HYDROGEN Safety Panel

TECHNICAL REPORT

Lessons Learned and Best Practices for Compressed Hydrogen Transport Trailers

A Hydrogen Safety Panel White Paper

As demand for hydrogen increases, more hydrogen transport trailers and modules are being built and operated to supply fuel to the growing number of end uses. Concurrently, recent incidents involving these trailers have highlighted common factors that have contributed to fires and/or explosions.

This report summarizes common contributors to inform recommendations and technical guidance for the design and operation of trailers and modules transporting hydrogen and expands on a previous white paper published by the HSP titled "Safety of Mobile Hydrogen and Fuel Cell Technology Applications". The contributing factors and best practice recommendations are not specific to transportation applications; however, the risk of collision, high vibration, frequent filling cycles, and high occurrence of recent incidents add emphasis to the focus of this report.

Document Scope

- Key risks and best practices for hydrogen transport
- Builds on prior HSP safety report
- Applies broadly, with transport emphasis
- Focus on collisions, vibration, refueling, incidents

Audience

Engineers, safety professionals, and regulators working with hydrogen systems

Document Type

Technical Safety Report — Lessons Learned and Best Practice

Focus Area

Compressed hydrogen transport trailers

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LESSONS LEARNED AND BEST PRACTICES FOR COMPRESSED HYDROGEN TRANSPORT TRAILERS

Summary

This report addresses the increasing safety risks associated with the transportation of compressed hydrogen, prompted by recent incidents involving fires and explosions on transport trailers. It provides a detailed analysis of the common factors contributing to these events, with a strong focus on the premature or spurious activation of thermally activated pressure relief devices (TPRDs) and the subsequent loss of hydrogen containment. The document examines key root causes, including internal heating during rapid filling operations, potential design flaws in relief devices, and critical failures in vent piping systems that can lead to the dangerous accumulation of flammable gas mixtures. In response to these findings, the report outlines a comprehensive set of best practice recommendations for the design, manufacturing, operation, and maintenance of hydrogen transport trailers to mitigate these risks and improve the overall safety and reliability of hydrogen transport.

Disclaimer

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1.0 Purpose

This report was initiated in response to recent incidents involving compressed hydrogen transport trailers and modules and includes best practice recommendations to improve safety and reliability. Information in this report originates from equipment vendors, a review of literature and codes and standards, and the combined experience of members of the Hydrogen Safety Panel (HSP). This document is published under the oversight of Pacific Northwest National Laboratory, through which HSP resources are managed.[1]

2.0 Scope and Introduction

As demand for hydrogen increases, more hydrogen transport trailers and modules are being built and operated to supply fuel to the growing number of end uses. Concurrently, recent incidents involving these trailers have highlighted common factors that have contributed to fires and/or explosions.

This report summarizes common contributors to inform recommendations and technical guidance for the design and operation of trailers and modules transporting hydrogen and expands on a previous white paper published by the HSP titled "Safety of Mobile Hydrogen and Fuel Cell Technology Applications" [1]. The contributing factors and best practice recommendations are not specific to transportation applications; however, the risk of collision, high vibration, frequent filling cycles, and high occurrence of recent incidents add emphasis to the focus of this report.

2.1 Incidents Informing this Report

The table below outlines the incidents that inspired the creation of this best practice document. This table presents relevant incidents that have been detailed in the public domain but is not a comprehensive list of recent transport-related events.

[1] https://www.h2tools.org

Table 1. Select transport-related incidents informing this report

Date	Location	Description	Relief Type/ Activation	Vent System Integrity	Combustion Event	References and CHS Available Content
February 2018	Diamond Bar, CA	Requalification error resulted in release and fire during road transit	CG-5 fuse backed rupture disk / Unexpected	Compromised	Fire in storage enclosure	NTSB Incident Report NTSB/HZM-19/02 PB2019-101398 [2]
June 2019	Santa Clara, CA	Valve position error and mis-communication during maintenance resulted in release and fire at a transfill facility	CG-5 fuse backed rupture disk / Anticipated by fire	Compromised	Explosion in storage enclosure and subsequent fire	Report on the June 2019 Hydrogen Explosion and Fire Incident in Santa Clara, California | H2tools | Hydrogen Tools [3]
February 2023	Delaware County, OH	Vehicle accident and resulting fire	Glass bulb TPRD / Anticipated by fire	Compromised	Fire at vent stacks and in storage enclosure	CHS Hydrogen Trailer Fire Incident Record [4]
September 2024	Ontario, CA	TPRD activation resulted in release and fire during filling	Glass bulb TPRD / Unexpected	Compromised	Fire in storage enclosure	CHS members
August 2024	Leuna, Germany	Trailer leak resulted in an explosion and fire at a transfill facility	None installed	Unknown	Fire in storage enclosure leading to rupture/ explosion of storage vessels	CHS GH2 Trailer Leak, Explosion, Fire [5]
March 2026	Colton, CA	Trailer leak resulted in an explosion and fire	Unknown	Unknown	Explosion in storage enclosure and subsequent fire	News outlets and CHS members

CHS is Center for Hydrogen Safety; TPRD is thermally activated pressure relief device.

2.2 Introduction to Relief Devices

Relief devices are valuable equipment used to protect against vessel rupture. Vessel rupture is the worst-case scenario for many applications, as a catastrophic rupture can result in high-pressure energy release, ejected shrapnel from the vessel, complete loss of containment, and the potential for fire and explosion. A gaseous vessel can rupture due to overfilling in excess of the burst pressure of the vessel, weakening of the structural materials due to prior in-service damage, and/or pressure increase and weakening of the structural materials caused by heat exposure. The appropriate type and size of the relief device will depend on the overpressure mechanism.

