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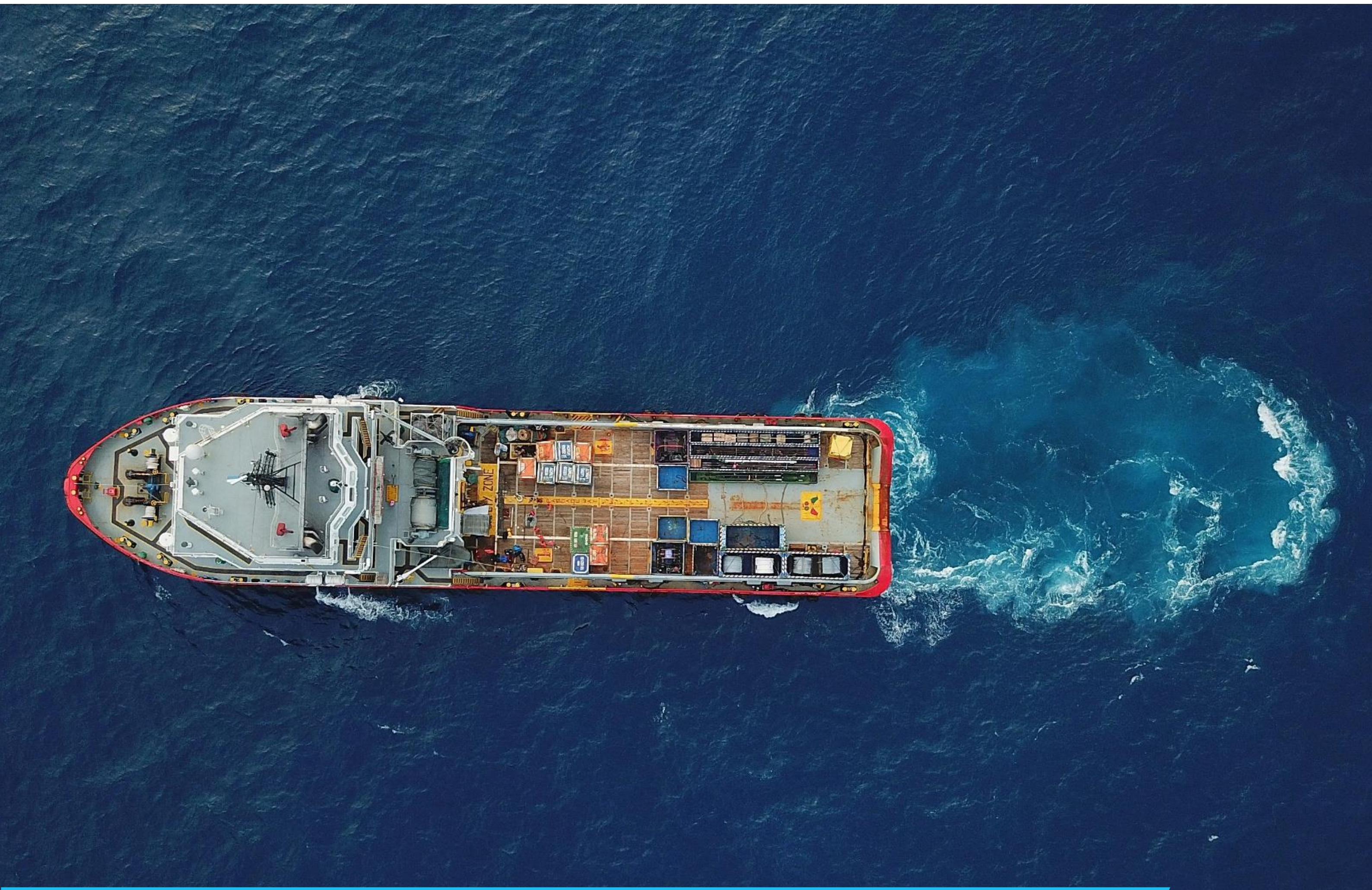

RISK ANALYSIS OF TWO SPECIFIC SHIP TYPES USING HYDROGEN AS FUEL

STUDY INVESTIGATING THE SAFETY OF HYDROGEN AS FUEL ON SHIPS

DELIVERABLE D.4

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About this study:

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Abstract

This report is developed as part of the project "EMSA study investigating the safety of hydrogen as fuel on ships". The overall objective of the project is to conduct a structured set of safety assessments and reliability analyses, resulting in a Guidance document which addresses 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 a fuel, which could demonstrate an important step towards decarbonising the sector.

