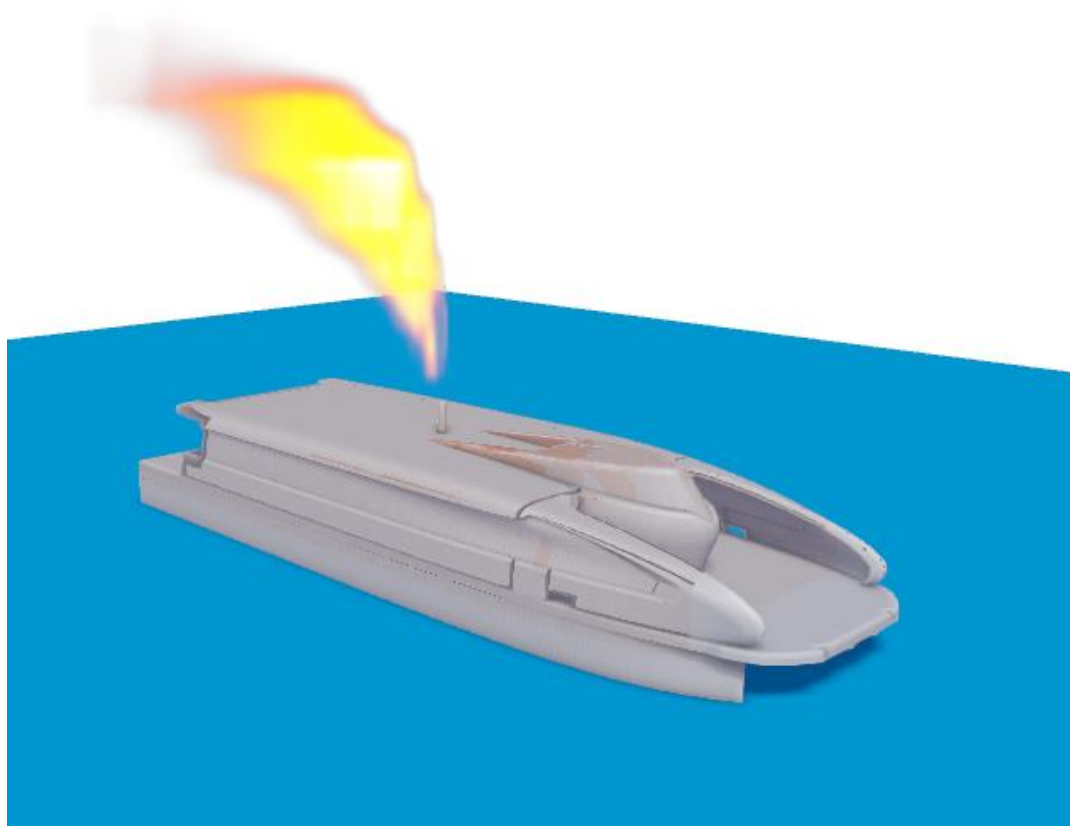




Hydrogen ship vent mast design – H2Vent

Jonatan Gehandler, Sixten Dahlbom, Paul Adams,
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Abstract

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To reduce greenhouse gas emissions, the maritime sector is undergoing rapid technological and regulatory development. Safety frameworks for the storage and utilisation of hydrogen on board ships are being developed, with specific focus on the management of high-pressure storage systems and controlled venting arrangements. Compressed hydrogen is stored under high pressure, and in the event of a fire, the gas must be released to prevent a pressure vessel explosion of composite storage containers. The vent mast design must be supported by case-specific risk assessments and CFD-based evaluations. This study evaluates six vent mast design configurations using the Beluga 24 prototype as a representative case. CFD-based simulations were conducted to analyze dispersion, jet flame radiation, and explosion hazards. For unignited hydrogen dispersion, results indicate that positioning the mast outlet at the highest point significantly reduces overall safety concerns. Nevertheless, the horizontal extent of the flammable envelope remains considerable across all release velocities, necessitating strict avoidance of air intakes and recirculation zones within this region. In contrast, thermal radiation from jet flames constitutes the dominant hazard, with required safety distances exceeding those associated with overpressure effects from gas explosions. Masts that release hydrogen vertically tend to require shorter mast heights to meet the radiation safety criteria. However, it is not evident that additional radiation from the vent mast constitutes a significant hazard during a fire scenario.

Key words: Maritime, Vent mast, Cold flare, Compressed hydrogen, Dispersion, Jet flame radiation, Explosion overpressure

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Preface

This report presents the results of the project Hydrogen Ship Vent Mast Design – H2Vent, financed by the Swedish Transport Administration (Trafikverket), reference TRV2024/29444. The project addresses the design and safety considerations for vent masts on hydrogen-powered ships, using Beluga24 as a reference case. The aim is to develop solutions that ensure safe venting of hydrogen during emergency scenarios, while balancing regulatory requirements, technical feasibility, and practical ship design constraints.

The work has been conducted by RISE Research Institutes of Sweden in collaboration with partners from Lund University and industry (Poseidon Konsult AB). Computational fluid dynamics (CFD) simulations and risk assessments form the basis of the design evaluations presented in this report.

We gratefully acknowledge the contributions of the following individuals and organizations for all the different perspectives that you enriched this project with during interviews and discussions:

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Their perspectives have helped ensure that the proposed solutions are grounded in practical experience and regulatory context.

The first version of this report was submitted to the financier on 2025-11-28.

This is the second version of the report, dated 2026-01-14. Future versions may include peer-reviewed papers currently under preparation.

Summary

För att minska utsläppen av växthusgaser utvecklas den maritima sektorn snabbt både tekniskt och regulatoriskt. Ett centralt område är säker hantering av vätgas ombord på fartyg vid lagring under högt tryck. Vid en extern brand kan gasen behöva släppas ut genom en kallfackla eller ventmast till en säker plats för att undvika tryckkärlsexplosion av kompositbehållare. Effektiviteten och utformningen av ett sådant system beror dock på flera parametrar: brandbelastningen och fartygets passiva och aktiva brandskyddsåtgärder; konfigurationen och brandmotståndet hos vätgaslagringssystemet; miljöförhållanden såsom vind, isbildning och nederbörd; samt operativa faktorer inklusive nödrutiner och placering av ventilationsintag och utrymningsvägar. Därför baseras utformningen av ventmasten på riskanalyser och simuleringar. Vid en ventilering av vätgas kan en tidig eller sen antändning inte uteslutas, vilket resulterar i en jetflamma respektive en gasmolnsexplosion.

I denna studie har sex olika ventmastkonfigurationer utvärderats med Beluga24-prototypen som referensfall. CFD-simuleringarna omfattade spridning av vätgas, värmestrålning från jetflamma samt övertryck vid fördröjd antändning. Resultaten visar att spridning utan antändning sällan utgör en kritisk säkerhetsrisk om mastens utlopp är den högsta punkten på fartyget. Däremot kan den horisontella utbredningen av den antändbara gasmolnszonen vara betydande, vilket kräver att luftintag och recirkulationszoner undviks inom detta område. Den dominerande faran är värmestrålning från jetflamma, som även är mer kritisk än övertryck från en gasexplosion. Det är dock oklart om strålningen från ventmasten utgör en betydande risk i relation till den brand som redan hotar gastankarna.

Studien visar att ventmaster som släpper ut vätgasen rakt uppåt i en lång men smal plym generellt kan dimensioneras med lägre höjd, eftersom strålningsbidraget som når fartyget då minskar. För Beluga24 krävs en enkelmast på 9.5 meter för att hålla värmestrålningen inom säkra nivåer för människor på väderdäck. En så hög mast innebär en betydande fartygsdesignutmaning.

Abbreviations and definitions

CHSS	Compressed hydrogen storage system
Container	Pressure-retaining vessel specifically designed to store hydrogen gas at elevated pressures.
FRR	The fire resistance rating is the time a full container can withstand a fire until it ruptures.
HRRPUA	Heat release rate per unit area
LBB	Leak-before-burst. The container or other equipment starts to leak instead of rupture in case of failure due to pressure cycles, overpressure, or impact/penetration.
(m)LNB	(Micro-)Leak-not-burst. The container starts to leak by numerous micro leak paths instead of rupture in case of thermal exposure, e.g., fire.
LFL	Lower Flammability Limit.
PRD	Pressure relief device
PRV	Reclosing pressure relief valve that opens at a set pressure (safety device).
TPRD	Thermally activated (eutectic alloy plug or glass bulb) pressure relief device activated at a set temperature. Following activation, it remains open, i.e. single use and non-reclosing (safety device).
UFL	Upper Flammability Limit.
Vent	The act of discharging hydrogen gas (or any other gas) in a controlled manner.
Vent mast	Piping to vent hydrogen gas to a safe location (the atmosphere) without <i>actively</i> igniting it.
Vent mast height	Vertical distance from the weather deck (or designated reference deck) to the vent outlet.
SOC	State-of-charge

1 Introduction

1.1 Background

Shipping is currently, to a very large extent, dependent on fossil fuels. Hydrogen is an energy carrier that can be produced from “green” electricity, for example, solar cells, hydropower or wind power. Although the number of hydrogen-powered ships in service is small, it is an area of rapid development. For instance, Torghatten Nord has signed a contract to operate hydrogen ferries between Bodö and Lofoten in Norway¹ and Gotlandsbolaget in Sweden have ordered a high-speed catamaran that can run on hydrogen². The International Maritime Organization (IMO) is working to develop comprehensive prescriptive rules for hydrogen-powered ships in line with the IGF Code's (International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels) functional requirements, equivalent to those for natural gas. Classification societies such as LR, DNV and BV have published rules for the use of hydrogen on board.

Compressed hydrogen is stored under high pressure (typically between 250 and 700 bar depending on the application) and in the event of a fire, a safety measure is to release the gas through a vent mast/cold flare to avoid rupture of the compressed hydrogen storage system (CHSS). If the gas is not released, a container rupture can occur if the gas pressure exceeds the strength of the storage vessel, which in the case of composite cylinders can be weakened by fire exposure. Therefore, the cylinders are equipped with a thermally activated temperature release device (TPRD) that will release the gas if the containers are exposed to too high temperatures. The International Maritime Organization's Sub-Committee on Carriage of Cargoes and Containers (IMO CCC) have developed draft Interim Guidelines for the Safety of Ships Using Hydrogen as Fuel. The guidelines include a description of when venting should take place, how the vent mast should be dimensioned, and which standard is appropriate to follow (IMO CCC 10/3). A hot flare should not be used for venting, and hydrogen venting should not take place during normal operation (possibly during bunkering) for compressed hydrogen storage. The primary purpose of the vent mast is to act as a safety measure if hydrogen needs to be rapidly released to a safe location to avoid rupture, e.g., in the event of a fire. A vent mast for ships is proposed (e.g., IMO CCC, BV and DNV rules) to be designed according to standards for land-based applications (e.g. CGA G-5.5, EIGA 211/17 or API Std 521). As an example, the latter standard states that “*This standard is applicable to pressure-relieving and vapor depressuring systems. Although intended for use primarily in oil refineries, it is also applicable to petrochemical facilities, gas plants, liquefied natural gas (LNG) facilities, and oil and gas production facilities.*” (API Std 521) i.e., ships are not considered in the scope of the standard.

Previous research (Blaylock et al. 2022 and Blaylock & Klebanoff 2023) has investigated hydrogen dispersion from a small ship with 273 kg of hydrogen at 250 bar distributed in 10 cylinders and suggested that a rather tall vent mast that is needed, almost as high as

¹ Vegvesen.se accessed 2025-04-30 <https://www.vegvesen.no/en/fag/trafikk/ferje/hydrogen-ferries-to-lofoten/>

² Gotlandsbolaget.se accessed 2025-04-30 <https://gotlandsbolaget.se/destination-zero/horizonserien/gotland-horizon-x/>

the ship length³. Other risks associated with the release concerns jet flame radiation and explosion following gas cloud ignition.

For road vehicles, several high-profile incidents with CNG have occurred where 10 m long jet flames have been reported in the media (Cheromcha 2017). There is also anecdotal evidence from industry, where delayed ignition of emissions from cold hydrogen flares has resulted in significant pressure waves. This has been followed by research where the design of the TPRD has been proposed to have more and smaller outlets (Molkov 2023) to minimize risks linked to a jet flame or a gas cloud explosion, but at the same time achieve protection against container rupture. The recently completed project H2-By-The-Book (Olsson et al. 2024) states:

"A release via a vent mast that is dimensioned according to current practice for the land-based hydrogen industry is not necessarily an optimal solution for ships. In contrast, the development for road vehicles, where the gas is released through several, and smaller, holes, which results in smaller potential jet flames and gas clouds, and a faster dilution of the gas with ambient air. Future investigations could develop a similar concept specifically adapted for ships."

The current project is based on a prototype ship in the design stage, Beluga24. Beluga24 is a high-speed catamaran and passenger ship planned to be equipped with fuel cells and compressed hydrogen as fuel, see Figure 1. The CHSS consists of composite containers located on the weather deck, operating at a pressure of approximately 250 bar.



Figure 1 Artist's impression of the Beluga24 design (vent mast omitted).

1.2 Purpose

The current study aims to develop alternative solutions for safe venting of hydrogen for the ship design Beluga24, considering both the risk of gas dispersion, jet flame and explosion. The goal is to increase safety, improve functionality, and avoid negative publicity around hydrogen-powered ships.

³ Sandia.gov [accessed 2025-11-03] <https://www.sandia.gov/labnews/2023/09/21/invention-at-forefront-of-hydrogen-sea-change/>

1.3 Method

The methodology, schematically depicted in Figure 2, started with a literature review combined with interviews to gain an improved understanding of the maritime hydrogen vent mast context.

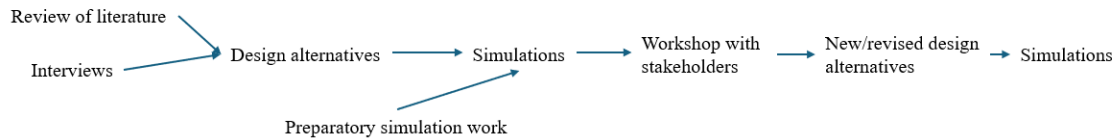


Figure 2 Schematic method overview.

A **review** of vent-mast requirements and designs was performed, including:

- an overview of the hydrogen system,
- the situations when the hydrogen containers need to be depressurized (e.g. fire, bunkering or maintenance),
- different practices within the process industry and for CNG/LNG/H₂ ships and road vehicles, and
- studies and methods to characterize the risk of gas dispersion, radiation from jet flame or gas cloud explosion.

The main sources for information were previous projects, Google, interviews, and ScienceDirect.

