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Safety Codes and Standards Review and Gap Analysis for Applicability to Hydrogen Rail Refueling, Defueling, Maintenance, and Storage

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ABSTRACT

Hydrogen-powered locomotives may present an alternative to diesel for achieving transportation-related decarbonization, energy security, and resilience goals. As an emerging technology, hydrogen locomotives may not have adequate representation in current safety codes and standards. NFPA 2 and other appropriate codes and standards were reviewed to identify technical gaps in the code for hydrogen rail defueling, refueling, maintenance, and storage. Several technical gaps pertaining to setback distances, allowable quantities, ventilation rates, and grounding have been identified. Fueling requirements can be informed by road vehicle standards but may need to be revised for larger quantity hydrogen locomotive systems. Since there are no hydrogen-specific locomotive design and safety standards, some aspects of diesel-based locomotive standards may apply. CGA G-5.5 currently provides the most guidance on height, placement, orientation, and design of vent systems, while other standards emphasize the importance of shielding vent stacks and provide requirements for orientation of their discharge.

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ACRONYMS AND TERMS

Acronym/Term	Definition
AAR	Association of American Railroads
ANSI	American National Standards Institute
API	American Petroleum Institute
APRR	average pressure ramp rates
CHSS	compressed hydrogen storage system
CFR	Code of Federal Regulations
CGA	Compressed Gas Association
CNG	compressed natural gas
EPA	Environmental Protection Agency
FMVSS	Federal Motor Vehicle Safety Standards
GH2	gaseous hydrogen
HPIT	hydrogen powered industrial trucks
ISO	International Organization for Standardization
L:D	length:diameter
LFL	lower flammability limit
LH2	liquid hydrogen
LNG	liquified natural gas
LPG	liquified petroleum gas
MAQ	maximum allowable quantity
MTTHE	mean time to hazardous events
NHTSA	National Highway Traffic Safety Administration
NFPA	National Fire Protection Association
OSHA	Occupational Safety and Health Administration
PSM	process safety management
RAGAGEP	recognized and generally accepted good engineering practice
RMP	risk management program
SAE	Society of Automotive Engineers
SCF	standard cubic feet
SOC	state of charge
TPRD	thermally-activated pressure relief device
UN GTR	United Nations Global Technical Regulations
V	volts

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1. INTRODUCTION

Hydrogen is emerging as an alternative to diesel fuel for locomotive applications, and as locomotive equipment companies, railways, and technology investors continue to develop infrastructure and methods for a transition to hydrogen, it is necessary to understand, comply with, and update any relevant regulations and requirements. To help ensure safe implementation of hydrogen locomotive defueling, refueling, and maintenance facilities, this report reviews the applicability of relevant regulations, listed in Table 1 below, and identifies the codes and standards that require reevaluation or revision.

Table 1: Referenced documents, in order of appearance

Document Number	Document Name
NFPA 2 [1]	Hydrogen Technologies Code
CGA H-5 [2]	Standard for Bulk Hydrogen Supply Systems
29 CFR 1910.119 [3]	Process Safety Management of Highly Hazardous Chemicals
40 CFR 68 [4]	Chemical Accident Prevention Provisions
29 CFR 1910.103 [5]	Hydrogen
SAE J2601 [6]	Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles
SAE J2601-2 [7]	Fueling Protocol for Gaseous Hydrogen Powered Heavy Duty Vehicles
SAE J2579 [8]	Standard for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles
SAE J2600 [9]	Compressed Hydrogen Surface Vehicle Fueling Connection Devices
SAE J2601-3 [10]	Fueling Protocols for Gaseous Powered Industrial Trucks
SAE J2601-5 [11]	High-Flow Prescriptive Fueling Protocols for Gaseous Hydrogen Powered Medium and Heavy-Duty Vehicles
AAR Section M [12]	Locomotives and Locomotive Interchange Equipment
ISO 13985:2006 [13]	Other Requirements
40 CFR 1033.115 [14]	Liquid Hydrogen – Land Vehicle Fuel Tanks
49 CFR 229 [15]	Railroad Locomotive Safety Standards
CGA G-5.5 [16]	Standard for Hydrogen Vent Systems
UN GTR 13 [17]	Hydrogen and Fuel Cell Vehicles
SAE J2578 [18]	Recommended Practice for General Fuel Cell Vehicle Safety

Documents such as the National Fire Protection Association (NFPA) Hydrogen Technologies Code, NFPA 2, provide guidance on designing and maintaining stationary hydrogen storage and fueling systems within the U.S. for both gaseous and liquid fuels. NFPA 2 is regularly cited for hydrogen system design and is referenced by many authorities having jurisdiction (AHJs) as a key document for fire safety requirements. Similarly, the Compressed Gas Association (CGA) document H-5 provides safety guidance for bulk gaseous and liquid hydrogen. Additional requirements are in federal regulations, such as 29 CFR 1910.119, 40 CFR 68, and 29 CFR 1910.103 for large amounts of stored hydrogen. These regulations are general documents published by the Occupational Safety and Health Administration (OSHA) and the Environmental Protection Agency (EPA) which apply to the storage of toxic and flammable gases and outline requirements for process

safety management, accident prevention, and risk management practices. The Society of Automotive Engineers (SAE) documents J2601, J2601-2, J2579, J2600, and J2601-3 are standards used for fulfilling light-duty, heavy-duty, and industrial truck hydrogen refueling requirements. The Association of American Railroads (AAR) Section M and 49 CFR 229 provides guidance on tank design and placement for diesel-electric locomotives while considering potential accident scenarios to prevent and mitigate accidental releases of fuel. These standards, along with the requirements outlined in ISO 13985 and 40 CFR 1033.115 can be a starting point for properly designing tanks for use on hydrogen locomotives. CGA G-5.5, 29 CFR 1910.103, UN GTR 13, SAE J2578, SAE J2579, and 49 CFR 229 represent important resources for the design, support, placement, sizing, height, and safe mounting of vent stacks attached to thermally-activated pressure relief devices (TPRDs).

The purpose of this document is to review existing relevant regulations which can aid in the development of hydrogen locomotive technology. These regulations are examined from the perspective of identifying gaps in the code which may require revision for large, heavy-duty transport systems such as hydrogen locomotives. The relevance of these codes and standards to hydrogen locomotive design is explored in the main body of this report. To highlight regulatory gaps which may require revision, specific sections within these codes and standards are itemized in Appendix A.

1.1. Comparisons with diesel and hydrogen automotive vehicles

The transition of diesel locomotives to hydrogen locomotives is a technological shift that has an analog in the road-vehicle space. The development of hydrogen fuel cell automotive vehicles required identifying the unique safety risks posed by hydrogen's thermochemical properties and the potential for leaks, venting, and fires. These unique safety risks prompted the modification of gasoline and diesel vehicle design to address hydrogen's flammability and leak potential, and similar considerations will be needed to redesign locomotives.

Table 2 below provides a high-level summary of the unique differences between diesel and hydrogen fuel systems for passenger and heavy-duty transport. Although different types of vehicles must comply with different codes and standards, these key safety differences can be used to guide preliminary hydrogen locomotive design.

Table 2: Key safety design differences between diesel and hydrogen road vehicles

Feature	Diesel Vehicles	Hydrogen Vehicles
Fuel Storage/Tank Design	Uses a standard liquid fuel tank which is less leak-tight compared to hydrogen tanks.	Because of hydrogen's unique flammability, diffusivity, thermochemical properties, and potentially low temperatures or high pressures, hydrogen tanks have different material properties and are designed to withstand many types of impacts. [19]
Battery Type	Diesel vehicles use 1-2 flooded (also known as conventional) or absorbed glass mat lead acid batteries, each at ~12-24 V. These batteries are traditionally	Hydrogen vehicles, such as those powered by fuel cells, typically feature lithium-ion batteries. The voltages of these batteries are considerably higher than the ~12-24 V for a diesel vehicle,

Feature	Diesel Vehicles	Hydrogen Vehicles
	less prone to fire and explosion compared to lithium-ion batteries. [20]	presenting an electric shock risk. [21] Lithium-ion batteries feature high energy density and are prone to thermal runaway, which could lead to battery fire, heating of the hydrogen tank, TPRD release, and explosion. [22] [23] [24] This necessitates proper isolation of the hydrogen tank from the battery system.
Fire Prevention and Suppression	Passenger vehicles do not require them, however heavy-duty diesel trucks must carry a manually-operated fire extinguisher. [25]	The tank and fuel cell system of hydrogen vehicles are equipped with sensors, shut off valves, and relief valves to prevent and mitigate leaks and fires. [26]
Fuel Venting	Diesel tanks have "breathers," or tank vents however, this is not explicitly for safety purposes since these devices are primarily used to allow air into and out of the tank during fuel consumption and fueling, respectively. [27] Without this venting, fuel cannot enter or exit the tank, inhibiting refueling and engine operation.	Hydrogen tanks must have some relief venting to prevent tank rupture. This may involve a TPRD, or a rupture disc, and vent stack. These devices are designed for safe dispersion of the fuel. [28]
Fueling	Liquid fuel is pumped through a fuel dispensing line, through a nozzle, and into the tank.	Hydrogen fueling requires specialized nozzle and connector combinations. High pressures are involved in gaseous hydrogen fueling, therefore connections must be leak tight in accordance with SAE or other standards. [29] Temperature and pressure are monitored to prevent overheating and over pressurization. [30] For liquid hydrogen fueling, nozzles and receptacles can become covered in ice and difficult to disconnect from one another. [31]
Defueling	Tank is not typically emptied during maintenance.	Defueling may be necessary for non-routine maintenance, so the vehicle must feature connectors to facilitate this process. [32]

Feature	Diesel Vehicles	Hydrogen Vehicles
Crash Safety	Must pass standard diesel vehicle crash tests according to NHTSA's Federal Motor Vehicle Safety Standards (FMVSS).	Hydrogen vehicles must pass additional National Highway Traffic Safety Administration (NHTSA) crash safety requirements to ensure tank integrity and prevention of leaks. The NHTSA sets requirements for maximum hydrogen leakage, electrical integrity of the fuel cell, and integrity of the tank post-crash. These requirements are designed to be consistent with the safety level of other types of vehicles such as diesel-powered automobiles and trucks (see NHTSA's Federal Motor Vehicle Safety Standards (FMVSS) #301, 303, 304, and 305). [33]

This comparison provides direction regarding aspects of the codes and standards which should be reevaluated for applicability to hydrogen locomotives. In addition to general hydrogen safety (covered in section 2.1), the codes and standards applicable to three of the main categories above, namely fueling (section 2.2), fuel storage/tank design (section 2.2.6), and fuel vent systems (section 2.4), are explored in more detail in this report.