This report presents the findings from the risk analysis of two specific ship types: a Platform Support Vessel with compressed hydrogen stored above deck and a Service Operation Vessel with liquefied hydrogen stored below deck. The report examines hazardous events with the potential to mechanically damage the hydrogen fuel system, to cause ignited hydrogen releases, as well as occupational accidents, analyses frequencies, and assesses potential safety implications. The bowtie technique is employed for risk analysis and barrier modelling, aiming to validate the requirements outlined in the guidance document.

The analysis builds on the generic hydrogen fuel system design concepts that were identified during the hazard identification process documented in "Hazard identification of generic hydrogen fuel systems" (EMSA, 2025a).

By systematically identifying hazards and potential safeguards, this report aims to provide valuable insights and recommendations for improving the safety of hydrogen technologies. We find that the likelihood of hydrogen leakages from piping systems and loss of tank vacuum insulation cannot be excluded in ship design and should be within the design capability of hydrogen-fuelled ships. The findings will contribute to the broader goal of delivering a Guidance document addressing ships using hydrogen as fuel.

Executive summary

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 in 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 fourth task of the study investigating the safety of hydrogen as fuel on ships.

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 critical 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 that pose different safety challenges compared to 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's "Generic guidelines for the development of goal-based standards" (IMO, 2019), and draws upon comprehensive risk assessment and reliability analysis.

What we did

This risk analysis includes two combinations of ship types and fuel system configurations based on actual designs developed by one of the study partners to support the development of the Guidance document:

- A Platform Supply Vessel (PSV) with compressed hydrogen stored above deck
- A Service Operation Vessel (SOV) with liquefied hydrogen stored below deck

The ship designs, including safety philosophy for the fuel systems, for the PSV and SOV are presented in detail in chapter 3 and 4 respectively. The specification of the fuel systems, with enhanced safety barriers, builds on the descriptions in the previous task *Risk analysis of generic hydrogen fuel systems* (EMSA, 2025b). The focus of this task has been to address ship-type-specific hazards and risks related to the two ship configurations chosen.

For the PSV, two hazardous events are analysed in depth: dropped objects onto fuel containment and the ignition of hydrogen released through the vent mast. For the SOV, collision and grounding, as well as occupational hazards, are addressed.

For each of the two selected ship types, frequency analysis, consequence analysis, and barrier modelling were conducted for the chosen hazardous events. Given the limitations of frequency analysis on conceptual ship designs, it was considered more appropriate to explain the methodology rather than attempt a precise analysis. This was followed by a qualitative consequence analysis focusing on safety, i.e., the potential impacts on people and the ship. Finally, barrier modelling was conducted by defining a bowtie, which included barrier functions and barrier elements for each hazardous event. The barrier functions defined in the bowtie support the validation of the functional requirements in the Guidance document by ensuring that the barrier functions are reflected in the functional requirements and vice versa.

What we found

Risk analysis of Platform Support Vessel with compressed hydrogen stored above deck

The key findings from the risk analysis of the PSV for the selected hazardous events are presented below:

- **Dropped objects onto fuel containment systems or piping**
  - **Frequency analysis approach:** Emphasis should be on identifying locations where dropped objects might fall and ensuring that hydrogen tanks are not situated in those areas. Subsequently, the approach for estimating the probability of a dropped object event is outlined.
  - **Consequence analysis:** A dropped object causing a tank puncture will lead to a massive release of hydrogen gas, likely resulting in immediate ignition and the potential for further escalation events. This scenario represents a worst-case situation for the PSV used as the basis for this analysis, due to the severe consequences of hydrogen ignition and its proximity to the accommodation and the bridge. Escalation events could trigger a domino effect, sequentially impacting other fuel tanks and piping systems. Escalation events could jeopardise the entire ship, increasing the risk of multiple fatalities.
  - **Safety barrier modelling:** The top event of the bowtie is "damage to fuel containment systems". The threat is "dropped object" while the potential consequences may endanger people, the ship and/or safety-critical functions. The preventive barrier functions that protect against the "top event" are listed in sequential order:
    - Minimize probability of damage to fuel storage tank incl. tank location
    - Minimize probability of dropped object

    If all preventive barriers fail and a tank puncture occurs due to a dropped object, it is important to note that this scenario is not typically accounted for in the ship's design or regulatory standards. Consequently, no significant credit is given to the mitigation of consequences for this event, and it is therefore omitted in the bowtie.

- **Hydrogen release through the vent mast**
  - **Frequency analysis approach:** Automatic or manual depressurization would only be needed in case of a major fire scenario, and the frequency analysis was provided in the risk analysis for generic hydrogen fuel systems. A detailed frequency analysis for overpressurization during bunkering would necessitate an assessment of the contribution of the human element to system failure.
  - **Consequence analysis:** A discharge of hydrogen to the vent mast introduces the potential for ignition inside the vent mast, jet fire from the vent mast outlet, deflagration or detonation on the open deck. Further, hydrogen released through the vent mast may reach ventilation intakes or other openings into the ship where ignition is possible.
  - **Safety barrier modelling:** The top event of the bowtie is "ignition of hydrogen release through vent mast". The threats are "automatic depressurization (TPRD)", "manual depressurization (blowdown) and "overpressurization during bunkering". The potential consequences may endanger people, the ship and/or safety-critical functions. The preventive barrier functions that protect against the "top event" are listed below:
    - Minimize probability of activation of TPRD or blowdown
    - Minimize probability of overpressurization during bunkering
    - Minimize probability of ignition

Should all preventive measures fail and the hydrogen release through vent mast be ignited, the mitigation focuses on:

- Vent line dimensioning
- Vent mast location and height with respect to escapeways, mustering stations and life-saving appliances
- Emergency procedures

Risk analysis of Service Operation Vessel with liquefied hydrogen stored below deck

The key findings from the risk analysis of the SOV for the selected hazardous events are presented below:

- **Ship collision or grounding impacting fuel containment and piping systems**
    - **Frequency analysis approach:** Damaging a hydrogen tank during a ship collision or grounding could lead to catastrophic results. Therefore, the design should aim to minimise the potential for such incidents as far as possible. Subsequently, the approach for estimating the likelihood of puncturing a hydrogen fuel tank following a collision, using a probabilistic method, is outlined.

      Consequence analysis: The hydrogen fuel storage tanks contain large amounts of flammable and cryogenic material, as well as significant potential energy from boiling liquid under pressure. Damage to fuel containment systems, and to a lesser extent, piping systems, are events that have the potential to release all the hydrogen stored onboard.
    - **Safety barrier modelling**: As for the dropped objects case, the top event of the bowtie is "damage to fuel containment systems". The threat is "Ship collision or grounding impacting tank" while the potential consequences include hydrogen deflagration, boiling liquid expanding vapour explosion and cryogenic damages. The preventive barrier function that protects against the "top event" is related to the placing tanks in a location protected against collision and grounding damages.

      If the preventive barrier fails and a tank rupture occurs, it is important to note that this scenario is not typically accounted for in the ship's design or regulatory standards. Consequently, no significant credit is given to the mitigation of consequences for this event, and it is therefore omitted in the bowtie.
- **Occupational hazards**
    - **Frequency analysis:** Studies indicates that the maritime industry suffers from significant underreporting of occupational accidents. Consequently, these statistics cannot be fully trusted for use in quantitative risk analysis, although they do provide valuable information for learning and improvements. An alternative approach is to model the risk and estimate the frequency of occurrence.
    - **Consequence analysis:** Occupational accidents related to the hydrogen systems with the potential of injury/fatality include asphyxiation, cryogenic burns, high pressure hydrogen release and jet fire, deflagration or detonation of released hydrogen.
    - **Safety barrier modelling:** The top event of the bowtie is "exposure to hydrogen or inert gases". The threat is "enclosed space entry". The potential consequences may endanger people onboard. The preventive barrier functions that protect against the "top event" are listed below:
        - Ensure that space is designed and arranged to enable safe entry
        - Ensure proper management systems, procedures and training