Relief devices have two basic types: reclosing and non-reclosing. For the vast majority of gaseous transportation applications, relief devices are non-reclosing, meaning once they are open, they remain open

until they are replaced or manually reset. While pressure relief devices (PRDs) operate directly based on high pressure, there is also a category of non-reclosing devices referred to as thermally activated pressure relief devices (TPRDs) that are activated only by elevated temperature. TPRDs are common in transportation-related applications. When deployed to protect against an external fire, the heat from the fire is used to open the TPRD device. TPRDs can be activated by means including but not limited to:

- Melting the seal material of a fusible plug (fusible link TPRD)
- Shrinking a trigger wire that in turn activates a valve
- Heating an expanding fluid that in turn triggers a release (e.g., glass bulb TPRD)

Combination devices integrate both a rupture disk (non-reclosing pressure-activated device) and a fusible link (temperature-activated fusible metal alloy). In a fire scenario, pressure increase alone may be insufficient to cause rupture; however, weakening of the vessel material due to heat in combination with high pressure may result in failure. Combination devices require both pressure and temperature to activate, which potentially reduces the probability of spurious operation; however, operation may be delayed by requiring both conditions to be met. Kostival et al. published additional information on relief device types and their applicability to hydrogen technology [6].

The design, qualification, and sizing of relief devices for trailers are governed by national regulations and typically incorporate by reference industry standards like those from the American Society of Mechanical Engineers (ASME), Compressed Gas Association (CGA), CSA Group / American National Standards Institute (ANSI), or European Transportation Pressure Equipment Directive. In the United States, relief device requirements for hazardous material transport equipment can be found in the U.S. Department of Transportation (DOT) 49 CFR 178, which also references CGA C-29 and CGA S-1.1. Alternatively, onboard fuel containers for motor vehicles are governed by different standards, including CSA/ANSI HPRD1, and/or the International Organization for Standardization (ISO) equivalent: ISO 19882. CSA/ANSI HPRD1 is a standard for TPRDs for compressed hydrogen vehicle fuel containers. Although the technology for hazardous material transport and onboard fuel storage is similar, regulations vary significantly and must be followed as applicable.

As stated, CGA S-1.1 is the relief device standard referenced by the DOT for hazardous material transport. The document instructs the user on the relief requirements based on the material being transported and the container type/size. CGA S-1.1 covers a variety of containers and materials, including fuel gases, inert gases, oxidizers, pyrophoric materials, toxic fluids, and more. Gaseous hydrogen is a single line item in a table that assigns device types. The relief requirements are based on a risk-reward analysis that evaluates the relative hazards associated with vessel failure versus release of its contents. Based on the flammable, but non-toxic, nature of hydrogen, S1.1 had traditionally required relief devices for compressed hydrogen. However, when the DOT adopted the 14th edition (2011) of CGA S-1.1 [7], the requirement for relief devices on steel cylinders transporting hydrogen was removed. This was justified in part based on successful previous experience within Europe as well as select special permits that allowed removal of PRDs on steel vessels. History and testing demonstrated a low probability of steel vessel rupture during a fire event, and there had been numerous incidents with spurious operation of relief devices.

Adding to the complexity of regulation around relief devices for hydrogen vessels, 49 CFR 178 and CGA S-1.1 do not currently include provisions for composite overwrapped pressure vessels (COPVs). Therefore, in the U.S., a transport application using COPVs must apply for a DOT special permit that grants an exemption for vessel design and the associated relief device protection(s) for the vessel.

Composed of an aluminum or plastic liner with a composite overwrap made of high-strength fibers and an epoxy resin, COPVs mark a significant advancement in gaseous vessels by enabling high-pressure storage with relatively low weight. However, trailers that incorporate steel vessels include inherent design attributes that cannot easily be replicated for designs using COPVs. These include bulkheads that separate the vessels from the piping, supports for the heavy steel vessels that improve crash worthiness, and metal materials of construction that are non-flammable and rapidly dissipate heat. This contrasts with the composite overwrap of COPVs, which are susceptible to weakening in a fire scenario.

As part of the special permit approval process, the vessel and associated protection must meet the requirements of CGA C-14, which includes a bonfire test. There are currently no requirements specifying the type of protection, which means that manufacturers may incorporate custom solutions for relief devices. The lack of regulatory specifications allows for creative solutions and technological advancements but also creates significant variability in the protection devices used on composite vessel hydrogen transport trailers. The most common devices for composite vessels used in U.S. transportable hydrogen applications are Type CG-5, a combination of a rupture disc with eutectic backing, or Type CG-10, which uses a fusible trigger to release the contents of the vessel.

Although this introduction to relief regulation is directly applicable to trailers in the United States, the same challenges, debate, and complexity exist for hydrogen transport in Europe and other jurisdictions based on how equipment is designed and operated.

2.3 Relief Device Reliability

While relief devices can certainly protect equipment in certain conditions, they may also be the root cause for release when a device activates spuriously, as illustrated by case studies described in Section 2.1. Early activation or leakage can lead to combustion events for flammable gases such as hydrogen. The use of a relief device to reduce the probability of a rupture for a vessel that may be exposed to excessive heat must be balanced against the unintended consequences of a relief device that can prematurely activate or leak. Reliability and failure mechanisms for devices depend largely on the type and installation.

The reliability of spring-actuated relief devices is regularly specified as 1:100 years in quantitative risk analysis (QRA) [8]; however, this is associated with failure to activate when called upon to operate. Jimenez et al. published a study on failure to operate, spurious operations, and external leak failures for PRDs in hydrogen systems [9]. The authors found that failure to activate is the least likely failure mode, while spurious activation is the most frequent. Using a limited set of data, a probabilistic time-based model was developed for spurious activation for use in hydrogen-specific QRA studies [8, 9].

