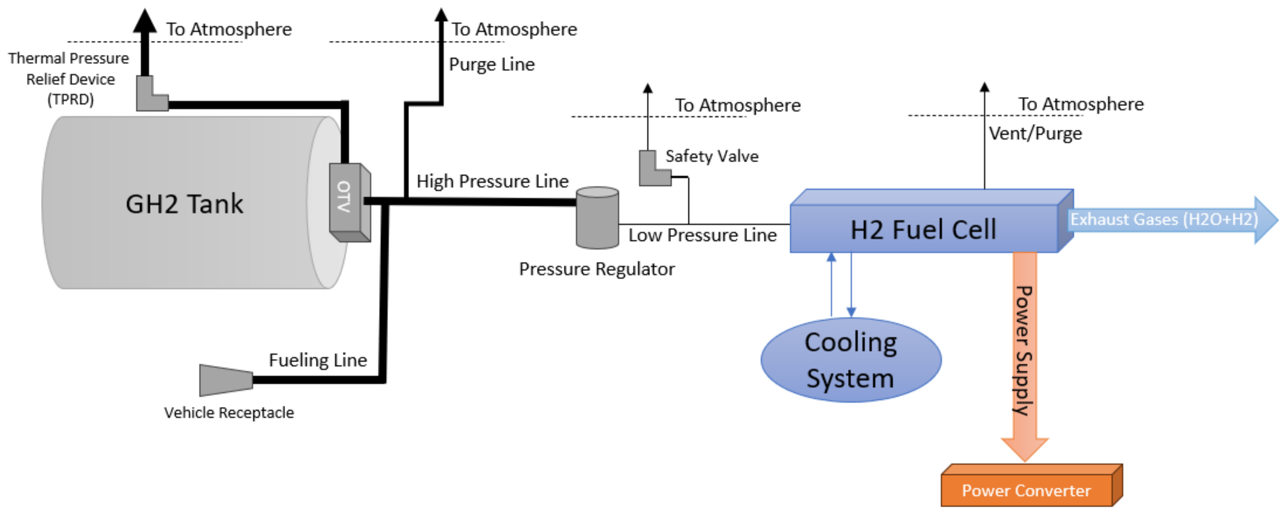
SAE J2799 – Hydrogen Surface Vehicle to Station Communications Hardware and Software

This standard specifies the communications hardware and software requirements for fueling hydrogen surface vehicles, such as fuel cell vehicles, but may also be used where appropriate, with heavy-duty vehicles and industrial trucks with compressed hydrogen storage.

Definitions

For the onboard hydrogen system, the following graphic identifies the various components utilized in this white paper:

FIGURE 1
Onboard Hydrogen System Components



alternative propulsion energy system: For the purposes of this white paper, this term is used generically to refer to the onboard traction battery system, and if used, the addition of an onboard hydrogen system for range extension.

battery: For the purposes of this white paper, onboard traction batteries unless otherwise noted. This white paper is intended to address those battery systems used for the onboard alternative propulsion energy system for traction power or traction power and auxiliaries. Batteries for just powering auxiliaries are out of the scope of this white paper.

battery box: Protective enclosure around the batteries used to mount the batteries to the carbody.

battery cell: Secondary cell where electrical energy is derived from the insertion/extraction reactions of Li-ions or oxidation/reduction reaction of lithium between the negative electrode and the positive electrode. The cell typically has an electrolyte that consists of a lithium salt and organic solvent compound in liquid, gel or solid form and has a metal or laminate film casing. It is not ready for use in an application because it is not yet fitted with its final housing, terminal arrangement and electronic control device. [IEC 62928:2017]

battery management system: System associated with a battery pack that monitors and/or manages its state, disconnects or isolates the battery pack, calculates secondary data, communicates data outside of the battery system and/or controls its environment to influence the battery's safety, performance and/or service life. The function of the BMS can be assigned to the battery pack or to equipment that uses the battery pack. Its functions include thermal control. [IEC 62928:2017]

