European Maritime Safety Agency

HAZARD IDENTIFICATION OF GENERIC HYDROGEN FUEL SYSTEMS

STUDY INVESTIGATING THE SAFETY OF HYDROGEN AS FUEL ON SHIPS

DELIVERABLE D.3.1

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Abstract

This report is developed as a part of the project “EMSA study investigating the safety of hydrogen as fuel on ships”. The project's overall objective is to carry out a structured set of safety assessments and reliability analyses, delivering a Guidance document addressing ships using hydrogen as fuel. The purpose is to support regulators and the industry navigating towards a safe and harmonised deployment of hydrogen as fuel which could demonstrate an important step towards decarbonisation of the sector.

This report presents a comprehensive Hazard Identification (HAZID) study for generic hydrogen fuel systems, which addresses key safety risks and possible measures to prevent and mitigate these risks. The analysis focuses on generic fuel system configurations, covering the systems and spaces relevant to the fuel systems, irrespective of ship type. The scope includes the processes of bunkering, storage, supply, conditioning and consumption.

By systematically identifying hazards and potential safeguards, this report aims to provide valuable insights and recommendations for improving the safety of hydrogen technologies. The findings will contribute to the broader goal of delivering a guidance document addressing ships using hydrogen as fuel.

Executive summary

This report is developed as a part of the project “EMSA study investigating the safety of hydrogen as fuel on ships”. The project's overall objective is to conduct a structured set of safety assessments and reliability analyses, delivering a Guidance document addressing ships using hydrogen as fuel. The purpose is to support regulators and the industry navigating towards a safe and harmonised deployment of hydrogen as fuel which could demonstrate an important step towards decarbonisation of the sector. This report is the result of the third part of the study.

The International Maritime Organization (IMO) updated its greenhouse gas (GHG) strategy in 2023 with a goal of achieving net-zero emissions by 2050. Together with new EU regulations, this will be crucial for decarbonising international shipping. Energy efficiency measures can lower GHG emissions from ships, but they will not bring the industry to net-zero emissions by 2050 without a change to zero-GHG fuels and potentially other technologies.

Most potential zero-carbon fuels, such as hydrogen, have properties posing different safety challenges from those of conventional fuel oils. This requires the development of IMO regulations and classification rules for safe design and use onboard ships in parallel with the technological progress needed for their uptake. It is important to take a systematic approach to ensure that the upcoming regulatory framework addresses all hazards associated with using hydrogen as fuel on ships.

This project uses the IMO goal-based approach outlined in IMO “Generic guidelines for the development of goal-based standards” (IMO, 2019), and draws upon comprehensive risk assessment and reliability analysis.

<u>What we did</u>

A comprehensive Hazard Identification (HAZID) study was performed for several generic hydrogen fuel systems, addressing key safety risks and possible measures to prevent and mitigate these risks. The foundation for the study was a set of generic conceptual designs of fuel systems commonly observed in the industry. This study concentrated on systems and spaces pertinent to the fuel systems, encompassing the entire process from bunkering to exhaust, including consumers of hydrogen gas. The HAZID primarily focused on scenarios involving hydrogen leakages within the fuel system and their potential to induce flammable and cryogenic effects.

The HAZID study was executed as a workshop with a multi-disciplined team of experts, covering ship and fuel system designers, engine makers, operators and regulators. The HAZID workshop was divided into three sessions with different topics each day:

- Compressed hydrogen (CH2) fuel systems
- Liquefied hydrogen (LH2) fuel systems
- Hydrogen fuel consumers

By systematically identifying hazards and potential safeguards, this report aims to provide valuable insights and recommendations for improving the safety of hydrogen technologies. The findings will contribute to the broader goal of delivering a guidance document addressing ships using hydrogen as fuel.

What we found

Hazard identification of CH2 fuel systems

The key findings from the hazard identification of CH2 fuel systems in different configurations are presented below:

- **Portable CH2 fuel tanks in open swap containers**
  Due to the extensive use of pipe fittings, there is a high risk of leakages from the tank piping, which could generate a critical cloud capable of causing significant damage if ignited. This cloud could develop within seconds, posing a severe threat to the ship and its systems. The main challenges with this concept are:

  - Lack of control over the leak and its direction.
  - Significant uncertainty regarding the detection of leaks. A critical cloud is likely to form long before the leak is detected.
  - Insufficient protection of tanks and nearby containers against hydrogen-initiated jet fires and explosions.

  There will be significant challenges in applying welded connections, and even if these connections are implemented, they are likely to be regarded as potential full-bore rupture sources due to uncertainties in weld quality. Tank isolation valves, combined with restrictive flow orifices or excess flow valves, have the potential to enhance safety. However, they may not be adequate to mitigate this hazardous event fully. While they can prevent larger leaks, smaller leaks may go undetected for a prolonged period due to the challenge of detecting gas leaks in an open environment.

  Unless tanks for CH2 fuel application are certified and approved for the specific ship concept they are intended for, there will be a risk that the tanks are not matching the applied safety concept.

- **Portable CH2 fuel tanks in swap containers with naturally ventilated tank connection enclosure**
  Unlike the open container concept, this concept has tanks that are stored in a designated tank enclosure within the container. In addition, the tank connections, pipes, fittings, valves, and instruments are located within a separate tank connection enclosure.

  The tank connection enclosure has certain advantages compared to open containers:
  - Improved control of leaks and detection capabilities.
  - Enhanced physical protection from jet fires and explosions.
  - Better protection against external mechanical impacts.

  However, a concept involving a naturally ventilated tank connection enclosure may be at risk of severe explosions and potentially DDTs within the enclosure, even in the case of smaller leaks. The probability of such leaks is relatively high when compared to larger leaks.

  The concept may also release un-ignited gas from the outlet of the tank connection enclosure during a leak, potentially generating a large cloud in the surrounding area. Depending on the natural ventilation outside, a subsequent explosion and fire may occur. Further investigations were recommended during the workshop, employing risk analyses and experimental testing to assess the overall fire and explosion risk associated with this concept.

- **Portable CH2 fuel tanks in swap containers with inerted tank connection enclosure**
  Inerted tank connection enclosures can reduce the risk of ignition inside the tank connection enclosure. However, the following are noted:
  - The HAZID team noted that when the container is not connected to the ship system (when the container is transported on shore, during lifting, and onboard before being connected to the ship system), the safety systems will not function. This is an inherent issue for all swappable containers.
  - Depending on the design and support of the tank connection enclosure, the lifting of containers may cause cracks and oxygen ingress as the container experiences torsion and bending.

- The IGF code requires systems to be designed, constructed and equipped to provide adequate means of access to areas that need inspection for LNG-fuelled ships.
- If gas-freeing the enclosure for inspection or maintenance, the primary safety barrier for preventing ignition will be removed. Even if the tank valve and secondary isolation valve are closed (double barrier), leaks may arise from the threaded connection where the valve arrangement is fixed to the tank, leaving the crew potentially exposed to 350 bar hydrogen with only a single barrier (an inherent issue with all current CH2 storage units). Given the intermittent use of swappable containers, there should be ample opportunities to perform inspection and maintenance on shore in empty conditions.

Due to the above, the workshop participants considered that the inert concept for CH2 would be easier to implement on a fixed fuel tank installation.

- **Fixed CH2 fuel tanks with inerted tank connection enclosure**
  Fixed hydrogen storage systems avoid many of the challenges of portable containerized storage systems, such as:
  - Dependence on non-permanent flexible hoses to connect tanks and ship systems.
  - Dependence on non-permanent connections of control and safety systems.
  - Difficulties in applying secondary enclosures.
  - Hazards of lifting tanks on/off the ship.
  - Dependence on non-permanent sea fastenings.

- **Common hazards for CH2 fuel systems (valid for all configurations)**
  One of the major hazards associated with the CH2 fuel system is the risk of fire or explosion affecting fuel storage tanks. Fires or explosions could arise from events in hydrogen systems or other non-hydrogen ship systems and areas (such as the engine room or cargo holds). If a hydrogen fuel system is exposed to an external fire, it will heat up, possibly compromising structural integrity and triggering the opening of safety devices on the tanks, leading to a subsequent release of hydrogen. Thermal Pressure Relief Devices (TPRD) are the current solution for preventing the rupture of pressure vessels in the event of a fire. The TPRD functions differently from a typical safety valve in that it opens when a sensor detects a high temperature, not pressure. When open, it will not close again. Uncertainties still remain regarding:
  - Can pressure vessels be subjected to jet fire impingement without activating the TPRD fuse? What should be the requirements for the placement of the TPRD sensor?
  - If the TPRD sensor is located within the tank space or the tank connection enclosure, it may take longer for the fuse of the TPRD to activate in the event of an external fire (i.e. when the device has responded to high temperatures).
  - The TPRD vent should be connected to the ship's vent system and led to a safe location.

Hazard identification of LH2 fuel systems

The key findings from the hazard identification of LH2 fuel systems are presented below:

- **Tank connection space arranged with mechanical ventilation**
  As a safety measure, mechanical dilution ventilation could prevent small leakages from accumulating an ignitable hydrogen atmosphere in the tank connection space (TCS), but it would not prevent potential ignition and jet fires. For more substantial hydrogen releases in enclosed spaces, forced ventilation should not be considered a dependable safety measure. It is important to note that the primary safety barrier employed in other industries is to eliminate the risk of hydrogen leakages in enclosed spaces.

- **Tank connection space arranged with inerting**
  Leakages of liquefied hydrogen from the piping into the TCS must be prevented by secondary enclosures. The following was noted:

- An inert atmosphere prevents access to the TCS during operation.
- It is unclear how a loss of tank vacuum and subsequent cooling of the TCS by cold tank surfaces will affect the primary safety barrier (nitrogen-filled TCS).
- Gas freeing after a leakage is a complex operation with the possibility of error.
- The main safety barrier is dependent on an active barrier (constant availability of nitrogen).

Preventing ignition by removing the oxidant is a sound principle, but the complexity of the solution, the wide explosive range of hydrogen, and the unknowns make prescriptive regulatory guidance difficult for this concept.

- **Tank connection space arranged with secondary enclosure for liquefied and gaseous piping**
An LH2 fuel system, where the piping systems for liquefied and gaseous hydrogen are protected against leakages by secondary enclosures for the complete system, would be possible to make safe from a flammability point of view.

  The feasibility of employing dilution ventilation as an additional safety barrier in cases where secondary enclosures cannot secure certain smaller leakage sources requires further investigation. This will depend on maximum leak rates, ventilation rates, and spatial layout. Jet fires from leakage points must be detectable and manageable without the risk of escalation. Inerting of TCS may also be a possible compensating measure in such instances.

- **Bunkering station for LH2 bunkering**
The liquefied hydrogen bunkering manifold should be situated on the open deck, avoiding areas where hydrogen gas may accumulate, as far as the ship's design permits.

  In instances where semi-enclosed bunkering station configurations are necessary due to the ship's design, the effects of an ignited leak should be mitigated by reducing the volume of the bunkering station that could potentially be subject to significant leaks.

- **Common hazards for LH2 fuel systems**
If the vacuum insulation of the storage tank fails, the following consequences may ensue: Liquefied air (flammability effects), solidification (low temperature), structural damage (cryogenic effects), and increased boil-off along with heightened pressure and cryo-pumping. Vessels storing liquefied hydrogen fuel must be designed and arranged to withstand any effects resulting from vacuum loss for both tanks and piping systems. A reliability analysis of vacuum systems to pinpoint specific failure modes and possibilities of air ingress should be considered (e.g., Failure Mode and Effect Analysis (FMEA), combined with reliability modelling).

  Other hazards addressed included leakages in LH2 fuel supply systems, where it was pointed out that the release of LH2 from fuel piping systems should be mitigated by applying secondary enclosures capable of safely handling cryogenic leakages.

  Additionally, fuel containment systems for liquefied hydrogen should be arranged to manage the fuel storage condition during normal operation to prevent the release of hydrogen.

Hazard identification of hydrogen fuel consumers

The key findings from the hazard identification of hydrogen fuel consumers, including fuel preparation and engine room, are presented below:

- **H2 leakage in the fuel preparation room**
  - A fuel preparation room for hydrogen compressors and buffer tanks represents an immature concept.
  - A higher tank pressure or lower fuel supply pressure could render the fuel preparation room unnecessary for low-pressure consumers.
  - Fuel preparation rooms should be situated on the open deck.
  - Mechanical ventilation of the fuel preparation room is excluded as an effective safety barrier due to the potential size of leaks from compressors and buffer tanks.
  - Double-walled piping and inerting should be considered.

- **H2 leakage in the inner pipe (after the master gas fuel valve)**
  - All fuel piping in enclosed spaces should be configured as double-walled piping.
  - Inerting the outer pipe is regarded as the best option for low, medium, and high-pressure engines.
  - The ESD-protected machinery space concept with single-walled piping in the engine room is unsuitable for hydrogen.

- **H2 leakage in Gas Valve Unit (GVU)**
  The GVU should be located within an inerted secondary enclosure.

- **Gas fuel consumer in the engine room**
  - All hydrogen fuel piping on the engine should be arranged as double-walled piping.
  - The engine's gas vent line, including the vent outlet, should be designed to withstand ignition and possible detonation.
  - For engine knocking and crankcase explosion risks, the same basic principles as for LNG fuel should be applied, but the implications due to hydrogen properties must be considered.

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List of Abbreviations

CFD	Computational Fluid Dynamics
CH2	Compressed hydrogen gas
DBB	Double block and bleed valve
DDT	Deflagration-to-detonation transition
DU	Dangerous undetected
EFV	Excess Flow Valve
EMSA	The European Maritime Safety Agency
ERC	Emergency Release Coupling
ERS	Emergency Release System
ESD	Emergency Shutdown
FMEA	Failure Mode and Effect Analysis
FSA	Formal Safety Assessment
FSHS	Fuel Storage Hold Space
GCU	Gas Combustion Unit
GHG	Greenhouse gas
GTAW	Gas Tungsten Arc Welding
GVU	Gas Valve Unit
H2	Gaseous hydrogen
ICE	Internal Combustion Engine
HAZID	Hazard Identification
IGF	The International Code of Safety for Ships using Gases or other Low-flashpoint Fuels
IMO	The International Maritime Organization
LEL	Lower Explosive Limit
LH2	Liquefied hydrogen
LNG	Liquified Natural Gas
LOC	Limiting Oxygen Concentration
MEGC	Multi-Element Gas Container
MLA	Marine Loading Arm
MSC	Maritime Safety Committee
PERC	Powered Emergency Release Coupling
PBU	Pressure Buildup Unit
PFD	Probability of Failure on Demand
PPE	Personal Protective Equipment
PRV	Pressure Relief Valve
QCDC	Quick Connect/Disconnect Coupling
RFO	Restrictive Flow Orifice

RT	Radiographic Testing
SCR	Selective Catalytic Reduction
SSL	Ship-shore-link
SWIFT	Structured What-if Technique
TCE	Tank Connection Enclosure
TCS	Tank Connection Space
TIG	Tungsten Inert Gas
TPRD	Thermal Pressure Relief Device
UT	Ultrasonic Thickness

List of general terms

Term	Description
Bunkering	Transfer of liquid or gaseous fuel from land based or floating facilities into a ships' permanent tanks or connection of portable tanks to the fuel supply system (DNV, 2024).
Cause	Event, situation, or condition that results, or could result, directly or indirectly in an incident.
Consequence	Direct, undesirable result of an incident sequence usually involving a fire, explosion, or release of toxic material.
Deflagration-to-detonation transition (DDT)	If the flames reach a high enough speed and encounters turbulence and flame instabilities, deflagration can transform into a detonation.
Double block and bleed valve (DBB)	Set of two valves in a series in a pipe, and a third valve enabling the pressure release from the pipe between those two valves. The arrangement may also consist of a two-way valve and a closing valve instead of three separate valves (DNV, 2024) .
Enclosed space	Any space which, in the absence of artificial ventilation, the ventilation will be limited and any explosive atmosphere will not be dispersed naturally (IEC, 1999).
Explosion pressure relief	Measures provided to prevent the explosion pressure in a container or an enclosed space exceeding the maximum overpressure the container or space is designed for, by releasing the overpressure through designated openings (IGF Code)
Failure	Termination of the ability of a functional unit to provide a required function or operation of a functional unit in any way other than as required (IEC, 2010).
Fuel containment system	The arrangement for the storage of fuel including tank connections. It includes where fitted, a primary and secondary barrier, associated insulation, and any intervening spaces, and adjacent structure if necessary for the support of these elements. If the secondary barrier is part of the hull structure it may be a boundary of the fuel storage hold space (IGF Code).
Fuel preparation room	Any space containing pumps, compressors and/or vaporizers for fuel preparation purposes (IGF Code)
Fuel storage hold space	The space enclosed by the ship's structure in which a fuel containment system is situated. If tank connections are located in the fuel storage hold space, it will also be a tank connection space (IGF code).
Gas consumer	Any unit within the ship using gas as fuel (IGF Code)
Gas valve unit space	Space or boxing containing valves for control and regulation of gas supply before the consumer (DNV, 2024).
Hazard	A potential source of harm (ISO, 1999).
Hazardous event	Event that may result in harm (IEC, 2010).
Open deck	Means a weather deck or a deck that is open to one or both ends and equipped with adequate natural ventilation that is effective over the entire length of the deck through permanent openings distributed in the side panels or in the deck above (DNV, 2024).
Piping	A system of pipes used to convey liquids and gases, including fittings, valves, and other devices.
Risk	Combination of the probability of occurrence of harm and the severity of that harm (ISO, 1999).
Safety	Freedom from unacceptable risk (ISO, 1999).
Safety systems	Systems, including required utilities, which are provided to prevent, detect/warn of an accidental event/abnormal conditions and/or mitigate its effects (e.g., ESD, PSD, fire & gas detection, PA/GA and emergency communication, fire-fighting system, etc.)
Semi-enclosed space	Space where the natural conditions of ventilation are notably different from those on the open deck, due to the presence of structures such as roofs, windbreaks and bulkheads, which are so arranged that dispersion of gas may not occur (IGF Code)

Term	Description
Swap container	Portable and standardized containers that are designed for easy transfer between different modes, such as road, rail and sea.
Tank connection space	A space surrounding all tank connections and tank valves that is required for tanks with such connections in enclosed spaces (IGF Code).

1. Introduction

DNV has been awarded the “EMSA study investigating the safety of hydrogen as fuel on ships”. The project's overall objective is to conduct a structured set of safety assessments and reliability analyses, delivering a Guidance document addressing ships using hydrogen as fuel. The purpose is to support regulators and the industry in navigating towards a safe and harmonised deployment of hydrogen as fuel, which could demonstrate an important step towards the sector's decarbonisation.

The International Maritime Organization (IMO) updated its greenhouse gas (GHG) strategy in 2023 with the goal of achieving net-zero emissions by 2050. Together with new EU regulations, this will be critical drivers for decarbonizing international shipping. Energy efficiency measures can lower GHG emissions from ships. Still, they will not bring the industry to net-zero emissions by 2050 without a change to zero-GHG fuels and potentially other technologies.

Most potential zero-carbon fuels, like hydrogen, present safety challenges that differ from those of conventional fuel oils. This necessitates the development of IMO regulations and classification rules for their safe design and use on board ships, alongside the technological advancements required for their adoption.

To ensure that all hazards associated with the use of hydrogen as fuel on ships are incorporated into the regulatory framework under development, it is essential to adopt a systematic approach, such as the IMO's “Generic Guidelines for the Development of Goal-Based Standards," and to build upon extensive risk assessment and reliability analysis.

This project will deliver a series of studies; this report is the third study and constitutes deliverable D.3.1 according to the tender specifications. The results from the first study were presented in the EMSA report titled “Mapping Safety Risks for Hydrogen-Fuelled Ships,” which characterised hydrogen safety hazards, system threats, and risks. It also outlined preliminary Guidance for controlling and mitigating these risks.

The second study focused on the reliability of hydrogen equipment and safety-critical systems, presenting a quantitative risk analysis framework for hydrogen-fuelled ships. The results from this second study were included in the EMSA report titled “Reliability and Safety Analysis (EMSA, 2024b).