Interviews were conducted with classification societies and hydrogen system designers and engineers. In total nine interviews were conducted. The interviews lasted for about 1 hour. The interviews were semi-structured meaning that background information and purpose was sent out, and a set of questions (without options) were prepared beforehand. Follow-up questions and new questions were invented during the interviews (Ejvegård 2003).

An **iterative design method** for the development of solutions was followed according to three steps:

1. Needs analysis and requirements specification
2. Concept development of design solutions and idea development with project and reference group.
3. Evaluation and selection based on modelling and simulations.

Modelling and simulation of gas dispersion, incident heat flux from jet flames and explosion pressure in the case of a delayed ignition were conducted for a set of starting conditions. Simulations were performed using computational fluid dynamics (CFD). The open-source model OpenFOAM was used for overpressure and the commercial software FLACS were used for dispersion and radiation.

The evaluation of the different solutions was based on harm-criteria for radiation/jet flame, concentration/dispersion, and overpressure/gas explosion resulting in required height for the different mast designs. Harm-criteria were identified from literature and agreed upon in discussion with the project- and reference-group.

1.4 Delimitations

The project has only focused on vent masts connected to CHSS at ambient temperatures. Other types of hydrogen storage e.g., as liquid or metal hydrides, were not included.

2 Compressed hydrogen storage system safety

In industrial processes the need for a pressure relief may have many causes e.g. faulty compressors and pump, chemical reactions, heat and sun radiation, and external fire. For ships and road vehicles that are being refuelled, the highest pressure is achieved just after refuelling. This is particularly true for compressed hydrogen since the temperature increases, mainly because of the volume-pressure work, but also due to the Joule-Thompson effect (Bergius et al. 2024). Following the filling, the pressure decreases as the gas cools down or when hydrogen is being consumed. In general terms, if the bunkering station is equipped with proper pressure control and safety measures to avoid over pressure, there is likely no other case except from external fire that may result in an over pressure in the hydrogen container(s).⁴ While hydrogen containers in metal can be protected with, e.g. pressure relief valves or burst discs, composite containers conduct heat less well and are heavily affected by temperatures above the glass transition temperature at around 120 °C (Kim et al., 2017). In particular, fully wrapped composite containers (Type 4) are vulnerable to fire. When the resin reaches the glass transition temperature, the material starts to lose its mechanical properties and, as heat is transferred into the material, the container may rupture. Therefore, the containers are equipped with thermally activated (temperature triggered) pressure relief devices (TPRD). TPRDs are single-use, non-reclosing devices and immediately release the gas, either directly to the atmosphere, or via a vent line/stack/mast. Onboard a ship, the vent mast could also be used to rapidly empty the hydrogen in one or several containers, e.g. in case of a leak or to avoid escalation in case of a fire. For road vehicles the situation is similar, where hydrogen containers are equipped with one or more TPRD (UN ECE GTR 13 and UN ECE R134), while other types of pressure relief may be used outside the CHSS.

2.1 Compressed hydrogen containers

For high pressure hydrogen storage, the container types listed in Table 1 are typically referred to. While the detailed descriptions or definitions may differ from one application or regulation or standard to another the underlying construction is similar.

2.1.1 Maritime applications

For storage onboard ships, e.g. Bureau Veritas (BV) suggests standards for testing of the containers (cf. Table 1). Fire resistance is one of the many properties evaluated according to ISO 11119:2020. The purpose of the test is to show that the container either will not burst when exposed to a test fire when using a specified pressure relief device; or will

⁴ Even if this generally true, it needs to be addressed and evaluated in each particular case.

withstand a minimum specified time in the test fire when a pressure relief device is not to be used in service. A uniform fire source of 1.65 m length that engulf the entire diameter of the container and producing a temperature of 590 °C or greater is to be used. For containers intended to be fitted with a specified pressure-relief device, the containers shall vent through the pressure-relief devices. Containers may also leak through the container wall, other surfaces, or devices (e.g., the valve).

Table 1. Summary of Type 1–4 containers and requirements according to BV.

Type	Description	Design and construction according to BV
1	All metal	NR467, Pt C, Ch 1, Sec 3 for class 1 pressure vessels, type approved according to e.g., the ISO 9809 series
2	Hoop wrapped (structural fibre/resin composite) container with a metallic liner	Recognised standard accepted by BV, e.g. ISO 11119-1:2020
3	Fully wrapped (structural fibre/resin composite) container with a metallic liner	Recognised standard accepted by BV, e.g. ISO 11119-2:2020
4	Fully wrapped (structural fibre/resin composite) container with a non-metallic liner	Recognised standard accepted by BV, e.g. ISO 11119-3:2020

2.1.2 Road vehicle storage systems

An in-depth review of road vehicle storage systems is presented in Appendix 3.

Type 3 and increasingly Type 4 containers are used for road vehicle CHSS and other weight sensitive transport modes. Linerless composite containers are referred to in literature (sometimes as “Type 5”) and prototypes are under development, however, at present the concept has not been developed sufficiently for production batches and road vehicle hydrogen storage. The concept was to have been included in a stationary storage standard but will not be included at present due to lack of development.

The original European hydrogen road vehicle type-approval regulations (EU79/2009 & 406/2010, now withdrawn) were developed by considering the specific hazards of hydrogen and the experience gained from CNG vehicles including:

- Rupture of CNG containers due to corrosion and chemical abuse
- Thermally activated or temperature triggered pressure relief devices (TPRD) that failed to vent properly during a fire
- TPRD’s had not provided container fire protection under all conditions of fire exposure, such as during exposure to localised fires. (A localised fire may impinge on a container at some distance from the TPRD increasing the internal gas

pressure while simultaneously degrading the structural integrity but not causing the TPRD to trigger.)

The underlying philosophy behind hydrogen vehicle regulations is to prevent container rupture, initially relying on TPRDs to rapidly relieve internal pressure, though increasing external fire risk. Newer research focuses on safer hydrogen discharge through design innovations or elimination of TPRDs. Lessons from CNG incidents revealed that localized fires can weaken containers without activating TPRDs, prompting the adoption of a 10 min localized fire test, now part of UN ECE GTR13, though concerns remain about the vague fire specification in the standard that do not specify the HRR. Current regulations and standards require a two-stage fire test (first localized and then engulfing) and highlight the limitations of TPRDs as point sensors, which may be inadequate for long containers. While only one TPRD is required according to GTR13, compliance may demand multiple devices or fire protection measures. Regulations have become more performance-based, granting type-approval only to complete storage systems (CHSS) that pass stringent fire tests, including safety critical components such as containers, primary closures including TPRDs and defined non-pressure-bearing protective attachments under UN ECE R134 Rev.1 Amend.3.

2.1.3 Storage in land-based industries

Unlike when hydrogen is used as a fuel and needs to be stored in large quantities to allow for longer voyages, hydrogen in land-based industries can more easily be produced on demand. The on-demand production reduces the need to store large quantities of compressed hydrogen, which reduces the overall risk. Some industries rely on liquid hydrogen bulk transport. Furthermore, on land, space is not as restricted as on ships, thus enabling separation of dangerous materials and applying safety distances.

The pressure equipment directive (PED, 2014/68/EU) applies to equipment and assemblies whose maximum allowable pressure exceeds 0.5 bar(g), and includes pressure vessels, piping, safety accessories, and pressure accessories. According to the directive, pressure equipment must be safe, meet essential safety requirements covering design, manufacturing, and testing, comply with appropriate conformity assessment procedures, and bear the CE marking and other necessary information.

Since weight and volume are of less importance in fixed installations, the weight of Type 1 containers is less problematic even if Type 4 have become more common even for fixed installations. Another viable option being considered is to store compressed hydrogen underground, e.g., in caverns or boreholes. Furthermore, the volume is not as restricted as e.g., on ships, and storage at lower pressure could therefore be an option. Storage at lower pressure may open for other solutions than conventional containers.

For the design of vent masts on land, there are several standards. Some examples are NFPA 2 Hydrogen Technologies Code, CGA G-5.5, Hydrogen Vent Systems, and API 521 Pressure-relieving and Depressuring Systems (cf. Table 2), EIGA 211/24 and ISO19880-1.

Table 2. Summary of selected standards for the design of vent masts.

Standard	Summary
NFPA 2	- The vent system shall be in accordance with CGA G-5.5. - Discharge outdoors, away from personnel areas, ignition sources, air intakes, building openings, and overhangs. - The height of the mast shall be the greatest of: - o The thermal radiation and impingement distance determined in accordance with CGA G-5.5; the extent of hazardous area determined according to IEC 60079-10-1; or a minimum of 3 m above ground, 0.6 m above adjacent equipment, or 1.5m above rooftops.
CGA G-5.5	- A vent stack fire should be considered a design event. The vent system shall be designed so burning the discharged hydrogen proceeds safely in accordance with API521. - The pressure drop in the vent system shall not exceed 10% of the lowest relief valve setpoint. - The vent system should be equipped with drains. - Vents shall be directed vertically upwards and exits shall be elevated sufficiently to reduce thermal radiation doses to levels recommended in API 521.
API 521	- This is a comprehensive standard for the design of the system. Refer to the document for details. - Contains design scenarios to be considered.
ISO19880-1: 2022	- This standard provides comprehensive general and safety requirements for the design of gaseous hydrogen refueling stations for road and other land vehicles, including associated vent masts (§7.8 provides extensive requirements). - Vent outlets may be oriented in any direction between horizontal and vertical. - For vertical venting, the higher the discharge velocity the smaller the safety distance around the vent as the higher momentum is less affected by crosswinds to bend the flammable plume to the side or ground. - For T-venting, the smaller the discharge velocity the smaller the safety distance recommendations in the axis of discharge as the lower momentum reduces the projected footprint of the potentially flammable plume.
EIGA 211/24	- Applies to the design, installation and maintenance of hydrogen vent systems used for equipment located at a customer site and is not applicable to vent systems with a capacity exceeding 5000 Nm³/hr of hydrogen. - Provides guidance on vent mast design considerations.

Standard	Summary
	- Vertical venting (upward discharge) is the preferred option, the higher the discharge velocity the smaller the separation distance requirements around the vent.

2.2 IMO regulation and ship requirements

In the project “H2-by-the-book” (Olsson et al. 2024) the requirements for Beluga24 were outlined. Beluga24 is a high-speed passenger ship planned to be equipped with fuel cells and compressed hydrogen as fuel. The ship is covered by the EU Directive 2009/45/EC on safety regulations and safety standards for passenger ships, which has been incorporated into Swedish law through the Swedish Transport Agency's regulations (TSFS 2019:120) on passenger ships on domestic voyages. In the absence of specific rules for hydrogen, i.e. a fuel with a low flash point, the functional requirements found in the IGF code becomes dimensioning. However, interim guidelines for hydrogen are in the process of being drawn up within the International Maritime Organisation (IMO) CCC⁵. For instance, it is stated that venting of compressed hydrogen should only be allowed in emergency situations, e.g. to maintain the fuel container integrity. The outlet from the venting system should be directed upwards or at an angle upwards. The height of vent exits is normally not to be less than $B/3$ or 6 m, whichever is greater, above the weather deck, working areas and walkways. Where B is the width of the ship. However, vent mast height could be limited to a lower value according to special consideration by the Administration based on a dispersion analysis. The vent outlet should be located at least 10 m from the nearest air intake [at similar or higher elevation], air outlet or opening to accommodation, service and control spaces, or exhaust outlet from machinery installation (IMO CCC 10/3).

An indication of what future rules regarding hydrogen vent masts for compressed hydrogen ships may include is also given by a recent EMSA (2024) report:

- The vent mast shall have a design pressure not less than 20 bar(g).
- Vent mast exits shall be arranged to safely disperse any release, to prevent its ignition, and limit the consequences of ignited gas (i.e. thermal radiation and fire impingement). Safe distances shall be determined from gas dispersion analysis and heat radiation analysis according to EIGA 211/17 Hydrogen Vent Systems for Customer Applications or other relevant standards, where the boundary is determined by the greater of the LEL or 6 kW/m², which shall not be less than $B/3$ or 6 m above the weather deck. Extension of hazardous areas and safety distances shall be considered based on the result of the analysis.
- The vent mast height shall be sufficient to prevent thermal radiation from affecting the personnel, life-saving appliances, fuel containment system and structures on board.
- Vent masts are to be equipped with fixed hydrogen gas detection and monitored.

⁵ SUB-COMMITTEE ON CARRIAGE OF CARGOES AND CONTAINERS

- Flammable concentrations may lead to a deflagration to detonation transition in vent lines of sufficient length. The ratio diameter/length of the vent system shall prevent that occurrence by design.
- The vent mast shall be designed to minimize the risk of self-ignition internally in the vent line.
- Vent masts shall be grounded to prevent build-up of static electricity.

However, within the IMO regulation there is a possibility (for instance, the alternative design process is explained in Olsson et al. (2024)) to design an alternative solution if it is proved to be equally safe, or safer. In the study by Olsson et al. (2024), a hazard identification (HAZID) was performed for Beluga24 as part of the alternative design process. The main hazard that required some kind of venting or release from the CHSS was a fire, most likely in the passenger compartment below the containers, that threatens the containers. According to an EMSA (2025) hydrogen risk assessment, hydrogen venting may result due to automatic activation of TPRD (i.e. due to fire threat), manual depressurization, or because of over-pressurization during bunkering (i.e. via a PRV).

2.3 Thermally activated pressure relief devices (TPRDs)

Appendix 3 provides a detailed overview of the development, function, and regulatory context of thermally activated pressure relief devices (TPRDs) in hydrogen-fueled road vehicles. Initially, compressed gas vehicles—especially those using CNG—lacked effective pressure relief systems, which led to several safety incidents. Over time, TPRDs were introduced to prevent catastrophic container ruptures during fire exposure. These devices are designed to activate at a specific temperature, releasing hydrogen gas to reduce internal pressure and avoid structural failure of the container.

However, early TPRDs were not always reliable, particularly in localized fire scenarios where the fire might not reach the TPRD, allowing the container to weaken while the internal pressure increased, and potentially rupture. This led to the development of more robust testing standards and performance-based regulations, such as UN ECE GTR13 and R134, which now require that the entire CHSS be tested under both localized and engulfing fire conditions. These tests ensure that the system can vent safely without rupture and that any flames from unintended leaks remain below a specified length.

Recent research has explored alternatives to traditional TPRDs, such as the micro-leak-not-burst (mLNB) concept. This approach allows hydrogen to escape through microscopic leaks in the container material during fire exposure, avoiding the need for a dedicated TPRD and significantly reducing the risk of explosion or long jet flames. While promising, mLNB systems are not yet widely accepted in regulations due to the need for further validation.