Burgess et al. studied high-pressure hydrogen relief devices and concluded that PRD failure modes in hydrogen service do not originate from a single root cause. Contributing factors include cyclic pressure and temperature, corrosion, deposits, creep, design, vibration, handling, maintenance, process upsets, and defects [10]. Barlen et al. also studied rupture disk reliability on Pipeline and Hazardous Material Safety Administration (PHMSA) transport cylinders and used hazard analysis to conclude that risks associated with PRD failure were greater than the risk of a pressure vessel burst [10, 11]. Through the work by Barlen et al. and associated CGA bonfire testing, CGA S-1.1:2011 was modified to remove the requirement for CG-1 type pressure relief disks on hydrogen 3AAX PHMSA cylinders [7].

TPRDs are of particular interest for hydrogen trailers as they are often installed to protect onboard vessels. Although all PRDs have some risk of early or spurious activation, TRPDs or combination devices are the relief

devices installed in the case studies reviewed and will be the main focus for the remainder of this report. Reliability data, especially for spurious activation, is scarce for TPRDs. Like PRDs, TPRD reliability is expected to vary widely based on device type, installation, and exposure conditions.

3.0 Root Cause Analysis

This study looks at the contributing factors for an early and unintended/spurious activation of a TPRD resulting in loss of containment and a possible combustion event. Fishbone diagrams are used to suggest how contributing factors collaborate in the errant behavior of the system. These factors can be categorized as two separate events: (1) relief device activation and (2) loss of containment and accumulation.

3.1 Relief Device Activation

Figure 1 is a fishbone diagram for TPRD activation. Unlike PRDs, which activate based on pressure, TPRDs are intended to activate from heat exposure. Heat on the device can derive from a variety of sources, including external heat, vessel heating during filling, and hydrogen impingement on the trigger. Improper specification, design pedigree, or quality assurance (QA) and quality control (QC); installation error; and in-service damage may also contribute to spurious activation.

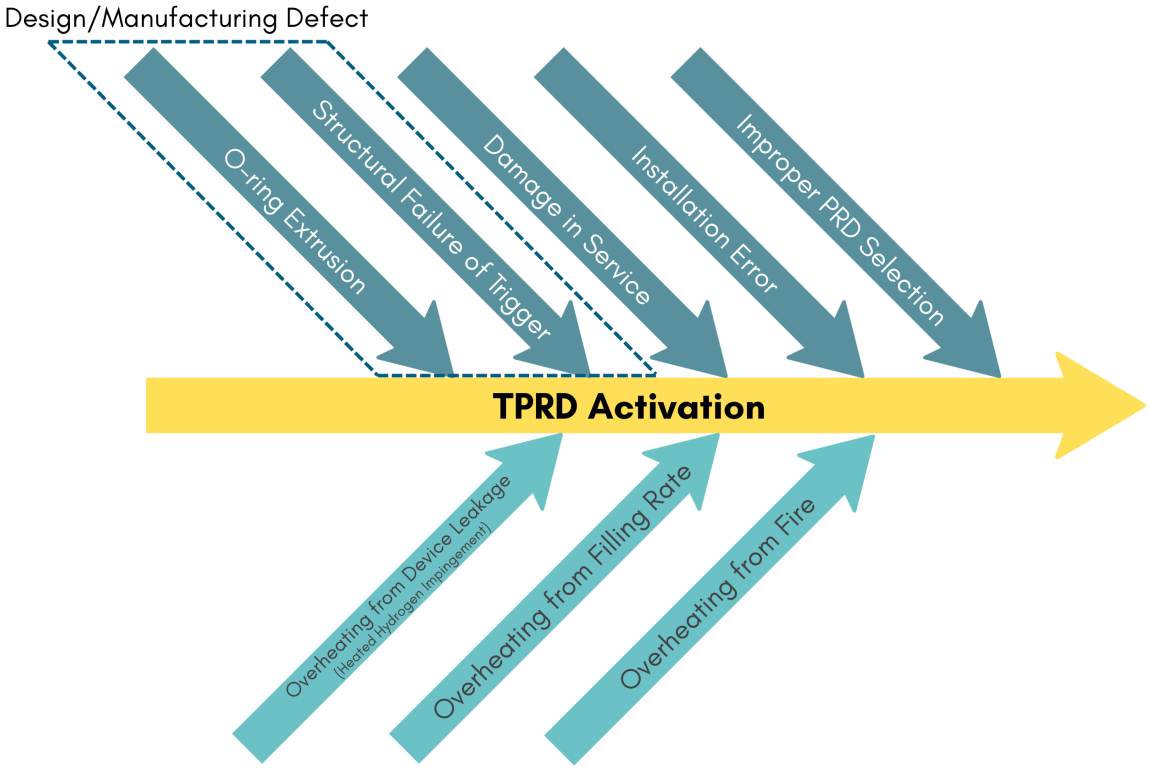


Figure 1. Fishbone diagram for TPRD activation.

3.1.1 External Vessel Heating

External heat exposure is the intended method for proper activation of TPRDs. Activation temperature varies by device type as specified in CGA S-1.1 or in a special permit, but is generally between 100 and 110 °C on high-pressure trailers that transport hydrogen. High heat exposure is the primary reason for the installation of TPRDs; however, due to the low radiant heat of a hydrogen flame, direct flame impingement on the vessel or TPRD exposure to nearby high heat is often necessary to activate the device. A single device may not be sufficient to protect multiple vessels or a long vessel, as fire at one location on the vessel may not impart sufficient heat at the TPRD location [12]. For COPVs, thermal damage can result from heat exposure to the epoxy above the vessel's temperature rating, typically 85 °C. Therefore, heat damage to the COPV combined with the potential pressure increase from elevated internal gas temperature may result in catastrophic rupture if the vessel is not sufficiently protected. Especially if fire is localized, vessel damage can occur prior to significant pressure rise due to heat. Bundling cylinders may also prevent activation if the TPRD location is protected from external heat exposure in the fire scenario.