This third study on Hazard Identification (HAZID) for generic ship design identifies key safety risks related to selected combinations of hydrogen fuel systems, offering insights on potential design solutions to prevent and mitigate these risks. The results of the HAZID serve as a vital input for subsequent risk analysis studies and will contribute to the EMSA Guidance for hydrogen-fuelled ships. The report has the following structure:

- Chapter 2 describes the methodology.
- Chapter 3 examines compressed hydrogen fuel systems.
- Chapter 4 examines liquefied hydrogen fuel systems.
- Chapter 5 examines gas fuel consumers.

By systematically analysing these three areas, this report seeks to offer valuable insights and recommendations for enhancing the reliability and safety of hydrogen technologies. The findings will contribute to the wider goal of producing a guidance document concerning ships utilising hydrogen as fuel.

2. Methodology

This chapter outlines the methodology employed in this report, providing a framework for understanding of the method used.

- Chapter 2.1 presents the general approach to the hazard identification work.
- Chapter 2.2 presents the detailed technique and stepwise procedure of the workshop.
- Chapter 2.3 presents the workshop participants (HAZID team).

2.1 Approach

The hazard identification study was executed as a HAZID workshop with a multi-discipline team of experts. The HAZID workshop was divided into three days with different topics each day:

- Day 1: Compressed hydrogen (CH2) fuel systems
- Day 2: Liquefied hydrogen (LH2) fuel systems
- Day 3: Hydrogen fuel consumers

The foundation for this HAZID study was a generic conceptual designs of fuel systems commonly observed in the industry. This work concentrated on systems and spaces pertinent to the fuel systems, encompassing the entire process from bunkering to exhaust, including consumers of hydrogen gas. The primary focus of the HAZID is on scenarios involving hydrogen leakage within the fuel system and their potential to induce flammable and cryogenic effects.

The workshop focused on addressing key safety risks and providing input on potential design solutions to prevent and mitigate these risks. The study focused on the most critical challenges and current issues for hydrogen fuel systems rather than covering all possible risks.

The HAZID addressed generic fuel system hazards and vessel-specific hazards for two (2) vessel arrangements. The ship-specific hazard identification and risk analysis findings will be documented in a separate report and will encompass hazards unique to the ship, such as external impacts (e.g., collision, grounding, dropped loads, etc.) on fuel tanks and piping systems, as well as the venting of gases from the vent mast and ventilation outlets.

The hazards of fuel cells were intentionally not addressed in this workshop, as the IMO's Maritime Safety Committee (MSC) approved the Interim Guidelines for the Safety of Ships Using Fuel Cell Power Installation at its 105th session in 2022.

2.2 Technique and procedure

A HAZID study is a structured approach to identifying risks and hazards involved with the design, operation or use of equipment and/or systems. The study was executed as a workshop with a multi-disciplined team of experts (see chapter 2.3).

The applied technique for the HAZID was the "Structured What-if Technique" (SWIFT), which is one of the outlined techniques as per IMO Formal Safety Assessment (FSA) Guideline Appendix 3 (IMO, 2018). This systematic, team-based workshop technique utilizes a set of 'prompt' words or phrases the facilitator uses to stimulate participants to investigate how a system will be affected by hazardous events and deviations from normal operations.

The prompt words that were typically used were "what if…", "what would happen if…", "could someone or something…", "has anyone or anything ever….". The intent was to stimulate the team to explore potential scenarios, their causes, consequences, and impacts.

The detailed procedure applied in this HAZID workshop followed the steps outlined below:

1) The generic hydrogen fuel systems under consideration were thoroughly discussed using flow diagrams and technical design assumptions, aiming to align the group and establish a shared understanding of the system before engaging in further discussions. These diagrams and descriptions are presented at the start of each of the following chapters, from Chapter 3 to Chapter 5.

2) The hazard identification followed a sequential node structure, with a briefing conducted for each node. For the compressed hydrogen (CH2) fuel systems on day one and the liquefied hydrogen (LH2) fuel systems on day two, the following sequential node structure was utilised:

   - Tank connections
   - Fuel storage tanks
   - Supply piping, incl. fuel preparation
   - Bunkering
   - Other

   For the consumers (day 3), the following nodes were used:

   - Fuel supply piping
   - Engines and connections
   - Exhaust
   - Gas vent line
   - Aux. systems
   - Other

3) Identification of hazards, hazardous events and their causes and consequences. Possible hazardous events were identified. For each hazard, potential causes, along with the potential consequences, were identified. The log sheets were partly pre-filled with hazard, cause and consequence based on knowledge about previous and existing hazard analyses for hydrogen.

4) Identification of potential preventive and mitigating measures: The next stage of the HAZID involved identifying potential measures for each hazardous event to prevent an incident from occurring (preventive measures), as well as those aimed at controlling its development or mitigating its consequences (mitigation measures).

The relationship between the hazard, hazardous event, cause, consequence and preventive and mitigating measures is illustrated in Figure 2-1 using a bow-tie diagram.

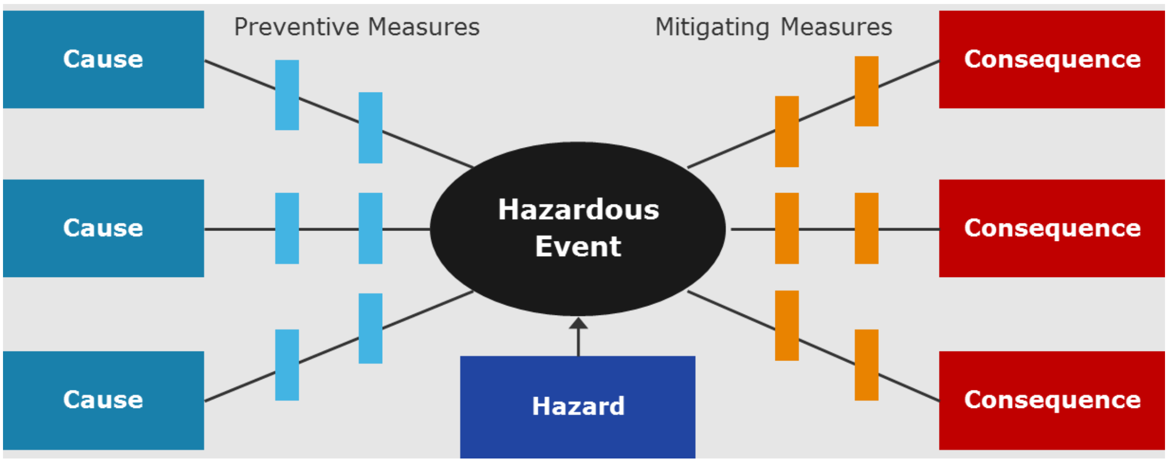

Figure 2-1: Bow-tie diagram (Source: DNV).

2.3 HAZID workshop participants

The HAZID workshop was held physically at DNV's office at Høvik 14th -16th January 2025. The sessions were attended by a multi-disciplined team of specialists and were facilitated by DNV, as listed in Table 2-1. The "*" in the table indicates online participants observing over Teams.

Table 2-1: Attendance of participants each day (HAZID Team).

Name	Company	Area of expertise	Day 1	Day 2	Day 3
Ivan Dehlic	DNV Maritime - Classification	Piping systems	O	O	O
Hans Jacob Horgen	DNV Maritime - Classification	Piping systems	O	O	O
Hans Jørgen Johnsrud	DNV Maritime Advisory	Risk management	O	O	O
Marius Leisner	DNV Maritime Advisory	Piping systems	O	O	O
Linda Sigrid Hammer	DNV Maritime Advisory	Piping systems	O	O	O
Ingeranne Nakstad	DNV Maritime Advisory	Environmental risk	O	O	O
Asmund Huser	DNV Energy Systems	Fire/explosion risk	O	O	O
Lanfranco Benedetti	EMSA	Maritime Safety	O*	O*	O*
Monica Ramalho	EMSA	Maritime Safety	O*	O*	O*
Beatriz Machado	EMSA	Maritime Safety	O*	O*	O*
Bernardo Crespo	EMSA	Maritime Safety	O*	O*	O*
Gunnar Heggebakk	Vard Design	Ship design	O	O	O
Philipp Henschen	MAN Energy Solutions	Hydrogen engines	O	O	O
Michael Bechstein	MAN Energy Solutions	Hydrogen engines	O	O	O
Simen Diserud Mildal	Norwegian Maritime Authority	Piping systems	O	O	O*
Ivar Ingvaldsen	Norwegian Maritime Authority	Piping systems	O	O	
Helge Brekke	Wartsila Power Systems	Hydrogen engines	O	O	O
Kaj Portin	Wartsila Power Systems	Hydrogen engines	O	O	O
Barbro Kvilekval	Hexagon Purus	CH2 containers	O		
Robert Haugen	Hexagon Purus	CH2 containers	O	O	O
Øyvind Hamre	Umoe Advanced Composites AS	CH2 containers	O		
Per Are Birkeland	Umoe Advanced Composites AS	CH2 containers	O		
Peter Dahl	MAN CRYO	LH2 storage and systems	O	O	O
Marko Parkkonen	MAN CRYO	LH2 storage and systems	O	O	O
Elin Utbult	MAN CRYO	LH2 storage and systems	O	O	O
Javier Martinez Gonzalez	Port Huelva	Ship systems	O*	O*	O*
Jesús Blanco	Balearia	Ship systems			O
Javier Cerveza	Alianza Net-Zero Mar	Ship systems	O	O	
Oscar Rodríguez Luna	Moeve	Energy production	O	O	
Javier Pastor	Moeve	Energy production	O	O	O
Felix García Rivas	Moeve	Energy production	O	O	
Pancho Corell	ESK	Bunkering	O*	O*	O*
Estela Iranzo	ESK	Bunkering	O*	O*	O*
Pedro Moscardo	ESK	Bunkering	O*	O*	O*

3. Hazard identification of compressed hydrogen (CH2) fuel systems

The hazard identification of CH2 fuel systems covers the following generic concepts:

- Portable CH2 fuel tanks in open swap containers
- Portable CH2 fuel tanks in swap containers with naturally ventilated tank connection enclosure
- Portable CH2 fuel tanks in swap containers with inerted tank connection enclosure
- Fixed CH2 fuel tanks with inerted tank connection enclosure
- Common hazards for CH2 fuel systems

There are fundamental differences between CH2 fuel system concepts and typical fuel systems seen for natural gas-fuelled applications for ships.

There is an increased risk of explosions in the event of a leak due to the adverse properties of hydrogen concerning ignition and the potential for detonations.

Hydrogen is stored in the gaseous phase at high pressures (200-700 bar) in pressure vessels, often referred to as tanks or cylinders. While such high pressure is typically necessary for natural gas-fuelled ship applications with two-stroke engines, it is usually limited to the fuel preparation room and the double-walled piping in the engine room. The CH2 concept, however, will function at the same or higher pressures but will maintain high pressure in the fuel containment system, including tank connections and bunkering systems, which are commonly proposed with single-walled fuel piping systems.

An increase in the number of pipe fittings raises the potential for leaks. Hydrogen containers, which are a type of Multi-Element Gas container (MEGC), can potentially accommodate 50-60 pressure vessels within a single container.

Hydrogen is stored in composite pressure vessels rather than the steel tanks commonly used for liquefied gas storage. These vessels are designed to limit pressure increases during a fire, but the composite material's degradation or the liner's melting can result in leaks and ruptures. As a result, these pressure vessels possess different characteristics in terms of leak prevention, fire insulation, and resistance to mechanical impacts and external fire compared to steel tanks.

The use of flexible hoses in the fuel system to connect portable tanks with the ship's systems introduces additional leak points and implies that the crew will be exposed to high-pressure hydrogen piping systems during connection and disconnection.

While MEGCs are commonly used in road transport in accordance with ADR regulations and as cargo on ships under IMDG regulations, additional hazards arise when these containers are employed as portable fuel tanks on ships. When transporting cargo by road or on ships, the container is closed with a double barrier—consisting of one tank or section isolation valve alongside an additional shut-off valve. This is in contrast to their utilisation as fuel tanks with open fuel supply valves to consumers, which are frequently arranged with single barrier leak sources and may be situated near accommodation areas, the bridge, or life-saving appliances and mustering stations.

These differences will introduce new hazards typically absent in current natural gas or other gas-powered applications, thereby posing challenges to the functional requirements specified in the IGF Code.

3.1 Portable fuel tanks in open swap containers

This section identifies hazards associated with a generic CH2 fuel system that utilises portable fuel tanks. These tanks are stored in an open swap container featuring no roof, side walls, or enclosures apart from the container frame. Consequently, all tanks and their connections are exposed to the environment. A flow diagram of the CH2 fuel system employing open swap containers with portable fuel tanks is displayed in Figure 3-1.

The connections to the tank are located in an open environment. Consequently, hazard identification focused on the piping system linking the pressure vessels to the hose connection. The leak locations, both upstream and downstream of the section isolation valves, are marked in Figure 3-1 with yellow indicators.

Basis for analysis

The concept used as the basis for workshop discussions has the following features:

- Hydrogen is stored onboard in swappable ISO 20 ft or 40 ft containers, either standard type or “high-cube”. Inside each container, a number of pressure vessels are stored. The analysis is not limited to a certain number of tanks or tank sizes.
- Tanks are mounted horizontally within the container frame to facilitate stacking.
- Tanks are type IV pressure vessels constructed entirely of composite materials, featuring a polymer liner with a carbon, hybrid carbon/glass fibre composite, or glass fibre/epoxy laminate. The design pressure of these pressure vessels is assumed to be 380 bar, while the operating pressure is assumed to be 350 bar.
- The fuel containment discussed comprised tank bundles of two (2) pressure vessels with section isolation valves. This implies that gas is present in the piping up to the section isolation valve at all times, and no tank valves are arranged (as illustrated in Figure 3-1).
- Single-walled stainless-steel piping with outer diameter in the range of 10-16 mm and 2.0 mm thickness.
- All piping connections in the hydrogen container are assumed compression fittings. These fittings use a compression nut, a compression ring (ferrule), and a compression seat. Tightening the nut compresses the ring onto the pipe, creating a seal. The pipe connection between the piping and the pressure vessels is assumed to be a threaded connection.
- The regulation of the fuel supply pressure to consumers is performed by a pressure reduction and control valve, with pressure reduction from storage pressure (typically 350 bar) to what is required by hydrogen consumers (typically 6-10 bar for fuel cells and low-pressure Internal Combustion Engine - ICE), which is part of the ship`s fixed fuel supply system. Only one container will be active during operation (fuel supply), which will be automated by the hydrogen fuel control and safety system on the ship.
- The safety philosophy is that, in the event of a leak from tank connections, the dilution of flammable or explosive concentrations is through natural ventilation on the open deck. The safety of the concept relies on quick detection of leaked gases by gas detectors.
- The hydrogen containers have the following connections to ship systems: Gas fuel line, vent line, instrument air and data signal. All tank connections and instruments are connected using Quick Connect Disconnect Coupling (QCDC) at one end of the container. The single-walled hoses are stored onboard when not in use.
- Pressure sensors, temperature sensors, and visual indicators are mounted on each container with data ports for connection to the ship control and monitoring system.

- It is noted that, in addition to flag/class approval, obtaining an ADR approval for the hydrogen storage container is a prerequisite for the overall container swapping concept.

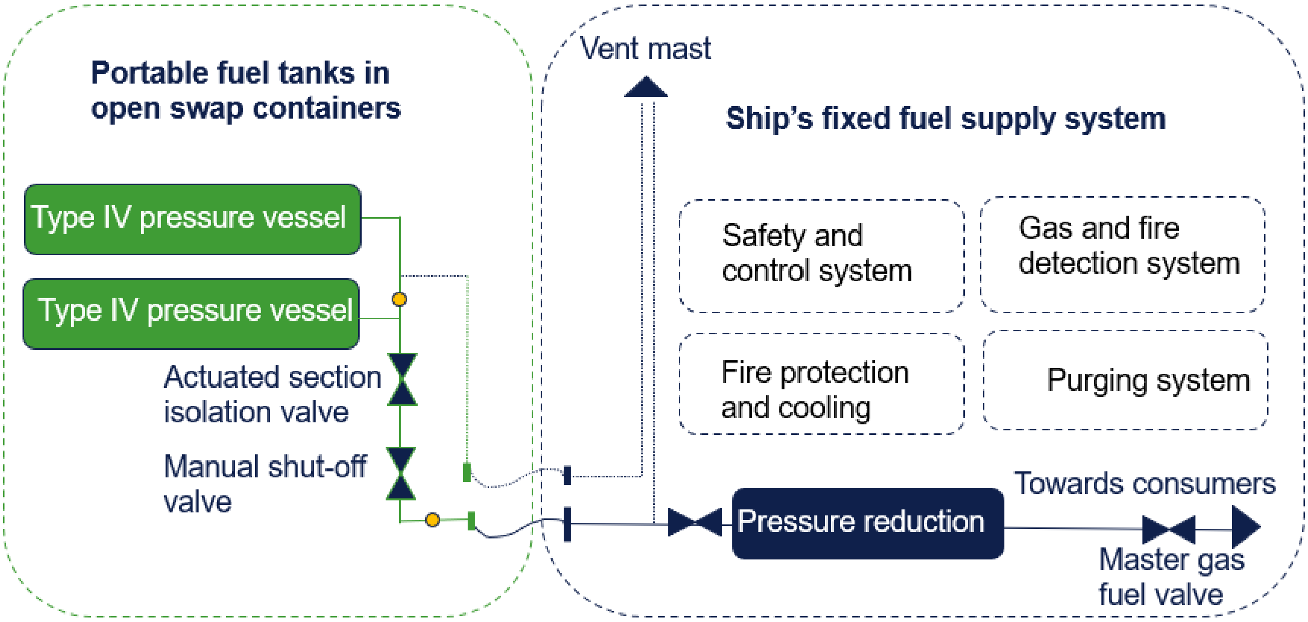

Figure 3-1 Flow diagram of the CH2 fuel system using portable fuel tanks in open swap containers (Source: DNV).

The design safety philosophy is to quickly detect any gas leaks, automatically isolate the leakage, and dilute the escaped gas with natural ventilation.

Hazard Identification results

Table 3-1 presents the hazard identified for the CH2 fuel system using portable fuel tanks in open swap containers. Note that common hazards for all hydrogen container concepts are presented in Chapter 3.5.

Table 3-1 Hazard 1.1.1 H2 leakage in piping upstream or downstream section isolation valve.

Hazard 1.1.1	Hazardous event: H2 leakage in piping upstream or downstream section isolation valve
Node	■ Tank connections.
Potential causes	■ Faulty connections and piping: Welds, flanges, threaded/screw/fitting connections and flexible hoses used to connect portable tanks. ■ Design error, fabrication or installation error, and/or operating conditions (e.g. vibrations) or operating outside design limits. ■ Leak potential from valve stems. ■ Impact events.
Potential consequences	■ If a leak occurs downstream of the section isolation valve, it can be stopped by closing the valve, provided the leak is detected by gas detectors. However, if a leak occurs upstream of the section isolation valve, it will result in an unstoppable leakage, releasing the entire contents of all tanks connected to that section.