In terms of venting, current regulations emphasize the importance of directing hydrogen discharges away from sensitive areas such as passenger compartments, wheel housings, and other containers. Vents must also be protected from environmental contamination and designed to prevent blockage. Overall, Appendix 3 highlights the evolving understanding of TPRD functionality and the regulatory shift toward performance-based

safety systems that account for real-world fire scenarios and promote innovation in hydrogen storage safety.

2.4 Leak before/not burst Container Concept

The “leak before break or burst” (LBB) concept is widely used in different industries to describe the concept that a pressurised component will develop a leak before a catastrophic break/ burst/ rupture will occur. LBB or “Leak Not Burst” (LNB) are terms increasingly used in discussions about CHSS for road vehicles. However, LBB is a term which is often misused in the context of its original meaning in the hydrogen road vehicle regulatory and standardisation sector as explained below.

The purpose of vehicle regulations for on-board hydrogen storage systems defined in UN ECE GTR 13 Amendment 1 is “*to minimize human harm that may occur as a result of fire, burst or explosion related to the vehicle fuel system.*” One of the primary goals is therefore to prevent rupture of the hydrogen pressure vessel. Regulators and standards writers have long considered it to be preferable that a crack or leak path forms in the pressure vessel walls even if it results in a major release to avoid a full rupture. A rupture is essentially an instantaneous release of the compression energy stored in the pressure vessel which results in high overpressures and fragmentation damage. Regulatory requirements address different failure modes, and LBB addresses failures due to pressure cycling as explained below.

In EU Regulation 79/2009 (withdrawn) a LBB performance test was required which addresses the pressure cycling failure mode (i.e., not fire exposure):

“The purpose of the test is to provide evidence that the hydrogen container fails by leakage before rupture. In order to prove this, pressure cycles are carried out on the container by increasing and decreasing the pressure to a specified value. The containers tested must either fail by leakage or exceed a specified number of test cycles without failure.

Similarly in UN ECE GTR13 Amend. 1, the rationale paragraphs no. 73, 74 and 75 also addresses “Leak before burst” performance in the context of the pressure cycling failure mode:

“Rationale for “Leak before burst” aspect of baseline pressure cycle life requirements

73. The baseline pressure cycle life requirement is designed to provide an initial check for resistance to rupture due to the pressure cycling during on-road service. The baseline pressure cycle test requires either (i) the occurrence of leakage (that is designed to result in vehicle shut down and subsequent repair or removal of the container from service (para. 5.2.1.4.3.)) before the occurrence of rupture, or (ii) the capability to sustain 22,000 full-fill hydraulic pressure cycles without rupture or leakage.”

Other failure modes in which containers are tested to ensure that rupture does not occur, include the localised/engulfing fire test and high strain rate impact test (formerly gunshot test). Note that the high strain rate impact test has been removed from regulations (GTR13 and R134), but is still included in the latest standards, i.e. ISO/FDIS

19881: 2025 and SAE J2578_202301, and in both the acceptance criteria is that the container shall not rupture.

The term “*leak not burst*” (LNB) has appeared in the context of Type 4 containers, when more recently “micro-leak-not-burst” (mLNB) has been used in reference to a solution advocated by Molkov (2023). Molkov’s solution to avoid rupture of fire exposed hydrogen containers for road vehicle use, is “*explosion free in fire self-venting (TPRD-less) composite tanks*” (Molkov et al., 2023 & 2024). The mLNB concept achieves an unprecedented level of safety according to Molkov (2023):

- No blast wave,
- No fireball,
- No projectiles,
- No long jet flames, and
- No formation of flammable hydrogen-air cloud under the ceiling of underground parking.

In the mLNB concept, Type 4 containers are designed to release the gas between the composite fibres as the polymer liner and composite resin melts in the fire. This results in many microscopic leak paths, resulting in many microscopic jets from the surface of the container which present a relatively minor fire hazard in comparison to a jet fire or rupture, and negligible explosion hazard as the hydrogen would be vented into the flames melting the container material. Since this form of release is directly triggered by a fire, the gas is burned around the container surface. mLNB Type 4 containers would not need to rely on a TPRD for pressure relief in the event of fire. The latest regulations and standards still require a TPRD, but do not exclude pressure reduction by mLNB principles. Regulation and standards bodies found that there was insufficient research at this time to rely exclusively on mLNB performance for Type 4 containers, and not least to ensure that new failure modes were not introduced. Adoption of mLNB as an alternative to TPRD means that the scenario of undesired TPRD activation is eliminated (a relatively low risk for hydrogen vehicles as TPRD require their own rigorous type approval testing in contrast to earlier CNG systems), as well as the elimination of vent lines.

2.5 Fire testing

All current regulations and standards for hydrogen vehicle CHSS adopt the 2-stage localised followed by engulfing fire performance test, with similar test and performance criteria. The original 2-stage test introduced with the first version of UN ECE GTR 13 has been significantly revised to improve repeatability between different test organisations.

The performance criteria are as follows:

UN ECE GTR13 Amend.1, §5.1.4

“Verification test for service terminating performance in fire

CHSS shall undergo the two-stage localized/engulfing fire test specified in paragraph 6.2.5.

During the test, CHSS are filled to 100 per cent state-of-charge (SOC) with compressed hydrogen as the test gas.

CHSS shall vent to less than 1 MPa within one hour [...]. If venting occurs from TPRD(s), the venting shall be continuous. The container shall not rupture during the CHSS fire test. Except for discharges from the exhausts of TPRD vents, any leakage, permeation, or venting from the CHSS, including through the container walls or joints, other components, and fittings, shall not result in jet flames greater than 0.5 m.

If the CHSS pressure has not fallen below 1 MPa when the time limit defined above is reached, then the CHSS fire test is terminated and the CHSS fails the fire test (even if rupture did not occur)."

UN ECE R134Rev.1, Amend.3

The latest R134 document adopts the GTR13, Amend.1 requirements but with a change to specify heavy duty road vehicles more clearly from a legal perspective, with respect to allowing depressurisation to 1MPa to take place over 2 hours instead of 1 hour.

ISO/FDIS 19881: 2025, §17.3.8

The latest version of ISO19881 is harmonised with the latest versions of GT13 and R134 above, except that there is no time limit for depressurisation to 1 MPa.

SAE J2579_202301

The fire test requirements of SAE J2579 are more complex than the regulations and ISO standard above, even though many criteria and fire configurations are similar. The most notable difference is that the "extended fire" test may not be required if a container satisfies the localised fire test requirements under "Method 1" for a generic vehicle installation, as opposed to a specific vehicle installation

3 Vent mast design considerations

3.1 Problem description

The IGF code applies for ships using gases or other low-flashpoint fuels. However, the IGF code was primarily developed for LNG powered ships. The IGF code states that:

"The probability and consequences of fuel-related hazards shall be limited to a minimum through arrangement and system design, such as ventilation, detection and safety actions. In the event of gas leakage or failure of the risk reducing measures, necessary safety actions shall be initiated."

"The design philosophy shall ensure that risk reducing measures and safety actions for the gas fuel installation do not lead to an unacceptable loss of power."

"Other than when necessary for safety reasons, the system shall be designed to prevent venting under all normal operating conditions including idle periods."

In other words, venting may be allowed for safety reasons, but it should not lead to an unacceptable loss of power or other dangers. The IGF Code further states that:

“Hazardous areas shall be restricted, as far as practicable, to minimize the potential risks that might affect the safety of the ship, persons on board, and equipment.” This implies that the hazardous area around the vent mast outlet and hydrogen storage system should be minimised. The IGF Code also reasons about pressure relief, which according to our interpretation has to do with liquified gases that cause a pressure increase due to boil-of-gasses (BOG) during normal operations. This is not the case for compressed gases. In particular not for hydrogen which is most warm during refuelling. Afterwards, and during use, the pressure is lowered.

Venting may be a solution to deal with the threat of fire that may heat and weaken hydrogen storage containers. For Beluga24, the main fire threat to the hydrogen containers located on the weather deck originates from the passenger compartment below. This compartment is to be *“incombustible”*, i.e., built with *“a material which neither burns nor gives off inflammable vapours in sufficient quantity to ignite at a pilot flame or other ignition source when heated to approximately 750° C”* (IMCO 1967). This also puts requirements on the composite material of the vessel that can be difficult to fulfil. The vessel composite material has an inherent fire risk unlike for instance steel.

The Beluga24 HAZID (Olson et al. 2024) mentioned above further specifies the preventive safeguard as follows *“Nothing combustible in the passenger compartment (fire-resistant material, all furniture made of aluminium etc.)”*. Two safety measures were to be further considered: *“fire division between passenger ceiling and tank area”*, and *“fire extinguishing system in the passenger compartment or cool deckhead from above”*. Such measures would decrease the probability for a fire that expose the containers, could blind the TPRD and reduce the need for TPRDs.

3.2 Design considerations

An external fire will likely be the design scenario for vent piping etc. A fire risk assessment should define the fire scenario.

3.2.1 Composite containers

3.2.1.1 Leak-not-burst

An LNB (μ LNB) container would release the gas in a controlled way through the fire exposed container surface in thousands of microscopic jet flames which would not worsen the fire situation significantly on open deck. However, in confined spaces this may increase the fire load. This concept would need further investigation and testing to verify functionality, and regulation and standards needs to be revised to allow LNB.

3.2.1.2 Fire resistance rating

The fire resistance rating (FRR) is the time a container at 100% SOC can withstand a fire until rupture. This time depends on the heat release rate per unit area (HRRPUA) but is rather stable at about 4–6 min for unprotected composite containers and a HRRPUA above 1 MW/m² (Molkov 2023).

3.2.1.3 TPRDs

TPRDs are the standard safety measure to deal with fire exposed composite containers and is for instance required by BV's rules (2025). These rules may not explicitly require more than one TPRD per container or even per group, e.g. MEG container, of several containers. But a risk assessment must be conducted. The number of TPRDs will be determined by this assessment. One issue in previous incidents in buses and even passenger cars that have much smaller containers is that the fire may be localised and weaken the container without heating the TPRD. Thus at least two TPRDs are required for longer containers, which is also tested and verified in a fire exposure test for road vehicles. Another option is to have valves (instead of the glass bulb that opens the TPRD) that release the gas triggered by fire detection, either automatically or manually, heat shields or heat guides (to TPRD), or thermal fuses wound around the container, or "linear TPRD" to ensure detection of localized fire. This is to be checked in risk assessment in the design process if a localized fire can occur. The TPRD could release in one or more directions in proximity to the container (possibly impinging on nearby containers), or in a specified direction, or via a vent mast.

3.2.2 Sprinklers or drencher systems

Sprinklers can be triggered manually or automatically in case of fire. They may offer full protection (e.g., cooling a steel plate under the containers) or partial protection, where containers are simultaneously heated by the fire and cooled by water. If the containers are partially protected, sprinklers could make it possible to release the gas at a lower rate. However, this is a question of reliability which might require the scenario that sprinklers do not work to be considered. On open deck water spray is needed according to BV and IMO rules with the same requirement as for LNG. This may also cool the TPRD and give rise to new risks. According to DNV (2024) classification rules, if a water spray system is installed for cooling and fire prevention for exposed parts of fuel containers located on open deck this system shall not interfere with the function of the heat radiation monitoring (e.g. TPRD). If the release point is close to the TPRD ignition can be assumed since the TPRD requires a fire to activate.

3.2.3 Sectioning

The storage containers may be divided into one or more sections. For instance, since Beluga24 is a catamaran with two independent hulls, the containers could be divided into two sections so that a failure or a fire in one of the sections do not affect the other section(s). On open deck this could be achieved with steel plates (possibly with sprinklers) or fire rated walls. Containers in different locations means only one fire scenario is considered. A60, i.e., a requirement for 60 min fire resistance, is required for containers indoors according to BV. For containers outdoors there is no formal way to section them. This would need to be investigated in a fire risk assessment. In the case with Beluga24 and a fire in the passenger compartment, compartmentalization of the containers may not help. The storage containers should be shielded from jet fires from the coupling(s).

3.2.4 Lightning protection

The ship and vent mast will in many cases be the highest point on the sea which means that lightning very well could hit the mast. IEC 60092-502 states that “Consideration should be given to the risk and effects of lightning attachment to high level gas or vapour vents” (p. 20). IEC 60092-401 requires lightning conductors for vent masts on composite ships (not required for steel/aluminum masts that are welded on steel/aluminum ships). While BV does not explicitly state any requirements for lightning protection or grounding (it may, however, be an outcome from the risk assessment in the approval process), DNV requires the vent mast to be grounded. CGA G-5.5 require all vent stacks to be grounded and meet the requirements of NFPA 70 National Electricity Code (and to be in accordance with NFPA 77 Recommended Practice on Static Electricity, and NFPA 780 Standard for the Installation of Lightning Protection Systems). Basically, it is required to connect all vent stacks to an engineered grounding grid. EIGA states that hydrogen vent piping and associated equipment shall be electrically grounded and bonded as required by IEC 60204-1 *Safety of machinery - Electrical equipment of machines - Part 1: General requirements* to protect against the hazards of electrical charges, stray electrical currents, static electricity, and lightning.

3.2.5 PRVs

PRVs may be needed downstream of the storage containers to protect equipment against over pressure. If the vent mast is common with storage containers, back pressure must be considered (may be better to use separate vents for this reason). PRVs are not needed for storage composite containers (road vehicles or ships). They would not be effective in the event of fire since the pressure increase in composite containers is slow and the containers will burst because the fire weakens the composite. They can either be connected to the same vent as TPRDs or another one.

3.2.6 Vent mast(s)

In this project, we will focus on the vent mast connected to the CHSS (that could be used for additional venting purposes). According to BV (2025) rules, “The venting systems are to be sized based on the maximum flow rate defined as the sum of the flow rates of hydrogen collected in the vent stack coming from all devices that could open simultaneously”. Vent masts need to work in all weather conditions such as ice, rain, wind, etc. Dispersion analysis is needed to verify that the gas does not reach ventilation inlets, evacuation areas, or other hazardous areas. In the event of fire, the fire plume and smoke are full of ignition sources so that early or late ignition may occur.

Another requirement is that the ship should be able to be evacuated during the worst scenario, i.e., jet flame or gas cloud that ignites.

The 6 m high mast and 10 m from ventilation inlet requirement comes from IGF code for LNG. However, BV (2025), for instance, does not have these figures in their rules for smaller ships they require an analysis on a case-by-case basis.

Formation of ice due to cooling from expansion needs to be considered.

3.2.7 Wind conditions or ship movement

Wind conditions or ship movement can push a hydrogen cloud sideways⁶ and different wind conditions need to be considered in dispersion analysis. Smaller ships such as Beluga24 may stop in the event of fire, while larger ships take longer time to reduce the speed and may continue or alter the set destination, depending on the situation. However, this has minor impact for modelling since wind or speed will have the same effect on the release. Usually, BV considers extreme weather cases. BV proposes to use “1F, 8D7” based on EverLoNG project⁸ analysis of weather statistics of several harbors around the world, or to use local data. But according to DNV (2024) intermediate wind (between 1 and 8 m/s) may provide larger flammable distance.