2. EVALUATION OF CODES AND STANDARDS

2.1. General Safety Requirements for Hydrogen Rail

The following codes and standards outline overall safety requirements for hydrogen systems and must be considered in hydrogen rail defueling, refueling, maintenance facility, storage, and component design.

2.1.1. NFPA 2: Hydrogen Technologies Code

The NFPA regularly publishes a Hydrogen Technologies Code, NFPA 2, most recently released in 2023. This gaseous hydrogen (GH2) and liquid hydrogen (LH2) code provides guidance such as setback distances for hydrogen storage and exposures in a hydrogen facility, emergency shutdown system design, fire protection and mitigations, and refueling protocols.

Overall, while this document is meant to support a wide range of hydrogen applications and has many sections that may apply to hydrogen locomotive refueling, some reevaluation or revision is required when designing a maintenance or refueling facility. **Chapter 6 discusses Maximum Allowable Quantity (MAQ) of hydrogen in a control area, minimum ventilation rates for enclosed areas, and discharge distances for physical structures which may need to be revised for larger systems such as locomotives and their fueling/defueling.** Chapters 7 and 8 respectively cover gaseous and liquid hydrogen storage. They both contain recommended setback distances between bulk hydrogen storage and exposures including lot lines, people not working at the facility, and buildings. However, large quantities of gaseous or liquid hydrogen on-site are not explicitly considered. The risk-informed methodologies used to determine the setback distances likely did not consider the additional hazards/risks posed by the large quantities of hydrogen that would likely be present at a locomotive refueling station. **Thus, the setback distances may need to be reviewed for larger systems like those likely used in locomotive refueling facilities. Likewise, maximum indoor quantities of liquid hydrogen may need to be reevaluated for tanks on hydrogen locomotives being serviced.**

Chapters 10 and 11 respectively cover gaseous and liquid hydrogen fueling operations. The type of guidance provided in these sections includes recommended **fueling flow rates, bonding and grounding requirements, electrical equipment installation distances, dispensing integrity tests, locations for dispensers, setback distances for emergency shutdown devices and buildings, and fueling nozzle design, all of which should be reevaluated for hydrogen locomotives.** Like in Chapters 7 and 8, quantitative guidance such as setback distances may depend on the amount of hydrogen on-site and should be verified for applicability to locomotive refueling conditions. **Additionally, since only fueling nozzle design and selection criteria for automotive refueling is provided, explicit guidance is needed for locomotive refueling.** Also, NFPA 2 does not currently have guidance for nonpublic fueling of LH2, which would likely be directly applicable to hydrogen-powered locomotives.

Chapter 18 presents guidance for repair garages for GH2-propelled vehicles (not LH2). **Allowances for non-mechanical/forced ventilation of facilities may be allowed, but this may be insufficient for locomotive repair facilities.** Separation distances for repair booths are provided, however, if hydrogen locomotives are serviced alongside diesel, liquified natural gas (LNG), liquified petroleum gas (LPG), compressed natural gas (CNG), or other trains or buses, **these separation distances or partition requirements should be evaluated for adequacy.**

Many aspects of NFPA 2 should be reassessed for relevance for hydrogen locomotives, their repair facilities, and defueling/refueling processes. **An itemized evaluation of NFPA 2 codes and standards' applicability to hydrogen locomotive systems can be found in** Table 3 **in Appendix A.**

2.1.2. CGA H-5: Standard for Bulk Hydrogen Supply Systems

The CGA provides safety standards for a range of applications and industries, including the usage of compressed gaseous and cryogenic liquid hydrogen. CGA H-5 is the standard that contains guidance for management of bulk hydrogen supply systems. The standard defines a bulk gaseous hydrogen system as one with more than 5000 scf (standard cubic feet) of hydrogen (which is approximately 11.8 kg) and a bulk liquid hydrogen system as one with more than 39.7 gallons of hydrogen (which is approximately 10.6 kg at 1 atm and 20K). It provides recommended setback distances that should be maintained between the hydrogen systems and exposures such as vent outlets and tank fill connections, as well as guidance for siting, fire protection, grounding, equipment selection, and testing of the system. The standard also specifies that additional considerations should be made for systems containing more than 10,000 lb of hydrogen; mainly, the system should comply with the OSHA Process Safety Management (PSM) guidelines under 29 CFR 1910.119 and the EPA Risk Management Program (RMP) 40 CFR 68. CGA H-5 currently applies to both bulk gaseous or liquid hydrogen storage systems used to service locomotives, however, some quantitative requirements may need to be reevaluated for hydrogen rail applications. **For example, the setback distances, fire protection time for barrier walls, and grounding resistance may need to be increased depending on the quantities of hydrogen considered.** The assumptions regarding bulk hydrogen locomotive refueling facilities should be examined as well. The latest version of CGA H-5 was published in 2020. An itemized evaluation of CGA H-5 codes and standards' applicability to hydrogen locomotive systems can be found in Table 4 in 0.

2.1.3. 29 CFR 1910.119: Process Safety Management of Highly Hazardous Chemicals

29 CFR 1910.119 is a federal standard published by OSHA that specifies process safety management practices for mitigating consequences from catastrophic releases of certain gases, including flammable gases like hydrogen, with a focus on fire or explosion potential. It was last updated in 2019. This document is also referenced as a requirement by CGA H-5. More specifically, the document applies to Category 1 flammable gases in quantities of 10,000 lbs. or more, with the exception of flammable liquids with a flashpoint < 100°F (37.8°C) stored in atmospheric tanks or transferred and which are kept below their normal boiling point without chilling or refrigeration. This exception does not apply to hydrogen because liquid tanks are slightly pressurized and cooling is necessary to maintain cryogenic temperatures in the system. Category 1 flammable gases are defined by 29 CFR 1910.1200 Appendix B to be gases, which at 20°C (68°F) and a standard pressure of 101.3 kPa (14.7 psi) are (a) ignitable when in a mixture of 13 vol% or less in air; or (b) have at least a 12 percentage point flammable range with air, regardless of the lower flammable limit. The hydrogen flammability limit in air is 4-74 vol% [34], which means both requirements are true, and hydrogen is therefore considered a Category 1 flammable gas as regulated by 29 CFR 1910.119.

The guidance in 29 CFR 1910.119 requires employers to perform a Process Hazard Analysis on applicable hydrogen systems, create written equipment documentation and operating procedures with specific steps, train employees and contractors on the process, ensure mechanical integrity of components in the system, document management of change processes, establish emergency

planning and response, and perform testing and quality assurance checks on all equipment. **Because this guidance applies to any highly hazardous chemical system, it is sufficiently general to also apply, as written, to hydrogen locomotive systems, their maintenance, refueling, and defueling.** An evaluation of OSHA's 29 CFR 1910.119 standards' applicability to hydrogen locomotive systems can be found in Table 5 in Appendix A.

2.1.4. 40 CFR 68: Chemical Accident Prevention Provisions

40 CFR 68 is an EPA document on Risk Management Prevention (RMP) and is referenced by CGA H-5. It was last updated in 2020. The purpose of 40 CFR 68 is to help ensure that facilities that handle hazardous chemicals such as hydrogen are equipped for preventing accidental releases and managing risks. 40 CFR 68 lists hydrogen in quantities of at least 10,000 lbs. as a regulated flammable substance. Risk management prevention requirements include analyzing worst-case release scenarios for affected distances of damaging overpressures from explosions and harmful heat fluxes from jet fires caused by accidental releases of flammable gases. Additionally, consideration and analysis of alternative release scenarios is also required. The risk management program should also consider the impacts of an accidental release of a stored substance on the offsite population and environment. The employer is required by this standard to develop and implement a written management system and emergency response program. In addition, they must document the system's five-year accident history. The RMP includes steps for prevention of accidental releases, such as hazard assessment, identifying potential release scenarios, evaluating likelihood, development of a prevention and emergency response program, documentation of operating procedures, adequate training for employees, regular maintenance, compliance audits, and investigation into incidents. This Risk Management Plan must be updated and resubmitted every five years in the manner specified by the EPA.

Flammable substances are excluded from all provisions when used as a fuel according to section 68.126, so this document may not apply to hydrogen fuel cell locomotives, but may apply to refueling facilities. Section 68.25(e) and (f)'s requirements are written for a worst-case scenario analysis for flammable gases and liquids. These should be reevaluated for applicability to GH2 and LH2 releases, since hydrogen releases are unique compared to releases of other flammable gases. An itemized evaluation of 40 CFR 68 provisions' applicability to hydrogen locomotive systems can be found in Table 6 in 0.