Hazard 1.1.1	Hazardous event: H_2 leakage in piping upstream or downstream section isolation valve
	■ The consequence may be a jet fire (if immediate ignition) or a flash fire/deflagration/detonation (delayed ignition) that may impact crew and/or safety-critical systems. There is also an escalation potential, i.e. initiating a domino effect where several other tanks and systems can be affected sequentially. In semi-congested areas, hydrogen leaks can form a flammable cloud much faster than other gases. A ‘critical cloud’ capable of causing significant damage through explosion or deflagration and posing a threat to the ship and its systems can develop within seconds. ■ Potential for hydrogen in-between tanks, hydrogen containers and ship structures to form gas pockets. For a high-momentum jet, the gas is driven by its momentum and not by buoyancy. Hence, the leak can go in any direction. ■ Explosions and jet fires may impact safety systems, hydrogen fuel systems (escalation), and other ship areas and spaces, including life-saving arrangements.
Possible preventive and mitigation design measures	Preventive measures: ■ **Welded connections**. Using welded connections for small-diameter piping is technically feasible for some parts of the piping system on the container, but manufacturers state that they need to use some fittings. However, even for parts where welding can be done, it comes with significant challenges: – It is considered that only the Gas Tungsten Arc Welding (GTAW), also known as Tungsten Inert Gas (TIG) welding, can be applied (low heating input welding). This is a more complex and slower process compared to other welding techniques. – Welds need to be tested. Ultrasonic Thickness (UT) is not considered to be possible. Only Radiographic Testing (RT) would be suitable, using X-rays or gamma rays. – It is considered that the likelihood of leakages is comparable for fittings and welding small-diameter piping. This means the dimensioning case for design and safety systems should be full bore rupture. This would be valid for fittings and small-diameter welded connections. ■ **Leak testing** every time tanks are filled and before containers are lifted onboard. Determining an equivalent test for fittings, similar to weld tests, is challenging. Leak testing alone may not reliably detect all leakages. ■ **Make piping more robust** by increasing pipe diameter. Feasibility of welded connections will improve by increasing the pipe diameter and size. ■ **Reduce leak points**. Reduction in the number of potential leak points is challenging as the container piping system will need pipe connections. It is not feasible to reduce the number of leak sources to zero. Mitigation (consequence reduction) measures: **Double wall piping** for small-diameter piping on the container is not considered technically feasible (see point above on welding). ■ **Tank isolation valve.** Workshop participants agreed that it should be possible to automatically isolate the piping systems for fuel at each tank boundary by applying a tank valve mounted as close as possible to the tank. This will reduce the possible gas outflow if there is a leak in the piping system. ■ **Excess Flow Valves (EFVs)** are mechanical safety devices designed to automatically shut off the flow of gas when it exceeds a predetermined rate. While EFVs are claimed to be effective in preventing large-scale gas leaks, they require a flow rate higher than normal usage to activate. This means they may not detect and prevent small to medium-sized leaks. ■ **Restrictive Flow Orifices (RFOs)** are devices designed to control the flow of fluids by introducing a mechanical restriction of flow diameter with no moving parts. The orifice prevents flow higher than a specified rate but will not stop the flow. It can also cause operational issues, such as too low flow at lower pressure.

<table>
<tr><th>Hazard 1.1.1</th><th>Hazardous event: H2 leakage in piping upstream or downstream section isolation valve</th></tr>
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Restrictive flow orifice on instrument tubes to reduce potential leak rate from instrument lines.
Gas detection. Point gas detectors are ineffective on an open deck, so the question is how reliable acoustic gas detectors are considering ultrasonic noise interference (from ventilation, machinery, etc.). Mapping of background noises is crucial. None of the workshop participants had seen any tests or had real-life experience with acoustic gas detectors.
Natural ventilation. The primary safety measure of this concept is natural ventilation to dilute gas concentrations below LEL in case of leaks. Hence, it is important to ensure open geometry, ventilation and no obstructions or congestion where gas can accumulate. Ventilation can be effective to dilute smaller leaks up to a certain size, and small leaks are more frequent than larger leaks. Since ventilation will not be able to dilute larger leaks, other measures are needed to prevent or mitigate larger leaks.
Definition of hazardous zones will be necessary but cannot be relied upon alone to prevent ignition due to the unique chemical and physical properties of hydrogen compared to methane. Hydrogen has a low ignition energy and a high potential for self-ignition. Experience has shown that in many hydrogen-related accidents, identifying the ignition source is challenging and often impossible, indicating high ignition potential.
Pressure reduction should be implemented as close to the tank as possible. However, the risks associated with placing it in the container must be carefully evaluated.

Potential leak points (two pressure regulating valves in series) will be transferred from ship to container.
The container will need additional pressure relief for the pressure-regulating valve piping. This needs to be connected to the vent mast.
It is noted that container manufacturers favour having pressure regulation on the ship.
Not moving pressure reduction to the container raises the critical question of whether a leakage from a 350-bar connection or hose is an acceptable risk. See hazard 1.5.1 (chapter 3.5).

All valves should be automatically activated (no manual valves needing crew attendance in emergency situations).
Automatic purging of piping system with inert gas after leaks are detected.

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<tr><td>Notes</td><td>

Pipe diameter is determined by factors such as pressure and flow. By increasing the diameter, the size of a potential leakage of a pipe rupture could also increase. Some workshop participants were of the opinion that it would be better to keep the pipe diameter as small as possible.
The temperature difference between the released gas and the ambient temperature has a minor effect on the dispersion. Gaseous hydrogen will not cool down surrounding structures (reverse Joule-Thompson effect).
Excess Flow Valves and Restrictive Flow Orifice:

Such valves/orifices may affect the filling of tanks since the fuel supply line will be used for this. This may lead to longer filling time since there will be constraints in the line. The same may apply to emergency manual venting (done via the fuel supply line), leading to longer venting duration. Particularly for orifices, it was claimed that this is unfavourable for filling operations. Also, it does not stop flow in case of leaks; it only limits the leak rate.
Swappable containers may have tanks with different settings on excess flow valves when they arrive at the ship. Hence, the container may not comply with the ship safety concept. This would not be an issue if swappable container is dedicated to specific ship.
It was claimed in the workshop that an excess flow valve could trigger within milliseconds, and the threshold can be set at 10 g/s (0.01kg/s).
Excess flow valves can fail when needed. According to industry guidelines, the default Probability of Failure on Demand (PFD) is 0.1, although a PFD of 0.01 can be justified for some systems.

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Hazard 1.1.1	Hazardous event: H2 leakage in piping upstream or downstream section isolation valve
	▪ Means of gas detection: – Participants were not sure whether pressure drop could be used as means of detection. – Participants were asked if infrared sensors could be applied, but they had no experience with this. ▪ Important to consider material compatibility between welding material and hydrogen. ▪ Rule of thumb; 60 - 80 g/kWh fuel supply required to ICE consumer (corresponds to an efficiency of 50% respectively 37.5%). Around 0.135 kg/s is needed for engine fuel supply. ▪ CFD calculations are likely needed to document sufficient natural ventilation around containers to dilute leaks and assess the consequences of explosion and jet fire. ▪ Vertical orientation can complicate stacking since leaks occurring at the connections on top of the container will be released at bottom of the container above. This could obstruct air ventilation and impede gas dilution. ▪ The dilution process of leaked hydrogen may be hampered by potential obstructions, such as the hydrogen containers themselves, the compartment structure around the containers, bulwarks, funnels, and other bulkheads designed to separate the hydrogen area from the cargo operation area. For high-momentum jets with a release rate above a certain size, the gas will be driven by its momentum, and not by buoyancy, and the cloud can therefore build up at all locations before it moves upwards (MarHySafe, 2021). Thus, the debate often centres on whether the storage area can be considered fully open or semi-enclosed, with the latter being more susceptible to the dangers of gas concentration build-up. ▪ The cloud build-up time for hydrogen leaks is extremely short compared to other gases. A ‘critical cloud’ that can cause significant damage and harm to the ship and its systems if ignited, can form within seconds. Recent studies by DNV indicate that this can occur in just 5 seconds with leaks in the range of 0.1 kg/s (DNV, 2019), (DNV, 2023). There is high uncertainty as to whether the gas detector system can prevent a critical gas cloud and explosion from occurring. Conventional point gas detectors are not fast enough, and there is uncertainty regarding the reliability of acoustic detectors often proposed for compressed hydrogen storage configurations on open and semi-enclosed decks. Several factors can hinder an effective response time, such as intermittent ultrasonic noise and noise interference. ▪ Some additional mitigation measures mentioned in the workshop: – Use the strength of walls, decks, piping, tanks and equipment as a mitigating measure to prevent escalations (after explosions). Dimensioning scenarios would then need to be established and used in design. – Separation from manned areas with blast-walls and fire-walls, and blast decks. – The tanks, valves, piping and hydrogen equipment may need coverage with passive fire protection to prevent escalation. Structure elements can also need fire protection in case of long-lasting fires from tanks.
Conclusion/ summary	**The fuel system, regarded as a "basis for analysis," poses a high risk for leakages generating a critical cloud, capable of causing significant damage if ignited. It could develop within seconds, threatening the ship and its systems.** The main challenges with this concept are: ▪ Lack of control of leak and leak direction. ▪ Significant uncertainty as to whether leaks can be detected. A critical cloud is likely to be created long before the leak is detected (if detected at all). ▪ Lack of protection of tanks and nearby containers for hydrogen-initiated jet fires and explosions.

Hazard 1.1.1	Hazardous event: H2 leakage in piping upstream or downstream section isolation valve
	■ There will be significant challenges to applying welded connections, and even if welded connections are applied, they are likely to be considered as potential full-bore rupture sources due to uncertainty in weld quality. Tank isolation valves, in combination with Restrictive Flow Orifices or Excess Flow Valves, have the potential to improve safety. However, they may not be sufficient to fully manage this hazardous event. While they can prevent larger leaks, smaller leaks might go undetected for an extended period unless identified by acoustic detectors, which are untested for maritime applications. Unless tanks for CH2 fuel application are certified and approved for the specific ship concept they are intended for, there will be a risk that the tanks are not matching the applied safety concept.

3.2 Portable fuel tanks in swap containers with naturally ventilated tank connection enclosure

This section identifies hazards associated with a generic CH2 fuel system that uses containerised portable fuel tanks, which are stored in a designated tank enclosure within the container. The tank connections, pipes, fittings, valves, and instruments are situated within a separate tank connection enclosure. The basis for analysis highlights the differences between this concept and an open container discussed in Chapter 3.1. A flow diagram of this concept is shown in Figure 3-2.

In line with the previous concept, the hazard identification concentrated on the piping system connecting the pressure vessels to the hose connection. The leak locations considered, both upstream and downstream of the section isolation valves, are marked in the figure with yellow indicators.

Basis for analysis

The concept used as the basis for the workshop discussions has the following features:

- The tank connection enclosure contains all the pipe fittings, connections, valves, and instruments, except for the hose connections to the ship's systems. This implies that any leaks from the aforementioned equipment will be released into this enclosure.
- The enclosure is ventilated naturally through louvres (slatted openings) that permit airflow, located at both the bottom and the top of the space. This enclosure has a volume of less than one cubic metre, rendering it too small for a person to enter. Its dimensions are akin to those of a cabinet. The enclosure has a cabinet-like door to provide access to the equipment.
- The safety philosophy is based on the premise that a small volume limits the potential explosion pressure in the event of leaks and ignition within the enclosure, thereby reducing explosion damage. The access doors for this enclosure are presumed to be equipped with mechanical stoppers to prevent them from being forcefully opened during an explosion, which could otherwise damage hoses and connections. In addition, doors will have vent panels to take the pulse load from the explosion, opening away from other systems. Additionally, a flame impingement in the case of a hydrogen-initiated jet fire is prevented by the separation between the tank space and the tank connection enclosure.

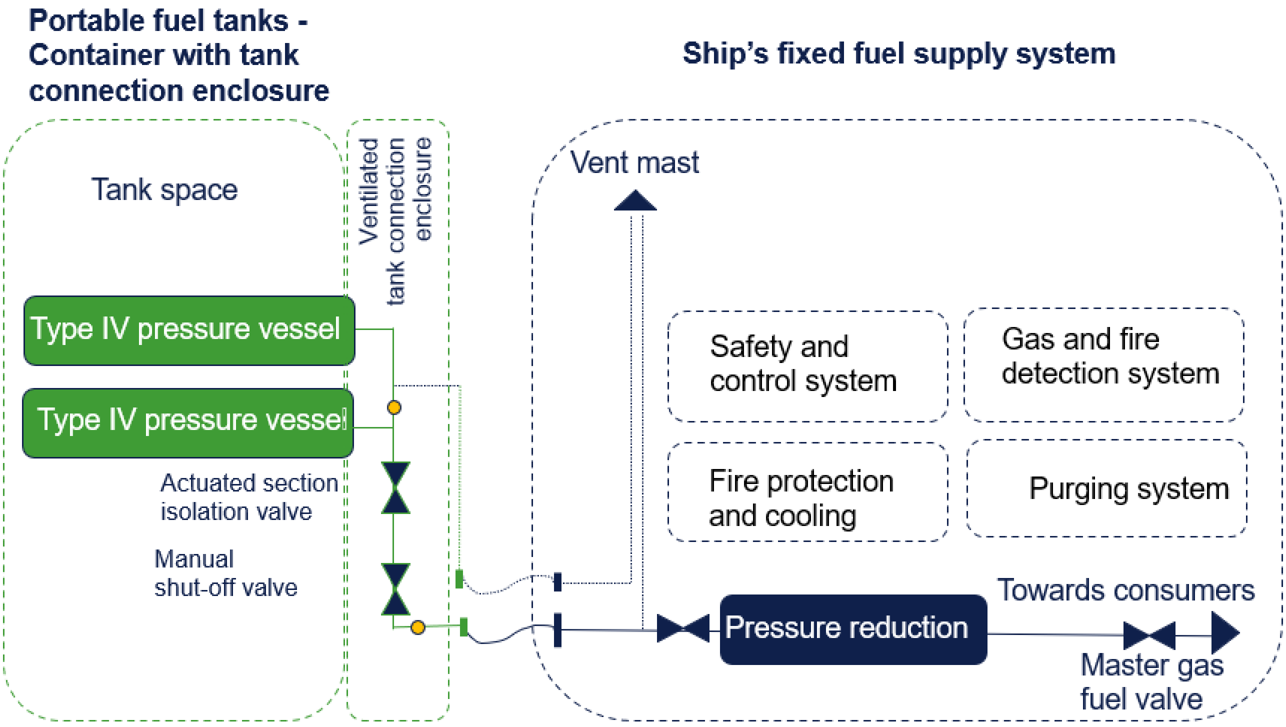

Figure 3-2 Flow diagram of the CH2 fuel system using portable fuel tanks in swap containers, with tank connection enclosure. (Source: DNV).

Hazard Identification results

Table 3-2 and Table 3-3 presents the hazards identified for CH2 fuel systems using containers with naturally ventilated tank connection enclosures. Note that common hazards for all hydrogen container concepts are presented in Chapter 3.5.

Table 3-2 Hazard 1.2.1 H2 leakage in piping upstream or downstream section isolation valve.

Hazard 1.2.1	Hazardous event: H2 leakage in piping upstream or downstream section isolation valve
Node	▪ Tank connections.
Potential causes	▪ Same as hazard 1.1.1
Potential consequences	▪ Ignition of leaks inside the enclosure. Ignition of a stoichiometric mix of gas and air inside the enclosure. The worst-case scenario considered is that the initial explosion causes significant damage to the piping, leading to the release of additional hydrogen (larger leak opening). A tank connection enclosure damaged by an explosion can also hurt or kill people in the vicinity. ▪ Since the tank connection enclosure has open louvres, unignited gas will be pushed out to the open deck. It will be possible for gas to accumulate between containers or between containers and the ship with a potential for explosion (delayed ignition) or a fire out of the louvre openings.
Possible preventive and mitigation design measures	Mitigation (consequence reduction) measures, in addition to measures for open containers: ▪ **Mechanical protection** (separating the tank space and tank connection enclosure) can prevent leakage from being directed directly into the cylinder rack. ▪ **Gas detection.** Having many system components inside an enclosure will make gas detection more reliable from these leak points. The space may also be physically sectioned, allowing for earlier gas detection. However, the gas detectors are not operative unless connected to ship systems.

Hazard 1.2.1	Hazardous event: H2 leakage in piping upstream or downstream section isolation valve
	The flexible hose connection located outside the enclosure for easy access could be provided with a separate enclosure (double cabinet).
Notes	■ Threaded connection to tank – a leakage will come into the connection space enclosure. ■ CFD tools and/or experimental tests to assess leaks and explosion potential inside the enclosure for various leak rates. ■ Scenario where there is something leaking before the container arrives at the ship.
Conclusion/ summary	**Tank connection enclosure has certain advantages compared to open containers:** ■ Improved control of leaks and detection capabilities. ■ Enhanced physical protection from jet fires and explosions. ■ Better protection against external mechanical impacts. A concept with a naturally ventilated tank connection enclosure may be subject to the risk of severe explosions and possibly DDTs inside the enclosure, also for smaller leaks. The frequency for such leaks is relatively high compared to larger leaks. The concept may also release unignited gas from the outlet of the tank connection enclosure during a leak. This can generate a large cloud in the area. A subsequent large explosion and fire can then happen depending on the natural ventilation outside. Further investigations were recommended during the workshop using risk analyses and experimental testing to establish the overall fire and explosion risk for this concept. While larger leaks may be limited through the automatic closing of isolation valves mounted directly on each tank and excess flow valves, additional evidence should be provided to demonstrate that the system and the enclosure can handle small and medium-sized leaks. This could be achieved using CFD tools and/or experimental tests at research facilities. Furthermore, a more detailed investigation into the reliability of excess flow valves and tank isolation valves (including their connection to the vent line) is necessary, as the safety philosophy heavily depends on these devices.

Table 3-3 Hazard 1.2.2 Permeation from pressure vessels.

Hazard 1.2.2	Hazardous event: Permeation from pressure vessels
Node	■ Fuel storage tanks.
Potential causes	■ Material properties: The polymer liner has inherent permeability to hydrogen. The molecular structure of these polymers allows hydrogen molecules to diffuse through them. ■ Pressure: Higher internal pressures increase the driving force for hydrogen permeation. However, increased pressure can also lead to a denser polymer structure, which might reduce the free volume available for hydrogen molecules to diffuse through. This could potentially slow down the permeation rate. ■ Temperature (in case of external fire): Elevated temperatures can increase the hydrogen diffusion rate through the polymer liner. ■ Liner thickness: Thinner liners are more susceptible to permeation because there is less material for the hydrogen to diffuse through. ■ Manufacturing defects: Imperfections in the liner material, such as micro-cracks or inconsistencies. ■ Cyclic loading: Repeated pressurisation and depressurisation cycles can cause mechanical fatigue. ■ Rapid draining of the tank may result in cooling, which can damage the lining material.

Hazard 1.2.2	Hazardous event: Permeation from pressure vessels
Potential consequences	■ The accumulation of gases inside the tank space can lead to an explosion.
Possible preventive and mitigation design measures	The safety philosophy for this hazard is that gas permeation through cylinder walls is vented by freely circulating ambient air, similar to the tank connection enclosure. ■ Gas detection inside the tank space. ■ Vent panels in tank space.
Notes	■ CFD calculations to assess the ventilation conditions inside the tank space. ■ ADR regulations have defined the maximum allowable permeation rate for hydrogen from composite pressure vessels. Manufacturers conduct in-house tests for permeation. ■ Temperature recognition in the roof to detect small, long-lasting fires which can deteriorate the synthetic materials.
Conclusion/ summary	**Permeation from pressure vessels to the open deck would pose a lesser hazard if it were not confined within a tank space enclosure. However, considering the assumed low permeation rate, which is significantly lower than that of minor leaks, this risk might be managed through adequate air circulation.** Nevertheless, ventilation simulations should evaluate whether natural ventilation can effectively manage the potential accumulation of gases.

3.3 Portable fuel tanks in swap containers with inerted tank connection enclosure

This section identifies hazards for a generic CH2 fuel system utilising containerised portable hydrogen tanks, where the tanks are stored in a designated tank space within the container. The main difference from the concept discussed in Chapter 3.2 is that the tank connection enclosure is inerted. A flow diagram illustrating this concept is presented in Figure 3-3. The leak locations considered, both upstream and downstream of the section isolation valves, are marked in yellow on the diagram.

Basis for analysis

The concept used as the basis for workshop discussions has the following features:

- The tank connection enclosure contains all the pipe fittings, connections, valves and instruments, except the hose connections to ship systems. This implies that all leaks from the mentioned equipment will be released into this enclosure.
- The enclosure is isolated and inerted with a slight overpressure of nitrogen, i.e. there is no consumption of inert gas.
- The safety philosophy is founded on the principle that the inert atmosphere within the enclosure will prevent the possibility of hydrogen gas ignition. Oxygen detectors will monitor the inert condition of the space.
- The space is less than one cubic metre in volume, making it too small for a person to enter. It is comparable to a cabinet in dimensions. The enclosure features a cabinet-like door for access to the equipment.
- Detection of leakage using pressure monitoring and/or hydrogen detectors.
- The space will have pressure relief (e.g. relief valve, burst disk).