Should all preventive measures fail and the people onboard be exposed to hydrogen or inert gases, the mitigation focuses on:

- Personnel Protective Equipment (PPE)
- Emergency response
- Escapeways
- First aid treatment
- Training and drills

Conclusion

Regarding the further drafting of a guidance document, we draw the following conclusions from the findings in this report:

1. Hydrogen may be released from compressed hydrogen tanks through the vent mast and may ignite inside the vent mast or on the open deck. Ships with this type of fuel system must be capable of handling any foreseeable consequences of this event.

While having a vent mast arranged to safely disperse any release of hydrogen from fuel storage tanks and piping systems is an important safety function, the risk of ignition of released hydrogen must be managed. This necessitates a case-by-case evaluation of the consequences of an ignition event. It must be ensured that the potential worst-case scenario regarding heat loads and pressure effects is acceptable in terms of the safety of the ship and its crew.

2. Dropped objects damaging compressed hydrogen tanks or fuel piping may result in rapid release of large quantities of hydrogen, with a corresponding risk of severe explosions and fires.

Damage to fuel containment systems, and to a lesser extent, piping systems, are events that have the potential to release all the hydrogen stored onboard, and it is an event a ship is not designed to survive. Consequently, recognising areas where dropped objects might land is crucial. Just as the segregation principle is used to prevent damage from collisions and groundings, priority must be given to positioning hydrogen tanks away from such locations. This is equally important for liquified hydrogen fuel systems.

3. Ship collisions and groundings damaging liquefied hydrogen tanks are events where it is difficult to apply mitigating measures to prevent severe consequences.

Liquefied hydrogen tanks contain large amounts of flammable and cryogenic material, as well as significant potential energy from boiling liquid under pressure. Damage to fuel containment systems, and to a lesser extent, piping systems, are events that have the potential to release all the hydrogen stored onboard, and it is an event a ship is not designed to survive. The IMO conducted a similar evaluation when developing regulations for LNG fuel tanks, arriving at the same conclusion. Therefore, it is reasonable to assume that the protective measures specified in the IGF Code for tank safeguarding can also be applied to hydrogen as a fuel.

4. New fuels introduce new occupational hazards.

The work activities related to the onboard hydrogen fuel system introduce new occupational hazards associated with direct exposure to hydrogen and its flammable and cryogenic properties, as well as asphyxiation effects. The crew must thoroughly understand the hazards associated with handling fuel and be aware of the integrated safety features, including their purpose, operation, and maintenance requirements. Therefore, it is vital to establish comprehensive training, operating procedures, and a robust safety culture to ensure the safe operation of the ship.

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List of Abbreviations

BLEVE	Boiling Liquid Expanding Vapor Explosion
CH2	Compressed hydrogen gas
EMCIP	European Marine Casualty Information Platform
EMSA	The European Maritime Safety Agency
ETA	Event Tree Analysis
FSHS	Fuel Storage Hold Space
FTA	Fault Tree Analysis
GHG	Greenhouse gas
GVU	Gas Valve Unit
H2	Gaseous hydrogen
HAZID	Hazard Identification
HSE	Health and Safety Executive (UK)
HRA	Human Reliability Analysis
IGF Code	The International Code of Safety for Ships using Gases or other Low-flashpoint Fuels
ILO	International Labour Organization
IMO	International Maritime Organization
ISM	International Safety Management Code
ISO	International Organization for Standardization
LAC	Limiting Air Concentration
LEL	Lower Explosive Limit
LH2	Liquefied hydrogen
OGP	The International Association of Oil & Gas Producers
PFD	Probability of Dangerous Failure on Demand
PPE	Personnel protective equipment
PRV	Pressure Relief Valve
PSV	Platform Support Vessel
SMS	Safety Management System
SOV	Service Operation Vessel
TCE	Tank Connection Enclosure
TCS	Tank Connection Space
TPRD	Thermal Pressure Relief Device