2.1.5. 29 CFR 1910.103: Hydrogen

29 CFR Section 1910.103, last updated in 2024, is a Code of Federal Regulations related to occupational safety and health which **covers gaseous hydrogen systems greater than 400 ft^3 (11.3 m^3, which is approximately 0.95 kg at 68°F and 1 atm) and liquid hydrogen systems greater than 150 L (which is approximately 10.6 kg at 1 atm and 20K), including portable tanks and trailers. This suggests that this regulation can be applied to hydrogen locomotive systems.** The regulation specifies safety protocols including design, installation, and maintenance of tanks, relief devices, piping, fittings, and equipment. It also provides setback distances for buildings, other gases, hot work, and people, based on the volume of hydrogen. Location of the hydrogen (outdoors, in a separate building, in a special room, or in non-special rooms with other occupancies) is based on the volume of hydrogen being stored and the materials of construction of the structure. This regulation also emphasizes proper ventilation, grounding, and bonding.

There is substantial overlap between this regulation and NFPA 2 since it specifies setback distances, but, unlike NFPA 2, 29 CFR 1910.103 does not explicitly discuss hydrogen production or

distribution. **Setback distances, inlet and outlet ventilation opening size, and provisions for explosion venting may need to be reevaluated for larger hydrogen locomotive systems.** We expect that when NFPA 2 is updated for larger systems such as trains, 29 CFR 1910.103 may also be updated accordingly. An itemized evaluation of this regulation's applicability to hydrogen locomotive systems can be found in Table 7 in 0.

2.2. Hydrogen Refueling

The following Society of Automotive Engineers standards can be applied to developing refueling standards for hydrogen rail systems.

2.2.1. SAE J2601: Fueling Protocols for Light-Duty Gaseous Hydrogen Surface Vehicles

SAE J2601 is a standard last revised in 2020 that details protocols for light-duty vehicle refueling, including a reference fueling time target and performance targets based on factors such as fuel temperature, maximum fuel flow rate, rate of pressure increase, and end pressure. It is a table-based fueling protocol which applies to 35 MPa and 70 MPa systems at -40°C, -30°C, or -20°C. Future versions of SAE J2601 are expected to include warmer temperatures, including -10°C and ambient temperatures. The standard applies to storage quantities of 49.7 to 248.6 L for both 35 and 70 MPa systems, and for quantities above 248.6 L for high-pressure systems. Its reference fueling target is 3 minutes, though fueling times may be longer depending on conditions. This standard includes fueling tables for systems that feature communication between the dispenser and vehicle as well as systems that do not have such features (non-communications fueling) with corresponding performance targets.

While this standard implicitly does not apply to hydrogen locomotive refueling since locomotives are considered heavy-duty applications, it raises helpful considerations for creating safe protocols for application-specific fueling. **Specifically, a revised version of this protocol or a corresponding locomotive-specific regulation would feature look-up tables for hydrogen locomotives' target pressures, average pressure ramp rates (APRR), and top-off APRR values based on various factors such as ambient temperature, compressed hydrogen storage system (CHSS) capacity category, and fuel delivery temperature.** This would determine the fueling process including startup time, main fueling time, shutdown time, and non-fueling events. These fueling tables would also vary based on whether on-board communications with the fueling system are present. Fueling time would need to be extended and pressures and APRRs would likely need to be adjusted for hydrogen locomotive systems since they are larger than light-duty vehicles and will likely require significantly more fuel.

Likewise, fueling protocols would need to be unique to the type of tank and fuel. For example, since this protocol is specific to gaseous hydrogen, a different fueling protocol is necessary for liquid hydrogen systems. Importantly, if composite tanks are used for compressed gas storage, specific protocols are needed to prevent overheating during tank refueling. Since this protocol is specific to light-duty vehicles and we are considering an entirely different system (hydrogen rail), we have <u>not</u> provided an itemized evaluation of SAE J2601's applicability to hydrogen locomotive systems in the Appendix.

2.2.2. SAE J2601-2: Fueling Protocol for Gaseous Hydrogen Powered Heavy Duty Vehicles

SAE J2601-2 is a fueling protocol last revised in 2023 that provides guidance for safe fueling of heavy-duty hydrogen vehicles. Currently, the document is aimed towards heavy-duty hydrogen transit bus applications at 35 MPa with a combined vehicle compressed hydrogen storage system of over 10 kg. **As some hydrogen locomotive tanks may be pressurized to 70 MPa, this protocol would need to be revised for higher pressures.** The protocol includes fueling rate options, dispenser performance verification, and safe boundary conditions for pressure and temperature during fueling. This protocol provides boundary conditions for H35 nozzle compressed hydrogen storage system fueling: -40 to 85 °C and 0.5 MPa to 43.8 MPa and maximum density = 100% State of Charge (SOC).

This protocol is not as detailed or prescriptive compared to SAE J2601: Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles. The considerations may be applicable to hydrogen locomotive refueling, but some of the recommendations such as the fueling boundary conditions may need revision based on a more locomotive-specific system. For example, the fast, normal, and slow fueling rates may need to be adjusted for locomotive tanks. Assumptions such as the type and amount of storage may change; for example, a locomotive may use liquid hydrogen and would likely hold much larger quantities than buses due to their longer range and larger loads. An itemized evaluation of SAE J2601-2 provisions' applicability to hydrogen locomotive systems can be found in
Table 8 in 0.

2.2.3. SAE J2579: Standard for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles

SAE J2579 is a surface vehicle standard last updated in January 2023 that provides requirements for hydrogen fuel storage for road vehicles. This standard **provides performance-based means of verifying prototypes, provides examples of test protocols, and discusses requirements for both gaseous and liquid hydrogen fuel systems.** For example, this standard provides requirements for test cycles for heavy-duty commercial vehicle fuel systems (such as those on trucks and buses) and outlines important processes for production-type storage tests which should be followed by performance tests.

SAE J2579 features two main sections: descriptions of general requirements and performance requirements for fuel systems. Although these two sections encompass safety features, process verification, fueling, defueling, and other considerations, this standard is written generally to apply to many different fuel system sizes and flowrates, and largely refers the reader to other codes and standards for specific design requirements. See Table 9 in 0 for an itemized list of SAE J2579's requirements and their applicability to hydrogen locomotive systems.

2.2.4. SAE J2600: Compressed Hydrogen Surface Vehicle Fueling Connection Devices

SAE J2600 covers the design and testing of gaseous compressed hydrogen vehicle fueling connectors, nozzles, and receptacles and was last revised in 2015. This standard **does not include liquid hydrogen surface vehicle fueling and does not specify any maximum fueling flowrate, nor maximum receptacle/nozzle/connector size.**

The requirements in this standard allow hydrogen vehicles to be fueled with pressure classes less than or equal to the vehicle pressure class, but not greater. The requirements also aim to prevent

vehicles from being fueled with the incorrect compressed gas, while ensuring that receptacles will be compatible with various appropriate manufacturers' gaseous hydrogen nozzles. This standard requires testing of nozzle and receptacle resistance to aging, oxygen, and hydrogen diffusion. Nozzles, receptacles, and connectors should be tested for leaks, and for their ability to withstand abnormal loads, drops, vibration, and thermal cycling. For leak testing, worn fit, loose fit, and tight fit connectors are test fixtures used to assess durability under various use conditions.

The requirements in Section 4 (receptacles and nozzles) and 5 (design verification tests) may require the greatest degree of revision for hydrogen locomotive applications. Section 4.3 discusses the geometry of **H11 to H50, and the H70 receptacles, which may not be appropriate for larger systems.** (For these receptacles, the numerical value after the letter H signifies the nominal working pressure in MPa at 15°C). Likewise, **receptacle mounting dimensions on the vehicle need to be revised** for the likely greater nozzle, connector, and receptacle dimensions of locomotives compared to automotive vehicles. It is important to note that if installation of larger nozzles on hydrogen locomotives is infeasible, more commonplace nozzles can be used with multiple tanks on each rail car.

In Section 5, **connection forces, disconnection forces, and torques will likely be adjusted for larger nozzles and connectors.** The maximum leakage rate requirements for low, room, and high temperature leak tests as well as hydrostatic strength tests need to be revised for larger fueling rates and larger tanks. The requirements for the tests outlined in 5.2, 5.3, 5.6-5.8, 5.10-5.13, 5.15-5.18, and 5.20 of SAE J2600 outline specific procedures for integrity testing designed to evaluate the performance of the receptacle and nozzles mentioned in this standard. **These tests most likely need to be revised for larger equipment.** An evaluation of SAE J2600 standards' applicability to hydrogen locomotive systems can be found in Table 10 in 0.

2.2.5. SAE J2601-3: Fueling Protocols for Gaseous Powered Industrial Trucks

SAE J2601-3, last updated in 2022, is a standard which provides fueling protocols for gaseous hydrogen powered industrial trucks (HPITs) with vehicle tank fueling systems above 18 L in volume. This standard does not apply to liquid hydrogen and **appears to be similar in scope and requirements compared to SAE J2601-2**: Fueling Protocol for Gaseous Hydrogen Powered Heavy Duty Vehicles.

This standard is typically applied to fuel cell hybrid electric vehicles such as forklifts, tractors, pallet jacks, and on- and off-road vehicles, but can be applied to other gaseous hydrogen vehicle types. **The document can apply to hydrogen locomotives since it provides fueling safety limits, pressure control methods, and protocols for three performance-based fueling methods**: fill to service pressure, fill to target pressure with fixed orifice, and fill to target pressure with variable flow rate. However, **other dispensers or fueling methods can be applied, so long as they meet the performance-based requirements outlined in the standard.** The standard also discusses fueling methods for H25 and H35 connectors and their temperature and pressure operating windows. An evaluation of SAE J2601-3 standards' applicability to hydrogen locomotive systems can be found in Table 11 in 0.