3.2.8 Deflagration and detonation in the vent pipe

According to the standard CGA G-5.5, deflagration is possible for systems with a pipe length to diameter ratio (L/D) of 60–100:1. If the L/D ratio is > 100:1, a detonation is possible. Furthermore, the standard states that the risk of deflagration or detonation is low since the geometry is simple (few turns and tie-ins) and since the operating scenarios are such that the formation of detonable hydrogen-air mixture is unlikely. The standard states that a system designed for 10 bar or more will withstand the event without rupturing (CGA 2024), on the other hand EIGA (2024) states that the detonation pressure may reach 120 bar and recommends a design pressure of at least 40 bar. In the rule notes by BV (2025) it is stated that “The venting system is to be designed to withstand the consequences of an ignition inside the vent line unless ignition within the vent is prevented for example by means of an inert gas purge or flame arrester.”.

Deflagration and detonation in the vent mast should be considered in all phases of operation e.g., before venting, at the initial venting, after venting. In a case with one or several (e.g., in a manifold) long horizontal pipelines, air (oxygen) slowly mixing with hydrogen may give rise to large pressure effects and forces on the pipelines – Something that is needed to be properly addressed.

3.2.9 Flame arrester

Flame arrestors work by the principles of thermal and chemical quenching. Thermal quenching means suppression by imposing heat loss to the flame while chemical quenching means that radicals are consumed by wall effects. If the vent mast is open to the atmosphere, without purging with an inert gas, it contains air which at the point of hydrogen release may cause an ignition in the piping. Following a release, oxygen may again enter the vent piping and mix with hydrogen. To reduce the risk(s) of an ignition in the vent piping, flame arrestors can be used. Whether it should be used or not is, however, not obvious and needs to be determined in each case. EIGA (2024) states that “vent lines shall not be fitted with flame arrestors or any other restrictions that prevent the free release of hydrogen” while BV (2025) states “The venting system is to be designed to withstand the consequences of an ignition inside the vent line unless ignition

⁶ Considering the high buoyancy of hydrogen, a downward flow is not expected.

⁷ Quiescent and 8 m/s with stability class D.

⁸ EverLoNG, D5.1.1, <https://everlongccus.eu/index.php/about-the-project/results>

within the vent is prevented for example by means of an inert gas purge or flame arrester. The use of flame arrester is to be considered in the risk assessment depending on the configuration as it prevents the free release of hydrogen.”.

4 Modelling

To compare different design alternatives of the mast outlet, a series of simulations have been performed in FLACS⁹ version 25.2 (dispersion and radiation) as well as in OpenFOAM¹⁰ version 2406 (Overpressure).

This chapter focuses on scenarios and results while more details on the technical aspects of the modelling will be presented in two planned peer-reviewed papers. The papers (open source) will be included as appendices to this report.

4.1 Release scenario

The mass flow needed for a safe venting, as well as the outlet velocity, will depend on the specific design of the hydrogen system. Since the main purpose of this study is not to quantify an exact height of a vent mast, but rather to compare different designs of outlets, the selection of release scenario is less sensitive. Therefore, a release scenario identical to that used in the “Sea Change 1” project performed by Sandia National Laboratories (Sandia, 2022) was used. The release scenario was based on ten Type-IV-containers at 250 bar(g) which each 27.8 kg of hydrogen. For more details, we refer to the report. The vent in this system has a dimension of 7” which corresponds to a diameter of 178 mm. The initial velocity is 800 m/s which then gradually decreases as the pressure in the containers reduce. To allow a fair comparison between design alternatives, the same velocity is maintained for all designs except the perforated case.

The Sandia hydrogen system design is like Beluga24 with identical pressure and number of containers, and a similar total amount of hydrogen.

Following a release, no ignition is most probable, followed by immediate ignition (probabilities range from 0.8 to 23 %), and delayed ignition (probabilities lie between 0.4 and 12 %) (Ehrhart et al., 2023).

4.2 Design alternatives

The following design alternatives were derived:

1. Single mast (Base case)
2. Two masts (one mast on each side of the ship with ½ flow in each)
3. Multiple outlet (five outlets, one straight up and four at a 45° angle upwards)
4. Perforated (1 m high cylinder with a diameter of 0.5 m with many small holes)
5. Co-flow (An annular air flow is used to reduce air entrainment into the plume. This was the final solution for the ferry Sea Change¹¹)

⁹ <https://www.gexcon.com/software/flacs/>

¹⁰ <https://www.openfoam.com/>

¹¹ [Invention at forefront of hydrogen sea change – LabNews](#) Accessed in January 2025.

6. Miter-cut (specified in CGA G-5.5; each vent mast release in two directions upwards at an 35° inclination)
7. Lambda shaped single mast

The last design, single mast with lambda-shaped outlet, is sometimes used to prevent water ingress. It was hypothesised that this design could allow for air entrainment from the lower opening. However, the amount of entrained air was minimal, see Figure 3 for visualization of the flow profile and the hydrogen mass fraction across the vent. Therefore, this design would, from a risk perspective, be the same as alternative 1, Single mast. It is therefore not treated as a specific design in this analysis.

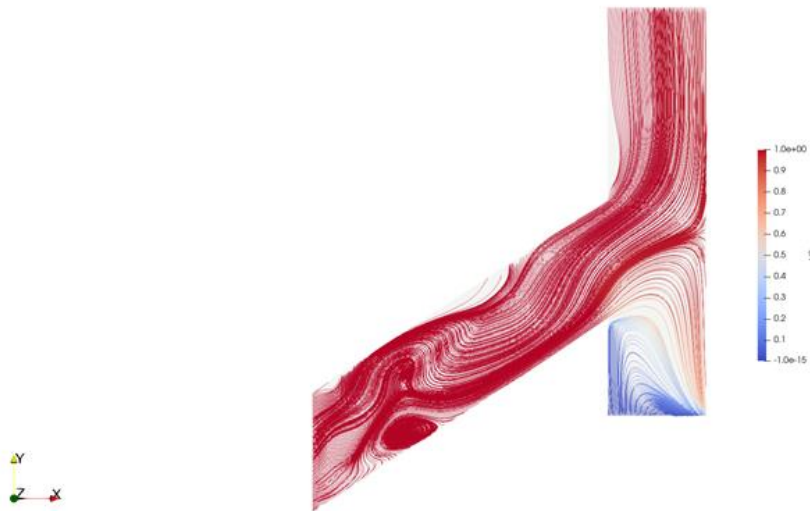


Figure 3 CFD simulation showing streamlines coloured with hydrogen concentration. The air entrainment into the downward opening of the lambda-shaped vent design is minimal.

Therefore, only the six first designs were modelled and evaluated, see Figure 4.

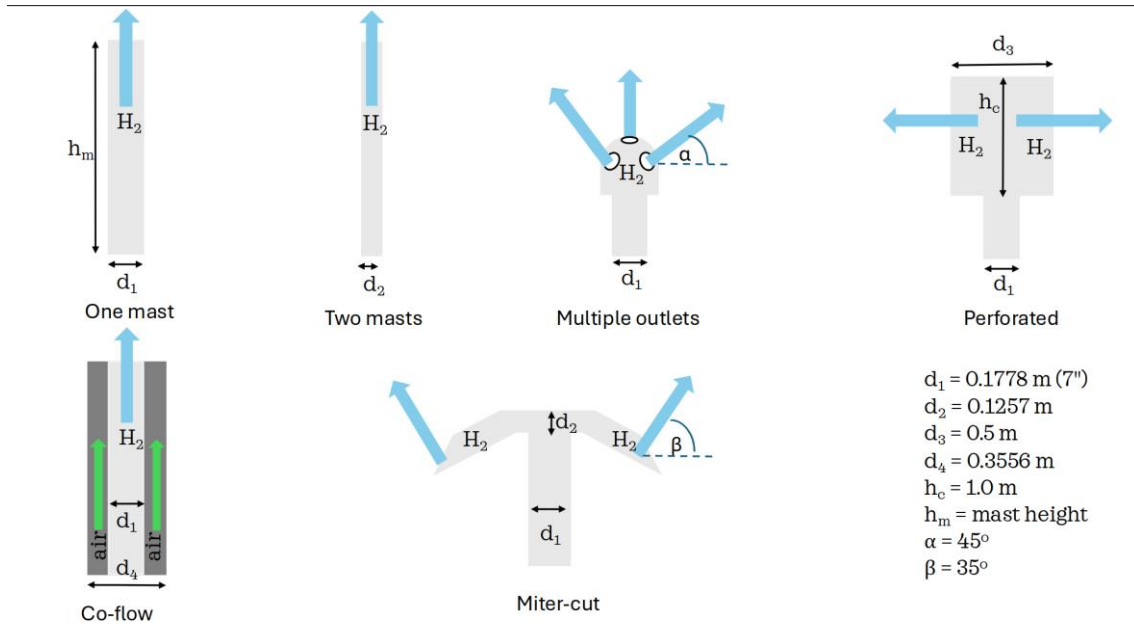


Figure 4 Illustration of the assessed mast designs.

4.3 Evaluation

4.3.1 Design scenarios

As described above, the release scenario is based on “Sea Change ver. 1” developed by Sandia (2022). In this scenario, the hydrogen is released through a 178 mm (7”) pipe with a peak velocity of 800 m/s. The velocity is then gradually decreased as the pressure in the vessels decrease. The velocity (and thereby total release area) is maintained for the different design alternatives assessed for comparative purposes.

Three outcomes from the release are assessed. Unignited release, posing a risk of flammable atmosphere at position of air intakes or people, direct ignition, exposing people and structures to heat radiation, and delayed ignition, causing overpressure.

If it is not obvious for the specific case, both a zero-wind and 8 m/s (stability class D) is simulated. The value of 8 m/s is based on recommendation from BV after an analysis of weather conditions in ports, but note that in the interview, DNV said that intermediate wind speeds can sometimes give longer flammable envelope. Ambient temperature is assumed to be 20°C.

4.3.2 Limitations

The effect of waves is not included in the analysis, and neither is variations ambient temperatures. While different wind conditions are assessed, the specific geometry of different harbours and buildings in their proximity is not considered. The effect of any wind due to speed is considered to be equal as the treated wind conditions.

Further, the effect of snow, rain and sea spray is disregarded as well as air humidity despite that water vapor absorbs infrared radiation, including that emitted by hydrogen

flames. The reason is that the study is primarily comparative which reduces the need for variation on this property since it can be expected to affect all designs similarly.

LNB and LBB containers are not included in the design scenarios. For these more inherently safe containers, the gas is only released (in a safe way) if the container material is damaged by either fire or collision. This means that power is maintained for longer. No need for vent masts or safety evaluation since the gas will be diluted or combusted near the container surface.

4.3.3 Harm criteria

For the risk assessment the harm criteria in Table 3 were used.

Table 3 Harm criteria.

Quantity	Limit	Source	Comment
Radiation	6 kW/m ²	(IACS, 2016)	For humans
	12.5 kW/m ²	(Law, 1963)	For equipment
Concentration	4%		At air intakes
Overpressure	25 kPa	(IACS, 2016)	For humans

4.4 Results

In this chapter, the results for the different designs are presented per scenario followed by a summary.

4.4.1 Direct ignition (Radiation)

Although the radiative fraction is significantly lower compared to, for example, methane (ref Schefer et al., 2006), the flame is very large, which influences both the view factor and the radiative fraction. Therefore, the radiation is high also quite far below the release point.

It should be noted that the duration of this phase is relatively short before the flame size decreases due to reduction in container pressure. This can be accounted for by specifying criteria based on heat dose, but this was not the case in any of the identified standards, instead a limit on peak radiative heat flux was employed, see Figure 5 with the single mast as an example.

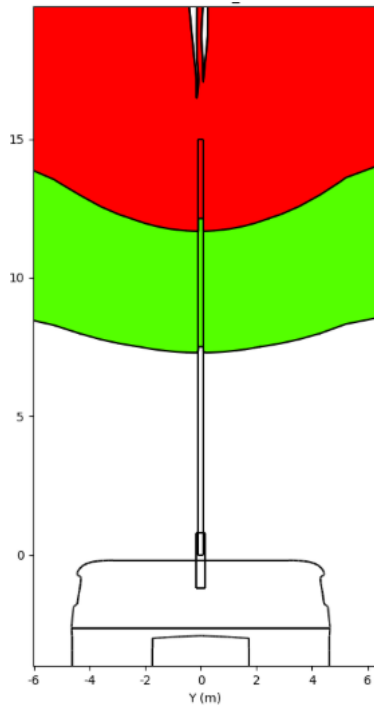


Figure 5 Example output form FLACS of 15 m single mast with contours for 6 kW/m² (green) and 12.5 kW/m² (red)

Two variations of this case were also assessed where one was a smaller nozzle with higher speed, and the second was adding a circular radiation barrier of 1 or 2 m diameter just below the nozzle. The smaller nozzle consisted of a 33% smaller area (12% smaller diameter) and thereby increasing the velocity from 800 to 1200 m/s. It was found that this only gave a 6-7% reduction in required mast height. Also, the second potential measure with radiation barrier was found to give very small (< 2m) reduction in mast height.

4.4.2 Delayed ignition (Overpressure)

The detonation cell size is a fuel specific property which can be measured experimentally. The detonation cell size is an indicator of the stability of detonation propagation within a flammable gas cloud. The used model for overpressure developed by Bauwens and Dorofeev (2019), using the detonation cell structure of the unignited cloud, determines the detonable region of the jet. This region occurs in the cloud where two conditions are met. The first condition is that the gradient of the detonation cell size in the cloud is less than 0.1 while the remaining condition is that where the first condition is met, at least 5 detonation cells can occupy the width of the jet along the transverse direction, see Figure 6 as an example for single mast. The energy release upon detonation by the mass of hydrogen in this region is assumed to contribute to the detonation pressure.