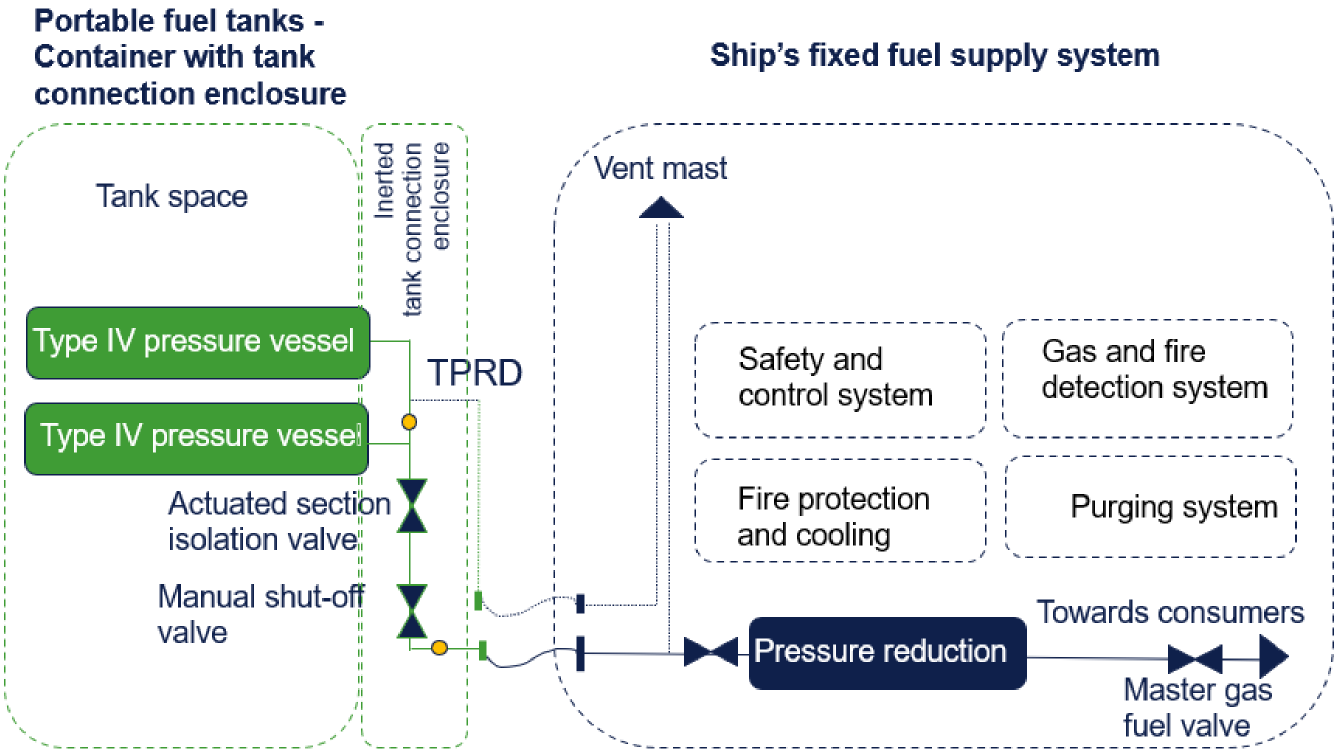

Figure 3-3 Flow diagram of the CH2 fuel system using swap containers with inerted tank connection enclosure (Source: DNV).

Hazard Identification results

Table 3-4 and Table 3-5 presents the hazards identified for the CH2 fuel system using containers with inerted tank connection enclosure. Note that common hazards for all hydrogen container concepts are presented in Chapter 3.5.

Table 3-4 Hazard 1.3.1 H2 leakage in piping upstream or downstream section isolation valve.

Hazard 1.3.1	Hazardous event: H2 leakage in piping upstream or downstream section isolation valve
Node	▪ Tank connections.
Potential causes	▪ Same as hazard 1.1.1
Potential consequences	▪ Overpressure of space. ▪ Fire/explosion (Failure on demand – inerting).
Possible preventive and mitigation design measures	▪ **Burst disk for overpressure prevention.** Burst disks provide immediate pressure relief by bursting full-bore open. However, when a disk bursts, fragments can potentially damage equipment. Also, applying burst discs for pressure control does not provide the opportunity to lead leaked gas to a safe area. A damaged burst disc can compromise the inert atmosphere inside the tank connection enclosure. ▪ **Relief valve for overpressure prevention**. Pressure relief valves can relieve pressure gradually or in small increments, which is beneficial for maintaining system stability. Also, it can be adjusted to open at specific pressures, providing precise control. PRVs can be part of a vent system that leads leaked gas to a safe area (e.g. vent mast).

Hazard 1.3.1	Hazardous event: H2 leakage in piping upstream or downstream section isolation valve
	■ **The inert gas system** onboard must have sufficient capacity and redundancy. In the event of leaks, it must be capable of managing several purge cycles, ensuring the safe evacuation of all hydrogen gases through the vent mast. ■ **Gas-tight enclosure (robust sealing system).** There is uncertainty about whether this can be achieved. When lifting the container, the container frame will experience torsion and bending. This may affect the sealing system, potentially creating cracks. Structural analysis, considering the dynamic loads during lifting, will be necessary to assess this risk in further detail.
Notes	■ Not all gas detectors work in an inert atmosphere. Most hydrogen gas detectors need some oxygen, if the purity is too high, H2 will not be detected if the wrong detector technology is chosen. ■ The container unit will typically not provide the system to purge the tank connection enclosure. Purging and gas-freeing systems will mainly have to be supplied by the ship. ■ Inerted tank connection enclosure may complicate access for maintenance and visual control on board.
Conclusion/ summary	**Inerted tank connection enclosures are preferred over naturally or mechanically ventilated enclosures for ship applications. However, the following are noted:** ■ The HAZID team noted that when the container is not connected to the ship system (when the container is transported on shore, during lifting, and onboard before being connected to the ship system) the safety systems would not function. This is an inherent issue for swappable containers. ■ Depending on the design and support of the tank connection enclosure, the lifting of containers may cause cracks and oxygen ingress as the container experiences torsion and bending. ■ The IGF code requires systems to be designed, constructed and equipped to provide adequate means of access to areas that need inspection for LNG-fuelled ships. When gas-freeing the enclosure for inspection or maintenance, the primary safety barrier for preventing ignition will be removed. Even if the tank valve and secondary isolation valve are closed (double barrier), leaks may arise from the threaded connection where the valve arrangement is fixed to the tank, leaving the crew potentially exposed to 350 bar hydrogen with only a single barrier (an inherent issue with all current CH2 storage units). Given the intermittent use of swappable containers, there should be ample opportunities to perform inspection and maintenance on shore in empty conditions. Due to the above, the workshop participants considered that the inert concept for CH2 would be easier to implement on a fixed fuel tank installation.

Table 3-5 Hazard 1.3.2 N2 leakage.

Hazard 1.3.2	Hazardous event: N2 leakage
Node	■ Tank connections.
Potential causes	■ Same as hazard 1.1.1
Potential consequences	■ There may be a risk of breathing in concentrated nitrogen if the inspection opening is opened while the enclosure is inert.
Possible preventive and mitigation design measures	■ **Inherently safe design for access.** Access to the enclosed space filled with inert gas needs to be restricted by design measures, not only procedures.
Notes	■ Slight overpressure of nitrogen is assumed.

Hazard 1.3.2	Hazardous event: N2 leakage
Conclusion/ summary	**The volume of the enclosure would typically contain limited amount of nitrogen, but caution should be used when opened up for inspection. The system used for nitrogen filling could also be used to purge the nitrogen with air before opening.**

3.4 Fixed fuel tanks with inerted tank connection enclosure

This section identifies hazards associated with a generic CH2 fuel system that utilises fixed hydrogen tanks, with the tanks stored in a designated area onboard. The connections, pipes, fittings, valves, and instruments for the tanks are located within a separate connection enclosure, filled with nitrogen to maintain an inert atmosphere inside. A bulkhead separates these two spaces. A flow diagram of this concept is shown in Figure 3-4.

Basis for analysis

The concept used as the basis for workshop discussions has the following features:

- The tank connection enclosure will have pressure relief, either via a relief valve or a burst disk. All piping on the ship consists of fixed piping.
- The hydrogen bunkering station (manifold) is situated on one side of the ship, and during bunkering, it will be connected to the bunkering facility via a high-pressure hose. Initially, hydrogen gas may be transferred directly from the supplier's storage tanks to the pressure vessel until the pressure equalises. To achieve the required high pressures (350 bar), compressors on the shoreside may be employed to further pressurise the hydrogen gas to the necessary levels for storage in pressure vessels.
- The tank connection enclosure contains pipes, pipe fittings, connections, valves and instruments. This implies that all leaks from the mentioned equipment will be released into this enclosure.
- The space is isolated and inerted with a slight nitrogen overpressure, meaning there is no continuous inert gas consumption. The safety philosophy is based on the premise that the inert atmosphere within the enclosure will eliminate the risk of igniting hydrogen gases inside the TCE. It is presumed that the inert condition is continuously monitored.
- The size of the TCE is assumed to be less than one cubic metre, making it too small for a person to enter. It is comparable in dimensions to a cabinet. The space features a cabinet-like door for access to the equipment.
- Detection of leakage using pressure monitoring and/or hydrogen detectors.
- The space will also be equipped with arrangements for gas-freeing the space for inspection or maintenance purposes.

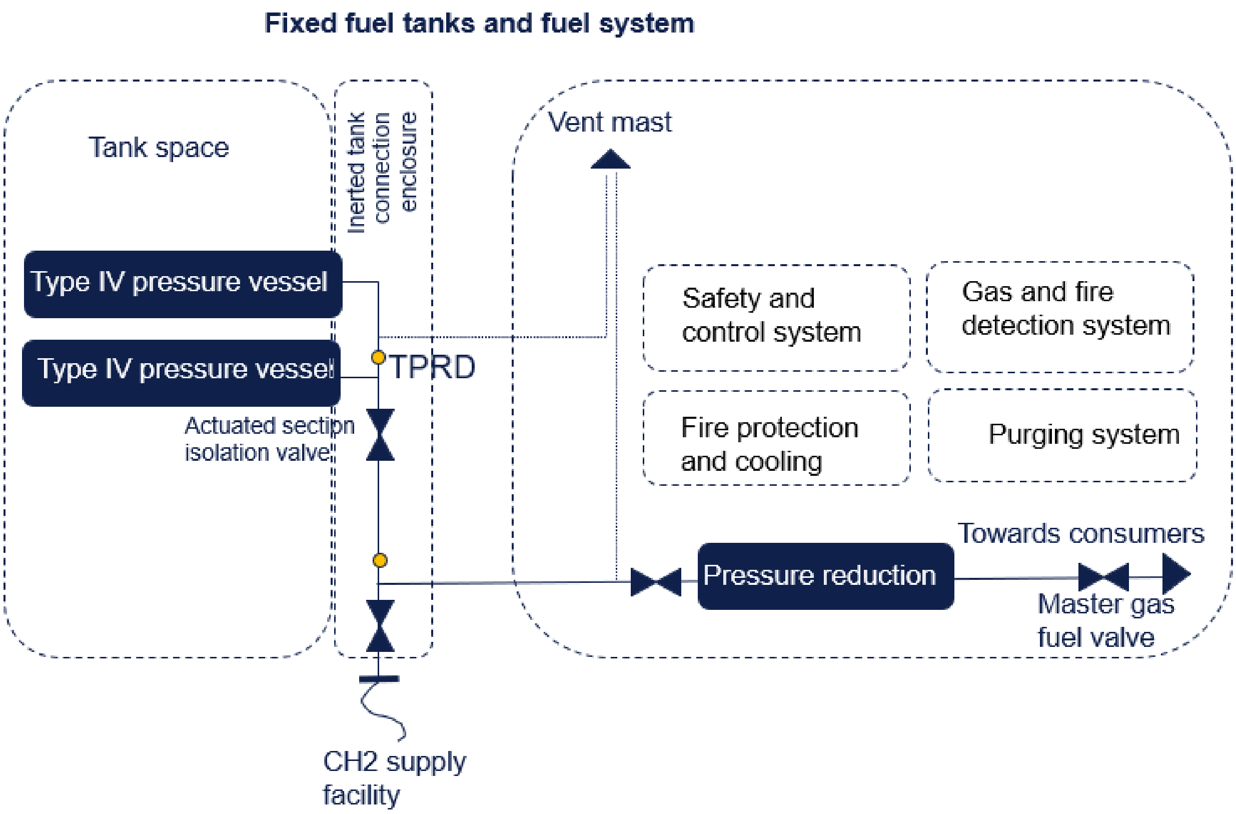

Figure 3-4 Flow diagram of the fixed CH2 fuel tank system, with inerted tank connection enclosure (Source: DNV).

Hazard Identification results

Table 3-6 and Table 3-7 presents the hazards identified for the CH2 fuel system using fixed CH2 fuel tanks with inerted tank connection enclosure. Hazards common for all CH2 fuel systems are presented in Chapter 3.5.

Table 3-6 Hazard 1.4.1 H2 leakage in piping (upstream or downstream section isolation valve)

Hazard 1.4.1	Hazardous event: H2 leakage in piping (upstream or downstream section isolation valve)
Node	■ Tank connections.
Potential causes	■ Faulty connections and piping: Welds, flanges, threaded/screw/fitting connections.
Potential consequences	■ Overpressure of space. ■ Fire/explosion (Failure on demand – inerting).
Possible preventive and mitigation design measures	Preventive measures: ■ **Welded connections.** Using welded connections for small-diameter piping is technically feasible for some parts of the piping system, but manufacturers state that they need to use some fittings. ■ **Testing of welds.** It is considered that Ultrasonic Thickness (UT) is not possible, only Radiographic Testing (RT) would be suitable, using X-rays or gamma rays. – It is considered that the likelihood of leakages is comparable for fittings and welding small-diameter piping. This means the dimensioning case for design and safety systems should be full bore rupture. This would be valid for fittings and small-diameter welded connections. – Make piping more robust by increasing pipe diameter. Feasibility of welded connections will improve by increasing the pipe diameter and size.

Hazard 1.4.1	Hazardous event: H2 leakage in piping (upstream or downstream section isolation valve)
	■ **Reduce leak points.** Reduction in number of potential leak points is challenging as the piping system will need many pipe connections. It is difficult to reduce the number of leak sources to zero. Mitigating measures: ■ **Burst disk for overpressure prevention in TCE.** Burst disks provide immediate pressure relief by bursting full-bore open. However, when a disk bursts, fragments can potentially damage equipment. Also, applying burst discs for pressure relief does not provide the opportunity to lead leaked gas to a safe area. A damaged burst disc can compromise the inert atmosphere inside the tank connection enclosure. ■ **Relief valve for overpressure prevention in TCE**. Pressure relief valves can relieve pressure gradually or in small increments, which is beneficial for maintaining system stability. Also, it can be adjusted to open at specific pressures, providing precise control. PRVs can be part of a vent system that leads to leaked gas to a safe area (e.g. vent mast). ■ **The inert gas system** onboard must have sufficient capacity and redundancy. In the event of leaks, it must be capable of managing several purge cycles, ensuring the safe evacuation of all hydrogen gases through the vent mast. ■ **Gas-tight enclosure (robust sealing system).** A fixed system will not be subjected to the same stresses as a containerised unit, making the engineering challenge of a gas-tight enclosure easier. ■ **Gas-freeing system** for inspection and maintenance.
Notes	The rapid expansion of the gas in case of a leak into the inert space may cause pressure build-up in the space. Therefore, it is critical to design the relief systems (burst disc, vent panels, etc) with adequate capacity. Workshop participants considered that CFD modelling could be used for this before standardized solutions are established.
Conclusion/ summary	**Inerted tank connection enclosures are preferred over naturally or mechanically ventilated enclosures for ship applications.** **Fixed hydrogen storage systems avoid many of the challenges of portable containerised storage systems, such as:** ■ Dependence on non-permanent flexible hoses to connect tanks and ship systems. ■ Dependence on non-permanent connections of control and safety systems. ■ Difficulties in applying secondary enclosures. ■ Hazards of lifting tanks on/off the ship. ■ Dependence on non-permanent sea fastenings. However, the risk of refuelling is moved from shore facilities to the ship.

Table 3-7 Hazard 1.4.2 Overpressure or temperature issues of the CH2 tank during bunkering.

Hazard 1.4.2	Hazardous event: Overpressure or temperature issues during bunkering
Node	■ Bunkering.
Potential causes	■ Too high pressure delivered to the ship.
Potential consequences	■ Overpressure of piping or tanks. ■ Fire/explosion.
Possible preventive and mitigation design measures	■ **Overpressure protection** is required for the bunkering line to safeguard the tank against being subjected to high pressures from the bunkering facility. ■ **Chilling the hydrogen before delivery to the ship.** It is assumed that units to cool the fuel will be arranged on the shoreside, not on the vessel. ■ **Temperature and pressure sensors** in the bunkering line.

Hazard 1.4.2	Hazardous event: Overpressure or temperature issues during bunkering
Notes	-
Conclusion/ summary	**Overpressure protection of tanks and piping will be needed.**

In addition, this concept will need to manage the risks associated with inert gas leakage and possible exposure to the crew. This was addressed in Table 3-5.

Furthermore, a concept involving mechanical ventilation of the connection space was evaluated. However, it was determined that managing a 250-bar pressurised leak through mechanical ventilation would be highly challenging. Maintaining concentrations below the Lower Explosive Limit (LEL) at all times would necessitate an extremely high ventilation rate. This would also make effective gas detection nearly impossible. Excess flow valves or restrictive flow orifices may help to reduce the leak rate. Nevertheless, uncertainty remains regarding their capacity to effectively manage small and medium-sized leaks, akin to the challenges encountered in naturally ventilated spaces discussed above.

3.5 Common hazards for CH2 fuel systems

By common CH2 fuel system hazards, we mean hazards that are not dependent on the concept of the fuel storage tank. The hazard identification assessed the following risks:

- Fire/explosion affecting fuel storage tank and piping by heat ingress.
- H2 leakages in the ship's fuel supply piping.
- High-pressure H2 supply introduced into ship's low-pressure supply system.

Basis for analysis

- Each fuel tank section has one or more Thermal Pressure Relief Devices (TPRDs) installed for pressure release in case temperatures exceed 110°C at the TPRD location. For portable tanks, the pressure relief system is connected to a fixed venting system on the ship, vented via a vent mast.
- For portable storage systems, containers are secured to the ship's structure using twist locks or similar devices in accordance with relevant sea fastening standards. The crew will be responsible for securing the container and ensuring that the flexible hoses and instrument lines between the container and the ship are properly connected.
- A fire on the ship (unrelated to the hydrogen system) can be managed by cooling the associated equipment or structure with water mist systems or similar methods provided by the vessel. Hydrogen fires should be extinguished by halting the hydrogen supply. Using water to extinguish the fire while gas continues to be released can lead to an explosion.
- Single-walled gaseous piping on ship.
- The fuel pressure regulation to consumers is performed by a pressure reduction and control valve assembly reducing the pressure from 350 bar to around 10 bar. Pressure reduction is currently not part of the containerised storage assembly for portable storage systems and is, therefore, a part of the fixed ship piping system.
- The fuel supply inlet pressure to the engine is assumed to be 6 to 7 bar in this case, indicating that compressors will not be required.

Table 3-8 to Table 3-10 present the hazards identified for common CH2 fuel system hazards.

Table 3-8 Hazard 1.5.1 Fire/explosion affecting fuel storage tanks by heat ingress.