2.2.6. SAE J2601-5: High-Flow Prescriptive Fueling Protocols for Gaseous Hydrogen Powered Medium and Heavy-Duty Vehicles

SAE J2601-5 [11] is a high-flow fueling protocol standard currently under development for larger medium and heavy-duty vehicles. After fueling protocols have been field tested, this standard is planned for publication and release. It will provide process limits for compressed gaseous hydrogen fueling at peak flow rates between 60-300 g/s and volume capacities of 248.6-7500 L. A similar fueling protocol standard such as this might need to be developed for locomotive applications.

2.3. Hydrogen Locomotive Tank Design

Since most locomotive standards focus on diesel fuels and not hydrogen, the standards reviewed in this section identify potential requirements which may currently, or in the future, apply specifically to gaseous and liquid hydrogen locomotive tanks and their design. This section also identifies several gaps in the standards which should be addressed to appropriately include hydrogen rail systems.

2.3.1. AAR MSRP Section M: Locomotives and Locomotive Interchange Equipment

AAR (Association of American Railroads) Manual of Standards and Recommended Practices (MSRP) Section M covers locomotives and associated equipment. The latest version was released in 2020. Topics include locomotive design, construction, maintenance, and operation for safe equipment interchangeability between different railroads. More specific topics include crashworthiness design considerations, electronics system and controls architecture, and performance requirements for locomotive fuel tanks.

Standard S-5506 in this manual provides performance requirements for external diesel-electric locomotive fuel tanks, showcasing different accident scenarios where a fuel tank could be punctured, leading to an unintended fuel release. **While this standard is written for diesel-electric locomotives, the considerations are relevant to hydrogen locomotives since the potential accidents leading to unintended releases can inform the proper design and placement of hydrogen fuel tanks.** For example, the standard specifies that the fuel tank's structural strength should protect it from the sudden acceleration caused by unexpected loads, rollovers, or impacts from the side. Additionally, the penetration resistance of the fuel tank should be equivalent to a 5/16" steel plate at 25,000 psi yield stress and the penetration resistance of the lower 1/3 of tank end plates should be equivalent to a ¾" steel plate at 25,000 psi yield stress. These considerations are important for hydrogen as well as diesel-electric locomotives. Standard S-5506 applies to external fuel tanks. Requirements for internal fuel tanks are provided by 49 CFR 229.217, which references S-5506.

Other standards for fuel tanks, receptacles, nozzles, sensors, and other refueling-related equipment are written for diesel refueling (RP – 5503) and should be revised for the unique fueling protocol of GH2 and LH2 locomotives. An itemized evaluation of AAR Section M's recommended standards' applicability to hydrogen locomotive systems can be found in Table 12 in 0.

2.3.2. ISO 13985: Liquid hydrogen - Land vehicle fuel tanks

ISO 13985, last published in 2005, is a standard reviewed every five years and will be soon replaced by ISO/WD 13985. This standard outlines **design and testing requirements for liquid**

hydrogen land vehicle fuel tanks to prevent fire and explosions which may result in fatalities and loss of property. This standard does not include requirements for gaseous hydrogen fuel tanks.

Since the appendices of this standard outline numerous test requirements, it should be consulted prior to designing a liquid hydrogen tank. Tank design requirements include considerations of mechanical stresses, thermal stresses, materials selection, insulation, accessories, manufacturing, and assembly. Type testing requirements include new design approval, inner tank burst pressure, thermal autonomy, and maximum filling level. Routine tests include those for pressure, leaks, dimension verification, destructive, non-destructive, and visual inspection. This standard also provides requirements for marking and labeling tanks.

Some requirements within sections 4, 6 and Annex D of ISO 13985 relating to **mechanical stress thresholds, elongation of the outer jacket before fracture, length of time before TPRD release, pressure retention time, and minimum/maximum tank elongation** should be reevaluated for larger hydrogen tanks such as those on locomotives, and composite tanks. An itemized evaluation of ISO 13985 standards' applicability to hydrogen locomotive systems can be found in

Table 13 in 0.

2.3.3. 40 CFR 1033.115: Other Requirements for locomotive emissions standards

The federal regulation 40 CFR 1033.115 [14] contains other requirements for locomotive emissions standards for new locomotives. These requirements include emissions testing and engine idling requirements, as well as requirements specifically for volatile fuels. In particular, these requirements specify that emissions from evaporation and refueling should be minimized during normal operation for volatile liquid fuels, as well as requirements that gaseous-fueled locomotives cannot vent to atmosphere during normal operation. Hydrogen is not mentioned specifically in these regulations, but these requirements may apply to hydrogen under the definition of volatile liquid fuel as defined in 40 CFR 1042.901.

2.3.4. 49 CFR 229: Railroad Locomotive Safety Standards

The safety standards presented in 49 CFR 229, last amended in 2024, are the minimum safety requirements for all locomotives that are a part of the general railroad system, excluding rapid transit systems in urban areas and steam-powered trains. Therefore, this standard could currently apply to liquid and gaseous hydrogen locomotive systems, though there is no specific mention of hydrogen or other alternative fuels.

Like AAR Section M, **this standard appears to be focused on internal combustion engine diesel-electric locomotives,** so some important requirements may need to be reevaluated for applicability to hydrogen, fuel cells, or other gas- or liquid-powered fuels. Specifically, section 229.217 requires that locomotives comply with AAR S-5006 standards, described above in section 2.3.1 of this report. This AAR standard applies to diesel-electric locomotive tank design, not necessarily hydrogen tanks. For tanks mounted on car bodies (i.e., "internal tanks"), requirements include protecting the tank from penetration by debris or collision and ensuring that tank vents do not create fuel loss in the case of rollover. This vent requirement is not applicable for hydrogen tanks since they are not designed to allow air intake, unlike diesel tanks.

Some important sections of this standard should be consulted before a tank is designed. Appendix E: Performance Criteria for Locomotive Crashworthiness outlines the **requirements for car**

integrity in the case of head-on and oblique front end 30 mph collision scenarios and should be considered when designing and positioning a tank on a hydrogen locomotive. Likewise, Appendix F: Recommended Practices for Design and Safety Analysis outlines the requirements of component design to minimize risk. This appendix requires that all components and interconnected subsystems should undergo a safety assessment including risk assessment and analysis, calculation of Mean Time to Hazardous Events (MTTHE), a hazard log identifying all relevant hazards and their maximum threshold limits, a hazard mitigation analysis, a human factors analysis, and a safety assurance analysis during normal operation, systemic failure, random failure, common mode failure, and external influences, among other requirements. These requirements are important considerations for hydrogen rail tank and other rail component designs. An itemized evaluation of 49 CFR 229 standards' applicability to hydrogen locomotive systems can be found in Table 14 in 0.

2.4. Hydrogen Locomotive Vent Systems

The standards discussed in this section identify design, sizing, placement, height, configuration, and other requirements for gaseous and liquid hydrogen TPRD vent stacks.

2.4.1. CGA G-5.5: Standard for Hydrogen Vent Systems

CGA G-5.5, last updated April 2021, is a standard which applies to gaseous and liquid hydrogen atmospheric manual or automatic vent systems and is referenced in NFPA 2. This standard includes the design, installation, and operation of vent systems, **emphasizing sizing, height, placement, configuration, grounding, rain cover design, materials selection, and maintenance of vent system mechanical integrity**. Though it is generally focused on compressed gaseous hydrogen, the standard also provides additional options for venting liquid hydrogen and cryogenic gaseous hydrogen. Avoiding fire, deflagration, and detonation are driving factors for the design of vent systems incorporated in these requirements.

The most helpful aspects of this regulation are provided in the figures. Figure 1 in this standard presents an example of a typical vent stack and how it should be mounted and grounded on a supply tank. Figures 2 and 3 of the standard provide more detailed views of the vent stack design as well as acceptable and unacceptable configurations of rupture discs, relief valves, and purge valves. Figures 4-14 of the standard present acceptable and unacceptable designs for vent exits or caps, though there are other designs that may be compliant. **This standard does not provide explicit guidance on vent stack sizing, except to say that Recognized And Generally Accepted Good Engineering Practice (RAGAGEP) should be applied.** There is some guidance regarding vent stack aspect ratio (see the first item in the bulleted list below.)

This standard defines the vent system as beginning at the discharge of a relief or hydrogen control device (such as a manual or control valve) and ending where hydrogen in the atmosphere is below the lower flammability limit (LFL), which is 4 vol% in air. [34] The following are a condensed list of the main design requirements in the standard.

- Although detonation or deflagration caused by the vent stack is unlikely, the aspect ratio (length:diameter) of the vent stack should be minimized as much as possible and an L:D above 60:1 should be avoided.
- Venting piping should be the same diameter or larger than the outlet port of the TPRD.
- A vent stack fire should be considered a design event, and so vent exits should be at a sufficient elevation so that thermal radiation is within the level recommended by the American National Standards Institute/American Petroleum Institute's ANSI/API RP 521 [35], or 10 ft above grade, or 2 ft above adjacent equipment, or 5 ft above rooftops, whichever is greater.
- Pressure drop through the vent stack should not impede the TPRD from relieving pressure.
- Back pressure must not exceed 10% of the relief device set pressure.
- Interconnection of vent sources to a common stack is allowed so long as there is no over-pressurization of any portion of the vent system.
- Cold gas should not be discharged at ground level.
- Austenitic (300 series) stainless steel is the preferred material choice for hydrogen vent systems.