battery module: Also referred to as a battery pack. Energy storage device composed of one or more cells electrically connected. The battery module incorporates a protective housing and is provided with terminals or other interconnection arrangement. It includes at least monitoring circuitry, which provides information (e.g., cell voltage, temperature) to a battery system. It may include a protective device and control circuitry. [IEC 62928:2017]

battery system: System that incorporates one or more cells, modules or battery packs, including battery management system and thermal management system, as well as disconnecting and/or isolating devices (contactors, disconnectors, fuses, etc.). [IEC 62928:2017]

external leakage test: A test designed to provide evidence that the hydrogen components are free from external leakage. The hydrogen components must not show evidence of porosity. [EC No. 79]

fittings: Connectors used in a piping, tubing or hose system. [EC No. 79]

high-pressure line or system: Part of hydrogen system that includes components such as fuel lines and fittings containing hydrogen at a nominal working pressure greater than 3.0 MPa (435.1 psig). [EC No. 79]

hydrogen compatibility test: A test designed to provide evidence that metallic hydrogen components (i.e., cylinders and valves) are not susceptible to hydrogen embrittlement. In hydrogen components that are subjected to frequent load cycles, conditions that can lead to local fatigue and the initiation and propagation of fatigue cracks in the structure must be avoided. [EC No. 79]

hydrogen conversion system: Any system designed for the conversion of hydrogen into electrical, mechanical or thermal energy; includes, for example, the propulsion systems or auxiliary power units. [EC No. 79]

leakage: For battery: visible escape of liquid electrolyte. [IEC 62928:2017] For hydrogen: release of contents through a defect or crack (excludes permeation). [CSA/ANSI HGV 2]

lithium-ion batteries: Batteries that utilize lithium as the base element. Covers Li-ion batteries in various chemistries and levels of performance suited for passenger rail equipment at the time of the publication of this white paper.

low-pressure line or system: Part of the hydrogen system that includes components such as fuel lines and fittings containing hydrogen at a nominal working pressure up to and including 0.45 MPa (65.3 psig). [EC No. 79]

medium pressure line or system: Part of the hydrogen system that includes components such as fuel lines and fittings containing hydrogen at a nominal working pressure greater than 0.45 MPa (65.3 psig) and up to and including 3.0 MPa (435.1 psig). [EC No. 79]

pressure regulator: A device used to control the delivery pressure of gaseous fuel to the hydrogen conversion system. [EC No. 79]

purge line: Used for the controlled release of hydrogen.

safety valve: A reclosing pressure activated device that, when activated under specified conditions, is used to release fluid from a pressurized hydrogen system. [EC No. 79]

stranded energy: The energy remaining in a cell after efforts to safely discharge the stored energy in damaged Li-ion cells. Residual, stranded, DC energy within damaged Li-ion batteries presents a significant fire and shock hazard, particularly to emergency responders. [NFPA Research Foundation – Stranded Energy within Lithium-Ion Batteries]

tank: A device for storing a raw fuel for the fuel cell. [SAE J2574:2011] In the case of compressed gaseous hydrogen, a high-pressure cylinder is used. Working pressures for hydrogen cylinders range from 25 MPa to 70 MPa (3625.9 psig to 10,152.6 psig).

temperature cycle test: A test designed to provide evidence that the hydrogen components are capable of resisting high variations of temperature. To prove this, the hydrogen components are submitted to a temperature cycle of specified duration from the minimum operating temperature up to the maximum operating temperature. [EC No. 79]

thermal pressure relief device: A pressure relief device that is activated by elevated temperature. [SAE J2578:2023] TPRDs are used to protect the pressure vessel.

vent line: Used to direct an emergency release of hydrogen to a specific location.

Abbreviations and acronyms

BMS	battery management system
CFD	computational fluid dynamics
CFR	Code of Federal Regulations
FRA	Federal Railroad Administration
Li-ion	lithium-ion
MPa	megapascal
MSDS	material safety data sheet
NDE	nondestructive examination
O&M	operations and maintenance
OCS	overhead contact system
OEM	original equipment manufacturer
OJT	on-the-job training
OTV	on tank valve
psig	pounds per square inch in gauge
TPRD	thermal pressure relief device

Document history

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