Hazard 1.5.1	Hazardous event: Fire/explosion affecting fuel storage tanks by heat ingress
Node	■ Fuel storage tanks.
Potential causes	■ Fire/ explosion originating from hydrogen systems events or other non-hydrogen ship systems/areas (e.g. engine room or cargo areas) or outside of ship boundary. ■ Typical high fire-risk areas are the cargo area, engine rooms, battery spaces, etc.
Potential consequences	■ A hydrogen fuel system subject to an external fire will heat up, promoting the opening of pressure relief devices with subsequent hydrogen release. ■ The fire may damage the safety systems needed to control the fuel system and potentially the tank itself. ■ A hydrogen fuel system subject to an external explosion may be mechanically damaged (piping, tank) with subsequent rupture and explosion/deflagration, detonation or fireball. ■ A hydrogen fuel system subject to an external fire may experience a reduction in strength, with subsequent rupture and explosion/deflagration, detonation or fireball. ■ Steel hull structure losing strength due to fire onboard – influencing fuel containment system. ■ A fire may impinge on a pressure vessel without triggering the fuse of the TPRD.
Possible preventive and mitigation design measures	■ **Fire prevention and suppression systems in fire-risk areas,** in accordance with SOLAS and class regulations, may prevent exposure to hydrogen fuel systems. ■ **Water spray system** for cooling of fuel tanks and tanks surrounding. However, it should be noted that a water spray system can prevent the TPRD system from being triggered. ■ **Location of tanks and fuel system**, considering high fire-risk areas/areas of explosion risk onboard. ■ **Distance and/or cofferdams.** Minimum 900 mm free space (distance), and/or cofferdams. ■ **Thermal Pressure Relief Devices (TPRDs)** are employed to discharge the tank contents in the event that temperatures exceeding 110°C are detected at the TPRD location. This system is designed to safely vent the vessel's contents before the walls are compromised by heat, thus preventing catastrophic failure. The positioning of fuse sensors is crucial, as there is a risk of pressure vessel impingement from jet fire without the fuse reaching 110°C. ■ **A vent line for each tank** should be connected before the tank valve. Redundancy for TPRD should be considered in case of TPRD failure on demand. The reliability of TPRD needs to be investigated. Controlled blowdown may be accepted as a secondary means of venting (see point below). ■ **Controlled blow-down** through the fuel line to the vent mast is manually activated to reduce the pressure in the tanks. With lower pressure, the vessels will last longer (reduced pressure increases survivability). The risk of automatic release of TPRDs during an activated blow-down operation should be taken into account. Once gas or fire is detected, valves with ESD function are automatically closed, preventing manual blow-down unless all valves on the fuel line are reopened. This implies that a blow-down cannot be executed in critical situations when ESD is initiated; it must be employed before situations become critical or unmanageable. ■ **Passive fire insulation** of tanks and piping. ■ **Tank connection enclosure** provides protection against external fire. ■ **Tank connection enclosure** protects against impingement of jet fires to pressure vessels.

Hazard 1.5.1	Hazardous event: Fire/explosion affecting fuel storage tanks by heat ingress
Notes	■ Type IV pressure vessels are constructed from composite materials, which are more prone to heat damage than pressure vessels made of steel. ■ Fire resistance tests conducted during the ADR approval process demonstrated that pressure vessels could endure a direct flame for approximately 30 minutes before failing (simulating a deck fire on a truck) without reducing pressure via TPRD. ■ Tests show that the temperature and pressure inside the pressure vessels did not increase significantly before failure. This is due to the insulation performance of materials; the materials degrade until the tank fails. For this reason, a pressure relief valve is not considered an appropriate safety device. ■ If a TPRD fuse is activated, the entire CH2 content will be vented through the venting line, as TPRDs remain open after triggering. ■ Manufacturers of pressure vessels conduct in-house tests (i.e. burst testing, bonfire). ■ Temperature sensors inside the pressure vessel are possible. ■ Pressure monitoring of tanks.
Conclusion/ summary	**TPRD is the existing solution for preventing rupture of pressure vessels in case of fire.** However, there are still uncertainties relating to: ■ Can pressure vessels be exposed to jet fire impingement without the fuse of TPRD being activated? Requirement for location of TPRD sensor? If TPRD sensor is inside tank space or tank connection enclosure, it may take longer time before fuse of TPRD is activated in case of external fire (i.e. device has responded to high temperatures). **TPRD vent should be connected to ship's vent system and led to safe location.**

Table 3-9 Hazard 1.5.2 H2 leakages in the ship's fuel supply piping.

Hazard 1.5.2	Hazardous event: H2 leakages in the ship's fuel supply piping
Node	Supply piping, incl. fuel preparation.
Potential causes	■ Faulty connections and piping: Welds, flanges, fitting connections. ■ Design error, fabrication or installation error, and/or operating conditions (e.g. vibrations) or operating outside design limits. ■ Leak from valve stems. ■ Impact events.
Potential consequences	A leak before the pressure regulation will be a high-pressure leak, while downstream of the pressure reduction system, the leak pressure will be around the delivery pressure to the consumer. The consequence may be a jet fire (if immediate ignition) or a flash fire/deflagration/detonation (for delayed ignition) that may impact crew and/or safety-critical systems.
Possible preventive and mitigation design measures	■ **Double-walled piping** for all hydrogen fuel supply lines on the ship, including on the open deck. ■ **Mechanical protection of piping.**
Notes	A fuel supply piping system will have to be arranged from the fuel containment system to the consumers. Any leakages along the open deck routing will be difficult to detect and control. Reliable leakage detection and consequence-reducing measures are essential for ship safety.

Hazard 1.5.2	Hazardous event: H2 leakages in the ship's fuel supply piping
Conclusion/ summary	**Piping systems for compressed hydrogen should be arranged to include leak protection by employing secondary enclosures that can safely contain any leakages. A double barrier system will also facilitate reliable gas detection.**

Table 3-10 Hazard 1.5.3 High-pressure H2 supply introduced into ship's low-pressure supply system.

Hazard 1.5.3	Hazardous event: High-pressure H2 supply introduced into the ship's low-pressure supply system
Node	■ Supply piping, incl. fuel preparation.
Potential causes	■ Failure of pressure regulation system.
Potential consequences	■ Overpressure. ■ Pipe rupture. ■ Fire/explosion.
Possible preventive and mitigation design measures	■ Two-stage pressure regulation. ■ Pressure relief.
Notes	If a pressure-regulating device fails, the downstream part of the system may be exposed to significantly higher pressures than it was designed to handle. A commonly implemented mitigating measure involves protecting the low-pressure system with a pressure relief device that ensures the system pressure remains within design limits.
Conclusion/ summary	If a pressure-regulating device fails, the downstream part of the system may be exposed to significantly higher pressures than it was designed to handle. **The workshop participants considered that two-stage pressure regulation and pressure relief can ensure the system pressure remains within design limits.**

4. Hazard identification of liquefied hydrogen (LH2) fuel systems

This section discusses a standard LH2 fuel system employing vacuum-insulated hydrogen tanks designed as pressure vessels (IMO Type C), situated below deck. A flow diagram of the LH2 fuel system is shown in Figure 4-1.

Basis for analysis

The concept used as the basis for workshop discussions has the following features:

- Hydrogen will be stored onboard in vacuum-insulated pressure vessels designed in accordance with requirements for an IMO Type C fuel tank.
- The tanks are located in a dedicated fuel storage hold space in accordance with the requirements for natural gas in the IGF Code Part A-1.
- All tank connections are arranged in dedicated Tank Connection Spaces (TCS).
- The fuel system is designed in accordance with the requirements for natural gas fuel systems as laid out in the IGF Code Part A-1.
- Maximum design pressure of these pressure vessels is approximately 10 bar or less.
- TCS is arranged with leakage detection and automatic closing of tank valves upon detected leakages.

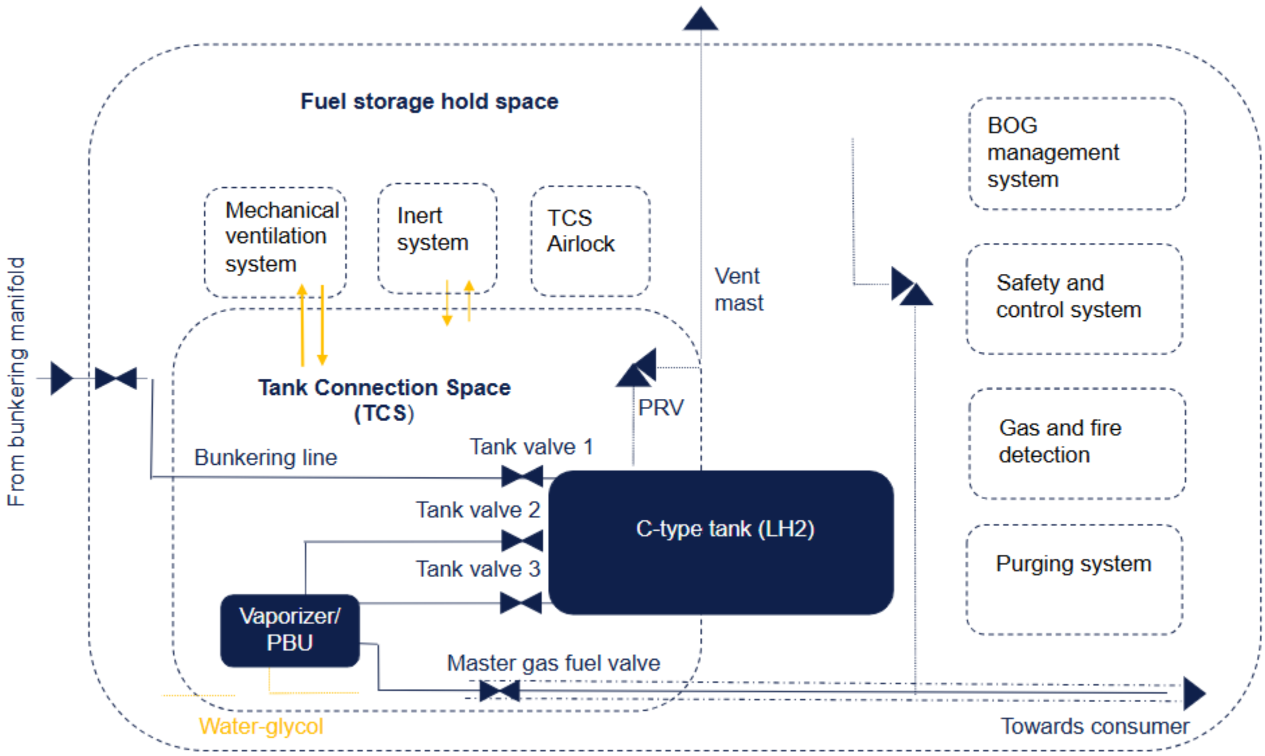

Figure 4-1 Flow diagram of the generic LH2 fuel system (Source: DNV).

Three TCS protection strategies are investigated:

1. The TCS is arranged with mechanical ventilation intended to dilute any leakage below the lower flammability limit.
2. The TCS is arranged with an inerted atmosphere to prevent ignition of any leaked hydrogen.
3. The TCS is arranged with secondary enclosures around the complete hydrogen system.

The following reflects the findings and discussions of the HAZID team on the subject of storing liquefied hydrogen below deck/in enclosed spaces.

4.1 Tank connection space arranged with mechanical ventilation

Where the necessity for numerous piping components renders fitting a secondary enclosure around the piping impractical, the IGF Code permits these components to be situated in dedicated gas-tight spaces where it is feasible to manage the ignition sources in a natural gas atmosphere. Examples of such spaces include tank connection spaces, fuel preparation rooms, and gas valve units.

Hazard Identification results

Table 4-1 presents the hazard identified for a gas leak inside a mechanically ventilated tank connection space. Common hazards for LH2 systems are presented in Chapter 4.5.

Table 4-1 Hazard 2.1.1 Gas leak inside mechanically ventilated TCS.

Hazard 2.1.1	Hazardous event: Gas leak inside mechanically ventilated TCS
Node	▪ Tank connections.
Potential causes	▪ Leaking pipes, pipe connections or components in liquefied or gaseous hydrogen fuel system.
Potential consequences	▪ Jet fire (immediate ignition). ▪ Deflagration/detonation (delayed ignition). ▪ Cooling of structure and equipment. ▪ Overpressure. ▪ Asphyxiation. ▪ The explosion pressure from a deflagration in an enclosed space may damage bulkheads and possibly other safety barriers and allow the leak to spread further, escalating the situation.
Possible preventive and mitigation design measures	Preventive measures: ▪ **Minimise the probability of leakages.** All fuel piping systems should be designed and arranged to minimise the probability of leakages. This implies using materials that are not deteriorated by hydrogen, are suitable for the system's design temperature, are arranged and supported to ensure that operational conditions do not cause undue stresses and are connected by welding as far as possible. Where welding is not possible, joining methods are chosen to minimise the probability of leakage. ▪ **All fuel piping systems for LH2 should be arranged with a system to manage the heating up and corresponding pressure** increase of trapped volumes of LH2 and vent it to open air at the safest location possible. ▪ **Piping systems for hydrogen should be arranged for nitrogen purging.** Introducing hydrogen into an empty piping system could lead to ignition and higher pressure than the system is designed for.

Hazard 2.1.1	Hazardous event: Gas leak inside mechanically ventilated TCS
	Mitigating measures: ■ **The fuel containment and piping systems should be designed to ensure that the operational releases from purging, gas freeing and pressure relief are managed safely.** This is also applicable for emergency releases due to system leaks and loss of vacuum insulation on tanks and systems. ■ **Low temperature protection.** The potential for low temperatures in a space or area due to cryogenic leakage or vacuum loss should not compromise the integrity of structural materials, the functionality of safety systems or components necessary for the ship's safety. ■ **Any leaks from tanks and piping systems should be detectable and automatically isolated from the source of the hydrogen supply.** Segregation valves should be arranged to limit the amount of hydrogen discharged after a leakage is detected and stopped. ■ **The number of ignition sources should be minimised.** However, due to the ease of hydrogen ignition, relying on ignition control to manage hydrogen leakage does not provide a reliable safety barrier. ■ **Fuel piping systems should be designed to minimise the consequences of leakage** by limiting the inventory of hydrogen in the system to what is necessary for operation.
Notes	■ A Gexcon study[2] for a room size equivalent to a 20-foot container showed that, even with 10x the original ventilation rate (10,000 m^3/h), the gas from a 0.5 mm^2 leak will fill the entire enclosure within seconds, and a maximum cloud size is developed after only 10 seconds. Further, while the 10x ventilation rate would use approximately 40 seconds to reduce the flammable volume (m^3) to zero, the original rate would use more than 80 seconds (Gexcon, 2022). A 20-foot ISO container has a volume of 32.6 m^3, implying that the ventilation rates in this example correspond to 30 and 300 air changes/hr. ■ Ventilation as a possible risk mitigation measure for hydrogen installations has also been discussed and analysed in the MarHySafe project[3]. CFD analyses of hydrogen releases in enclosed spaces indicate that a release of 220 grams hydrogen over a 30-second period in a typically sized maritime room (80 m^3) with a ventilation rate of 100 air changes per hour (more than 3 times what is required in the IGF Code for natural gas) can generate an explosive atmosphere. As a safety barrier, ventilation could be used to prevent small leakages from building up an ignitable hydrogen atmosphere but would not prevent possible ignition and jet fire. For more significant hydrogen releases in enclosed spaces, forced ventilation should not be considered as a reliable safety barrier. It should be noted that the main safety barrier applied in other industries is to exclude the possibility of hydrogen leakages in enclosed spaces. ■ To make hydrogen storage in enclosed spaces/below deck a viable alternative, additional safety barriers must be implemented in tank connection spaces and fuel preparation rooms to reduce the likelihood of a hydrogen explosion to a minimum.
Conclusion/ summary	As a safety barrier, dilution (mechanical) ventilation could prevent small leakages from building up an ignitable hydrogen atmosphere in TCS but would not prevent possible ignition and jet fire. For more significant hydrogen releases in enclosed spaces, forced ventilation should not be considered a reliable safety barrier. It should be noted that the main safety barrier applied in other industries is to exclude the possibility of hydrogen leakages in enclosed spaces. **The HAZID participants concluded that designing the system to meet IGF Code standards for natural gas while protecting the TCS with a dilution ventilation system would not adequately safeguard against explosions following a leak of liquefied or compressed hydrogen.** Note that concept with TCS arranged with secondary enclosure for liquefied and gaseous hydrogen piping systems is analysed in Chapter 4.3.

[2] Gexcon - FLACS-CFD User Group (FLUG) Meeting: Is ventilation your trustworthy old friend when it comes to hydrogen?
[3] MarHySafe - Handbook for hydrogen-fuelled vessels. MarHySafe JDP Phase 1. DNV, 1st edition (2021- 06).

4.2 Tank connection space arranged with inerting

As discussed in the previous chapter, dilution ventilation is not considered a suitable mitigation strategy for hydrogen. An alternative could be to operate with an inert atmosphere in the TCS to prevent leaking hydrogen from mixing with an oxidiser.

Hazard Identification results

Table 4-2 presents the hazards identified for a gas leak inside an inerted tank connection space. Common hazards for LH2 systems are presented in Chapter 4.5.

Table 4-2 Hazard 2.2.1 Hazardous event: Gas leak inside an inerted TCS.

Hazard 2.2.1	Hazardous event: Gas leak inside an inerted TCS
Node	▪ Tank connections.
Potential causes	▪ Leaking pipes, pipe connections or components in liquefied or gaseous hydrogen fuel system.
Potential consequences	▪ Jet fire (immediate ignition). ▪ Deflagration/detonation (delayed ignition). ▪ Cooling of structure and equipment. ▪ Overpressure. ▪ Asphyxiation.
Possible preventive and mitigation design measures	Preventive measures: ▪ **Preventive measures listed for mechanically ventilated TCS will also be applicable to the inerted TCS.** Mitigating measures: ▪ **Mitigating measures listed for mechanically ventilated TCS will also be applicable to the inerted TCS**. ▪ **Secondary enclosures for the LH2 system** capable of containing any leaks and leading the leaks to a safe area on the open deck. ▪ **An inert gas system** able to purge the TCS of air and keep an inert atmosphere in the space at all times. ▪ **An inert gas reservoir** sufficient to purge any leaked hydrogen safely from the TCS to a safe area on the open deck. ▪ **A gas-freeing system** able to safely lead the nitrogen/hydrogen mixture to a safe area on the open deck. ▪ **A monitoring system able to measure the oxygen content** in the TCS at all times. ▪ **A pressure relief system** with sufficient capacity would have to be arranged to prevent damage due to pressure rise from rapidly evaporating LH2 or CH2.
Notes	▪ The cryogenic temperature of LH2 leaks can influence the aggregate state of the inert gas and quickly alter the pressure within the TCS. A leakage of LH2 can cool down the space below the condensation temperature of nitrogen in seconds, as demonstrated at DNV's Spadeadam facility in the UK[4]. The HAZID team concurred that it would be sensible to prevent liquid leakages by installing secondary enclosures around potential leak points in the LH2 system to alleviate these effects. Operationally, LH2

[4] FFI - Large scale leakage of liquid hydrogen - tests related to bunkering and maritime use of liquid hydrogen.

<table>
<tr><th>Hazard 2.2.1</th><th>Hazardous event: Gas leak inside an inerted TCS</th></tr>
<tr><td></td><td>lines are likely to be vacuum insulated. Additional protection should be arranged around valves and other components in the LH2 system. Further discussions on the suitability of inert gas protection of the TCS assumed that leakages would only come from the “warm” gaseous fuel system.

■ Even with secondary enclosures safeguarding LH2 piping, losing vacuum insulation can cause nitrogen condensation on cold surfaces. The primary risk here is the vacuum loss from the tank, as the tank boundary is a significant part of the TCS boundary. It is unclear how this will affect the flammability of the TCS atmosphere.

■ Maintaining an inert atmosphere would require that ventilation arrangements are closed off to prevent the inert gas from escaping. This implies that the protected space is vulnerable to pressure increases due to leaks. A pressure relief system with sufficient capacity would have to be arranged to prevent damage due to pressure rise from rapidly evaporating LH2 or CH2.

■ An inert atmosphere will prevent access for inspection and maintenance. If the TCS is gas-freed for entrance, the primary safeguard that prevents an explosion would be removed. In order to do this safely, it would be necessary to gas-free the complete hydrogen fuel system, including the fuel tank. Also, removing the possibility of close-up inspection and maintenance during operation could have an unfavourable effect on the reliability of essential safety functions.