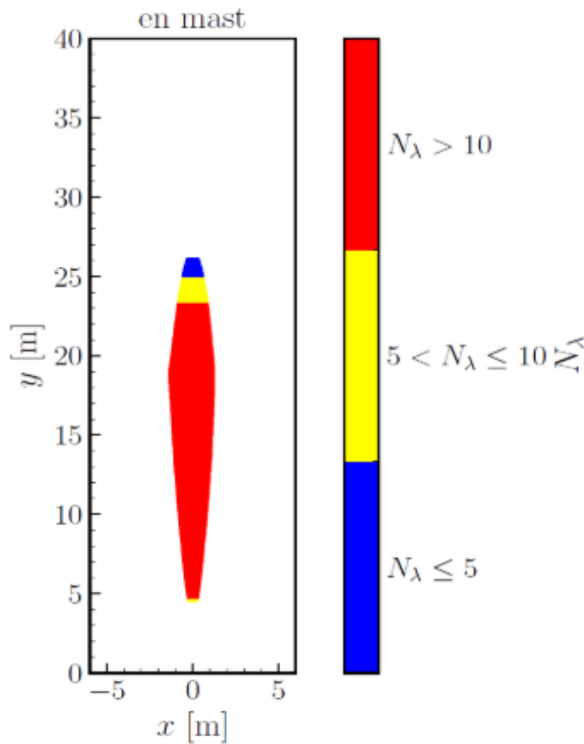


Figure 6 Number of detonation cells (N_λ) spanning the hydrogen jet. A number above five indicate possible contribution to the overpressure.

4.4.3 No ignition (Hydrogen concentration)

For dispersion, the horizontal extent of the flammable envelope is relatively constant for velocities in the range of 50 to 800 m/s, but the height above the release where this extent is found increases with increasing release velocity. For the base case, the maximum horizontal extent is approximately 25 m and the height above the outlet where this extent is found varies between 5 and 15 m with release velocities between 50 and 800 m/s, see Figure 7.

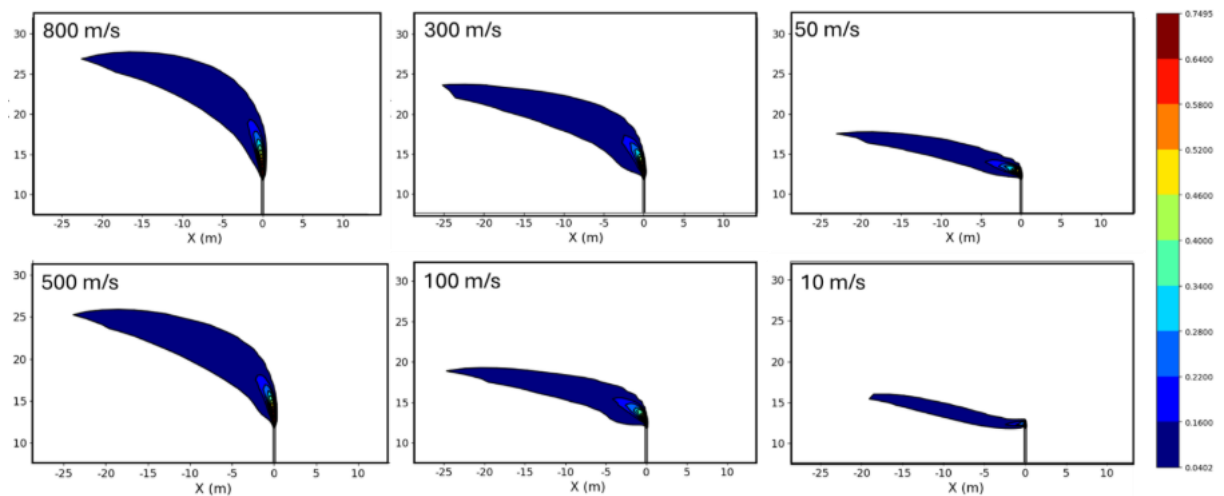


Figure 7 FLACS result showing the flammable envelope of the base case at 8 m/s cross wind for different release velocities.

Generally, it was found that single release points gave a much shorter extent of flammable envelope compared to designs with multiple outlets or with a perforated plate.

4.4.4 Summary of results

In Table 4, the vertical distance from the vent outlet to harm criteria for radiation and overpressure can be found.

Table 4 Minimum vertical distance from the vent outlet to reach criteria on radiation and overpressure.

	Radiation		Overpressure
	6 kW/m ²	12.5 kW/m ²	25 kPa
Single mast	7.7 m	3.3 m	0 m ^(a)
Two masts	5.5 m	2.4 m	0 m ^(a)
Multiple outlet	14.2 m	8.9 m	0.4 m
Perforated	13.1 m	7.4 m	10.3 m
Co-flow	7.7 m	3.3 m	0 m ^(a)
Miter-cut	14.7 m	9.6 m	1.5 m

^(a) A value of 0 m indicates that the overpressure criterium is reached above the point of release.

Besides this, the naturally buoyant hydrogen must be prevented from exposing air intakes to high concentrations of hydrogen. To achieve this, the mast needs to be far enough horizontally from air intakes as well as from recirculation zones where the hydrogen can follow the air stream downwards. The needed horizontal distance is found below.

- Single mast (base case): 25 m
- Two masts: 11 m
- Multiple outlets: 39 m
- Perforated: 2 m
- Co-flow: 30 m
- Miter-cut: 17 m

5 Discussion

Because of hydrogen's high buoyancy, vented gas generally disperses upward unless influenced by strong downward wind components. In most scenarios, hydrogen exits either horizontally, such as during low-speed venting under crosswind conditions near the end of a blowdown, or vertically when no wind is present or during high-speed

releases, where a momentum-driven jet dominates and wind effects are minimal. Consequently, consistent with previous studies (Blaylock, 2022; Van Sickle, 2025), a hemispherical exclusion zone above the vent mast is typically sufficient. Provided that the vent mast outlet is positioned higher than any air intakes, evacuation routes, or occupied areas, dispersion in non-ignition cases does not present a significant safety concern.

Modelling results indicate that jet flame length and associated thermal radiation are the primary factors determining vent mast height. Radiation is minimized in designs with a single upward-facing exit. In case of delayed ignition, this design also provides a significant distance between the most reactive parts of the jet and potential targets thereby reducing the potential consequences. This configuration also benefits radiation control: a narrow, elongated flame reduces the visible radiant area from the vessel. An attempt to further reduce radiation using a 1 m or 2 m radius shielding disc proved ineffective, as similar heat flux levels still reached exposed surfaces outside the shadowed zone. A more practical solution could involve installing a false ceiling capable of withstanding high heat flux, such as one coated with intumescent paint, to protect personnel and exterior surfaces. This approach could allow for a reduction in vent mast height, especially considering that the dynamic release intensity decreases exponentially over time.

Since venting is expected during a fire that exposes the hydrogen containers, it is unclear why radiation from the vent mast would pose a significant problem. For Beluga24, where the containers are located on the weather deck, does it really matter if radiation from the vent mast exceeds 12.5 kW/m^2 for a short duration? Moreover, if a fire occurs in the passenger compartment beneath the tanks, would there even be crew or passengers left to protect by the time the tanks vent?

Initial expectations were that the multi-outlet approach used in road vehicle TPRDs would also offer advantages in this application. However, for vent mast releases, distributing the flow through several outlets significantly increases thermal radiation exposure, as more flame surface become visible from different directions. This contrasts with the original intent behind multi-outlet TPRDs, which were developed for scenarios such as releases inside enclosed parking garages, where enhanced early dispersion helps reduce gas cloud size and associated explosion risks.

A hydrogen flame burns almost invisibly in clean air because the combustion products are mainly water vapor. It contains no soot particles to emit visible light. Its radiation spectrum is dominated by strong infrared bands from hot water vapor, which carry nearly all the radiated energy. At sea, air with high absolute humidity (the mass of water vapor per unit volume of air) absorbs a significant portion of this radiation, reducing its hazard at greater distances. In contrast, hydrocarbon flames emit strongly in the visible and near-infrared due to soot and carbon-based species, making them bright and easily detectable even at a distance. Because most of their energy lies outside water vapor absorption bands, transmission losses in humid air are minor compared to hydrogen flames. FLACS currently uses the weighted sum of gray gases model (WSGGM) developed by Yin (2013) for radiative absorption and this model is based on black-body radiation and thereby not accounting for the specific radiative spectrum of hydrogen flames. This likely leads to an underestimation of the radiative absorption since air

humidity is more efficient in absorbing the hydrogen specific spectrum rather than general black-body radiation.

6 Conclusions

- **Fire vulnerability:** High-pressure hydrogen storage containers, typically made from composite materials, are vulnerable to rupture when exposed to fire. Venting through a dedicated mast is the standard mitigation strategy on ships.
- **Design complexity:** The effectiveness and design of vent masts depend on multiple factors:
 - Fire load and ship's passive and active fire protection measures
 - Container configuration and fire resistance rating
 - Environmental conditions such as wind, icing, and precipitation
 - Operational factors such as emergency procedures, ventilation inlets, and evacuation routes
- **Regulatory emphasis:** Dispersion analysis is highlighted in IMO, BV, and DNV frameworks. However:
 - When the vent mast outlet is the highest point, hydrogen dispersion under non-ignition conditions generally poses minimal risk.
 - Radiation from an ignited release (jet flame) is the primary factor determining mast height.
 - However, it is not evident that additional radiation from the vent mast is a meaningful hazard during a fire that already threatens the hydrogen containers.
- **Modelling results:**
 - For unignited releases, the horizontal extent of the flammable envelope can be considerable regardless of release velocity and within this zone it is important to not have air intakes or wind induced recirculation zones.
 - Vertical release designs require significantly shorter mast heights to meet radiation criteria.
 - Overpressure from delayed ignition generally does not influence mast height requirements.
- **Design implications for Beluga24:**
 - Immediate ignition probability is about 10%, so jet flame scenarios must be considered.
 - Required vertical clearance for equipment is 3.3 m from the vent mast outlet for a single-mast design, and radiation criterion for human exposure is 7.7 m.
 - If personnel are expected on the weather deck, the single-mast height should be approximately 9.5 m (assuming 1.8 m human height).
 - Such mast height introduces significant design constraints, underscoring the need to balance safety requirements with practical ship design and future innovations.

7 Future Research

Further research is recommended to explore mitigation strategies and design optimizations such as:

- Investigate whether existing radiation models accurately account for **water vapor absorption**, which is particularly important for hydrogen flames due to their water-dominated emission spectrum.
- **Superstructure with intumescent paint**: Investigate whether applying intumescent paint to exposed superstructure surfaces above the hydrogen storage area could reduce thermal radiation impact and allow for shorter vent mast designs.
- **Water mist integration**: Assess the feasibility and effectiveness of introducing water mist into the hydrogen jet plume to enhance cooling and reduce flame radiation.
- **Pressure regulator** that results in a more even flow from start of venting to end to avoid the large drop in pressure and initial peak values.
- Emerging concepts such as **micro-leak-not-burst** (mLNB) containers could fundamentally alter venting requirements by eliminating large jet flames and reducing external hazards. While promising, these technologies require regulatory adaptation and validation before widespread adoption.

These topics could contribute to safer and more compact vent mast solutions.

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Appendix 1: Peer-reviewed paper on mast design alternatives

[The full text of the paper will be added after it is published]

Appendix 2: Peer-reviewed paper on method for overpressure quantification

[The full text of the paper will be added after it is published]

Appendix 3: Road vehicles

Introduction

Type 3 and increasingly Type 4 containers are used for road vehicle hydrogen storage and other weight sensitive transport modes. Type 5 linerless composite containers are referred to in literature and prototypes are under development, however, at present the concept has not been developed sufficiently for production batches and road vehicle hydrogen storage. The concept was to have been included in a stationary storage standard but will not be included at present.

The original European hydrogen road vehicle type-approval regulations (EU79/2009 & 406/2010, now withdrawn) were developed by taking into account the specific hazards of hydrogen and the experience gained from CNG vehicles including:

- Rupture of CNG containers due to corrosion and chemical abuse
- In CNG service thermally activated or temperature triggered pressure relief devices (TPRD) sometimes failed to vent properly during a fire
- TPRD's had not provided container fire protection under all conditions of fire exposure, such as during exposure to localised fires. (A localised fire may impinge on a container at some distance from the TPRD increasing the internal gas pressure while simultaneously degrading the structural integrity, but not causing the TPRD to trigger.)

The aim of EU79/2009 and 406/2010 was to provide a European type-approval route allowing low number demonstration or small production series hydrogen road vehicles to be placed safely on the public road. In some countries, the absence of a legal requirement against which to grant an approval for a road vehicle with new technology may prohibit the testing of that vehicle on the public road. It should be noted that in Sweden prototype vehicles demonstrating new technologies can be put on the road using the so-called manufacturer's "green plates" (saluvagnslicens) where internal approval is sufficient. As well as providing harmonized European type approval requirements, the two regulations initiated a move from traditional prescriptive based vehicle fuel system regulation, towards a more performance-based approach. For example, type approval moved from type approval of every component in a system as was common for CNG systems, to a focus on type approval of critical components and system level tests. This transition was completed with the adoption of UN ECE GTR13 for hydrogen road vehicles and the transposed type-approval regulation UN ECE R134 which was adopted within the European Union and elsewhere including for example Japan, Korea and Australia.

TPRD development

Gambone (2007) offers an overview for how safety of compressed gas tanks in road vehicles (initially CNG, methane) have evolved. Initially, in the 1980s, they were not equipped with any pressure relief device at all. Then a burst disc or reclosing pressure

relief valve (PRV) was introduced, which, however, were prone to failures. The thermally triggered (temperature activated) pressure relief device (TPRD) was introduced in the 1990's and were initially also prone to failures and premature activation which prompted the performance-based standard (ANSI/IAS PRD 1) for TPRDs in 1998. Since then, the number of unintended releases have decreased dramatically.

All hydrogen vehicle regulations have sought to avoid container rupture. Early hydrogen road vehicle TPRD were intended to avoid container rupture by relieving the pressure in a container as fast as possible, but in doing so increasing the potential fire load outside of the system. More recently, research has looked at ways of mitigating the potential effects of the discharged hydrogen by, for example, dispersion heads on the vent outlet, different release orientations, or elimination of the TPRD through use of the mLNB concept.

While regulations require a TPRD they do not prohibit other fire protection measures for the containers such as thermal insulation around the containers, e.g. intumescent paint, or thermal fuses coiled around the container which can act as remote triggers to TPRD.

Pressure vessel explosions have occurred for CNG vehicles without the TPRD release the gas as intended. This has partly been attributed to a local fire exposure that weakens composite tank material without reaching or triggering the TPRD (Lowell 2013). For such a scenario a PRV will not work either since the pressure increase is marginal. Scheffler et al. (2011) proposed to add a 10 min localized fire for H₂ vehicles that was later included in the Global Technical Regulation for hydrogen road vehicles (UN ECE GTR13). However, Molkov (2023) argues that the specified localised fire heat release rate per unit area is too low so that a real more powerful localized fire still may rupture a type-approved/certified tank within 10 min of localised fire exposure. Current hydrogen vehicle regulations and standards adopt a 2-stage localised fire followed by engulfing fire performance test.