3.1.2 Internal Vessel Heating

Rapid filling of vessels may unintentionally cause gas temperatures high enough to activate the vessel TPRD, localized heat damage, or a fatigue-type failure to the COPV composite overwrap or relief device(s). When filling a high-pressure hydrogen vessel, isenthalpic heating from the Joule-Thomson (JT) effect combined with the isentropic heat of compression can significantly increase the internal gas temperature. Depending on the geometry of the vessel and turbulent mixing during filling, stratification within the vessel will likely occur, resulting in high localized temperature even though the bulk averaged gas temperature remains within COPV temperature limits. Temperature control of the gas and vessel being filled is one of the main reasons for defined fueling protocols, gas precooling, and restricted fill rates. However, protocols for filling hydrogen fuel tanks on light- or heavy-duty vehicles are often not used or are not applicable to filling high-pressure gas trailers.

Many cylinder fill locations do not measure the internal gas temperature, and those that do usually only use a single sensor to measure the temperature in the vessel. While some use thermal cameras to monitor temperature evolution, the external surface temperature is not representative of the peak internal gas temperature due to the insulating effect of the vessel itself. In particular, COPVs dissipate heat slowly and have less thermal capacitance due to their construction materials [13]. Cylinder bundling and enclosed trailers may also prevent easy access to all portions of the vessels and can result in higher temperatures due to reduced air flow around the cylinder during filling. Additionally, vessels with a long length-to-diameter (L/D) ratio are particularly susceptible to stratification, and may result in inaccurate temperature readings from installed thermal sensors. The recorded temperature is highly dependent on the location of the sensor within or on the exterior surface of the vessel and often does not measure the peak temperature during filling. TPRD location relative to the heat generation will dictate exposure temperature during filling.

As a representative example, Li et al. studied the internal pressure and temperature of type IV on-board hydrogen storage cylinders using a 2D axisymmetric computational fluid dynamics model [14]. Gas temperatures as high as 395 K (122 °C) were predicted for a 367-L cylinder ambient filled at 0.361 MPa/s from 5 to 70 MPa in a 3-minute fill. The authors concluded that larger capacity vessels with L/D ratios similar to their smaller counterparts are more prone to overheating during filling, necessitating more stringent temperature control strategies.

3.1.3 Hydrogen Impingement on the Trigger

Some TPRD designs rely on an O-ring sealed plug that is held against the cylinder pressure by a triggering device such as a fluid-filled glass bulb. One such configuration is shown in Figure 2, where item 3 is the glass bulb and item 11 is the sealing O-ring. Another configuration is shown in Figure 3.

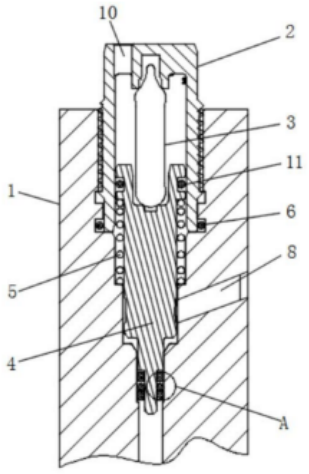


Figure 2. Example cross section of a glass bulb style TPRD with an O-ring sealed plug (shown as item 11) from Chinese Patent #CN217056498U [15].

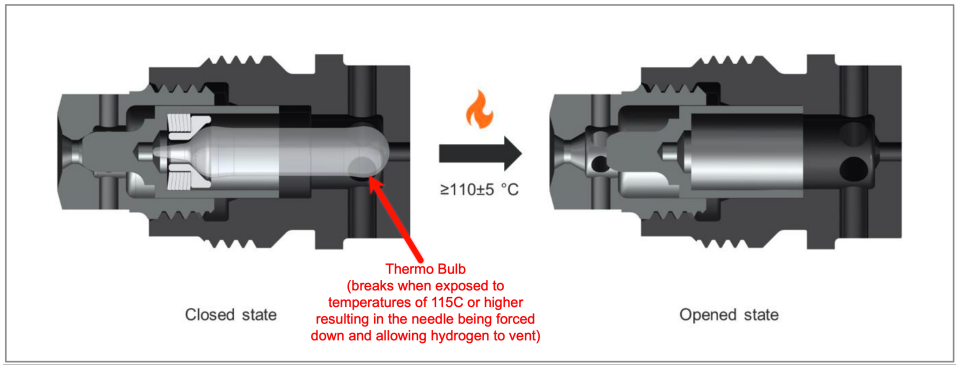


Figure 3. Example cross section of a glass bulb style TPRD with an O-ring sealed plug from Poppe+Potthoff TPRD 1.3 item No 016280-K [16].

A hypothesized potential mechanism for unintended activation of such a TPRD is heating due to O-ring leakage or failure. Hydrogen gas can leak past the O-ring when the O-ring extrudes out of its retaining groove. Such leaks have occurred in both TPRDs and other fittings and valves that rely on O-rings in high-pressure hydrogen service. Manufacturing tolerances, the hardness and hydrogen compatibility of the ring material, and/or improper lubricants can all contribute to leakage or failure of the O-ring. If the triggering element is directly downstream of the leak, the impinging hydrogen will flow directly past the triggering device.

Understanding the temperature of the impinging hydrogen is fundamental to predicting if such a leak will trigger the TPRD and allow the leak to progress to a full activation. A stream of hydrogen leaking across a small hole will experience JT heating and will be hotter than the feed of hydrogen to the leak. For example, suppose

hydrogen leaks past a TPRD trigger from 625 bar (9065 psig) while the gas temperature is elevated to 80 °C after filling. JT heating can be approximated at 3 °C temperature rise per 1,000-psi pressure drop, resulting in a gas temperature of ~107 °C. Assuming sufficient heat transfer, this is high enough to activate the temperature trigger. Testing would be needed to establish if this heating mechanism is sufficient to activate the temperature trigger for a given TPRD geometry and installation location, particularly when the gas temperatures are elevated from vessel filling. Although the likelihood of this scenario remains to be established, the repeated exposure of a eutectic alloy TPRD design to temperatures nearing its melting point may also initiate a creep mechanism that could activate the device over time.