■ Hydrogen can ignite with less oxygen than the ignition of natural gas would require (5% vs 12%). This would put stricter requirements on inert gas quality. The presence of ventilation systems could introduce air into the inert space.

■ The inert gas system is safety critical. If there is an oxygen concentration level above the Limiting Oxygen Concentration (LOC) in the TCS, which is undetected (dangerous undetected failure), and a leak occurs, the consequences can be severe due to high ignition probability and subsequent fire and explosion effects. The safety system should ensure that there is always an inert atmosphere in the space during operations:
– Need to monitor for oxygen in the space.
– Low oxygen alarm for the tank hold space.
– Sufficient to monitor for oxygen or monitor for 98% nitrogen.
– Slight overpressure in TCS and unventilated fuel storage hold space.
– Gas-tight integrity of TCS is important.
– Redundancy in detection important.
– Prior to entering, verifying oxygen level.
– Considering layering of gases.
– Access should be through a bolted hatch to avoid entering an inerted space.

■ Following a leak, the TCS will be filled with hydrogen and inert gas that must be safely vented to the atmosphere. This procedure poses a risk of inadvertently introducing oxygen into the TCS, which could lead to an explosion. To effectively dilute the TCS with nitrogen, the ship must maintain a supply of nitrogen, necessitating adequate storage facilities. There are many phase transitions here (hydrogen-air - nitrogen - oxygen) / the automation system role (or procedures) is crucial to do the right action with the right intensity based on the thermodynamics of the space.</td></tr>
<tr><td>Conclusion/ summary</td><td>■ Liquefied hydrogen leakages from piping into the TCS must be prevented by secondary enclosures.

■ An inert atmosphere prevents access to the TCS during operation.

■ It is unclear how a loss of vacuum will affect the primary safety barrier (nitrogen-filled TCS).

■ Gas freeing after a leakage is a complex operation with the possibility of error.

■ The main safety barrier is dependent on an active barrier (constant availability of nitrogen).</td></tr>
</table>

Hazard 2.2.1	Hazardous event: Gas leak inside an inerted TCS
	Preventing ignition by removing the oxidant is a sound principle, but the complexity of the solution and the unknowns make prescriptive regulatory guidance difficult for this concept.

4.3 Tank connection space arranged with secondary enclosure for liquefied and gaseous piping

Considering the IGF Code's premise that a hydrogen-fuelled vessel should be as safe as a conventional oil-fuelled vessel, neither dilution ventilation nor space inerting offers sufficiently robust safety barriers to lower the probability of an explosion.

One approach could be to require secondary enclosures for liquefied and gaseous hydrogen piping systems within tank connection spaces, fuel preparation rooms, and other spaces where hydrogen leaks may occur. A functioning double barrier around the piping systems might minimise the risk of creating an explosive atmosphere in enclosed spaces to a point where the serious consequences of an explosion become justifiable. Furthermore, given the TCS's limited capacity for containing releases from the primary barrier, the debate over potential leakage rates becomes less significant, as the protective secondary enclosure must safely manage any leakage filling the annular space, whether it results from a small or medium-sized leak or a full-bore rupture.

Hazard Identification results

Table 5-3 presents the hazards identified for a gas leak inside a tank connection space arranged with secondary enclosures for all hydrogen piping.

Table 4-3 Hazard 2.3.1 Gas leak inside a TCS where a secondary enclosure protects all leak sources.

Hazard 2.3.1	Hazardous event: Gas leak inside a TCS where all leak sources are protected by a secondary enclosure
Node	▪ Tank connections.
Potential causes	▪ Leaking pipes, pipe connections or components in liquefied or compressed hydrogen fuel system.
Potential consequences	▪ Jet fire (immediate ignition). ▪ Deflagration/detonation (delayed ignition).
Possible preventive and mitigation design measures	Preventive measures: ▪ Preventive measures listed for mechanically ventilated TCS will also be applicable to the TCS arranged with secondary enclosures for all H2 piping. Mitigating measures: ▪ Mitigating measures listed for mechanically ventilated TCS will also be applicable to the TCS arranged with secondary enclosures for all H2 piping. ▪ Piping systems for liquefied and compressed hydrogen should be arranged with **secondary enclosures** around the complete system to protect the TCS against leakages. ▪ **Pressure relief of the outer pipe** must be arranged for secondary enclosures. For vacuum-protected systems, the relief system must not compromise the vacuum inside.
Notes	▪ The IGF Code concept of mechanically ventilated secondary enclosures for natural gas piping systems is unsuitable for hydrogen piping systems due to the risk of ignition and deflagration/detonation of leaked hydrogen in the outer pipe. In a piping system for gaseous hydrogen, an inert gas filling may be used to prevent flammable mixtures in the outer pipe. This is not an alternative for LH2, as nitrogen may condense due to the low temperature on the surface of the inner pipe', since the inner pipe will always be too cold for N2 to be a suitable inert gas for the double barrier, also without any leak scenario. Vacuum (or helium) in the outer pipe may be used.

Hazard 2.3.1	Hazardous event: Gas leak inside a TCS where all leak sources are protected by a secondary enclosure
	■ Ventilated secondary enclosures should not be used due to the risk of ignition and deflagration/detonation of leaked hydrogen in the outer pipe. ■ Piping systems for LH2 should be arranged with a vacuum in the outer pipe to prevent flammable mixtures, as nitrogen may condense due to the low temperature on the surface of the inner pipe. ■ Piping systems for gaseous hydrogen could use an inert gas to prevent an ignitable atmosphere in the outer pipe. ■ Pressure relief of the outer pipe must be arranged with closed double barrier systems. For vacuum-protected systems, the relief system must not compromise the vacuum inside. ■ The HAZID team believed that it was feasible to have a fuel system safeguarded with double barriers at the main leak points. Still, it stressed that it is important to recognise that minor leakage points will be difficult to eliminate completely. This applies to small instrument lines for pressure sensors and to the flanged connection of tank safety valves. ■ Small leakages can still be a hazard when it is not possible to have secondary enclosures around minor leakage points. The discussion then becomes whether a mechanically ventilated or inerted TCS is feasible if leakage points are minimised. ■ Installing flow-limiting orifices is one effective method to minimise leakages from instrument lines. These orifices reduce the cross-sectional area of the potential leak point if the instrument line downstream of the orifice becomes damaged. Additionally, instrument lines should be avoided in liquid lines because the impact of leakages is significantly greater due to the vaporisation of liquid hydrogen. This may be a challenge in bunkering lines, where system pressure information is important to perform bunkering safely. If needed, an open deck location for such sensors should be considered. ■ When the volume of a space and the ventilation rates are known, it is possible to estimate the maximum leakage rate that can be tolerated. However, to consider the effects of the location of ventilation inlets and outlets, the structure inside the TCS, and the position of the leaks, a Computational Fluid Dynamics (CFD) analysis may be necessary. However, it would be resource demanding and a source for project uncertainty to evaluate results from CFD for each project individually. It would be beneficial from a regulatory standpoint to establish clear guidelines, such as acceptable orifice openings and ventilation rates. This would provide easy-to-follow guidance for designers and shipyards. To explore the relationship between maximum probable leakage and a ventilation system that ensures safety against the formation of an explosive atmosphere, maximum leak rate estimates, possibly combined with a CFD study, could indicate the feasibility of this approach. ■ To reduce the risk of creating an explosive atmosphere, several measures could be taken. These include minimising the diameters of orifice openings, designing the TCS geometry to prevent the accumulation of hydrogen gas, and optimising the ventilation system to address leak points and ensure a uniform change of atmosphere throughout the TCS. ■ It was noted that a high ventilation rate would make it more difficult to detect smaller leakages. Early detection of leakages is important to prevent the development of a less manageable scenario. ■ Even if it would be possible to arrange a ventilation system that can mitigate the explosion risk, it is not possible to prevent the ignition of a leakage and a small or larger jet fire from the leakage point. If detected, it was assumed that it would be possible to design for such a fire scenario. The ability to detect such fires would be a necessity from a regulatory point of view.
Conclusion/ summary	**A liquefied fuel containment system, where the piping systems for liquefied and gaseous hydrogen are protected against leakages by secondary enclosures for the complete system, would be possible to make safe from a flammability point of view.**

Hazard 2.3.1	Hazardous event: Gas leak inside a TCS where all leak sources are protected by a secondary enclosure
	The feasibility of applying dilution ventilation as an additional safety barrier if some smaller leakages sources cannot be protected by secondary enclosures must be further investigated. This will depend on maximum leak rates, ventilation rates and space layout. Jet fires from leakage points must be detectable and manageable without risk of escalation. Inerting of TCS could also be a possible compensating measure in such cases.

4.4 Bunkering station for LH2 bunkering

Fuel transfer introduces additional leakage hazards and system threats, which must be carefully managed to ensure safe bunkering. If the bunkering station is situated on an open deck without significant congestion or any semi-enclosed spaces nearby, natural dilution can help disperse any leakages. An open environment will also reduce the impact of an ignited gas cloud.

In cases where vessel geometries do not allow for an open bunkering station, managing the risks associated with fuel transfer becomes more challenging. It is reasonable to assume that a hydrogen leak can quickly create an explosive atmosphere in the bunkering station, and the possibility of ignition cannot be ruled out.

Basis for analysis

A concept illustration of the liquefied hydrogen bunkering arrangement is provided in Figure 4-2. The following assumptions for arrangement, including control and safety functions, are made for the bunkering station and interface with the bunkering supplier:

- The LH2 is led from the bunkering station to the IMO type C tank(s) via a vacuum-insulated double-walled piping system preventing air condensation.
- Dry Quick Connect/Disconnect Couplings (dry QCDC), allowing easy connection/disconnection without the use of manual intensive operation (such as tightening bolts), whilst including self-containing stop valves at the female and male ends to avoid spillage of hose and receiving line content that may possibly be contained in the lines.
- One bunkering line (and one vapour return line, if used).
- Interface with inert gas supply system.
- Detection system for leaks (low temperature), gas, and flames, including alarms and automatically operated isolation valves.
- Control and monitoring system, including tank level alarm and monitoring systems.
- A ship-shore-link (SSL) or equivalent means for ESD communication between the receiving ship and supplier.
- Pressure relief lines (routed to vent mast).
- Drip tray.
- Communication system.

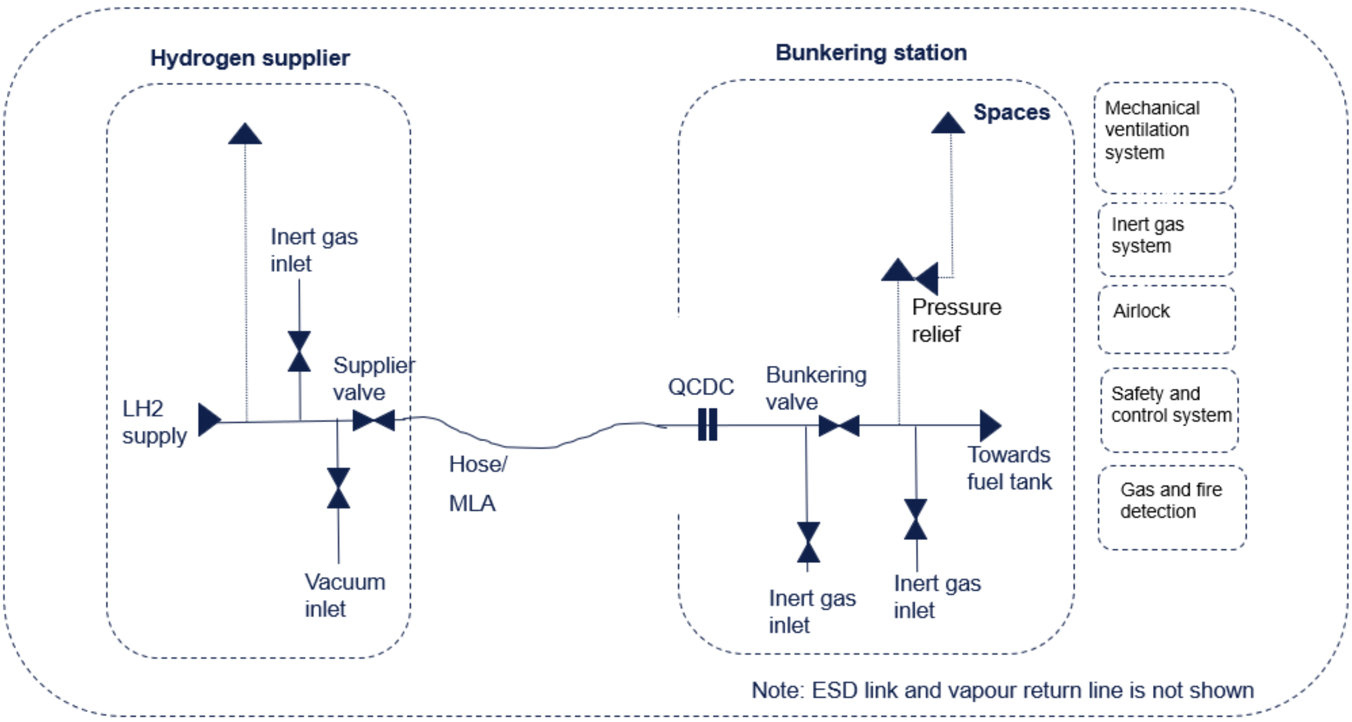

Figure 4-2 Flow diagram of the generic LH2 bunkering system (Source: DNV).

Other essential non-ship systems, equipment and arrangements that influence the risk picture but are typically not covered by regulations or rules applicable to the ship:

- Bunkering hose (cryogenic, vacuum insulated flexible) or use of Marine Loading Arm (MLA). Flexible hoses may also be supported by an MLA.
- Emergency Release System (ERS) in case of ship drift-away incidents. The general functionality of ERS includes a break-away coupling or Emergency Release Coupling (ERC) and emergency shutdown function. If powered (remote actuated), this system is referred to as Powered Emergency Release Coupling (PERC). This is located at one end of the transfer system, either the receiving ship end or the bunker supplier end. The coupling gives way before excessive pull causes the hose to break or other damage.
- Shoreside safety zones.

Hazard Identification results

Table 4-4 presents the hazard identified for hydrogen leakage during bunkering for a generic LH2 bunkering system.

Table 4-4 Hazard 2.4.1 Hydrogen leakage during bunkering.

Hazard 2.4.1	Hazardous event: Hydrogen leakage during bunkering
Node	■ Bunkering.
Potential causes	■ Leaking pipes, pipe connections or components in liquefied hydrogen fuel bunkering system.
Potential consequences	■ Deflagration/detonation (delayed ignition). ■ Cryogenic damages.

Hazard 2.4.1	Hazardous event: Hydrogen leakage during bunkering
	■ Cooling of structure and equipment. ■ Overpressure. ■ Asphyxiation.
Possible preventive and mitigation design measures	Preventive measures: ■ Piping systems used for bunkering hydrogen should be designed **to minimise the probability of leakages**, contain leakages if they occur, and avoid cold surfaces where air can condense. ■ **The construction and support of the ship bunkering manifold** should be strong enough to prevent damage to the bunkering system in a drift-off, where the bunkering hose is the only point connecting the ship to the bunkering facility (i.e. be dimensioned for the forces from the dry-break away coupling). Mitigating measures: ■ **Bunkering stations should be located on the unobstructed open deck,** if feasible, based on the ship's design. ■ **All leak sources related to the bunkering system onboard must be safeguarded by secondary enclosures** designed to contain leaks and direct them to a secure location. This would leave the bunkering connection as the high-risk leakage point. ■ **Minimising the volume of the bunkering station.** In cases where semi-enclosed bunkering station arrangements are required due to the ship's design, consequences of an ignited leakage could be reduced by minimising the volume of the bunkering station that could potentially experience large leaks. One way to do this is by separating the area of the bunker manifold connection point from the rest of the bunkering station. The separation should aim to ensure that this part of the bunkering station can withstand the effects of an ignited leak. ■ **PPE.** Personnel involved in bunkering operations should be outfitted with appropriate personal protective equipment (PPE). ■ **Dry break-away coupling.** The bunkering hose should be arranged to separate the ship and the bunkering facility without releasing hydrogen or overloading the ship or bunkering facility manifolds (dry break-away coupling). ■ **Leakage detection and shutdown.** The bunkering system should be arranged with means to detect leakage and systems to automatically stop the bunkering process. ■ **Shut-down valve.** The bunkering system should be arranged with a shut-down valve in the bunkering station to facilitate emergency closing of the bunkering supply. ■ **An emergency shut-down communication system** should be arranged between the ship and the bunkering facility.
Notes	■ The IGF code mandates that a bunkering line for natural gas must be inerted when not engaged in bunkering unless safety can be assured without it. Similar language is suggested in the forthcoming draft interim guidelines for hydrogen. When dealing with LH2, the bunkering pipe becomes extremely cold right after bunkering, and N2 can solidify in the fuel system unless the lines are adequately purged beforehand. The presence of N2 in the hydrogen poses both purity and safety concerns. ■ Mistakes in bunkering procedures may introduce frozen nitrogen or air, which may contaminate the LH2 piping system. To prevent contaminations, it could be possible to purge the air-filled bunkering line with nitrogen and then purge the nitrogen with hydrogen gas prior to introducing cryogenic hydrogen. ■ In onshore industries, it is a standard procedure to maintain lines filled with gaseous hydrogen under slight overpressure to prevent the intrusion of contaminating gases. ■ Bunkering with vapour return – It is assumed that the pressure in LH2 tanks can be managed similarly to the process used in LNG bunkering. This involves alternating between bottom filling and top filling. In top filling, the warmer vapour space within the tank is cooled by spraying cold hydrogen from the bunkering facility, which helps to reduce the pressure in the tank. The lack of a vapour return system will lower the number of potential leak points. Additionally, bunker suppliers are often hesitant to accept

Hazard 2.4.1	Hazardous event: Hydrogen leakage during bunkering
	vapour from tanks where they cannot ensure the quality of the fuel. Furthermore, the bunker supplier's facility may not be equipped to handle the warm gas flow coming from the ship. ■ Specified bunkering time will affect the dimensions of the bunkering line (shorter bunkering time dictates a larger bunkering line diameter). As opposed to CH2 tanks, LH2 tanks will have a separate bunkering line. Example: DN100 is used for quick bunkering of 2x200 m^3 fuel tanks, with a half-hour bunkering. This implies a large PERC and QCDC. Trailer connections are typically DN40. Many trailers have the possibility for vapour return, but they normally do not want to use it.
Conclusion/ summary	**The liquefied hydrogen bunkering manifold should be positioned on the open deck, avoiding locations where hydrogen gas may accumulate, as much as the ship's arrangement allows.** In cases where semi-enclosed bunkering station arrangements are required due to the ship's design, the consequences of an ignited leakage should be reduced by minimizing the volume of the bunkering station that could potentially experience large leaks. The process of inerting of LH2 bunkering piping with N2 between the bunkering operations needs to be further considered, since the added complexity will introduce more risk of failure, and since any N2 is remaining in the piping when liquid H2 is introduced this will give risk of clogging of valves and piping. Keeping H2 with a slight overpressure, similar to what is done in land applications, may prevent air ingress in bunkering line.

4.5 Common hazards for LH2 fuel systems

Basis for analysis

Liquefied hydrogen (LH2) is stored at an extremely low temperature of -253°C. This temperature is much lower than the temperatures at which nitrogen and oxygen in the air condense into liquids. Specifically, nitrogen condenses at around -196°C and oxygen at about -183°C (solidification temperature N_2 -210°C, O_2: -218°C).