List of general terms

Contact	A casualty caused by ships striking or being struck by an external object. The objects can be: Floating object (cargo, ice, other or unknown); Fixed object, but not the sea bottom; or Flying object. (EMSA, 2024c).
Ship collision	A casualty caused by ships striking or being struck by another ship, regardless of whether the ships are underway, anchored or moored. This type of casualty event does not include ships striking underwater wrecks. The collision can be with other ship or with multiple ships or ship not underway (EMSA, 2024c).
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.
Dropped object/load	Refers to loads (objects) either unintentionally released from a lifting device or else swinging and impacting some part of the installation structure (or vessel, if the lift is to/from a vessel). (OGP, 2010).
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).
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 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).
Grounding	A moving navigating ship, either under command, under Power, or not under command, Drift(ing), striking the sea bottom, shore or underwater wrecks (EMSA, 2024c).
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).
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).
Threat	Threat refers to any potential cause that could lead to the top event.

1. Introduction

DNV has been awarded the “EMSA study investigating the safety of hydrogen as fuel on ships”. The projects’ 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 sectors decarbonisation.

The objective of this part of the study is to conduct a hazard identification and risk analysis of two specific ship types that builds on the hazard identification and risk analysis of generic fuel systems reported in “Hazard identification of generic hydrogen fuel systems” (EMSA, 2025a) and “Risk analysis of generic hydrogen fuel systems (EMSA, 2025b), as illustrated in Figure 1-1. The findings and conclusions from the risk analysis described in this report will be used to support the drafting of the Guidance document.

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, they 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, such as hydrogen, present safety challenges that differ from those of conventional fuel oils. This requires the development of IMO regulations and classification rules for safe design and use on board ships, in parallel with the technological progress needed for their uptake.

To ensure that all hazards related to the use of hydrogen as fuel on ships are covered in the regulatory framework under development, it is necessary to use a systematic approach, such as the IMO “Generic guidelines for the development of goal-based standards” (IMO, 2019), and to build on extensive risk assessment and reliability analysis.

This project will deliver a series of reports (deliverables) reflecting the findings from the project tasks. This report (Deliverable D4) is the deliverable for the fourth task. An overview of all study tasks and deliverables are provided in Figure 1-1.