• Flanged joints must have a metal-to-metal seal or a gasket made with fire-resistant material. Joints should preferably be welded.

• Shields, catch pans, or thermal barriers can be used to minimize component and human exposure to cold vent piping. Insulation, when used, should be vacuum jacketed or made with a noncombustible material with a vapor-tight outer covering to prevent condensation of air.

• Vent structures must be able to withstand effects of ice, wind, and seismic stresses. Additionally, since support system members shrink in cold conditions, material contraction should be considered.

• All vent stacks must be properly grounded directly to a grounding grid with resistance to the earth of no more than 25 ohms. See NFPA 70 for more guidance on grounding. [36]

• Vent stacks are not required to be inerted, except before or during repair work.

• Water should never be sprayed onto a hydrogen vent stack discharge, as this could lead to freezing and potentially obstructing the vent stack outlet.

There are several specific additional requirements for liquid hydrogen systems. This standard requires that for liquid hydrogen or systems with cold hydrogen vapor, the portions of the vent stack which cannot withstand cold temperature must be isolated from liquid air and the condensation which inevitably forms at low temperatures. For example, the vent stack should be thermally isolated from the steel shell of the tank, since condensed air can migrate from the stack to the shell and cause embrittlement. This means self-draining angle and channel support brackets should be installed so that condensed air is diverted away from the tank (see section 5.2 Vent Stack Supports – Cold). Also, the stack must have a water accumulation drip leg or chamber to collect condensed water which is drained as needed. This accumulation collector must be located an appropriate height above ground level. If cold gas is vented, embrittlement of the vent stack material should be considered, and appropriate materials selected. Also, liquid hydrogen should be converted to gas or supercritical phase before entering the vent stack.

2.4.2. 29 CFR 1910.103: Hydrogen

This standard's applicability to general hydrogen safety was discussed in section 2.1.5. **While there are no explicit requirements for vent stacks or tubes specifically, this regulation does require that gaseous hydrogen safety relief devices must discharge upward,** unobstructed to the open air and not impinging on the container, adjacent structure, or people. **Liquid hydrogen safety relief devices must be designed the same way, except they should be discharged "outdoors," with no directionality specified.** Additionally, moisture must not collect and freeze such that it interferes with proper functioning of the relief device.

2.4.3. UN GTR 13: Hydrogen and Fuel Cell Vehicles

The United Nations (UN) Global Technical Regulation (GTR) 13, last updated in 2013, **does not explicitly require the presence of vent stacks or vent lines for pressure relief devices; it only states that gases must be vented in a controlled way without rupturing the supply vessel.** However, if vent stacks are present, there are some requirements regarding caps, venting direction, and requalification.

Paragraph 5.2.1.3.1(a) prescribes that the vent line for thermally-activated pressure relief devices (TPRDs) and pressure relief devices (PRDs) should be protected by a cap to prevent blockage by dirt, stones, and freezing water or other objects. **The gas discharge from TPRDs should not be**

directed into enclosed or semi-enclosed spaces, toward any vehicle wheel housing, hydrogen gas containers, forward from the vehicle, parallel to the road, from the back, nor from the side of the vehicle. Paragraph 5.1.4 requires re-qualification of fire testing when vent lines are changed. **No requirements regarding vent stack diameter or length were found in this regulation.**

Other pressure relief devices, such as burst disks, cannot be directed toward exposed electrical terminals, switches, or other ignition sources, into or toward passenger or cargo compartments or vehicle wheel housing, or hydrogen gas containers.

2.4.4. SAE J2578: Recommended Practice for General Fuel Cell Vehicle Safety

SAE J2578, last updated in January 2023, provides guidelines, criteria, and methods on the safe design of fuel cell and hydrogen internal combustion engine vehicles. This standard's guidance regarding TPRDs, shields, and flow barriers is based on Appendix G of SAE J2579 but has been modified so that it applies to all vehicular hydrogen storage and handling systems. This standard is unique from the others discussed in this section because it discusses flow barriers for venting systems.

This standard emphasizes that vent lines should not inhibit functionality of the TPRD. The vent line should be routed to avoid constrictions or choked flow and it should remain functional and unobstructed in case of collision. **The vent line discharge should not be directed toward passenger or luggage compartments, wheel housings, hydrogen storage systems, or the front of the vehicle.** Additionally, the activation of the TPRD should not create external hazards such as projectiles. Vent lines and their caps should be designed to prevent ingress of foreign material, rain, and moisture, especially due to vehicle washing. Vent line materials should be selected so that elevated thermal and pressure conditions and accumulation of electrostatic charge during high pressure gas release can be withstood. Material selection should also consider potential corrosion of the line.

This standard emphasizes **using TPRD flow barriers to direct vent flow away from people**, both inside and outside the vehicle, especially in situations where the storage system is located within passenger, luggage, or cargo compartments. Vent boxes and gas-tight housings can be used as flow barriers, but they (and other flow barriers) should not interfere with the functionality of the TPRD. TPRDs also should not be connected in series unless this configuration has been verified to function properly in the case of a release. Although not required, shields may be used to protect the hydrogen storage system from heat, ultraviolet (UV) rays, and local thermal exposure (such as the heat coming from wheel wells). They may also be used to direct potential leaks away from confined spaces. Solar shields should be used for any equipment containing hydrogen as well as any of its adjacent components to protect against heat and UV damage. An itemized evaluation of SAE J2578's recommended practices for venting systems can be found in Table 15 in 0.

2.4.5. SAE J2579: Standard for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles

This standard's applicability to refueling was discussed in section 2.2.3 above. Its applicability to vent stack design is largely discussed in its Appendix G: Guidance For Compressed Hydrogen System Integration **and its requirements significantly overlap with that of SAE J2578**, described above and therefore will not be restated in this section.

One key difference between this standard and J2578 is **this standard's requirement of proving the adequacy of flow capacity via the extended engulfing fire (bonfire) test.** Additionally, this standard uniquely requires that the vent line and caps must be inspected at the same time as the TPRD.

2.4.6. 49 CFR 229: Railroad Locomotive Safety Standards

This standard's applicability to railroad safety and fuel tank design was discussed above in section 2.3.4. Though this standard is more focused on traditional diesel locomotives, it does present some requirements for gas venting. Subpart C: Safety Requirements requires that pipes carrying hot gases be placed in non-hazardous locations and equipped with guards to prevent injury to people. Combustion **gases must be released outside the cab and be of sufficient height to prevent gases from entering the cab.** Section 229.95 on venting also requires **that fuel tanks may not vent from the roof or in between the rails.** This requirement may need to be updated for hydrogen locomotives since tank vents (or "breathers") for diesel locomotive are quite different in design and purpose compared to vents for a hydrogen system.

3. SUMMARY AND CONCLUSIONS

The focus of this report was to review the standards within current relevant hydrogen safety and vehicular codes and protocols to determine whether they are appropriate in coverage and applicability for hydrogen rail applications. Our analysis included a high-level overview of safety differences between diesel and hydrogen vehicles including fuel storage/tank design, fire prevention and suppression, fuel venting, defueling, refueling, and crash safety. These differences can provide direction regarding reevaluation of codes and standards for hydrogen locomotive applicability.

Due to its applicability to rail facilities, the standards within NFPA 2 were reviewed to identify sections pertinent to locomotive defueling, refueling, maintenance facilities, and storage applications, specifically identifying parts of the code which may need further evaluation. The standards in several other documents which address chemical hazards, refueling, tank design, and TPRD vent stack design have also been reviewed for hydrogen rail applicability.

The scopes of NFPA 2, CGA H-5, 29 CFR 1910.119, 40 CFR 68, and 29 CFR 1910.103 are sufficiently broad and relevant to apply to hydrogen locomotive refueling since these regulations apply to gaseous and liquid hydrogen storage and fueling within certain quantity limits (usually up to 10,000 lbs.) However, the basis for quantitative guidance in these standards should be reevaluated to determine if proximity, barrier requirements, quantity limits, ventilation rates, discharge distances, fueling flow rates, grounding requirements, dispensing integrity tests, dispenser locations, nozzle design, and worst case scenario analysis requirements are appropriate for locomotive defueling, refueling, maintenance facilities, and storage. Additionally, since large fleets or long-range locomotive depots may be required for long distance rail applications, these safety codes and standards should be reevaluated for the quantities of fuel required.

SAE J2601, J2601-2, J2579, J2600, and J2601-3 were examined for appropriate hydrogen locomotive refueling requirements. Though these standards apply mainly to light, heavy, and industrial duty vehicles, the requirements for target pressures, temperatures, average pressure ramp rates, fueling rates, and receptacle types are an important basis for developing hydrogen locomotive refueling requirements. Since these protocols already encompass hydrogen refueling, they can be revised to include larger vehicles such as trains. Something similar is in progress with the establishment of high flow refueling protocols which apply specifically to medium- and heavy-duty vehicles (SAE J2601-5).

Drawing from existing diesel-based locomotive standards for tank design requirements, AAR MSRP Section M, ISO 13985, and 49 CFR 229 emphasize safe fuel tank placement on diesel-electric locomotives. The accident scenarios, tank design testing requirements, and impact resistance requirements included in these standards should be considered when selecting fuel tank placement for hydrogen locomotives.