One of the main weaknesses of TPRD is that they are point sensors mounted on one or both of the domed ends of a cylindrical container, but have to protect containers that may significantly exceed 1m in length. Regulations require one TPRD, but the CHSS has to pass the appropriate localised and engulfing fire test meaning that additional TPRD or fire protection measures may be necessary. Regulations and standards have become performance based to encourage innovation, and any container fire protection system must satisfactorily fulfil the required test conditions, e.g. not rupture in the specified fire conditions time. In other words, there are no prescriptive requirements on the number of TPRD required on a container. Furthermore, a full type-approval is only granted for a specific "compressed hydrogen storage system" (CHSS) with a specific container, primary closures including TPRD function, and any container attachments offering additional protection that has successfully passed the "verification test for service terminating performance in fire". The latest road vehicle regulation applicable in the EU, UN ECE R134 Rev.1 Amend.3 (R134) defines the following:

§2.5 defines "Container Attachments" as *"non-pressure bearing parts attached to the container that provide additional support and/or protection to the container and that may be only temporarily removed for maintenance and/or inspection only with the use of tools."*

§2.24 defines "Thermally-activated pressure relief device (TPRD)" as meaning "*a non-reclosing PRD that is activated by temperature to open and release hydrogen gas*",

§2.28 defines "Pressure relief device (PRD)" as "*a device that, when activated under specified performance conditions, is used to release hydrogen from a pressurized system and thereby prevent failure of the system*". The latest road vehicle regulation applicable in the EU (UN ECE R134 Rev.1 Amend.3) requires that a primary closure device incorporating the function of a TPRD is mounted directly on or within each container (§5, Part I, (a) & (b)).

In §5.4 "*Verification test for service terminating performance in fire*" it is the CHSS that is tested and approved, i.e. container, primary closures incorporating TPRD function and container attachments (if any). The CHSS is filled to 100 per cent state-of-charge (SOC), (i.e. NWP at 15 °C) with compressed hydrogen and undergoes a specified two-stage localised and engulfing fire test. In order to be approved the CHSS must meet the following conditions:

"The CHSS shall vent to less than 1 MPa within 1 hour for vehicles of categories M1 and N1 or within 2 hours for vehicles of categories M2, M3, N2 and N3. If venting occurs from TPRD(s), the venting shall be continuous. The container shall not rupture during the CHSS fire test. Except for discharges from the exhausts of TPRD vents, any leakage, permeation, or venting from the CHSS, including through the container walls or joints, other components, and fittings, shall not result in jet flames greater than 0.5 m.

If the container pressure has not fallen below 1 MPa when the time limit defined above is reached, then fire testing is terminated and the CHSS fails the fire test (even if rupture did not occur)."

Approval is granted if the container does not rupture and the CHSS pressure is reduced to less than 1MPa in the specified time. Depressurisation need not occur via the TPRD, but in that case any jet flames shall not exceed 0.5m,

The latest version of GTR13 and R134 still have an engulfing burner length of approximately 1.65m. The 1.65m long fire source is a standard length in CNG and hydrogen regulations and standards. This fire length is derived from a US DOT fire test developed in the 1970s for application to composite air-breathing cylinders of relatively small size [https://rosap.nhtl.bts.gov/view/dot/34572/dot_34572_DS1.pdf].

The recently approved ISO/FDIS 19881:2025 §13 requires that containers are protected from rupture in a fire situation by one or more thermally-activated pressure relief device(s) that passes the specified localised/ engulfing fire test (§17.3.8). Additionally, alternative configurations may be allowed in installation standards if they can demonstrate adequate levels of safety. Also, to optimise safety vehicle manufacturers may specify additional TPRD locations for specific vehicle installations. The approval requirements are similar to R134. In summary at least one TPRD must be fitted as part of a road vehicle CHSS in the EU, and during the fire test the container must not rupture and must vent to less than 1MPa (R134 specifies a time limit in which venting must take place, ISO FDIS 19881 does not), TPRD discharges must be continuous when triggered, and any other mode of discharge during the test must not result in a flame longer than 0.5m.

For road vehicles recent research points to reducing the outlet diameter of TPRDs to reduce the risks related to hydrogen releases in enclosures such as car parks. Then the fire resistance rating (FRR) of the tank needs to be taken into consideration, so that the tank does not rupture. The *FRR* is defined as the time to rupture of the tank in a fire without a TPRD. The *FRR* is a function of the fire intensity, the heat release rate per unit area (*HRRPUA*). According to Molkov (2023) the *FRR* is saturated for *HRRPUA* above 1 MW/m² to 4-6 min for most type 4 tanks. For the car park scenario considered a 10-point release at a 45° angle downwards gave the overall best result.

A solution advocated by Molkov (2023) to deal with fire exposed tanks is to use “explosion free in fire self-venting (TPRD-less) composite tanks” (Molkov et al., 2023 & 2024), also called micro-leak-not-burst (mLNB), tanks.

TPRD Vent Requirements

Typical road vehicle TPRD vents currently use metal tubes to direct the TPRD discharge towards the outside of the vehicle envelope, with simple caps protecting against the ingress of dirt or water and that can be easily blown off by the discharge. One question that has been discussed in vehicle regulatory forums for many years is if there should be requirements on the direction(s) of discharge from the TPRD vents. Earlier regulations had restrictions on discharge directions from TPRD vents to:

- Provide a known safe approach path for emergency responders to a vehicle
- A safe exit route from vehicles, and especially buses
- Protect other road users and adjoining buildings from potentially harmful discharges/jet fires directly
- Avoid discharges forming hazards within the vehicle envelope

Restrictions on discharges beyond the vehicle have been removed in more recent regulations, leaving only guidance in some. Detailed directional requirements are provided for appropriate regulations and standards in Appendix 1. The current requirements in the EU (from UN ECE R134, Rev.1, Amend. 3) are as follows:

"7.1.3.1. Pressure relief systems (Annex 5, paragraph 6. test procedure)

(a) The outlet of the vent line, if present, for hydrogen gas discharge from TPRD(s) of the CHSS shall be protected from ingress of dirt and water (e.g. by a cap);

(b) The hydrogen gas discharge from TPRD(s) of the CHSS shall be directed such that the hydrogen exhaust does not impinge upon:

(i) enclosed or semi-enclosed spaces;

(ii) any vehicle wheel housing;

(iii) hydrogen gas containers;

(iv) the vehicle's REESS “ [battery pack(s)]

UN ECE R134, Rev.1, Amend. 3 requirements are identical to UN ECE GTR13 Amend.1, however, GTR13 also includes recommendations in the rational (point 123) which are not included in R134:

“Horizontal discharge, i.e., parallel to the road surface, should be avoided in order to protect first responders, other road users and adjoining buildings from potentially harmful ignited discharge directly. Vertical discharge direction should consider potential releases in tunnel and underground car parking garages. In addition, it is recommended to not direct the TPRD towards any exits of buses to avoid hindering passengers from leaving the vehicle in case of a breakdown or accident.”

The latest version of ISO standard 19881, currently ISO/FDIS 19881: 2025, and as with previous versions, is a component approval standard and does not address installation issues such as TPRD vent considerations.

ISO 19882: 2025 is a component standard and does not contain requirements on handling discharges from TPRD, however, it does contain recommendations on the “pressure relief device discharge vent system routing” (§A4.3.3) which are similar to SAE J2578 below, and recommends against discharges towards the front of the vehicle, while minimising risk to humans inside and outside the vehicle, or the progression of hazards within the vehicle or surroundings.

The previous version of SAE J2578 201408 provides recommendations summarised as follows:

§4.2.5 Indicates that hydrogen discharges following an accident or fault should be vented to the outside of the vehicle passenger, luggage, and cargo compartments, and the placement and direction of vent flows should minimise exposure to humans inside and outside the vehicle, or the progression of hazards within the vehicle or surroundings.

Appendix E gives further guidance on directing the flow of hydrogen recommending the minimisation of risk to both occupants or people outside the vehicle, as well reducing the risk of progression of hazards within the vehicle or its surroundings. The PRD discharge should not be directed into or toward the passenger or luggage compartment, into or toward wheel housings, toward hydrogen storage systems, or toward the front of the vehicle. Furthermore, the design and installation should minimise the risk from external hazards resulting from activation, e.g., projectiles.

In the current version of J2578_202301 §4.2.5 and Appendix E have been revised to ensure that discharges from CHSS in enclosed spaces of a vehicle are properly managed and directed.

In summary, requirements and recommendations from regulations and standards for road vehicle TPRD vents recommends against discharges towards the front of the vehicle to give a safe approach path, while minimising risk to humans inside and outside the vehicle, or the progression of hazards within the vehicle or surroundings.

The following sections provide extracts or detailed summaries of requirements from regulations and standards related to the venting of road vehicle TPRD.

EU Regulation 79/2009 (WITHDRAWN)

In relation to TPRD Vent Requirements the following requirements apply to all container types:

Annex IV, cl.2 *“test procedures to be applied for the type-approval of hydrogen containers designed to use compressed (gaseous) hydrogen must include: ...*

(d) Bonfire test: the purpose of the test is to provide evidence that the container with its fire protection system does not burst when tested under specified fire conditions. The container, pressurised to working pressure, must only vent through the pressure relief device and must not rupture.”

Annex VI , cl. 12, *“In the event of an accident, it must be ensured so far as is reasonably practicable that the pressure relief device and the associated venting system remain capable of functioning. The venting system of the pressure relief device must be adequately protected against dirt and water.”*

EU Implementing Regulation 406/2010 (WITHDRAWN)

Annex IV, Part 1

cl. 1.6: *“All pressure relief devices, other safety components and vent lines shall be protected against unauthorised interference so far as reasonably practicable.”*

“cl. 5. PRESSURE RELIEF DEVICE(S)

5.1. For the purposes of containers designed to use compressed (gaseous) hydrogen, a pressure relief device shall be a non-reclosing thermally activated device that prevents a container from bursting due to fire effects.

5.2. A pressure relief device shall be directly installed into the opening of a container or at least one container in a container assembly, or into an opening in a valve assembled into the container, in such a manner that it shall discharge the hydrogen into an atmospheric outlet that vents to the outside of the vehicle.

5.3. It shall not be possible to isolate the pressure relief device from the container protected by the pressure relief device, due to the normal operation or failure of another component.

5.4. The hydrogen gas discharge from pressure relief device shall not be directed:

(a) towards exposed electrical terminals, exposed electrical switches or other ignition sources;

(b) into or towards the vehicle passenger or luggage compartments;

(c) into or towards any vehicle wheel housing;

(d) towards any class 0 component;

(e) forward from the vehicle, or horizontally from the back or sides of the vehicle.

5.5. The internal dimensions of the vent shall not impede the function of the pressure relief device.

5.6. The vent of the pressure relief device shall be protected against blockage, e.g. by dirt, ice, and ingress of water, so far as is reasonably practicable.

5.7. The outlet of the pressure relief device shall be orientated such that if the vent becomes detached from the pressure relief device, the resulting gas flow does not impinge directly on other containers or container assemblies unless they are protected.”

In summary, Cl. 5.4 e) was intended to provide a known, safe approach path to the vehicle in the event of an incident. Cl. 5.5 was required as, at the time of writing of the 406/2010, it was considered that avoiding container rupture was more important than restricting venting either unintentionally or intentionally to limit the external fire load.

UN ECE GTR13 (Original Version)

The original version of GTR13 dated 19th July 2013 was based on a global rethink of hydrogen vehicle regulations based on the latest global research and existing regulatory texts Europe, Japan and the USA. It also represented a move towards performance based requirements.

Requirement

“5.2.1.3.1. Pressure relief systems (para. 6.1.6. test procedure)

(a) Storage system TPRDs. The outlet of the vent line, if present, for hydrogen gas discharge from TPRD(s) of the storage system shall be protected by a cap;

(b) Storage system TPRDs. The hydrogen gas discharge from TPRD(s) of the storage system shall not be directed:

(i) Into enclosed or semi-enclosed spaces;

(ii) Into or towards any vehicle wheel housing;

(iii) Towards hydrogen gas containers;

(iv) Forward from the vehicle, or horizontally (parallel to road) from the back or sides of the vehicle.”

Rationale

The Requirements of GTR13 were largely carried over from the earlier European regulations with some adjustments to the precise wording. The specific rationale to para. 5.2.1.3.1 (rationale no.78) refers only to point a) and the need for a protective cap.

UN ECE R134 (Original version)

UN ECE R134 is the transposed type approval version of UN ECE GTR 13 and which was adopted within the European Union. It was published in the Official Journal of the European Union on 17th May 2019. It has since been replaced by a new version of R134 (Rev.1, Amend.3) based on GTR13 Amend.1.

“7.1.3.1. Pressure relief systems (Annex 5, paragraph 6 test procedure)

(a) Storage system TPRDs. The outlet of the vent line, if present, for hydrogen gas discharge from TPRD(s) of the storage system shall be protected by a cap;

(b) Storage system TPRDs. The hydrogen gas discharge from TPRD(s) of the storage system shall not be directed:

(i) Into enclosed or semi-enclosed spaces;

(ii) Into or towards any vehicle wheel housing;

(iii) Towards hydrogen gas containers;

(iv) Forward from the vehicle, or horizontally (parallel to road) from the back or sides of the vehicle.

UN ECE GTR13, Amend.1

In the latest version of UN ECE GTR 13, i.e. Amend.1 dated 21st June 2023, the directional restrictions on TPRD vents have been removed from the regulatory text, and replaced by the text below. However, the rationale to the requirement (para. I. D. 2. (a) (iii) a. 123, see page 52 of the GTR) includes directional recommendations. The wording of the requirement has also been changed from “...shall not be directed:” to “...shall not impinge upon...” in effect removing all directional restrictions so long as the hydrogen does not make contact with the specified locations.

Requirement

“5.2.1.3.1. Pressure relief systems (para. 6.1.6. test procedure)

(a) The outlet of the vent line, if present, for hydrogen gas discharge from TPRD(s) of the CHSS shall be protected from ingress of dirt and water;

(b) The hydrogen gas discharge from TPRD(s) of the CHSS shall be directed such that the hydrogen exhaust does not impinge upon:

(i) enclosed or semi-enclosed spaces;

(ii) any vehicle wheel housing;

(iii) hydrogen gas containers;

(iv) the vehicle’s REESS.”

Rationale

“123. The vent line of storage system discharge systems (TPRDs and PRDs) should be protected to prevent blockage by intrusion of objects such as dirt, stones, and freezing water. Horizontal discharge, i.e., parallel to the road surface, should be avoided in order to protect first responders, other road users and adjoining buildings from potentially harmful ignited discharge directly. Vertical discharge direction should consider potential releases in tunnel and underground car parking garages. In addition, it is recommended to

not direct the TPRD towards any exits of buses to avoid hindering passengers from leaving the vehicle in case of a breakdown or accident.”