3.1.4 Improper Specification

Device selection is critical to preventing spurious operation and enabling operation in a fire scenario. Both activation temperature and device type must be considered. A low activation temperature in an installation location that experiences repeated elevated temperature during filling presents a higher risk of spurious operation. On the other hand, specifying too high of an activation temperature may delay or prohibit activation in a fire scenario. The use of combination devices (e.g., CG-5) to protect COPVs should also be carefully considered. The thick composite overwrap on high-pressure COPVs insulates the gas from heat exposure, limiting the gaseous pressure increase in the vessel. While the heat from the fire may be sufficient to impact the structural integrity of the composite, the internal pressure may remain lower than the rupture disk burst pressure necessary to activate the device and relieve the pressure in the cylinder. In this case, composite damage may lead to catastrophic failure of the vessel.

3.1.5 Design Pedigree

Control of the robustness of a TPRD to activate only as expected starts with the design of the device. Mechanical or design defects can contribute to early activation. Dimensional tolerance buildup can create unintended loads on thermal triggers that can lead to structural failure of the trigger. Issues with design and materials can lead to O-ring seal extrusions that begin as leaks across the seal or extrusion of the seal itself.

Qualification to design standards, risk assessments, and performance testing are important means to assess and improve reliability. TPRD designs are informed by performance requirements and design standards. As introduced in Section 2.2, two prominent design standards are CGA S-1.1 and CSA/ANSI HPRD1 / ISO 19882. CGA S-1.1 provides general design guidelines and equations for determining flow capacities. However, outside of referencing CGA C-14 for fire testing, the standard does not cover QA measures to ensure production reliability of relief devices. In contrast, CSA/ANSI HPRD1 and ISO 19882 standards provide risk-based recommendations for design qualification and a battery of qualification tests with specific performance requirements. Production batch testing is prescribed based on the design critical components identified in the risk-based design study. QA measures are not specifically prescribed in CSA/ANSI HPRD1 and ISO 19882 standards, but are required to be established. As a result of the qualification, quality, and test requirements per the predominant global standards, there may be significant variability between devices qualified per CGA S-1.1 versus CSA/ANSI HPRD1 / ISO 19882.

3.1.6 Installation Error

In some instances, such as the event in Diamond Bar, CA, in 2018, installation of an incorrect relief device can result in unintended operation of a PRD [2]. Maintenance errors may also include improper installation. Defined maintenance procedures – including verification steps, available spare parts, trained staff, and

management of change procedures – will all decrease the potential for errors during installation and maintenance.

3.1.7 Damage In-Service

Damage to a relief device in-service, including through maintenance activities, may result in unintended activation, failure to vent as intended, or failure to open at its activation temperature. Devices can be corroded due to exposure to water or contaminants or become blocked by dirt, debris, or ice. For hydrogen service, hydrogen embrittlement of incompatible materials and/or high stress in the design may also lead to failure. Excessive vibration can also cause damage and is especially a concern for glass bulb style TPRDs. In transport, collision that damages the device or source lines may also lead to loss of containment.

In all instances, relief devices and their source piping directly interface with the storage volume and remain pressurized while in service. In some designs, vessels are manifolded together so that activation of a single relief device or loss of containment in the upstream source piping will cause multiple vessels to vent simultaneously. A release at the relief device, source piping, or interface of the vessel cannot be isolated and therefore the entire contents of the vessel(s) will be released. These components are at greater risk of in-service damage than releases occurring downstream of the isolation valve, which are only pressurized during filling or dispensing and can be isolated.

3.2 Loss of Containment and Accumulation

For both intended and spurious activation of a TPRD, Figure 2 explores the resulting loss of containment. A combustion event requires hydrogen, air, and an ignition source. Ignition sources for a hydrogen-air mixture are plentiful since the minimum energy requirement for ignition is so low for hydrogen-air mixtures. While electrical ignition sources can be anticipated, even the shock or friction of the gas release itself can provide sufficient energy to initiate combustion. Because ignition can be unpredictable, Figure 2 focuses on factors contributing to a hydrogen-air mixture outside of the vent piping. Lack of mechanical integrity, improper sizing of vent piping, and lack of support for the thrust loads can all lead to hydrogen leaks in unanticipated locations. Leaks in enclosed spaces may accumulate, leading to flammable concentrations and a potential combustion event. Similarly, local hydrogen leaks that are improperly vented due to equipment failures may impinge directly on nearby vessels, leading to vessel failure or activation of additional TPRDs.