Although vent stack design requirements within current codes and standards such as 29 CFR 1910.103, UN GTR 13, SAE J2578, SAE J2579, and 49 CFR 229 tend to emphasize direction of discharge and protective shielding, CGA G-5.5 currently provides the most guidance on height, placement, orientation, rain cover design, grounding, materials selection, and design. There is currently limited guidance on vent stack sizing.

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Appendix A. Codes and Standards Evaluation for Hydrogen Locomotive Applicability

Table 3: NFPA 2: Hydrogen Technologies Code

Chapter/Section	Guidance	Implication or Comments
1 (Administration)	1.1 Scope of the code: production, storage, transfer, and use of hydrogen (GH2 and LH2)	NFPA 2 overall currently applies to hydrogen locomotive refueling stations but not to the hydrogen-powered or hydrogen-carrying locomotives themselves.
	1.3.1 Use: stationary, portable, and vehicular infrastructure applications	
	1.3.3 States the code does not apply to hydrogen transport, propulsion of hydrogen vehicles, or onboard hydrogen storage systems	
4 (General Fire Safety Requirements)	4.1.1 Structural requirements	NFPA 2 does not prescribe code requirements for hydrogen storage, refueling, or maintenance structures. Instead, jurisdiction codes for structures must be followed.
	4.3.1 Assumptions of the Code: neither multiple simultaneous fire incidents nor multiple simultaneous unauthorized releases from different locations are considered	Since locomotives may have multiple tanks and/or cars within close proximity, the risk of multiple simultaneous fires or releases should be considered.
6 (General Hydrogen Requirements)	6.4.1.1.1 Maximum Allowable Quantity (MAQ) of hydrogen in a control area (a building or portion of a building or outdoor area within which hazardous materials are allowed to be stored, dispensed, used, or handled)	If hydrogen locomotives are serviced and defueled indoors, the current MAQ may be too low for such a facility. This may not prohibit hydrogen storage in these control areas, but other requirements may need to be followed. The current maximum allowable quantities of hydrogen in a control area are for gaseous hydrogen: 1000-4000 scf (which is approximately 2.4 to 9.5 kg at standard conditions of 68°F and 1 atm), for liquid hydrogen between 0-45 gallons (which is approximately 0-12 kg at 1 atm and 20 K), depending on room ventilation and presence of sprinklers.

Chapter/Section	Guidance	Implication or Comments
	6.4.1.1.2 Required venting of pressure relief devices directly outdoors or to an exhaust hood when hydrogen is in an enclosed area	Since hydrogen locomotives may have multiple pressure relief devices due to multiple tanks or multiple connected rail cars, an indoor facility system that easily and effectively vents these relief devices directly outdoors may be challenging to design and implement.
	6.18.1 Minimum ventilation rate for enclosed areas	Since hydrogen locomotive tanks have large volumes and may be defueled and serviced in large facilities, the ventilation rate of 1 scf/min/ft^2 may be inadequate by itself when there are localized leaks. This volumetric flow rate may also be difficult to consistently achieve and maintain throughout a large facility.
	6.18.2.1.7 Minimum ventilation discharge distances for physical structures	Since hydrogen locomotive tanks may have greater amounts of hydrogen discharged to the atmosphere during defueling, the distance from property lines, building openings, walls, and roofs may need to be revised.
	6.22.1 Requirements prior to service or system changes/parts replacement	Requirements as written mean servicing a hydrogen locomotive fuel system will require extensive time for piping inspection, defueling, and systematic cleaning/purging. Due to the size and number of tanks on rail cars, this required inspection, defueling, cleaning, and purging will significantly prolong the amount of time the tank or rail car is not in use.
7 (Gaseous Hydrogen)	7.1.5.4 Cylinders, containers, and tanks containing residual gas	GH2 cylinders, containers, or tanks containing residual hydrogen must be considered full, except when examined, serviced, or refilled by a gas manufacturer, authorized cylinder re-qualifier, or

Chapter/Section	Guidance	Implication or Comments
		distributor. This may mean that tanks must be completely emptied before being brought into a facility for service.
	7.3.2.3 Bulk outdoor storage GH2 setback distance tables	Setback distances may need to be revised based on larger quantities for locomotives compared to cars and lighter duty vehicles. Currently, NFPA 2 does not have explicitly stated requirements for bulk storage based on mass for gaseous hydrogen systems, only based on volume. These limits are 1000-4000 scf (which is approximately 2.4 to 9.5 kg at standard conditions of 68°F and 1 atm) depending on the type of control area. NFPA 2's maximum allowable quantities of LH2 range from 0-45 gal depending on control area (which is approximately 0-12 kg at 1 atm and 20 K).
8 (Liquid Hydrogen)	8.3.2 Bulk LH2 storage setback distance tables	
	8.3.2.2.1.4 Requirements for LH2 storage depending on volume	Currently, the Code does not allow > 600 gallons of LH2 in any building, only outdoors, which might require defueling a locomotive before it enters a facility.
10 (GH2 Vehicle Fueling Facilities)	10.1.1 Fueling for any size GH2 application	Chapter 10 currently applies to locomotive fueling since system capacity or vehicle type is not specified.
	10.3.10.1 Fueling nozzles for dispensing fuel into hydrogen motor vehicles	The motor vehicle-specific language for refueling connectors does not currently appear to consider non-road vehicles such as locomotives. The standards cited are SAE J2600, which applies to pressure classes of H11, H25, H35, H50, or H70, and ISO 17268, which applies to nominal working pressures or hydrogen service levels up to 70 MPa.

Chapter/Section	Guidance	Implication or Comments
	10.3.11.2 Additional static protection is not required when GH_2 is transferred by conductive hose, flexible metallic tubing, or pipe connections where both halves of the metallic coupling are in continuous electrical contact.	Additional bonding/grounding for locomotive systems may be required due to larger tanks and greater fuel transfer compared to light and heavy-duty vehicles.
	10.4.6.1 Electrical equipment installation distances	These requirements for distances of electrical equipment from outdoor or indoor enclosures or discharge from relief valves may need to be revised based on the size and location of locomotive tanks.
	10.4.7 Minimum size portable fire extinguisher with discharge rate for fire protection	The size, quantity, discharge rate, and placement distance may need to be reevaluated for larger quantities of onsite hydrogen for locomotive refueling compared to light or heavy-duty motor vehicle refueling.
	10.5.1.1.2 Hydrogen dispensing integrity tests during fueling	The requirements of stopping flow and checking pressure decay for 5 seconds during 350 bar fueling may need to be increased for larger tanks such as those on locomotives.
	10.5.1.5 Fueling Protocols for medium- and heavy-duty hydrogen motor vehicles (no maximum flowrate specified)	Maximum fueling flowrates are not provided for vehicles larger than light-duty. The basis and assumptions behind any quantitative guidance should be reviewed for applicability to hydrogen locomotive refueling.
	10.5.2.2.1.4 Outdoor hydrogen dispenser setback distances for buildings, streets, sidewalks, etc.	Since the tank size and amount of hydrogen transferred will be greater for locomotives, these setback distances should be reconsidered.
	10.5.3.4.1.8 Building requirements for indoor refueling	The maximum allowable quantity of fuel dispensed (4.2 kg) prohibits full refueling of hydrogen locomotive indoors.

Chapter/Section	Guidance	Implication or Comments
	10.5.3.4.3.6 Emergency shutdown device locations in the dispensing area	Requirements of not less than 20 ft and not more than 100 ft in the path of egress may need to be modified based on the layout and locations of hydrogen dispensing for locomotives.
11 (LH2 Vehicle Fueling Facilities)	11.1 LH2 storage and dispensing as an engine fuel for vehicles of all types	This chapter applies to LH2 dispensing systems for LH2-powered locomotives.
	11.2.7 Location and size of fire extinguishers	The size, quantity, discharge rate, and placement distance may need to be reevaluated for larger quantities of onsite hydrogen for locomotive refueling compared to light or heavy-duty motor vehicle refueling.
	11.2.8.6 Static protection is not required when vehicles or equipment are loaded or unloaded by conductive hose, flexible metallic tubing, or pipe connections where both halves of the metallic coupling are in continuous electrical contact.	Additional bonding/grounding for locomotive systems may be required due to larger tanks and greater fuel transfer compared to light and heavy-duty vehicles.
	11.2.12.1 Electrical equipment installation distances for LH2 Fueling	These requirements for distances of electrical equipment from points of discharge or connection may need to be increased based on the size and location of locomotive tanks.
	11.3.1.8 & 11.3.1.12 Emergency shutdown system with shut-off valve within 10 ft of dispenser	Depending on the typical layout of a hydrogen locomotive refueling station, this distance may need to be reconsidered.
	11.3.2 Indoor LH2 public fueling is prohibited	Public refueling (which is likely not the application of interest for locomotive refueling) must occur outdoors, and this rule may also serve as a guideline for H2 locomotive refueling. This means refueling cannot occur in a temperature- or climate-controlled environment, such as a maintenance facility.