If the storage tank vacuum insulation is lost, the following consequences may occur:

- **Liquefied air:** The exterior of the liquefied hydrogen (LH2) tank can become so cold that it causes the oxygen and nitrogen in the air to condense into liquids. This liquid air, which contains a high concentration of oxygen, can be highly flammable as oxygen supports combustion.
- **Solidifying:** If the insulation fails and the temperature drops significantly, it is also possible for the surrounding air to reach these extremely low temperatures and solidify.
- **Structural damage:** If this very cold liquid air touches the ship’s steel, it can make the steel brittle and cause it to crack or break quickly. This is because extremely low temperatures can make materials like steel lose their ductility, a process known as low-temperature embrittlement.
- **Increased boil-off and increased pressure:** The heat input to storage tanks and piping systems will increase rapidly, resulting in increased boil-off from the tank and the discharge of the stored LH2 through the vent mast, as the tank will not have the capacity to contain the pressure build-up. The consequences of igniting the released hydrogen will depend on the circumstances.
- **Cryo-pumping:** This may occur if the vacuum is compromised due to an issue with the outer jacket. Air leaking into the vacuum space will continuously solidify and restore the vacuum.

Hazard Identification results

Table 4-5 presents the hazard identified for loss of vacuum insulation on LH2 tanks or LH2 piping systems.

Table 4-5 Hazard 2.5.1 Loss of vacuum insulation on LH2 fuel tanks or LH2 piping systems.

Hazard 2.5.1	Hazardous event: Loss of vacuum insulation on LH2 fuel tanks or LH2 piping systems
Node	■ Fuel storage tanks.
Potential causes	■ Loss of vacuum insulation on LH2 tanks or in LH2 piping systems.
Potential consequences	■ Structural damage or loss of safety functions due to cooling. ■ Excessive boil-off from fuel containment system due to increased heat input, which may ignite on deck. ■ Cryo-pumping of air into cold low-pressure reservoirs (e.g. vacuum insulation, piping systems).
Possible preventive and mitigation design measures	Preventive measures: ■ **Minimise the probability of air entering the vacuum space and hydrogen leaking into the vacuum space.** The outer tank of a vacuum-insulated fuel containment system and the piping systems connecting the inner tanks to the tank exterior should be designed to minimise the probability of air entering the vacuum space from outside and hydrogen leaking into the vacuum space from the tank side, compromising the vacuum insulation. ■ The inner pipe of a double walled piping system should be designed to **minimise the probability of hydrogen leaking into the vacuum space and compromising the insulation**. ■ **Double-walled piping in the tank vacuum space** should be considered. ■ **Pressure relief systems fitted to relieve pressure in the vacuum space** should also be arranged to avoid air entering the vacuum space from the outside. ■ Fuel containment and piping systems should have **effective insulation** to avoid unnecessary boil-off under normal operating conditions. Mitigating measures: ■ **The design and capacity of the pressure relief arrangements** should be suitable for situations in which LH2 containment systems or piping lose insulation properties. ■ **Ship's design capabilities.** If the fuel containment systems or piping systems for LH2 lose insulation through vacuum loss, managing the resulting cooling of the surroundings should be within the ship's design capabilities. ■ **Avoid ice formation on cold surfaces.** The fuel containment and piping systems should be designed to avoid ice formation on cold surfaces from moisture in the air under normal operating conditions. ■ **Manage the possibility of air condensing on cold surfaces upon loss of insulation.** The fuel containment and piping systems, including the piping for the pressure relief arrangements from the tank and systems, should be designed to safely manage the possibility of air condensing on cold surfaces upon loss of insulation. ■ **The ship is arranged to manage the resulting lower temperatures** in fuel storage hold spaces, tank connection spaces, and other spaces that may be affected. Issues to cover include: – Using materials able to perform as intended in the lowest temperature they may be subjected to. – Ensure that all components of safety systems required to mitigate hydrogen safety events can continue to operate at the lower temperature after loss of tank or system vacuum insulation. ■ **Vent mast design:** – Vent mast surface temperature remains above the condensation temperature of the air or arrangements are made to collect the condensed air safely. The vent system must also be designed to manage the contraction of the piping system when it is cooled down to approximately the storage temperature of the hydrogen. – Vent mast designed for detonation pressure would mitigate a worst-case ignition of hydrogen/air mixture during a hydrogen release. Another option is to constantly supply inert gas to the vent mast. ■ If hydrogen discharged to the open deck is ignited, the consequences for the ship with respect to pressure effects and heat load should be manageable. This includes scenarios with flash fire, jet fire,

Hazard 2.5.1	Hazardous event: Loss of vacuum insulation on LH2 fuel tanks or LH2 piping systems
	and deflagrations. Deflagration-to-detonation and detonation should be avoided by design. Manageable implies that heat loads and pressure shocks should be at a level that allows people to evacuate the area without injuries and that access to muster stations, escape routes, and life-saving appliances is not restricted.
Notes	▪ Assuming that the application of double barriers can exclude direct cooling as a result of LH2 leakages, the worst-case scenario from a cooling perspective is the loss of the vacuum on the tank. ▪ The consequence of vacuum loss depends on the vacuum insulation design. It is expected that tanks with insulation medium in the vacuum space (e.g. perlite) will behave differently than tanks without. Multi-layer insulation on the inner tank is better for normal operation. Glass bubbles or perlite will lead more heat into the storage tank. At a loss of vacuum, you will lead air into glass bubbles or perlite. If you have multi-layer, you will only have air in the space. Requiring one or the other is not considered a regulatory issue – it is up to the designer and shipowner. ▪ Ventilation of the annular space is typically directed into the TCS for LNG tanks. This will not be a suitable solution for hydrogen tanks. In the case of single hydrogen piping in an annular space, any leaked hydrogen would be directed into the TCS. It should be directed to the vent mast if double walled piping is not arranged in the vacuum space. ▪ The Fuel Storage Hold Space (FSHS) must be expected to see significant cooling when the surface temperature of the vacuum jacket is close to the storage temperature of LH2. Also, it cannot be excluded that the FSHS atmosphere starts to condense on the cold surface of the tank. This may necessitate the arrangement of drip trays to protect the ship structure from direct exposure and cooling. Another approach could be to fit conventional insulation on the outside of the vacuum jacket to prevent the surface temperature from falling below the condensation temperature of the air. Increasing the ventilation rate would add heat to TCS. ▪ The same cooling effect can cause issues in the TCS, where the tank wall is typically a part of the TCS boundary. Even though the TCS should be designed to handle air liquefaction since the material typically withstands cryogenic temperatures, low temperatures may affect the proper functioning of the safety systems (valve operation, gas detection, etc.). A similar effect may be caused by the loss of vacuum insulation in the LH2 piping system, but this will probably be less pronounced than for vacuum loss of the tank. ▪ Heat balance calculations must likely be performed on a case-by-case basis to evaluate the vacuum loss thermal effects on fuel storage hold space and TCS. Inerted spaces without air circulation would likely become colder than mechanically ventilated spaces. ▪ A worst-case scenario involving hydrogen ignition on the open deck is a delayed ignition of an established hydrogen plume above the ship, continuing as a jet fire from the top of the vent mast. The risk of a damaging pressure build-up from a deflagration of the initial hydrogen cloud will depend on the geometry around the release point at the top of the vent mast. The heat load from the jet fire depends on hydrogen mass flow, the height of the vent mast and the geometry around the release point. ▪ Calculations estimating maximum boil-off rates and the consequences of delayed ignition and a subsequent jet fire from the top of the vent mast must likely be performed on a case-by-case basis. Ship standards base the worst-case scenario on fire engulfment of the tank. Shore-based standards also require checking for loss of vacuum. ▪ Leakages in LH2 vaporisers are not unlikely, as this has been a common problem for LNG fuel systems. Hydrogen gas will likely accumulate in the glycol circuit expansion tank, which must be arranged to detect and safely manage this. Reduced or stopped glycol circulation could result in the freezing of the glycol inside the vaporiser. This must be accounted for in design (calculations, temp sensors, stop of LH2 supply etc). ▪ Gaseous hydrogen systems must be purged with nitrogen before hydrogen is supplied. N2 system connections must be protected against the back-flow of hydrogen.

Hazard 2.5.1	Hazardous event: Loss of vacuum insulation on LH2 fuel tanks or LH2 piping systems
	■ Confining surfaces and obstacles such as pipes, tanks, and enclosure walls can significantly elevate the flame speed to hundreds of meters per second in a process known as flame acceleration (slow/fast deflagration). If the flame reaches a high enough speed and encounters turbulence and flame instabilities, deflagration can transform into a detonation. This is called a deflagration-to-detonation transition (DDT), and the potential hazards are further increased if detonation results. A deflagration can evolve into a detonation in a partially confined enclosure. The geometry and flow conditions (turbulence) strongly affect the transition from deflagration to detonation. If ignited, it will likely result in a constant jet fire from the vent mast outlet after the initial event described above.
Conclusion/ summary	**Vessels using liquefied hydrogen as fuel must be designed to withstand any effects of vacuum loss for tanks and piping systems.** Reliability analysis of vacuum systems to identify specific failure modes and air ingress possibilities should be considered (e.g. Failure Mode and Effect Analysis (FMEA), combined with reliability modelling).

Table 4-6 presents the hazard identified for LH2 leakages on open deck or enclosed spaces.

Table 4-6 Hazard 2.5.2 Leaking pipes, pipe connections or components in LH2 piping system.

Hazard 2.5.2	Hazardous event: Leaking pipes, pipe connections or components in LH2 piping system
Node	■ Supply piping, incl. fuel preparation.
Potential causes	■ Faulty connections and piping: Welds, flanges, threaded/screw/fitting connections. ■ Design error, fabrication or installation error, and/or operating conditions (e.g. vibrations) or operating outside design limits. ■ Leak potential from valve stems. ■ Impact events.
Potential consequences	■ Structural damage or loss of safety functions due to cooling. ■ Asphyxiation and/or hypothermia due to oxygen depletion and low temperatures (if people are present in the vicinity).
Possible preventive and mitigation design measures	Preventive measures: ■ Preventive measures listed for ventilated TCS will also be applicable. Mitigating measures: ■ Mitigating measures listed for ventilated TCS will also be applicable. ■ Piping systems for liquefied and compressed hydrogen should be arranged with secondary enclosures around the complete system to prevent cooling of the surroundings upon vaporisation of leaked LH2. ■ The ship should be arranged to manage the resulting lower temperatures in tank hold spaces, tank connection spaces, and other spaces that may be affected. Issues to cover include: Using materials able to withstand the lowest temperature they may be subjected to. ■ Ensure that all components of safety systems required to mitigate hydrogen safety events can continue to operate at the lower temperature after a leakage event. ■ If hydrogen discharged to the open deck is ignited, the consequences for the ship with respect to pressure effects and heat load should be manageable. This includes scenarios with flash fire, jet fire, and deflagrations. Deflagration-to-detonation and detonation should be avoided by design. Manageable implies that heat loads and pressure shocks should be at a level that allows people to evacuate the area without injuries and that access to muster stations, escape routes, and life-saving appliances is not restricted.

Hazard 2.5.2	Hazardous event: Leaking pipes, pipe connections or components in LH2 piping system
Notes	
Conclusion/ summary	**The release of LH2 from fuel piping systems should be managed by applying secondary enclosures that are able to handle cryogenic leakages safely.**

4.6 Boil-off gas management

Basis for analysis

Liquefied hydrogen has a normal boiling point of -253°C and is stored at temperatures over 90°C lower than LNG. This creates extra safety concerns for onboard hydrogen storage and distribution, including managing boil-off gas.

Boil-off gas management is challenging. To control the vapour pressure in the tank, the fuel system must be connected to the ullage space. Two viable methods are:

- Accumulating pressure.
- Utilizing vapour consumption to induce forced vaporization of LH2 within the tank for cooling.

According to the IGF Code, the release of fuel gases into the air is only allowed in an emergency. Typical holding time by pressure accumulation for vacuum-insulated type C LNG tanks is above 15 days. Calculations indicate that vacuum insulated type C LH2 tanks perform similarly or better.

Hazard Identification results

Table 4-7 presents the hazard identified for the continued release of hydrogen through the vent mast.

Table 4-7 Hazard 2.6.1 Continuous release of hydrogen through vent mast.

Hazard 2.6.1	Hazardous event: Continuous release of hydrogen through vent mast
Node	■ Fuel storage tanks.
Potential causes	■ The tank pressure becomes higher than the set-point of tank safety valves due to heat ingress or loss of insulation. ■ The safety valves are leaking.
Potential consequences	■ Released fuel may ignite on deck. ■ Hydrogen releases may have a negative climate effect.
Possible preventive and mitigation design measures	Preventive measures: ■ The fuel containment system should be designed to minimize operational discharges by preventing LH2 from heating up too quickly through effective tank insulation and providing the means to manage the boil-off gas in normal operation. Mitigating measures: ■ The fuel containment system and the system providing pressure relief should be arranged to ensure that any hydrogen discharged accidentally or through normal operation is routed to open air at the safest possible location onboard.
Notes	The IGF Code regulations for natural gas specify four methods for managing the fuel storage condition: 1. Reliquification of vapours. 2. Thermal oxidation of vapours. 3. Pressure accumulation. 4. Liquefied gas fuel cooling. Due to the low storage temperature of LH2, methods 1 and 4 will be very challenging to apply for hydrogen-fuelled ships. In addition to being a safety risk, venting hydrogen directly into the air will have an impact on the environment. Studies indicate that releasing hydrogen has an indirect climate impact by reacting with other gases. Research is

Hazard 2.6.1	Hazardous event: Continuous release of hydrogen through vent mast
	ongoing to quantify this. Venting of natural gas in normal operation is prohibited, being only allowed in an emergency.
Conclusion/ summary	**Fuel containment systems for liquefied hydrogen should be arranged to manage the fuel storage condition during normal operation to prevent the release of hydrogen.**

5. Hazard Identification of hydrogen fuel consumers

This section discusses a general concept of the fuel preparation room, engine room, and systems closely aligned with an LNG-fuelled application in a gas-safe machinery space concept, as illustrated in Figure 5-1.

The hazard identification covers the following:

- Fuel preparation room.
- Fuel supply piping to the consumer, including Gas Valve Unit (GVU).
- Piping systems on the engine including gas vent line.
- Engine (misfire, knocking and crankcase explosion).

Basis for analysis

The following is the assumed basis for analysis:

- The hydrogen is supplied from LH2 storage (type C tank with 9 bar design pressure) or CH2 storage (cylinders with 380 bar design pressure).
- The design pressure of the fuel supply system depends on the consumer with three possible options:

1. Low pressure ~ 8 bar
2. Medium pressure ~ 50 bar
3. High pressure ~ 600 bar

- The equipment required for fuel preparation, such as the compressor and buffer tank, is situated in a fuel preparation room outside the engine room.
- The master valve that automatically shuts off the fuel supply in the event of a leakage detection is situated in the fuel preparation room.
- The GVU is part of the double-walled piping system and is located in the engine room.
- The internal combustion engine is dual-fuelled with pilot fuel injection or gas only (pure hydrogen)-fuelled with spark ignition.

The same fundamental principles applicable to LNG fuel are maintained.

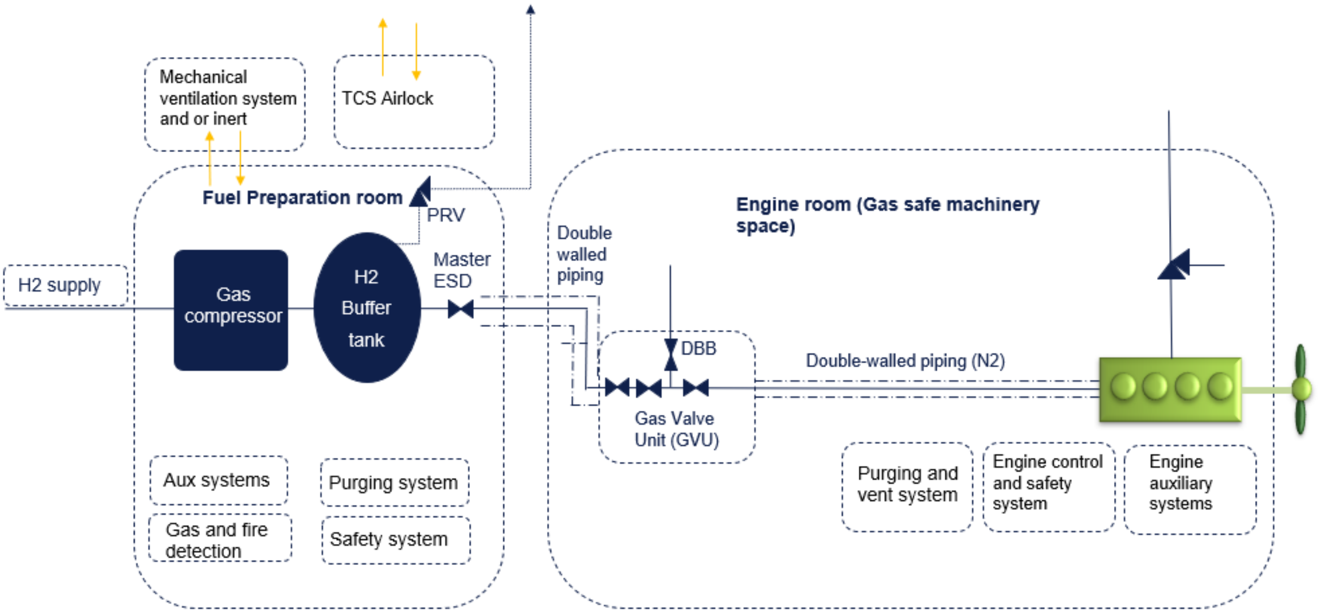

Figure 5-1 Flow diagram of the fuel supply system for engine consumers located in a gas-safe machinery space (Source: DNV).

5.1 Fuel preparation room and supply piping to gas consumer

Hazard Identification results

Table 5-1 presents the hazards identified for the fuel preparation room.

Table 5-1 Hazard 3.1.1 H2 leak in fuel preparation room.

Hazard 3.1.1	Hazardous event: H2 leak in fuel preparation room
Node	■ Fuel supply piping.
Potential causes	■ Leaking pipes, pipe connections, compressors, buffer tanks or other components in hydrogen fuel system.
Potential consequences	■ Jet fire (immediate ignition). ■ Deflagration/detonation (delayed ignition).
Possible preventive and mitigation design measures	Mitigation measures: ■ As discussed for TCS, dilution ventilation is not a suitable mitigation strategy for hydrogen. An alternative could be to operate with an inert atmosphere in the space to prevent leaking hydrogen from mixing with an oxidiser. However, this strategy would raise several design and operational issues related to access for inspection and maintenance, as discussed for TCS. ■ A possible additional measure is to provide double-walled piping/secondary enclosures for the hydrogen piping system in the fuel preparation room. ■ A fuel preparation room should be located on the open deck. ■ Intrinsically safe electrical motor for compressor inside compressor room.
Notes	■ The reliability and safety analysis performed in the EMSA study investigating the safety of hydrogen-fuelled ships showed a very high leak probability for compressors compared to other equipment (EMSA, 2024b). ■ All risks for CH2 fuel tanks will also be applicable to buffer tanks, including leaks, overpressure, etc. Buffer tanks should be located on the open deck.