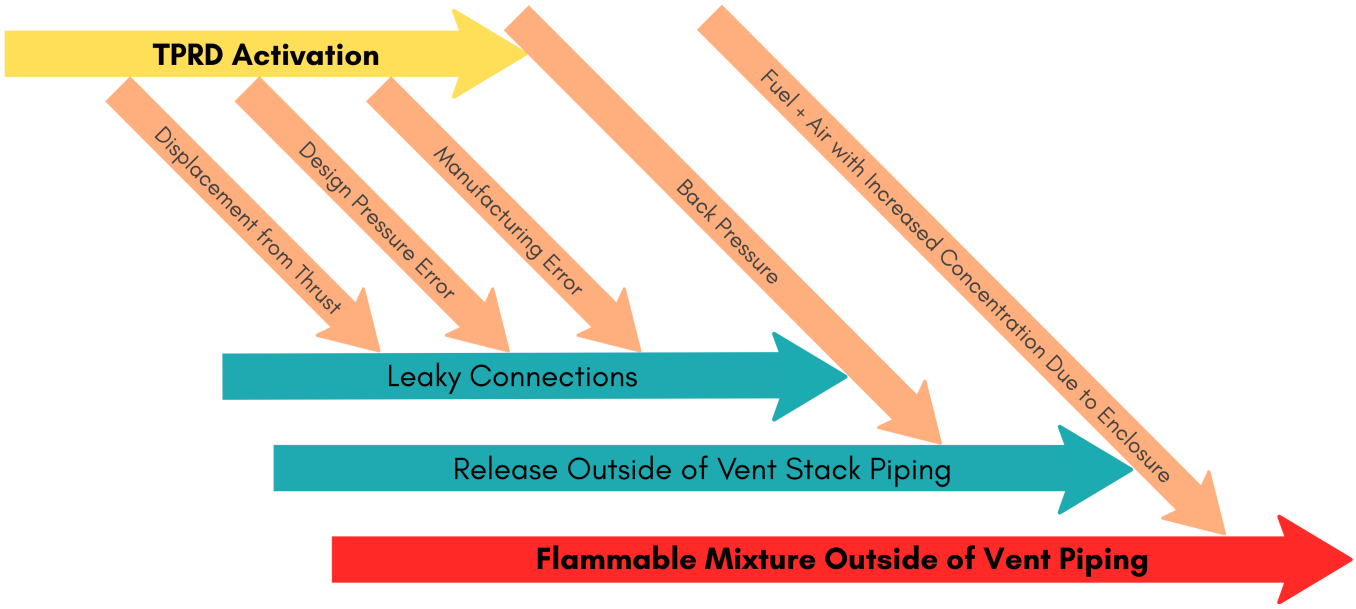


Figure 4. Fishbone diagram for loss of hydrogen containment.

3.2.1 Vent Pipe Sizing

When a vent system is activated, hydrogen is typically piped away to a safe vent outlet. That piping, sometimes referred to as "pipe-aways," may seem as innocuous as a rain gutter directing water away; however, the pressurized nature of the flow can create substantial back pressures. High flowrates through relief devices sized per applicable codes and standards can result in significant pressurization of the vent system piping, especially when restrictive outlet piping or components are used [17]. This back pressure, which occurs during venting, may overpressure the vent system and cause piping failure in an otherwise untested system.

The design capacity of a non-reclosing device is typically based on a choked flow condition at the device orifice. Based on an isentropic flow across an orifice, such a choked flow is unaffected by downstream pressure drop as long as the outlet pressure is maintained at around 50% or less of the inlet pressure. If the piping is restrictive enough to create an outlet pressure higher than this, the choked flow is no longer dictated by the relief device, but rather by the piping capacity. This will slow the release of stored pressure in the vessel upon device activation. In an extreme case, this could result in catastrophic vessel failure should structural integrity be lost during the time delay.

3.2.2 Vent Piping Mechanical Integrity

Although leak sources may be non-obvious to some since the pipe-away system normally contains air at atmospheric pressure, hydrogen back pressure during venting can result in leaks in the vent system. Even small leaks can accumulate to dangerous levels if the pipe-away is within an enclosure.

Due to the combustion risk of leaks, the choice for connections on piping must be considered. Mechanical joints on mobile equipment are subject to vibration and temperature and pressure swings, which can cause fittings to loosen over time. In addition, vent systems are often not pressure- or leak-tested when assembled initially, or after maintenance. As a result, latent issues may remain unknown until a relief device activation

provides the system with its ultimate test. This was part of the root cause in nearly all the stated incidents in Section 2.1.

If a vent system allows for ingress of moisture, debris, or insects, pressure in the vent piping will be further elevated, extending the duration of pressure blow down, increasing leak rates and quantity released at leak locations, and potentially causing vent piping failure. Vent piping should be appropriately shaped or protected with vent caps at the discharge location to mitigate the ingress of foreign material [18].

3.2.3 Thrust and Supports

Pressurized flow can create significant thrust loads, especially at the discharge where the gas exits the piping to atmosphere. As with several of the incidents in Table 1, thrust forces can cause fitting separation, resulting in a release at an unintended location, or cause piping to crimp, preventing proper de-pressurization of the vessel. Clamps should be used to secure piping, especially near the pressurized source and near direction changes.

To determine a thrust value at the vent exit, the pressure at the exit and mass flow rate must be determined. A conservative assumption is 50% of the relief pressure. Alternatively, the pressure drop in the piping and potential for choked flow at the vent exit can be used to determine vent exit pressures. The thrust can be calculated by the following equation [18]:

$$F = \frac{W}{366}\sqrt{\frac{kT}{(k+1)M}} + A \times P$$

where:

- F = reaction force (lb)
- W = mass flow of the gas (lb/hr)
- k = ratio of the specific heats (Cp/Cv) at the outlet conditions = 1.41 for hydrogen
- Cp = specific heat at constant pressure
- Cv = specific heat at constant volume
- T = temperature at the vent stack outlet (Rankin or °F +459.67)
- M = molecular weight of the gas (2.01 for hydrogen)
- A = area of the vent stack at the point of discharge (in^2)
- P = static pressure within the vent stack outlet piping (psia)

The effects of reaction forces on the stability of the vent pipe and its associated supports must be considered. Bending moments created on the vent piping should not allow a permanent deformation in the vent pipe. Failure of support structures can increase those bending moments, inducing unanticipated deformation of vent piping and potential loss of flow capacity or misdirected gas streams.

3.2.4 Hydrogen Accumulation

Hydrogen systems located inside of enclosures, especially with a roof or overhead structure, can produce higher concentrations and combustible volumes of hydrogen-air mixtures. This can render an otherwise benign leak into a fire or explosion. Additionally, explosion and fire consequences in enclosures are often greater due

to confinement, congestion, and the potential for fire spread. These considerations are covered in a related white paper by the HSP [19].

Areas subject to accumulation may be mitigated by continuous ventilation; however, ventilation will typically not mitigate against large leaks or a piping failure. While in transit, enclosed systems can be configured with ventilation options that can effectively eliminate accumulation. However, natural ventilation may be insufficient while the hydrogen trailer is stationary. It is also important to recognize that even if procedural controls are in place to keep isolation valves closed except while in use and/or detection occurs, many potential leak sources – such as relief devices, source piping, and all vessel fittings and connections upstream of shutoff valves – cannot be stopped in the event of a leak.