Chapter/Section	Guidance	Implication or Comments
	11.3.3.1.1 Dispensing devices should be at least 25 ft from the nearest non-LH2 facility, adjoining property lines, and fixed sources of ignition	The setback distances are for public fueling (which is likely not the application of interest for locomotive refueling) but it may be applied to locomotive refueling setback distances.
	11.3.3.1.5 For public refueling, a vehicle fueling pad is required. It must provide a surface under the fueling hose and be of concrete construction.	Though this applies to public refueling, some version may be adopted for H2 locomotives, though it should be revised to accommodate train tracks.
	11.3.3.4.7 For public refueling, emergency shutoff devices or electrical disconnects should be at least 20 ft, but less than 100 ft, from fuel dispensing devices	Though this applies to public refueling, some version may be adopted for H2 locomotives, and it should be reviewed for applicability to locomotive refueling systems.
	11.3.4 Outdoor Nonpublic Fueling (Reserved)	NFPA 2 does not currently have publicly available guidance for nonpublic fueling. This section is currently a placeholder for when the recommendations are developed.
	11.4.3.2.1 Stationary storage tanks' points of transfer should be at least 25 ft from the nearest non-LH2 facility, from the adjoining property line, or from fixed sources of ignition	Since LH2 storage tanks for locomotives may be larger than for other vehicles, the basis and assumptions behind this quantitative guidance should be reviewed.
13 (Hydrogen Generation Systems)	13.1.1.1 Permanently installed hydrogen generation of greater than 1.3 oz/hr (36 g/hr) and less than lb/hr (100 kg/hr)	This chapter will apply to a locomotive refueling facility within the given flow rate limits if hydrogen generation occurs onsite.
18 (Repair Garages)	18.2.1 Service and repair operation for GH2-propelled vehicles	This chapter applies to GH2 locomotives' maintenance and repair, but not to LH2 locomotives. Adding additional sections for LH2 locomotives should be considered.
	18.3.1.7.1 Repair booths should be separated from other operations by at least 3 feet or by an appropriate	If H2 locomotives are serviced alongside diesel, LNG, LPG, CNG, or other trains or buses,

Chapter/Section	Guidance	Implication or Comments
	partition, wall, floor, or ceiling assembly 18.3.1.7.1.1 At least 3 feet of space should be maintained on all sides and above the booth	these separation distances or partition requirements should be evaluated for adequacy.
	18.3.5.1 Natural ventilation can be allowed by the AHJ in lieu of a mechanical exhaust ventilation system	Natural ventilation may be insufficient for H2 locomotive repair facilities, where large amounts of hydrogen may be present. Directed, mechanical ventilation may be less hazardous compared to natural ventilation for repair facilities. [37]

Table 4: CGA H-5: Standard for Bulk Hydrogen Supply Systems

Chapter/Section	Guidance	Implication or Comments
2 (Scope)	Bulk gas hydrogen is considered to be >5000 scf (141.6 m^3, or approximately 11.9 kg). Bulk liquid is >39.7 gal (150 L, or approximately 10.6 kg at 1 atm and 20K). Maximum pressure is 103.4 MPa Can include above- or below-ground cryogenic tanks and gas storage vessels	Tanks on hydrogen locomotives may be considered bulk hydrogen, depending on the size of the tank or if a tender car is used, so this standard may apply to onboard storage. Storage vessels used to fuel the locomotive tanks would need to follow this standard.
5 (Site Selection)	5.1: Hydrogen supply systems should comply with NFPA 55 in terms of setback distances and NFPA 70 for electrical equipment setback distances from vent outlets, tank fill connections, or bulk supply system	Due to updated codes and standards, whether for hydrogen locomotives or for other hydrogen transportation, NFPA 2 will likely be the best resource for setback distances.
6 (Developing a suitable site for a hydrogen system)	6.3 Bulk Liquid System: LH2 supply systems must have a minimum 12' X 12' noncombustible (e.g. non-asphalt or bitumen) product transfer pad to prevent an oxygen-enriched atmosphere, which might facilitate combustion	For unloading LH2, the standard emphasizes using a concrete transfer pad. This should be evaluated for hydrogen locomotives, which are on rails, supported by potentially combustible material such as wood ties.

Chapter/Section	Guidance	Implication or Comments
8 (Equipment Selection)	8.7.4 Requirements for emergency shutoff valves for supply lines.	Liquid supply lines on tanks greater than 2000 gal shall have a remotely operated emergency shutoff valve as close to the container as possible. Whether for hydrogen locomotives or for other transportation, NFPA 2 is also an important resource for emergency shutoff valve requirements.
10 (Equipment Installation)	10.3.2 Direct burial of gaseous hydrogen storage tanks	Fracture mechanics methods are suggested to determine cyclic pressure life calculations. Vessels with flaws or inclusions > 5% of wall thickness or 3 mm (whichever value is less) must be decommissioned. However, these requirements likely apply more for metallic, not composite tanks, which are more likely to be used in hydrogen rail applications in the future.

Table 5: OSHA's 29 CFR 1910.119: Process Safety Management of Highly Hazardous Chemicals

Chapter/Section	Guidance	Implication or Comments
1901.1199(e)(1)(i)-1901.1199(e)(1)(v)	Deadlines for completion of Process Hazard Analysis	These deadlines, according to the online published document, are in the 1990s and should be updated.

Table 6: 40 CFR 68: Chemical Accident Prevention Provisions

Chapter/Section	Guidance	Implication or Comments
68.126 (Exclusion)	A flammable substance is excluded from all provisions when used as a fuel	This may mean that hydrogen used in locomotive fuel cells are exempt from 40 CFR 68 requirements.
68.25(e) (Worst-case release scenario analysis – flammable gases)	Flammable gases will vaporize resulting in a vapor cloud explosion. A yield factor of 10% of the available energy should be applied to determine the distance to the explosion endpoint if the model is based on TNT equivalence methods. Gases should be assumed	These assumptions for a worst case scenario should be examined for validity for gaseous hydrogen systems in use in locomotives, as these assumptions are based on flammable gases in general and do not take into account the unique properties of GH2.

Chapter/Section	Guidance	Implication or Comments
	to be released over a period of 10 minutes.	
68.25(f) (Worst-case release scenario analysis – flammable liquids)	Flammable liquids will vaporize forming a vapor cloud explosion. A yield factor of 10% of the available energy should be applied to determine the distance to the explosion endpoint if the model is based on TNT equivalence methods. The entire quantity of the vessel or pipe is assumed to be spilled instantaneously to form a liquid pool. The quantity that becomes vapor in the first 10 minutes is involved in the vapor cloud explosion.	These assumptions for a worst case scenario should be examined for validity for liquid hydrogen systems in use in locomotives, as these assumptions are based on flammable liquids in general and do not take into account the unique properties of LH2.

Table 7: OSHA's 29 CFR 1910.103: Hydrogen

Chapter/Section	Guidance	Implication or Comments
1910.103 (Hydrogen)	1910.103(b)(2)(ii)(c) Table H-2: Setback distances for buildings, structures, wall openings, flammable liquids, flammable gases, oxygen, fast and slow burning solids, open flames, inlets or intakes, and number of people	This table has setback distances for people, chemical hazards, and structures based on volume of hydrogen. For volumes > 15,000 cubic feet of GH2 (which is approximately 35.6 kg), these setback distances may need to be reevaluated for large hydrogen locomotive maintenance facilities and the chemicals and repair equipment (such as air compressors and air intakes) that may be present. Setback distances have been updated more recently in codes such as NFPA 2 and so may be more appropriate for facility siting.

Chapter/Section	Guidance	Implication or Comments
	1910.103(b)(3)(ii)(b) and 1910.103(c)(3)(ii)(b) Inlet and outlet openings to the outdoors must have a minimum area of 1 ft^2/1000 ft^3 of room volume	Since hydrogen locomotive tanks may be serviced in large facilities, the ventilation openings and explosion vent sizes may be inadequate.
	1910.103(b)(3)(ii)(c) and 1910.103(c)(3)(iii)(c) Explosion venting area must be at least 1 ft^2/30ft^3 of room volume	
	Table H-4: Setback distances for buildings, wall opening, inlets or intakes, flammable gases and liquids, liquid hydrogen containers, open flames, oxygen, and number of people	This table specifies setback distances for different volume ranges. The highest volume range is 15,001 to 30,000 gallons LH2 (which is approximately 4020 to 8040 kg of LH2 at 1 atm and 20K). If more than 30,000 gallons (114 m^3) is present in or near a hydrogen locomotive refueling or maintenance facility, these distances would need to be revised. Setback distances have been updated more recently in codes such as NFPA 2 and so may be more appropriate for facility siting.

Table 8: SAE J2601-2 – Fueling Protocol for Gaseous Hydrogen Powered Heavy Duty Vehicles

Chapter/Section	Guidance	Implication or Comments
1 (Scope)	This protocol provides safety limits for gaseous hydrogen fuel dispensers used to fuel 35 MPa hydrogen transit buses	This protocol has limited applicability for hydrogen locomotives since is not to be used for LH2 fueling and it is meant for transit buses. Since some hydrogen locomotive tanks are filled to 70 MPa, this protocol has limited application to this higher pressure range.
5.1 (Operating Conditions of the Vehicle Fuel System)	Figure 1: Normal H35 Boundary Conditions	The temperature, pressure, and density limits presented in this figure may need to be adjusted for larger tank sizes and higher

Chapter/Section	Guidance	Implication or Comments
		pressures used in hydrogen rail applications.
5.3 (Process Fueling Limits)	5.3.7 Table 1: Fueling Options for Heavy Duty Hydrogen Surface Vehicle Fueling	These prescribed fueling rates for fast, normal, and slow fueling may need to be adjusted for locomotive tanks.

Table 9: SAE J2579 – Standard for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles

Chapter/Section	Guidance	Implication or Comments
4.1 (Design Considerations)	4.1.2.5 calculation of number of start/start cycles and number of fill cycles	These values, which are used to predict component lifetime, assume an average trip length of 20 km (which may be too short) and 15-25 years of service (which may be too long) for hydrogen locomotives applications.
5.2 (Compressed hydrogen storage system)	5.2.2(b) For performance verification tests for design qualification, the expected service test cycles = 1,000, durability test cycles = 15,000, ambient temperature pressure cycles = 9,000, and extreme temperature pressure cycles = 6,000	These requirements are based on heavy-duty commercial vehicles such as trucks and buses and may or may not be appropriate for locomotive systems.