UN ECE R134, Rev.1, Amend.3

A new version of R134 (Rev.1, Amend. 3) dated 27 September 2024 was transposed from GTR13 Amend.1. As with the new version of GTR13, directional restrictions outside of the vehicle are effectively removed.

Requirement

“Paragraphs 7.1.3.1., amend to read:

7.1.3.1. Pressure relief systems (Annex 5, paragraph 6. test procedure)

(a) The outlet of the vent line, if present, for hydrogen gas discharge from

TPRD(s) of the CHSS shall be protected from ingress of dirt and water

(e.g. by a cap);

(b) The hydrogen gas discharge from TPRD(s) of the CHSS shall be

directed such that the hydrogen exhaust does not impinge upon:

(i) enclosed or semi-enclosed spaces;

(ii) any vehicle wheel housing;

(iii) hydrogen gas containers;

(iv) the vehicle’s REESS.”

ISO/FDIS 19881:2025

The latest version of ISO standard 19881 and as with previous versions, is a component approval standard and does not address installation issues such as TPRD vent considerations.

ISO 19882:2025

ISO 19882: 2025 is a component standard and does not contain requirements on handling discharges from TPRD, however, it does contain recommendations on the “pressure relief device discharge vent system routing”, see Annex A, para. 4.3.3, which are similar to SAE J2578 below, and recommends against discharges towards the front of the vehicle, while minimising risk to humans inside and outside the vehicle, or the progression of hazards within the vehicle or surroundings.

SAE J2578

The previous version of SAE J2578 201408 provides recommendations summarised as follows:

§4.2.5 Indicates that hydrogen discharges following an accident or fault should be vented to the outside of the vehicle passenger, luggage, and cargo compartments, and the placement and direction of vent flows should minimise exposure to humans inside and outside the vehicle, or the progression of hazards within the vehicle or surroundings.

Appendix E gives further guidance on directing the flow of hydrogen recommending the minimisation of risk to both occupants or people outside the vehicle, as well reducing the risk of progression of hazards within the vehicle or its surroundings. The PRD discharge should not be directed into or toward the passenger or luggage compartment, into or toward wheel housings, toward hydrogen storage systems, or toward the front of the vehicle. Furthermore, the design and installation should minimise the risk from external hazards resulting from activation, e.g., projectiles.

In the current version of J2578_202301, §4.2.5 and Appendix E have been revised to ensure that discharges from CHSS in enclosed spaces of a vehicle are properly managed and directed.

Appendix 4: DNV Rules for classification

According to “DNV’s rules for classification, Part 6 Additional class notations, Chapter 2 Propulsion, power generation and auxiliary systems”, following is required for the vent mast system and other selected parts of the hydrogen system (DNV 2024):

- Compressed hydrogen tanks shall be provided with a suitable pressure-relief device, taking into account the design and construction of the tank.
- Fuel containment systems shall be located in such a way that the risk of excessive heat input from a fire is minimized.
- Adequate means shall be provided to depressurize the tank in case of a fire which can affect the tank. This may include temperature-actuated safety relief systems, e.g. thermal pressure relief devices. The relieving capacity and area of the safety relief devices shall be designed and calculated to ensure the rated capacity.
- Hydrogen fuel tanks shall be provided with a pressure relief system appropriate to the design of the fuel containment system, and connected to a vent mast system complying with requirements in this chapter. Pressure control systems specified in [4.7.1] shall be independent of the pressure relief systems.
- In the vent piping system, means for draining water from places where it may accumulate shall be provided. The PRVs and piping shall be arranged so that water under no circumstances can accumulate in or near the PRVs.
- Each gas cylinder shall be fitted with at least one pressure relief valve or emergency relief valve and be connected to the vent mast. Controlled blow-down shall be possible from a safe location.
- Gas cylinders shall be fitted with heat radiation monitoring (e.g. TPRD) that automatically prevents overpressure in case of external fire.
- The pressure relief devices shall be capable of fully venting the cylinder content, also during emergency venting scenarios. Multiple cylinder arrangement shall be possible to be vented simultaneously
- during a controlled blow-down- or emergency venting scenario.
- The vent mast shall have a design pressure not less than 20 bar.
- The design loads and temperature effects used for the design of the venting system and vent mast shall be documented in the pipe stress analysis.
- The vent mast outlet/PRV outlet shall be located at least 10 m from nearest air intakes, air outlets or openings to accommodation spaces, service spaces, and control stations, or other non-hazardous area, exhaust outlet from machinery or from furnace installation. Hydrogen gas dispersion analysis is to be carried out in order to be able to adequately size and determine the location of the vent mast.
- The pressure relief system/vent mast exits shall be arranged to safely disperse any release. The consequences of igniting released hydrogen shall be assessed (i.e. thermal radiation and fire impingement) in the qualitative risk assessment. The vent mast height shall be sufficient to prevent thermal radiation from affecting the personnel, life-saving equipment, fuel containment system, and structures onboard.
- The location of outlet from the pressure relief valves/vent masts shall be determined based on hydrogen gas dispersion analysis. The outlet shall be

located at least $B/3$ or 6 m, whichever is greater, above the weather deck and 6 m above the working area and gangways, where B is the greatest moulded breadth of the vessel in meters.

Guidance note: For vessels with length $L < 90$ m, and vessel types where the operation limits the possible location of the outlet, lesser heights than explicitly given above may be accepted.

- Suitable protection screens shall be fitted on vent outlets to prevent the ingress of foreign objects without adversely affecting the flow. The suitability shall be verified in the CFD analysis.
- The outlet from the pressure relief valves shall be so constructed that the discharge will be unimpeded and be directed vertically upwards at the exit. The outlets shall also be arranged to minimize the possibility of water or snow entering the vent system.
- Condensate drains are required on all hydrogen vent masts subject to cold vapours. Drip trays made of low-temperature materials may be permitted to prevent brittle fracture caused by liquid air formation.
- Flammable concentrations may lead to DDT in vent masts of sufficient length. The ratio diameter/length shall be designed to prevent that occurrence by design.
- The vent mast shall be designed to minimize the risk of self-ignition in the vent line.

Guidance note: Molecular seals in combination with inert gas supply to prevent air ingress at the vent mast outlet may be considered.

- Vent masts shall be grounded to prevent build up of static electricity.
- The pressure relief system and vent masts shall be designed and constructed to prevent blockage due to condensation or ice.
- A water spray system shall be installed for cooling and fire prevention to cover exposed parts of fuel tanks located on open deck.
- If a water spray system is installed for cooling and fire prevention of exposed parts of fuel tanks located on open deck this system shall not interfere with the function of the heat radiation monitoring as given in [5.2.4.3]. Release of the water spray system shall not be possible before the heat radiation monitoring (e.g. TPRD) is activated.
- The sizing of the vent pipe system shall comply with Pt.5 Ch.7 Sec.8 [4.2]:
 - 4.2: Pressure losses upstream and downstream of the PRVs, shall be taken into account when determining their size to ensure the flow capacity required by [4.1].
 - 4.1: PRVs shall have a combined relieving capacity for each cargo tank to discharge the greatest of the following, with not more than a 20% rise in cargo tank pressure above the maximum allowable relief valve setting.

Appendix 5: BV Rules for classification

According to “BV’s rules for classification of hydrogen-fuelled ships (NR678 – April 2025) following is required for the vent mast system and other selected parts of the hydrogen system (BV 2025):

- The layout of equipment is to be such that escape routes are not impacted from potential jet fires.
- Each pressure relief device on the hydrogen system and each hydrogen vent outlet is to be connected to a venting system.
- Relief valve sizing is to be undertaken for the most onerous scenario due to fire or due to loss of insulation.
- Individual cylinders are to be equipped with pressure relief devices designed to prevent the entry of foreign matter, the leakage of hydrogen and the development of any dangerous excess pressure. Pressure relief devices are to be connected to the ship fixed venting system. Composite cylinders are to be fitted with a TPRD.

Note: Pressure relief devices may be fitted for a group of cylinders subject to the satisfaction of the Society.

- For composite cylinders, the design of the containment and venting system is to ensure that, in case of exposure to external fire, the stored hydrogen is safely discharged before the cylinders burst. The total amount of hydrogen that can be discharged and the corresponding discharge time is to be verified in the risk assessment and based on: a) The worst-case scenario in terms of exposure of tanks to external fire (in particular whether local or engulfed fire applies) as determined in the risk assessment; b) The performance of the cylinders and associated pressure relief device (taking into account the results of the fire resistance test; and c) The routing and design of the venting system (e.g. pressure drop calculation).
- Venting systems are to be so constructed that the discharge will be unimpeded and be directed vertically upwards at the exit. The outlets are also to be arranged to minimize the possibility of water or snow entering the vent system. Distance from vent exits to non-hazardous areas and to openings to non-hazardous spaces is to be determined by a gas dispersion analysis.
- The venting system is to be designed to withstand the consequences of an ignition inside the vent line unless ignition within the vent is prevented for example by means of a inert gas purge or flame arrester. The use of flame arrester is to be considered in the risk assessment depending on the configuration as it prevents the free release of hydrogen.
- Where vents are grouped together, the design of the arrangement is to take into account potential for mis-directed flow, dead-ends and multiple vents operating simultaneously. Different vent stacks are recommended when the operating conditions are different (e.g. difference of pressure or temperature).
- In the venting system piping, means are to be provided for draining liquid, including water from condensation, from places where it may accumulate. The

pressure relief devices and piping are to be arranged so that liquid can, under no circumstances, accumulate in or near the pressure relief devices. Draining pipe discharging to the deck may be accepted provided it is fitted with a self-closing valve and a manual shutoff valve.

- The venting systems are to be sized based on the maximum flow rate defined as the sum of the flow rates of hydrogen collected in the vent stack coming from all devices that could open simultaneously.
- Openings leading to or leaving from a vent or pressure relief device are not to be obstructed in a way which could restrict or cut off the flow from the element to that device. The opening through all piping and fittings is to have at least the same flow area as the inlet of the pressure relief device to which it is connected. The nominal size of the discharge piping is to be at least as large as that of the pressure relief device outlet.
- Pressure losses upstream and downstream of the PRVs, are to be taken into account when determining their size to ensure the flow capacity.
- The pressure drop in the vent line from the tank to the PRV inlet is not to exceed 3% of the valve set pressure at the calculated flow rate.
- Where common vent headers and vent masts are fitted, calculations are to include flow from all attached PRVs that can open simultaneously. This maximum pressure drop from the PRV outlet to the location of discharge to the atmosphere, and including any vent pipe interconnections is generally not to exceed 10% of the lowest set pressure of all the relief valves which can open at the same time, and is not to exceed the maximum back pressure specified for any of these relief valves. Alternative values provided by the PRV manufacturer may be accepted.
- A water spray system is to be installed for cooling and fire prevention to cover exposed parts of fuel storage tank(s) located on open deck.
- The system is not to spray water directly on the valves of the hydrogen safety systems (e.g. valves associated to the pressure relief system). Alternatively, such valves are to be equipped with protection from water spray system.

Appendix 6: Stationary Storage Vent & Fire Requirements

Stationary hydrogen storage systems, as the name suggests, are used for the permanent storage of hydrogen at a specific location, without moving the system during its normal operation. Transportable hydrogen storage systems are intended for the transport of hydrogen from one place to another, e.g. from a production site to a consumer site. Transportable storage systems should not be confused with hydrogen storage systems for transport applications where the hydrogen is used as a fuel on-board the vehicle (see §2.3).

In the European Union (EU), the legal requirements for both stationary and transportable pressure equipment included compressed gaseous hydrogen storage systems, are defined by EU Directives. An EU Directive sets goals that member states must achieve, but they are free to decide their own laws on how to achieve them [https://european-union.europa.eu/institutions-law-budget/law/types-legislation_en]. In contrast, an EU Regulation, on the other hand, is a binding legal act that all EU countries must apply in its entirety, and this for example is often used for road vehicle legal requirements. Compliance with European or national legal requirements is mandatory when they apply to a specific product or service in a specific market that is within the scope of the legal requirement.

Compliance with standards, whether they be International such as ISO or IEC, or national such as SIS or DIN, is voluntary unless compliance is specifically referred to in a legal requirement. In Europe, a harmonised standard is a European standard developed by a recognised European standardisation organisation: CEN, CENELEC or ETSI [https://single-market-economy.ec.europa.eu/single-market/goods/european-standards/harmonised-standards_en?ettrans=sv&prefLang=sv]. However, international standards may also be recognised as a European standard, e.g. with the “EN ISO” prefix. Compliance with harmonised standards gives a presumption of conformity with the corresponding technical requirements specified in the relevant Directive. References to harmonised standards must be published in the Official Journal of the European Union (OJEU). As with international or national standards, the use of harmonised standards is voluntary, and another solution may be used to demonstrate conformity with the mandatory legal requirements. In the context of certain EU Directives or Regulations, voluntary European standards supporting the implementation of legal requirements are not called ‘harmonised standards’.

In the EU, hydrogen pressure equipment is within the scope of the Pressure Equipment Directive 2014/68/EU (PED) [https://single-market-economy.ec.europa.eu/single-market/goods/european-standards/harmonised-standards/pressure-equipment_en?prefLang=sv]. The Simple Pressure Vessels Directive 2014/29/EU (SPVD) does not apply to pressure vessels used to contain hydrogen.

The Swedish implementation of the PED is published by the Swedish Work Environment Authority (Arbetsmiljöverket) as regulation (föreskrifter) AFS 2023:5 (replaced AFS 2016:1). [<https://www.av.se/arbetsmiljoarbete-och->

[inspektioner/publikationer/foreskrifter/afs-20235/](#)]. The regulations apply to the design, manufacture and assessment of conformity for pressure equipment and assemblies with a maximum permissible pressure higher than 0.5 bar. 2 n)§ excludes ships from the scope. 2.12§ deals with external fire: “*Where necessary, pressure equipment must be designed and, where appropriate, equipped with appropriate accessories or prepared to be equipped with such accessories to meet the requirements for damage limitation in the event of an external fire, taking into account in particular the intended use of the equipment.* [Translation]”.