4.0 Best Practice Recommendations

The following best practices should be incorporated into the design, manufacture, maintenance, and operation of high-pressure compressed gaseous hydrogen trailers.

4.1 Practices Related to Relief Devices

4.1.1 Quality Control

Devices that have rigorous design and manufacturing quality controls are desired. QC measures become increasingly critical as the demand for performance goes up with respect to risks associated with failure to perform in an upset and failure to perform (stay sealed) during otherwise normal operation. Particular attention should be paid to design elements of relief devices that rely on O-rings. O-ring groove dimension, surface finishes, material, and sealants must be managed consistent with the sensitivity of the device performance if such attributes should deviate from design requirements.

4.1.2 Risk Assessments

Risk assessments for relief designs (such as risk-based failure modes and effects analysis in the case of CSA/ANSI HPRD1) should be performed to assess the probability of failure to perform and consequences of unintended operation. Risk reviews should include (but not be limited to) critical-to-function attributes such as:

- Material specification
- Dimensional requirements and tolerances
- Surface finishes
- Assembly needs
- Service conditions (e.g., vibration)
- Susceptibility to impact
- Effectiveness in potential fire scenarios

A periodic validation of device performance should be scaled to the likelihood of process limit excursions in production. When sub-vendors are used for components, the abovementioned provisions need to be affirmed and tracked.

4.1.3 Device Type, Quantity, and Installation Location

When installed, or required for code compliance, the position of TPRDs should consider the credible location of a fire and provide adequate coverage along the length of the vessel. Although multiple devices may be required, a balance must be found between increasing the risk of spurious operation by multiplying the number of components and adequately protecting the vessel in the event of an external fire.

As filling will increase gas temperatures, TPRDs should be located in a way that minimizes the potential for inadvertent operation, particularly when combined with the potential for internal leakage. They should also be installed in a location that has easy access for inspection or replacement but be protected from external impact in a vehicle accident.

TPRDs are not always required by code or design since there is a balance of risk between protection and unintended releases from spurious activation and leaks from non-isolatable leaks on the TPRD source piping and fittings. Alternative means to protect vessels from localized fire effects include coatings that insulate from heat (e.g., intumescent paint or epoxy coatings), wraps, and remote heat detection methods such as heat transfer liquid or metal tubes or fuse trip wire(s) [12].

The device type and activation temperature should also be carefully considered based on the vessel type and installation location(s). Pressure and temperature combination devices may not enable timely activation if thermal insulation inherent to the vessel design or surrounding the equipment prohibits significant pressure increase.

4.2 Practices Related to the Hydrogen System

4.2.1 Pressurized System

All pressurized vessels, piping, fittings, and components can be sources of hydrogen leaks. Whether pressure is continuous [e.g., vessels, source piping, isolation valve inlet(s), and relief inlet(s)] or intermittent (e.g., piping and components downstream of the isolation valve used for filling and dispensing and vent piping), the potential for leaks and their associated consequence should be carefully considered. Often, it is not possible to isolate leaks in continuously pressurized portions of the system. Pressurized piping systems for PRD/TPRDs are a particular challenge due to the large number of mechanical joints, exposed locations, and relatively fragile construction due to small piping sizes.

The design of high-pressure hydrogen transport trailers must prioritize structural integrity, pressure containment, and dynamic stability. Engineers must account for internal pressure loads while also considering stresses induced by vibration, braking, and road irregularities during transport and the potential for impact or rollover. Proper material selection, corrosion protection, vessel construction, and secure mounting are critical to preventing failure and leaks. Additionally, safety features such as relief valves and vent systems (where applicable), secure connections, and compliance with transportation regulations and nationally recognized piping code (i.e., ASME B31.3, B31.12) promote safe operation both in operation and in transit.

4.2.2 Vent Piping

The design of the pipe-away system and vent stack top works is critical to ensuring that hydrogen is vented to a safe location. Accordingly, the designer must establish and follow the pipe pressure rating, sizing, routing, top works shape, materials of construction, choice of fittings, securement, methods for assembly, and QA

procedures. The vent stack subsystem should not be overlooked in the design, risk assessment, or maintenance procedures.

Vent piping must be engineered to contain the pressurized flow. The mass flow rate is controlled by the relief device size and is generally considered to be an isentropic choked flow (sonic velocity) across the relief device orifice. As a choked flow, the rate is largely uninfluenced by the back pressure of the vent piping, as long as the back pressure does not influence the choked nature of the flow. Choked flow of hydrogen gas will be ensured if the absolute source pressure exceeds approximately twice the absolute pressure downstream of the device [20]. Using the mass flow rate of the relief device, the required vent pressure to sustain that flow can be predicted. This vent pressure should generally not be higher than 50% of the absolute inlet pressure for non-reclosing devices and 10% of the inlet pressure for reclosing devices. Accordingly, a pressure rating of at least 50% of the relief device set pressure is a reasonable design pressure and is a best practice for properly sizing a vent pipe to avoid compromising the flow rating of the device [21].

Small pipe sizing, flow restrictions, or vent stack top works can create unintended consequence in pressure drop, impeding the free flow of venting hydrogen or preventing pressure relief activation at the design pressure. Compliance with codes and standards to avoid excessive backpressure in the vent system is required.

Thrust from ejecting gases can create loads that may bend piping and in turn create restrictions or leaks. Consider back pressure for flow capacity and design pressure of pipe-aways. The design of the piping supports is critical to safety in supporting such load and retaining the flow integrity of the piping. Vent piping should be designed to a determined pressure level and the integrity of the piping tested during commissioning and after maintenance. Such pressure testing and inspections should take place in concert with the re-testing schedule for the PRDs.

Mechanical integrity of the pipe-away system must be enabled through design but sustained through best practice maintenance. While many types and designs of top works are deployed, versions that incorporate moving design elements must be properly maintained to ensure that moving parts function freely and do not impede the flow of hydrogen. Maintenance inspections to ensure that the vent remains free of moisture, debris, and insects and periodic leak detection are also important mitigation measures to ensure piping integrity.