Table 10: SAE J2600 – Compressed Hydrogen Surface Vehicle Fueling Connection Devices

Chapter/Section	Guidance	Implication or Comments
4.3 Receptacle	4.3.2 Specifies outside geometry of H11-H50 and H70 receptacles 4.3.5.2. specifies receptacle mounting	These receptacles and their mounting clearances may not be appropriate for larger hydrogen vehicles such as locomotives.
	4.3.4 Receptacles should be designed for 15,000 cycles and 15 years	This requirement may need to be adjusted depending on the increased surface wear of hydrogen locomotive receptacles.
4.5 Nozzle	4.5.3.1 Nozzles should be designed for 100,000 cycles	This requirement may need to be adjusted depending on the

Chapter/Section	Guidance	Implication or Comments
		increased surface wear of hydrogen locomotive receptacles.
5 Type (Design Verification) Tests)	5.2 User-machine interface test 5.3 Valve operating handle test 5.6 Room temperature leak test 5.7 Low and high temperature leak test 5.8 Hydrostatic (or ultimate) strength test 5.10 Receptacle vibration test 5.11 Abnormal loads test 5.12 Durability cycling test 5.13 Corrosion resistance test 5.15 Contamination test 5.16 Thermal cycle test 5.17 Pre-cooled hydrogen exposure test 5.18 Misconnected nozzle test 5.20 Rocking	The tests described in these sections are very specific to the receptacle, connector, and nozzle equipment discussed in this standard. These tests outline specific procedures for integrity testing designed to evaluate the performance of this equipment only, therefore these tests need to be revised for larger equipment.

Table 11: SAE J2601-3 - Fueling Protocols for Gaseous Powered Industrial Trucks

Chapter/Section	Guidance	Implication or Comments
5.1 Operating conditions of the vehicle fuel system	5.1.4 fueling protocol should be followed to ensure operating window (figure 5.1.4) is not violated	This would need to be revised for other nominal working pressure fuel systems, and larger flowrates to be applicable to hydrogen locomotives.
5.2 Vehicle storage systems (VSS)	5.2.1 specifies maximum pressure drop from the receptacle to the vehicle tank based on a low flow rate of fuel	
6 HPIT Dispenser Control Methods	6.1-6.3 various fueling methods (fill to service pressure, fill to target pressure with fixed orifice, and fill to target pressure with variable flow rate)	While other fueling methods may also be appropriate, these methods involve fueling at a maximum rate of 10 grams/second, which is likely impractical for locomotive applications. These protocols should be revised for larger systems.

Table 12: AAR MSRP Section M: Locomotives and Locomotive Interchange Equipment

Chapter/Section	Guidance	Implication or Comments
Standard S-5506 (Performance Requirement for Diesel Electric Locomotive Fuel Tanks)	4.0 – Structural strength requirements for locomotive fuel tanks in the case of a minor derailment, jackknifed car, side impact, sideswipe, or spill	The standard states the requirements of sudden acceleration the fuel tank must withstand in the case of unexpected loads, rollovers, or impacts from the side. These scenarios are important to consider when designing a metal or composite hydrogen tank and its placement/attachment on the rail car.
	4.1.4 Penetration resistance of the fuel tank should be equivalent to a 5/16" steel plate at 25,000 psi yield stress. Penetration resistance of the lower 1/3 of tank end plates should be equivalent to a ¾" steel plate at 25,000 psi yield stress.	These are good starting points for designing hydrogen tanks for rail applications, however, since many hydrogen tanks are made of composite materials, yield stresses are expected to be quite different than for metal tanks. Depending on the type and design of the tank, composite tanks might require steel enclosures for greater yield stress and penetration resistance.
	4.4 – Guidelines state that internal structure of the tank must not impede flow of 300 gpm	This implies tanks must accommodate a fuel fill flowrate of at least 300 gpm, which may not be reasonable for LH2 tank filling.
Recommended Practice RP – 5503 (Locomotive Fueling Interface)	2.2.2 - Performance Requirements – System - Specifies the maximum pressure drop across the fuel nozzle and receptacle, maximum pressure of fuel flow, automatic shutoff response time, fuel tank fitting proof pressure, and shutoff device characteristics	These are all for diesel fueling and should be reevaluated for GH2 and LH2 fueling.
	2.3 - Sensor Characteristics – Specifies tank requirements for sensor placement, size, calibration, operating limits, reliability, and performance for flowrates up to 600 gpm.	

Chapter/Section	Guidance	Implication or Comments
	2.5 - Fuel Receptacle Geometry and Construction – Specifies dimensions for fuel receptacle geometry and mating, proof pressure, burst pressure, and flow controls.	

Table 13: ISO 13985: Liquid Hydrogen – Land Vehicle Fuel Tanks

Chapter/Section	Guidance	Implication or Comments
4.2 (Mechanical Stresses)	4.2.2.1 Vehicles of categories M_3 and N_3 (such as locomotives) must have fuel tanks that are protected from acceleration of 6.6*g in the direction of travel and 10*g horizontally perpendicular to the direction of travel. No structural damage to the fuel tank or its accessories nor uncontrolled release can occur.	This standard pertains to land vehicles and therefore these acceleration protection requirements should be reevaluated for large rail systems.
4.4 (Materials)	4.4(b) The outer jacket ensuring the integrity of the insulation system must elongate at least 12% before fracture at the temperature of liquid nitrogen.	For a large liquid nitrogen tank, this elongation may be substantial and may not be appropriate for a composite tank. Also, this degree of elongation may exceed the containment for the tank system on the locomotive.
4.6 (Insulation)	4.6.1 A fuel tank should retain thermal autonomy for at least 5 minutes during the thermal autonomy test which is conducted at 590 C.	Thermal autonomy refers to the length of time before the TPRD opens. The 5-minute limit should be reevaluated for the higher risk related to a larger hydrogen release for locomotives.
6.2 (Pressure Test)	6.2 Inner tanks must maintain test pressure for at least 10 minutes to confirm pressure is not decreasing	This time requirement may need to be adjusted for larger tanks.
Annex D (Accessory Type Tests)	D.7 Resistance to dry-heat D.8 Ozone ageing test These tests specify a minimum and/or maximum tank elongation	These elongation percentages range from -30% to 20% and may be too substantial for locomotive tanks and not appropriate for composite tank tests.

Table 14: 49 CFR 229: Railroad Locomotive Safety Standards

Chapter/Section	Guidance	Implication or Comments
Subpart C (Internal Combustion Equipment)	Subpart C discusses internal combustion engine requirements	This standard does not include requirements for non-internal combustion engines nor alternative fuel (H_2, LNG, CNG) engines and their fuel tanks. Another section should be added to this standard to address alternative fuels (including hydrogen) and fuel cells.
Subpart C 229.95 (Venting)	Fuel tank vent pipes may not discharge on the roof or between rails	This likely refers to diesel tank breathers, and not TPRDs found on hydrogen tanks, so this requirement should be reevaluated for applicability for hydrogen systems.
Subpart D 229.217 (Fuel Tank)	(a) Tanks outside the car body (a.k.a. external fuel tanks) must comply with AAR S-5006: "Performance Requirement for Diesel Electric Locomotive Fuel Tanks"	These requirements are based on diesel fuel tanks and should be revised to include hydrogen tank designs, including composite tanks.
	(b) Tanks within the locomotive body (a.k.a. internal tanks) must comply with 238.223 (see below)	
Subpart D 238.223 (Internal Fuel Tanks)	Internal fuel tanks (tanks mounted on train car bodies) must be protected from penetration by debris or collision and tank vents must not create fuel loss in the case the tank is upside down.	This vent requirement is not applicable for hydrogen tanks since they are not designed to allow air intake like diesel tanks require.

Table 15: SAE J2578 – Recommended Practice for General Fuel Cell Vehicle Safety

Chapter/Section	Guidance	Implication or Comments
Appendix E (Guidance for the packaging of hydrogen systems including PRDs, shields, and flow barriers)	E.2 Flow barriers should be used direct vent flow away from people, both inside and outside the vehicle, especially in situations where the storage system is located within passenger, luggage, or cargo compartments. Vent boxes and gas-tight housings can be used as flow barriers, but they (and other	This section emphasizes use of flow barriers, but repeatedly states that they should never interfere with the functionality of the TPRD.

Chapter/Section	Guidance	Implication or Comments
	types of flow barriers) should not interfere with the functionality of the TPRD.	
	E.2.1 TPRDs also should not be connected in series unless this configuration has been verified to function properly in the case of a release.	
	E.2.2 Solar shields should be used for hydrogen systems and well as any adjacent components to protect against heat and UV damage.	
	E.3.1 Vent line materials should be selected so that elevated thermal and pressure conditions and accumulation of electrostatic charge during discharge can be withstood. Material selection should also consider potential corrosion of the line.	This section focuses on vent line materials of construction, protection from restriction, appropriate discharge direction, and the importance of preventing debris and water ingress due to rain, snow, or washing.
	E.3.2 The vent line should be routed to avoid constrictions or choked flow. It should remain functional and unobstructed in case of collision.	
	E.3.3 The vent line discharge should not be directed toward passenger or luggage compartments, wheel housings, hydrogen storage systems, or the front of the vehicle. The activation of the TPRD should not create external hazards such as projectiles.	
	E.3.4 Vent lines should prevent ingress of foreign material and moisture. Vent line caps should prevent water ingress due to rain or vehicle wash. Vent lines should not inhibit functionality of the TPRD.	

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