A summary of references to harmonised standards published in the Official Journal of the European Union for Directive 2014/68/EU (PED) [<https://ec.europa.eu/docsroom/documents/64634>]. The list does not contain any standards with hydrogen in the title, nonetheless many of the standards may be applicable to stationary hydrogen storage systems. The Swedish/ European standard series SS-EN 13445 (Unfired Pressure Vessels) are harmonised standards for PED. More relevant to this work is the PED harmonised Swedish/European/ International standard series SS-EN ISO 4126 (Safety devices for protection against excessive pressure) and in particular the following:

- SS-EN ISO 4126-1:2013 “*Safety devices for protection against excessive pressure - Part 1: Safety valves*”: Applicable to safety valves having a flow diameter of 6 mm and above which are for use at set pressures of 0.1 bar gauge and above.
- SS-EN ISO 4126-2:2019 “*Safety devices for protection against excessive pressure - Part 2: Bursting disc safety devices*”: Specifies the requirements for bursting disc safety devices.
- SS-EN ISO 4126-3:2020 “*Safety devices for protection against excessive pressure - Part 3: Safety valves and bursting disc safety devices in combination*”: Specifies requirements for a product assembled from the in-series combination of safety valves or CSPRS (controlled safety pressure relief systems), and bursting disc safety devices, installed upstream of the valve within five pipe diameters of the valve inlet.
- SS-EN ISO 4126-4:2013 “*Safety devices for protection against excessive pressure - Part 4: Pilot-operated safety valves*”: General requirements for pilot operated safety valves, and where the the operation is carried out by the fluid in the system to be protected. Applicable to pilot operated safety valves having a valve flow diameter of 6 mm and above which are for use at set pressures of 0.1 bar gauge and above.
- SS-EN ISO 4126-5:2013 “*Safety devices for protection against excessive pressure - Part 5: Controlled safety pressure relief systems (CSPRS)*”: Requirements for Controlled Safety Pressure Relief Systems. Applicable for main valves having a flow diameter of 6 mm and above which are for use at pressures of 0.1 bar gauge and above.
- SS-EN ISO 4126-6:2014 “*Safety devices for protection against excessive pressure - Part 6: Application, selection and installation of bursting disc safety devices*”:

Guidance on the application, selection and installation of bursting disc safety devices used to protect pressure equipment from excessive pressure and/or excessive vacuum. Annex C provides guidance for determining the discharge capacity, for single phase fluids, of a pressure relief system that contains a bursting disc safety device. Annex F provides typical performance characteristics for various bursting disc safety device types.

There is also a related but non-PED harmonised Swedish/ International standard SS-ISO 4126-9:2020 “*Safety devices for protection against excessive pressure - Part 9: Application and installation of safety devices excluding stand-alone bursting disc safety devices*” which covers the application and installations of safety devices such as safety valves, safety valves and bursting disc safety devices in combination, pilot-operated safety valves and controlled safety pressure-relief systems to protect static pressure equipment assuming single-phase flow of the fluid discharged from the safety device. Equipment connected together in a system by piping of adequate capacity, which is free from potential blockages and does not contain any valve that can isolate any part, can be considered to be a safety system for the application of pressure relief. §8 of Part 9 contains a section on outlet lines.

SS-EN 17533:2025 §5.2 requires that “*the owner/operator shall assess the outcome of a risk analysis to demonstrate that in case of a fire, overall safety will be maintained*”. A fire test is only needed “*when regulations or risk analysis require the installation of a pressure relief device*” (§5.2), also §8.3.3.9, §A.9 and Annex G. Only examples of the bonfire test are provided, not specific requirements. Example bonfire test options require either controlled release or to determine a time to rupture (test not lasting more than 60 minutes) with a 30 % safety margin subtracted to give a lifetime in a fire.

The non-PED harmonised European standard for stationary hydrogen storage systems, Swedish Standard SS-EN 17533:2025 “*Hydrogen - Gas cylinders and large cylinders for stationary storage*” does not include requirements or recommendations for pressure relief device vents. A similar ISO draft ISO/FDIS 19884 Ed.1.0 dated 2019 was rejected in the FDIS ballot, and work has now started under ISO TC197/ WG15 on ISO/AWI 19884-1 Gaseous Hydrogen - Pressure vessels for stationary storage, Part 1: General Requirements, but it is not expected to cover pressure relief device vents as the ISO abstract for the future standard states “*This document is not applicable to closures, valves, fittings, plugs or external piping.*” [<https://www.iso.org/standard/87726.html>].

Despite the lack of guidance for PRD vent stack design in standards from International or European standards organisations such as ISO or CEN, a number of industry standards or codes of best practice have been identified:

- API Std 521 “*Pressure-relieving and Depressuring Systems*”, 7th Edition, includes Errata 1 (2022) is applicable to pressure-relieving and vapor depressuring systems. Although intended for use primarily in oil refineries, it is also applicable to petrochemical facilities, gas plants, liquefied natural gas (LNG) facilities, and oil and gas production facilities. The standards gives guidelines for:
 - Examining the principal causes of overpressure;
 - Determining individual relieving rates;

- Selecting and designing disposal systems, including such component parts as piping, vessels, flares, and vent stacks.
- ASME B31.12 – 2023 “*Hydrogen Piping and Pipelines*” does not specifically address vent design.
- NFPA 2 (2023) “Hydrogen Technologies Code” requires that vent stacks discharge in the open and adhere to CGA G-5.5 (see below). Additional requirements deal with location including areas where personnel have access, ignition sources, building opening, intakes or overhangs. IEC 60079-10-1 shall be used to assess the hazardous volume around the vent outlet. Guidance on the height of the vent exit, and horizontal separation distances are also provided.
- CGA G5-5, Edition 4, April 2021 “Standard for Hydrogen Vent Systems” provides design guidelines for hydrogen vent systems used in gaseous and liquid hydrogen systems at user sites and provides recommendations for safe operation of these vents. The scope of the standard begins at the discharge port of the pressure relief device and ends at the point where hydrogen concentration in the atmosphere is below the lower flammable limit. The standard contains design requirements such as flow capacity, thrust balancing, rain protection, etc. (\$88) https://legacy.cganet.com/pubs/toc/G-5.5_4%20toc.pdf
- EIGA Doc.211/24, Sept. 2024 “*Hydrogen Vent Systems For Customer Applications*” provides recommendations and a methodology for the safe design of venting systems for hydrogen installations and equipment located at a customer site (hydrogen refuelling stations with standard supplies of hydrogen (liquid, gas bulk, gas cylinders, on-site production of less than 5000 Nm³/hr of hydrogen). Vent systems on vehicles themselves are excluded from the scope. The standard aims at preventing Deflagration to Detonation Transition (DDT) and mitigating the hazards from fires, deflagration and DDT if it occurs. The document focuses on the following hazards:
 - Deflagration due to the delayed ignition of the explosive hydrogen/air mixture coming out of the vent stack
 - Thermal radiation generated by the jet fire (the flame coming out of the vent stack)
 - DDT inside the vent system due to the acceleration of the combustion of the air/hydrogen mixture that can be present inside the venting system (in the presence of an ignition source). This hazard is relevant if air can enter the venting system.

Design aspects considered include:

- Design and environmental loads inc. overpressure generated by an internal hydrogen/air mixture
- Thrust resilience of the vent
- Vent silencers

- Vent exit design
 - Blockage prevention
 - Grounding
 - No flame arrestor (to avoid flow restriction)
 - Outlet location based on specified heat radiation, hydrogen concentration and overpressure criteria
- ISO 19880-1: 2022 “*Gaseous hydrogen – Fuelling stations – Part 1: General requirements*” provides comprehensive general and safety requirements for the design of gaseous hydrogen refuelling stations for road and other land vehicles, including associated gaseous hydrogen vent systems in §7.8. General recommendations, the vent outlet, vent sizing, and handling of multiple relief devices are covered. Vent outlets may be orientated in any direction between horizontal and vertical, and there are further recommendations on the cut plane of the outlet depending on the vent outlet. Hydrogen dispersion and radiated heat calculations shall be carried out to establish the location and height of vent stack outlets. Vent stacks shall be designed to avoid the collection of water and potential ice formation, and organic debris, insect nests, etc which may fully or partially restrict the venting process. Drains shall be protected from freezing to avoid blockage or breaking of the vent stack. The standard also gives guidance on some basic principles for dispersion from vent stacks:
 - For vertical venting, the higher the discharge velocity the smaller the safety distance around the vent as the higher momentum is less effected by cross-winds to bend the flammable plume to the side or ground.
 - For T-venting, the smaller the discharge velocity the smaller the safety distance recommendations in the axis of discharge as the lower momentum reduces the projected footprint of the potentially flammable plume.

In the case of multiple relief devices serviced by a single vent stack, full vent capacity should be available if any of the manifolded relief devices are isolated.

Appendix 7: Transportable Storage Vent & Fire Requirements

General

EU Directive 2010/35 on Transportable Pressure Equipment (TPED) applies to the design, manufacture, conformity assessment, periodic inspection, intermediate inspection, exceptional checks and reassessment of conformity of pressure receptacles and tanks used for the transport of Class 2 gases, covered respectively in [<https://eur-lex.europa.eu/eli/dir/2010/35/oj>]. Hydrogen is classified as a Class 2.1 (flammable) gas under transport of dangerous goods regulations (see below). As well as the pressures vessels, TPED covers associated valves and other accessories with direct safety function, where appropriate, and includes both refillable and non-refillable pressure vessels.

The Swedish implementation of TPED is published by the Swedish Civil Contingencies Agency (MSB) as MSBFS 2011:3 Regulations On Transportable Pressure Equipment [<https://www.msb.se/sv/amnesomraden/skydd-mot-olyckor-och-farliga-amnen/farligt-gods/lag-forordning-och-foreskrifter/transportabla-tryckbarande-anordningar/>]. MSBFS 2011:3 is primarily an administrative regulation and does not contain specific requirements, which are instead primarily contained in MSBFS 2024:10 “föreskrifter om transport av farligt gods på väg och i terräng” (ADR-S) and MSBFS 2024:11 “föreskrifter om transport av farligt gods på järnväg” (RID-S). ADR-S and RID-S are the Swedish implementations of the agreement concerning the International Carriage of Dangerous Goods by Road (ADR) published by the United Nations Economic Commission for Europe (UN ECE) [https://unece.org/adr-2025-files] and International Carriage of Dangerous Goods by Rail (RID) published by the Intergovernmental Organisation for International Carriage by Rail (OTIF) [https://otif.org/fileadmin/docs/LegalTexts/COTIF/DangerousGoodsRID/RID/RID_2025_e_1_January_2025.pdf] respectively.

By Road

MSBFS 2024:10 “föreskrifter om transport av farligt gods på väg och i terräng” (ADR-S) and MSBFS 2024:11 “föreskrifter om transport av farligt gods på järnväg” (RID-S). ADR-S and RID-S are the Swedish implementations of the agreement concerning the International Carriage of Dangerous Goods by Road (ADR) published by the United Nations Economic Commission for Europe (UN ECE) [https://unece.org/adr-2025-files],

Chap. 6.7 of ADR deals with portable tanks and UN multiple element gas containers (MEGC), while Chap.6.8 covers fixed tanks (tank-vehicles), demountable tanks, tank containers and tank swap bodies with metallic shells, and battery vehicles and non-UN MEGC.

§6.7.5.4.1 *“If required by the competent authority of the country of use, MEG containers for other gases shall be fitted with pressure relief devices as determined by that*

competent authority.” §6.7.5.4.2 requires that every element of group of elements within a MEGC that can be isolated shall be fitted with one or more PRD. The type is not specified. §6.7.5.7.1 requires that vents discharge to the atmosphere in such a way that only a minimum back pressure acts on the pressure-relief device. §6.7.5.8.1 requires that a vented flammable gas be directed such that it does not impinge on the other elements in the MEGC. Heat-resistant protective devices that divert the gas flow are permitted, provided that they do not reduce the required vent capacity.

Chap.6.8 does not provide requirements for PRD for gaseous tanks.

Chap.6.9 deals with fibre reinforced plastic (FRP) portable tanks, and §6.9.2.2.3.15 requires that a “tank shall be designed to withstand, without significant leakage, the effects of a full engulfment in fire for 30 minutes...”.

Chap.6.13 deals with fibre reinforced plastic (FRP) fixed and demountable tanks, and §6.13.1.13 requires that a “*tank shall be designed to withstand, without significant leakage, the effects of a full engulfment in fire for 30 minutes...*”.

By Rail

MSBFS 2024:11 “föreskrifter om transport av farligt gods på järnväg” (RID-S). RID-S is the Swedish implementations of the International Carriage of Dangerous Goods by Rail (RID) published by the Intergovernmental Organisation for International Carriage by Rail (OTIF) [https://otif.org/fileadmin/docs/LegalTexts/COTIF/DangerousGoodsRID/RID/RID_2025_e_1_January_2025.pdf]

The RID requirements including section numbers are similar to those for ADR above.

By Sea

There are similar regulations for the transport of dangerous goods by sea published by the International Maritime Organisation (IMO), The International Maritime Dangerous Goods Code (IMDG). In Sweden, Amendment 40 (2020) as modified by Amendment 41 (2022) of the IMDG is still currently valid, and is implemented as the Swedish Transport Agency’s regulation (föreskrifter) TSFS 2022:52 “The Transport Of Packaged Dangerous Goods By Sea” [https://www.transportstyrelsen.se/sv/om-oss/dina-rattigheter-lagar-och-regler/forfattningssamling/ts-foreskrifter-i-nummerordning/2022/details?RuleNumber=2022:52&ruleprefix=TSFS] as amended by TSFS 2023:64 “Föreskrifter om ändring i Transportstyrelsens föreskrifter (TSFS 2022:52) om transport till sjöss av förpackat farligt gods” [https://www.transportstyrelsen.se/TSFS/TSFS%202022_52_k.pdf]. It should be noted that a more recent version of the IMDG exists, Amendment 42 (2024), but has not yet been implemented in Swedish law [£195].

TSFS 2022:52, Kap.6.7, §6.7.5 contains the requirements for the design, manufacture, inspection and testing of MEG (multi-element gas) containers intended for the carriage of non-refrigerated gases, with key points extracted below:

§6.7.5.4.1 *“If required by the competent authority of the country of use, MEG containers for other gases shall be fitted with pressure relief devices as determined by that competent authority.”*

§6.7.5.7.1 *“The passage openings of all piping and blow-off lines shall have at least the same flow cross-section as the inlet of the pressure-relief device to which they are connected. The nominal size of the blow-off lines shall be at least the same as the outlet of the pressure-relief device. The blow-off line from the pressure-relief device, when used, shall discharge the discharged vapour or liquid to the atmosphere in such a way that only a minimum back pressure acts on the pressure-relief device.”*

§6.7.5.8 *“The devices, if fitted, shall be so positioned that the escaping vapour can be freely discharged upwards and the impact of the escaping gas or liquid on the MEG-container, its elements or personnel is prevented. For flammable, pyrophoric and oxidizing gases, the gas shall be led away from the element in such a way that it cannot hit other elements. Heat-resistant protective devices that divert the gas flow are permitted, provided that they do not reduce the required blow-off capacity.”*

§7.8.7.2 *“Measures shall be taken to prevent leaking gases from entering any other part of the ship.”*

§6.10.2.7.1.5 requires a 30 minute fire resistance test UN tanks with a fibre reinforced polymer (FRP) shell.

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