4.2.3 Quality Control

As with all systems, component QC and workmanship during fabrication play an important role in overall system integrity. Without appropriate QA/QC, significant variation between trailers can persist, leading to potential safety events.

4.2.4 Risk Assessments

In addition to risk assessments for the relief device components (Section 4.1.2), a risk assessment should also be performed for the balance of the designed hydrogen system. It is important to recognize that adopted standards may not prescriptively protect against all risks associated with the design of compressed hydrogen transport trailers. The risk assessment should consider all fire scenarios and address integrity for the selected components. Although components may pass standard bonfire tests, these tests may not be representative of the specific installation details and/or fire scenarios identified in the risk assessment. For example, adopted standards may not fully consider exposure to a high-pressure-volume jet fire, a vehicle battery fire from

adjacent equipment, or structure details of the vehicle design that can inadvertently affect the fuel storage system. Therefore, more stringent survivability testing and/or additional layers of protection may be required.

4.3 Practices Related to Equipment Enclosures

Enclosing pressure vessels offers nominal impact protection, security from vandals, protection from solar radiation, improved esthetics, and a convenient location for graphics. However, enclosures have several unintended consequences that must be considered. First, the cylinders will heat up when filled. The level of heating depends on the fill rate and the vessels' ability to transfer that heat to the environment. Enclosures can increase the ambient temperature around the cylinders and impede the heat transfer portion of this balance. Enclosures can also make it difficult to assess the external temperature of the cylinders as part of procedural controls. Second, in the event of a release inside the enclosure, gas concentrations will increase depending on the leak rate and level of ventilation provided. Explosion consequence is also made worse through congestion and confinement resulting in increased overpressure.

Accordingly, the potentially detrimental implications of enclosing a storage system should be weighed against any advantages gained from the enclosure. Designers should consider alternative means for security (e.g., perforated plate) and COPVs that can withstand effects of ultraviolet radiation to allow for an open roof. Due to combustion risk, code requirements for stationary applications prohibit large-volume indoor use or courts without extensive safety controls and mitigations (including ventilation). Great care should be taken in the design to ensure that all potential leak sources are effectively swept by sufficient airflow to allow for rapid dispersion of a credible hydrogen-air mixture. The same best practice for indoor applications should apply to mobile applications in enclosures. A thorough risk assessment can assist in reviewing and implementing recommendations that improve the overall design safety.

4.4 Practices Related to Maintenance and Operations

4.4.1 Procedures

Operations, maintenance, and emergency procedures should be developed in the design phase of the project and analyzed as part of hazards analysis / risk assessment studies. Incorporating these procedures upfront ensures that equipment layout, access, controls, and safety systems are designed with real-world use and intervention in mind, rather than forcing operators and maintenance personnel to work around design limitations later. Procedures should never be treated as an afterthought, as they play a central role in preventing incidents, minimizing human error, and ensuring consistent, safe operation throughout the lifecycle of the facility.

Well-developed procedures also provide a critical link between engineered safeguards and human interaction with the system. They should clearly define roles, responsibilities, required competencies, and communication protocols, especially during abnormal or emergency conditions. Isolation and repair procedures, in particular, should include discrete, step-by-step instructions that are unambiguous and easy to follow under pressure. These steps should address energy isolation (e.g., lockout/tagout), verification of zero-energy states, use of personal protective equipment, and safe restoration to service. Additionally, procedures should be validated through walkthroughs or simulations, regularly reviewed, and updated to reflect operational experience, modifications, and lessons learned from incidents or near misses.

4.4.2 Filling Operations

The temperature of the cylinders and the coincident temperature of TPRDs should be monitored during filling operations. This can be accomplished by active measurements with thermocouples installed or by other non-invasive heat-measuring devices. Great care should be taken when relying on external temperature measurements as the peak internal temperature may not correlate well, especially for high-pressure COPVs with thick composite overwraps. Experimentation to establish safe fill procedures for a given application should be performed, especially if the design falls outside of existing standards. The manifold design, number of vessels/banks filled simultaneously, vessel valve assembly design, vessel L/D ratio, and ambient temperature will all affect temperature evolution during filling. Controlling the internal gas temperature is essential to protecting COPVs from damage and reducing spurious activation of TPRDs that are repeatedly exposed to high temperatures. When uncertainty around peak temperature persists, use slower fill rates.

4.4.3. Preventative Maintenance

Periodic inspections should include leak checks and proper fitting assessments and corrective actions for the entire system, including the vent piping. Records of any adjustments are critical to tracking areas that are especially susceptible to loosening. When such records show the need for pervasive fitting adjustments, design changes should be considered.

4.4.4 Training

Training for employees working on or around a compressed hydrogen trailer is essential to safe and reliable operation. Human error remains one of the most common contributors to incidents, making effective training a critical layer of protection. Training programs should not only convey technical knowledge, but also actively motivate safe behavior by reinforcing the consequences of unsafe actions and the importance of adhering to procedures.

Both initial training and periodic refresher training are important to maintaining competency and addressing knowledge gaps over time. Refresher sessions provide an opportunity to reinforce critical safety concepts, introduce updates based on procedural changes or incident learnings, and ensure continued compliance with regulatory and company requirements. Incorporating hands-on exercises, drills, and scenario-based training can further strengthen understanding and preparedness. Training effectiveness should also be evaluated regularly through assessments, observations, and feedback to ensure that employees are not only informed, but are capable of consistently applying safe practices in the field.

4.4.5 Management of Change

Management of change is a key parameter of continuous diligence in safety management. Performance deviations should initiate root cause and corrective actions that in turn are documented. Hazard analysis and other elements of design, construction, and operation process safety management must be considered for any change. The safety planning guide offered at H2tools can be a valuable resource [22].

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