Hazard 3.1.1	Hazardous event: H2 leak in fuel preparation room
	■ Medium/high-pressure engines will introduce a need for fuel preparation due to the need for a high supply pressure (compressors and/or pumps), and thereby the need for a fuel preparation room. ■ A compressor will be needed for CH2 installations with 350 bar storage tanks if the consumer requires a 50 bar fuel supply pressure, as the delta is too small to ensure fuel supply without a compressor when one considers the usable storage volume. A buffer tank would probably be needed for the compressor to cater for sudden load changes. It should have an enclosure around the compressor due to noise. ■ Gas-freeing the buffer tank (up to 600 bar) is challenging. It can be an option to move the buffer volume to the piping system if the required volume is not too large. Alternatively, it was proposed to use the compressor to move hydrogen from the buffer tank back to the storage tank. ■ A high-pressure pump for LH2 could be a better option with subsequent heat exchange in the TCS. The question is if there are suppliers of hydrogen pumps with these high pressures. ■ Low-pressure fuel supply (~ 8 bar) can, in principle, be supplied by the fuel tank pressure if there is a sufficient delta between the fuel tank operating pressure and the required fuel supply pressure. Hence, there would not be a need for pumps and/or compressors located in a fuel preparation room. ■ Type C tanks for liquefied hydrogen have a design pressure of 9 bar. The operating pressure would typically be lower (~ 4 bar) due to holding time considerations. This means that a pump (or a compressor) would be needed to supply 8 bar to the consumer. A low-pressure pump could, in principle, be located in the TCS, and a compressor (rotating machinery) must be located in a fuel preparation room. The pump technology is available for onshore applications (thermos bucket with hydrogen pump inside, similar to LNG fuel transfer pumps located in TCS), however it would need to be marinized. ■ Installing hydrogen pumps (or compressors) would make the hydrogen fuel installation more complex. To avoid the need to install pumps and/or compressors for low-pressure installations, a higher design pressure than 9 bar for the storage tanks could be considered. Road trailers transporting hydrogen have a design pressure of 12-13 bar in their storage tanks. On the other hand, the IGF Code requirements applicable for natural gas have a limitation of maximum 10 bar design pressure and 9 bar working pressure for LNG tanks. The question is if this requirement should be made applicable for LH2 storage. The difference between LNG and LH2 in this respect should be considered. Another option would be to feed low-pressure engines with a lower fuel supply pressure (e.g. ~ 4 bar). Otto engines will work with the pressure they get. ■ No known concept for fuel preparation room for hydrogen fuel (so far not considered by engine manufacturers). ■ Challenging to make a fuel preparation room (or compressors in double enclosure) gas safe in the engine room. Challenging to protect the space itself.
Conclusion/ summary	■ Fuel preparation rooms for hydrogen compressors and buffer tanks is an immature concept. ■ A higher tank pressure or lower fuel supply pressure can make the fuel preparation room obsolete for low-pressure consumers. ■ Fuel preparation rooms should be located on open deck, not in the engine room. ■ Mechanical ventilation of the fuel preparation room is ruled out due to the potential leak size for compressors and buffer tank. Double walled piping and inerting should be considered.

Table 5-2 presents the hazards identified for fuel supply piping between the fuel preparation room and the consumer.

Table 5-2 Hazard 3.1.2 H2 leakage in the inner pipe (after master gas fuel valve).

Hazard 3.1.2	**Hazardous event: H2 leakage in inner pipe (after master gas fuel valve)**
Node	▪ Fuel supply piping.
Potential causes	▪ Leaking pipes, pipe connections or components in hydrogen fuel system.
Potential consequences	▪ Jet fire (immediate ignition). ▪ Deflagration/detonation (delayed ignition).
Possible preventive and mitigation design measures	▪ **System integrity:** All fuel piping systems should be designed and arranged to minimize the probability of leakages. This implies using materials not deteriorated by hydrogen, are suitable for the system's design temperature, are arranged and supported to ensure that operational conditions do not cause undue stresses and are connected by welding as far as possible. Where welding is not possible, joining methods are chosen to minimize the probability of leakage. ▪ **Double walled piping:** All fuel piping systems located in enclosed spaces should be protected within a secondary enclosure that can contain any leakage and vent the hydrogen to open air at the safest location possible. Two possible options for the arrangement of the annular space of the double-walled piping to safely handle leaks from the inner pipe: 1. **Inerting to prevent an ignitable atmosphere.** A safety valve should be installed at the outer pipe to get rid of the hydrogen/nitrogen mix. 2. **Mechanical ventilation:** Hydrogen leaks into the outer pipe can ignite by static electricity since air is present. An explosion would need to be assumed. If the double-walled pipe is long enough, it can result in a detonation (if the outer pipe is designed for 600 bar, it can survive a detonation). This is a similar situation as discussed for the vent mast. Furthermore, the narrow annual space between the inner and outer pipe makes it very difficult to install and balance proper ventilation of the outer pipe. A huge ventilation system would need to be installed. ▪ **Leakage detection:** Any leaks from piping systems should be detectable and automatically isolated from the source of the hydrogen supply. Segregation valves should be arranged to limit the amount of hydrogen being discharged after a leakage is detected and stopped. The inert gas pressure in the outer pipe affects the ability to detect leakages in the double-walled piping system: - A permanent flow of nitrogen in the outer pipe makes it hard to detect leakages while a constant inert gas pressure enables detection of any pressure changes. - Keeping the inert gas pressure in the outer pipe higher than the gas fuel pressure in the inner pipe enables the detection of a leak in the double-walled piping, but not immediately whether it is in the inner or outer pipe. - Keeping the inert gas pressure in the outer pipe lower than the gas fuel pressure in the inner pipe enables detection of leaks both in the inner and outer pipe by increasing or decreasing inert gas pressure.
Notes	▪ The connection to the engine is a double-walled flexible hose (with O-rings in the flange to ensure tightness) – not different from LNG. There are more potential for leakages with hydrogen. ▪ It is expected that 4-stroke low-pressure engines will be the first hydrogen-fuelled engines to market. ▪ 2-stroke high-pressure engines are expected to be used in the future for blending hydrogen in LNG fuel (blending in somewhere in the fuel supply system). Acceptable mixing ratios before we leave the IGF Code threshold for LNG would need to be decided. ▪ For H2-fuelled gas turbine concepts, the main challenge is that the fuel supply cannot be double-walled. Hence, the concept of ESD-protected machinery space is proposed and must be further investigated. ▪ In the IGF Code Part A-1 applicable for natural gas, the ESD-protected machinery space concept with single-walled piping in the engine room is an alternative to the gas-safe machinery space concept with double-walled piping. The ignition of hydrogen released into the engine room cannot be avoided by a high ventilation rate and the disconnection of non-certified electrical equipment at gas detection as per the concept of ESD-protected machinery space due to the high flammability of hydrogen. This leads to the conclusion that the ESD-protected machinery space concept is not suitable for hydrogen-fuelled

Hazard 3.1.2	Hazardous event: H2 leakage in inner pipe (after master gas fuel valve)
	ships. Double-walled piping, as per the gas-safe machinery space concept, should be arranged for ships using hydrogen as fuel. ▪ Mixing of H2 and LNG: There are different manufacturers and concepts for pre-combustion carbon capture, which makes H2 from LNG onboard. The H2 is injected back into the methane in the fuel supply to the engine (or used directly in a fuel cell). The space would need to be considered a hydrogen space. Ensuring the correct mix is crucial (e.g. what if you end up with 100% hydrogen). Suitable materials, etc, must be provided. Some are allowing 25% hydrogen in the mix based on IEC standard. However, a release will separate into H2 and methane. An immediate leakage can probably be handled as a natural gas leakage. ▪ Falling loads from cranes in the engine room will break double-walled pipes. This can happen – the same risk for other fuels. Operational – no lifting above fuel pipes. The piping should be routed in protected locations and be marked as hydrogen fuel pipes (yellow). Piping routing should also accommodate for vibrations. ▪ In the event of a fire in the engine room, stop hydrogen fuel supply, depressurize and purge.
Conclusion/ summary	**All fuel piping in enclosed spaces should be arranged as double-walled piping.** **Inerting the outer pipe is considered the best option for low, medium and high-pressure engines.** **The ESD-protected machinery space concept with single-walled piping in the engine room is not suitable for hydrogen.**

Table 5-3 presents the hazards identified for the gas valve unit.

Table 5-3 Hazard 3.1.3 H2 leakage in Gas Valve Unit (GVU).

Hazard 3.1.3	Hazardous event: H2 leakage in Gas Valve Unit (GVU)
Node	▪ Fuel supply piping.
Potential causes	▪ Leaking pipes, pipe connections or components in the hydrogen fuel system.
Potential consequences	▪ Jet fire (immediate ignition). ▪ Deflagration/detonation (delayed ignition).
Possible preventive and mitigation design measures	▪ **System integrity:** All fuel piping systems should be designed and arranged to minimize the probability of leakages. This implies using materials that are not deteriorated by hydrogen, are suitable for the system's design temperature, are arranged and supported to ensure that operational conditions do not cause undue stresses and are connected by welding as far as possible. Where welding is not possible, joining methods are chosen to minimize the probability of leakage. ▪ **Secondary enclosure:** The GVU should be arranged in a secondary enclosure able to contain leakages. It should be inerted to prevent an ignitable atmosphere, the same as double-walled piping. A GVU enclosure with slight inert gas overpressure would work. A ventilation connection is needed after a leakage. With a high-pressure installation, it is harder to have a large space. ▪ **Leakage detection:** Any leaks from piping systems should be detectable and automatically isolated from the source of the hydrogen supply. Segregation valves should be arranged to limit the amount of hydrogen being discharged after a leakage is detected and stopped.
Notes	▪ The GVUs, previously installed no more than 5 meters from low-pressure engines in the engine room, can now be positioned up to 30 meters away. This change allows for the possibility of GVU installation in the TCS. In high-pressure LNG fuel systems, the GVU is placed in the fuel preparation room, which is located outside the engine room. The engine control system manages the operation of the GVUs. ▪ For LNG fuel, a manual isolation valve for maintenance purposes is installed at GVU before Double-block and Bleed (DBB). Positioning all manual isolation valves outside the engine room should be considered to minimise the risk of hydrogen leakages within the engine room. ▪ Each engine should be maintainable while other engines are operating. Avoid using a common isolation valve for multiple engines. ▪ Engine manufacturers are employing the same “double-block-and-bleed” valve arrangement used for LNG fuel to safely isolate the engine from the pressure of the fuel supply system. This comprises two shut-off valves in series, with a bleed valve positioned between them that connects to the vent mast. It

Hazard 3.1.3	Hazardous event: H2 leakage in Gas Valve Unit (GVU)
	is important that the bleed valve does not introduce oxygen into the hydrogen fuel system unless the vent mast is maintained in an inert state. The installation of a non-return valve to prevent air ingress has proven to be ineffective, as they are not sufficiently airtight. Monitoring the pressure could be an option; if it rises, the bleed valve may open. Current class regulations permit the use of a pressure relief valve (as an alternative to the bleed valve) that activates at a low set point to curb pressure build-up and allow venting mast.
Conclusion/ summary	**The GVU should be located within an inert secondary enclosure.** It can be situated in the TCS to avoid placement in the engine room.

5.2 Gas fuel consumer in engine room

The following tables presents the hazards identified for the gas fuel consumer and auxiliary systems.

Table 5-4 presents the hazards identified for the piping systems on the engine.

Table 5-4 Hazard 3.2.1 H2 leaks from piping systems on engine.

Hazard 3.2.1	Hazardous event: H2 leaks from piping systems on engine
Node	■ Engines and connections.
Potential causes	■ Faulty seals and fittings. ■ Pipeline vibration. ■ Component fatigue.
Potential consequences	■ Jet fire (immediate ignition). ■ Deflagration/detonation (delayed ignition).
Possible preventive and mitigation design measures	■ **Double walled piping, as for fuel supply system.** ■ **Leakage detection.** ■ **Inert gas purging.**
Notes	■ The most safety-critical part of the engines is the fuel supply system where hydrogen is present. ■ Injection system – double-walled pipe with a main gas valve. The gas valve is not totally sealed, there are leakages. ■ Issues as for natural gas, when operating on diesel only, air can be pushed into the hydrogen fuel supply system. Hence, the engine's hydrogen fuel system must be purged before and after operating on hydrogen to avoid an explosive atmosphere in the piping system. ■ Minor leakages in the injection system will cause micro build-up in the annular system of the double-walled piping. The engine is vibrating. Small leaks can be detected with inerting. This will cause a shutdown of hydrogen fuel supply and a switch to diesel. Hence, such minor leakages are more of an availability issue than anything else. ■ The potential for backflow of hydrogen into auxiliary systems: – The oil fuel always has higher pressure than the hydrogen, and the only point of contact between the two fuels is in the cylinder. – It is possible to get pre-mixed combustion gas in the cooling water. For high pressure systems, it is possible to contaminate the nozzle cooling system with hydrogen. Would need three failure cases for this to happen. Has not been experienced. – Backflow of hydrogen into inert gas system. Same double block and bleed arrangement as for LNG to prevent back-flow of fuel gas to the inert gas system. – Mix of hydrogen in the lubrication oil. Not found hydrogen in lubrication oil (find it for ammonia, not for methane).
Conclusion/ summary	**All hydrogen fuel piping on the engine should be arranged as double-walled piping.**

Table 5-5 presents the hazards identified for the engine gas vent line.

Table 5-5 Hazard 3.2.2 Ignition of vented gases in the vent line.

Hazard 3.2.2	Hazardous event: Ignition of vented gases in the vent line
Node	▪ Gas vent line.
Potential causes	▪ Open gas valve on the engine vent line when switching from hydrogen to diesel, or in longer periods due to internal leak or valve open unintended.
Potential consequences	▪ Increased fuel consumption. ▪ Explosion in the vent line or at the vent outlet in the open air.
Possible preventive and mitigation design measures	▪ **Design vent line and outlet for explosion pressure.** ▪ **Gas detection and alarm in vent line/vent mast.**
Notes	▪ The end of the gas pipe for the engine has a blow-off vent pipe with a vent valve to enable evacuation and purging of the gas piping. ▪ The piping is double-walled up to the vent pipe, similar to that for LNG. ▪ The flexible compensator for the vent pipe is a single failure point. ▪ A leak test before starting should be performed to ensure high level of integrity (testing with hydrogen). ▪ When switching from hydrogen operation to diesel operation all the hydrogen between the GVU and the engine will be vented to the open air and form a cloud which can ignite. Self-ignition in the outlet has a high probability. Hence, the vent line should be designed for ignition and possible detonation. This scenario must be calculated and handled. ▪ The outlet of the vent pipe needs to be led to a safe place. The outlet is arranged separately, not led to the vent mast for hydrogen tanks. ▪ The vent valve could be stuck in the open position. Depending on the valve position and the fuel consumption, it is possible for the valve to leak significantly without detection since the pressure drop in the fuel system might not be adequate for detection. Such leaks could become apparent during higher fuel consumption or manifest as a "peculiar noise from the roof". This is a situation that requires further investigation. ▪ It could be an option not to install such a vent valve, as it may not strictly be needed. Could vent from the GVU DBB. ▪ Consider hydrogen detection in the vent mast or any other vents. However, this vent valve is used in normal operation, i.e., causing alarm in normal operation.
Conclusion/ summary	**The gas vent line from the engines, including the vent outlet, should be designed to withstand ignition and possible detonation.**

Table 5-6, Table 5-7 and Table 5-8 presents the hazards identified for engine misfire, engine knocking and crankcase explosion.

Table 5-6 Hazard 3.2.3 Engine misfire.

Hazard 3.2.3	Hazardous event: Engine misfire
Node	▪ Engines and connections.
Potential causes	▪ One or more cylinders fail to ignite the air-fuel mixture, due to. e.g. faulty ignition systems, fuel injectors, engine control, air supply/charge air or fuel leaks.
Potential consequences	▪ Incomplete combustion.

Hazard 3.2.3	Hazardous event: Engine misfire
	■ If not ignited, the engine will stop with hydrogen in the cylinders. ■ Unburned or excess fuel can pass through the combustion chamber and enter the exhaust system. ■ Ignition of hydrogen in the exhaust system will cause an explosion.
Possible preventive and mitigation design measures	■ **Design the exhaust system with the strength to withstand the worst-case overpressure due to ignited gas leaks.** ■ **Provide an explosion relief system, either explosion relief valves or burst disks.** ■ **Arrange the exhaust system to avoid the possibility of accumulation of unburned gas.** ■ **Provide separate exhaust system for hydrogen consumers.** ■ **Purging of the exhaust stack after an emergency stop or a failed start.**
Notes	■ Unburnt hydrogen in the exhaust system in case of misfire cannot be excluded. ■ This will be detected quite fast, but less hydrogen is needed for an explosion compared to natural gas. ■ Half of the engine cylinders could have a misfire before the fuel supply is stopped. It could be more, depending on the engine. When switching to diesel fuel, the remaining gas will be burnt in the cylinder. ■ Could add a time step, the time it takes to detect a misfire. ■ Check ignition in the cylinders before hydrogen is admitted. ■ Spark test for spark-ignited engines. ■ Previously, it was not allowed to start in gas mode for LNG-fuelled engines. ■ No difference between low, medium, and high pressure - same quantities of gas - same problem? ■ There can be hot spots which may ignite a hydrogen mixture. The resulting detonation pressure could be up to 20 bar – the exhaust system is not designed for this. ■ Hydrogen is burning much faster than natural gas. This can be a challenge for explosion relief devices and can be an issue with pressure relief as the explosion can happen within milliseconds. ■ Testing indicates that pressure relief valves for the crankcase are working well. However, there is a different environment in the exhaust system. ■ Explosion relief valves are fast, typically open on 2 bar, springs can be adjusted. It should be calculated whether pressure relief valves can handle it. ■ Rupture disks may open more quickly. Nevertheless, they may open unintentionally because of low opening pressure and vibrations. They need to be designed to be very light and react quickly. The HAZID participants had not seen such discs for exhaust systems, only for rooms. It isa very thin sheet. ■ Additional measures should be considered, e.g. designing the exhaust system more robust for 1 bar. The weakest point is the exhaust gas boiler and Selective Catalytic Reduction (SCR), needed for dual fuel engines in diesel mode. ■ To design the exhaust system for the explosion pressure is an option. ■ Another scenario that should be considered is whether the explosion in the exhaust system can carry on outside after the pressure relief has opened.
Conclusion/ summary	**The exhaust system for 4-stroke engines must be designed for the worst-case overpressure to account for ignited gas leaks, either by providing an explosion relief system or by inherent strength.**

Table 5-7 Hazard 3.2.4 Engine knocking.

Hazard 3.2.4	Hazardous event: Engine knocking
Node	■ Engines and connections.
Potential causes	■ Air-fuel mixture in the cylinder ignites prematurely or unevenly due to, e.g. incorrect ignition timing, faulty knock sensor, etc.
Potential consequences	■ The underlying issues causing engine knocking can contribute to incomplete combustion, which may result in unburned fuel entering the exhaust system.
Possible preventive and mitigation design measures	■ Engine control system. ■ Engine knock sensors.
Notes	■ Engine knocking poses a similar issue for hydrogen as it does for natural gas. ■ Hydrogen is prone to pre-ignition. There will be a high cylinder pressure if it ignites too early. This issue has to be taken care of to keep the engine in one piece.
Conclusion/ summary	**The same basic principles as for LNG fuel are applied, e.g., through engine control system and engine knock sensors, but the implications due to hydrogen properties must be considered.**

Table 5-8 Hazard 3.2.5 Crankcase explosion.

Hazard 3.2.5	Hazardous event: Crankcase explosion
Node	■ Engines and connections.
Potential causes	■ Presence of hydrogen within the crankcase, due to e.g. combustion gases leaking past the piston rings into the crankcase. ■ Ignition of hydrogen by the presence of hot spots, non-ex certified electrical equipment located inside the crankcase, e.g. temperature sensors, or external ignition sources in way of crankcase vent outlets.
Potential consequences	■ Explosion into engine room. ■ Release of hydrogen gases.
Possible preventive and mitigation design measures	■ Intrinsically safe electrical equipment inside the crankcase. ■ Flame arrestor on crankcase vent outlet. ■ Explosion relief valves. ■ Regular maintenance and inspection of the engine components.
Notes	■ Crankcase explosion cannot be totally avoided. Need to be designed for it. ■ Testing indicates that pressure relief valves for the crankcase are working well. ■ Crankcase with explosions with hydrogen has been tested (100% LEL), but not the worst-case scenario. ■ Gas concentration in the crankcase for an Otto-cycle engine is typically very close to 100% LEL. Blow by on pistons, unburnt hydrogen pressed to the crankcase. Over 30 min you get 40/50-60% LEL. ■ Crankcase atmosphere composition is typically 80% from the air, and 20% from gas from the engine. In a failure situation you can get higher concentration. ■ Crankcase breathers normally vented to open deck for gas engines with active ventilation. Less probable that it ignites in the vent pipe than in the crankcase. Could be led to vent mast. ■ Stratification and build-up of gases in the natural crankcase ventilation have not been an issue for gas engines.

Hazard 3.2.5	Hazardous event: Crankcase explosion
	■ Concentration of hydrogen in the cylinder at 100% LEL during normal operation. Would maximum expect LEL levels at the outlet.
Conclusion/ summary	**The same basic principles as for LNG fuel are applied, e.g., explosion relief valves, but the implications due to hydrogen properties must be considered.**

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