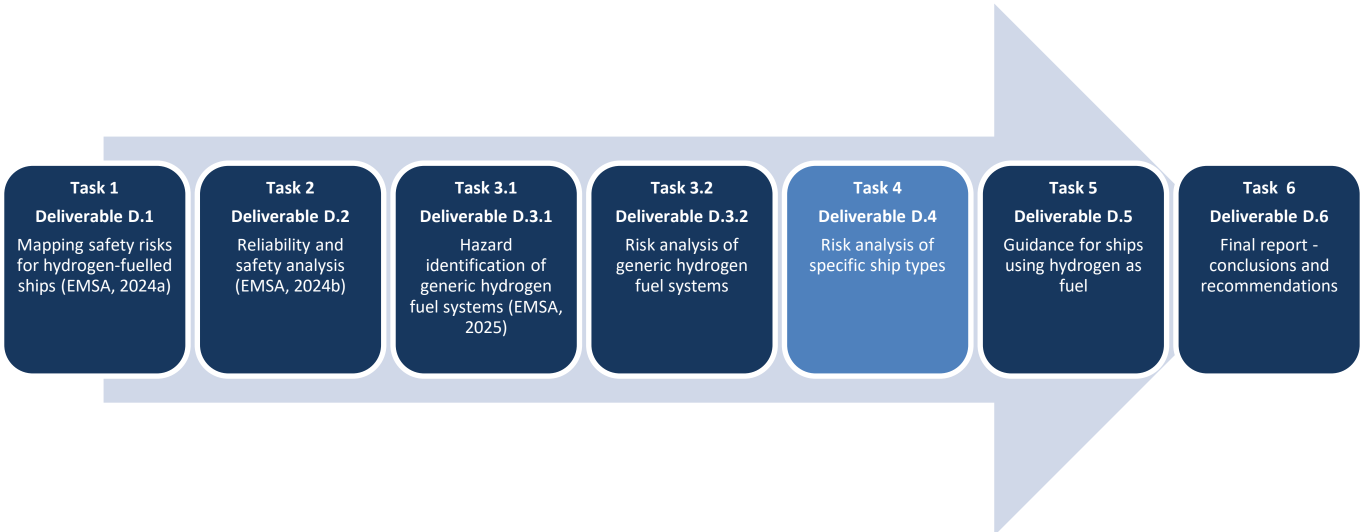

Figure 1-1 Study tasks and deliverables. This report presents the findings from the fourth task (Task 4).

The results from the first task were presented in “Mapping safety risks for hydrogen-fuelled ships” (EMSA, 2024a) characterising hydrogen safety hazards, system threats, and risks. It also drew up a preliminary Guidance for controlling and mitigating these risks.

The second task addressed the reliability of hydrogen equipment and safety-critical systems, presenting a quantitative risk analysis framework for hydrogen-fuelled ships. The results from this second task were presented in “Reliability and safety analysis” (EMSA, 2024b).

The first part of the third task on Hazard Identification (HAZID) for generic ship design identified key safety risks for selected combinations of hydrogen fuel systems, providing input on potential design solutions to prevent and mitigate these risks. The results of the HAZID served as a critical input for subsequent risk analysis studies and will contribute to the EMSA Guidance for hydrogen-fuelled ships (EMSA, 2025a).

The second part of the third task focused on the risk analysis of two generic hydrogen fuel systems: one based on compressed hydrogen storage and the other on liquefied hydrogen storage. These two conceptual fuel systems have been identified as potential candidates for developing prescriptive guidance (EMSA, 2025b).

This report presents the findings from the fourth task, which includes a hazard identification and risk analysis of two specific ship types. The analysis builds on the hazard identification and risk analysis of generic fuel systems reported in “Hazard identification of generic hydrogen fuel systems” (EMSA, 2025a) and “Risk analysis of generic hydrogen fuel systems (EMSA, 2025b). The focus in this task has been to address hazards and risks related to the specific ship’s configuration chosen.

This report has the following structure:

- Chapter 2 describes the methodology.
- Chapter 3 examines the first specific ship type – Platform Support Vessel.
- Chapter 4 examines the second specific ship type – Service Operation Vessel.
- Chapter 5 draws the conclusions with respect to further drafting of the Guidance document.

By systematically analysing these two systems, 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 and the basis for the different aspects of the risk analysis:

- Chapter 2.1 provides the selection of ship types for risk analysis.
- Chapter 2.2 presents the selection of hazardous events chosen for risk analysis.
- Chapter 2.3 presents the method chosen for the risk analysis and the basis for frequency analysis, safety barrier modelling and consequence analysis.

2.1 Selection of specific ship types for risk analysis

To support the project end goal of drafting an EMSA Guidance with provisions for ships using hydrogen as fuel, it is important to cover the particulars of different hydrogen storage concepts and storage locations. These particulars can broadly be categorised by whether the hydrogen is compressed or liquefied, and if it is stored on the open deck or in a confined space. Consequently, we have chosen two ship conceptual designs covering a combination of the four options to perform this analysis. These are based on actual designs of a Platform Support Vessel (PSV) and Service Operation Vessel (SOV) developed by one of the study partners to support the development of the Guidance document.

Although both ship types are within the offshore segment, each of them is equipped with different fuel systems and tank locations. The ship designs, including safety philosophy for the fuel systems, for the PSV and SOV are presented in detail in chapter 3 and 4 respectively. The specification of the fuel systems, with enhanced safety barriers, builds on the descriptions in the previous task (EMSA, 2025b). It should be noted that the illustrations of the arrangements in this report are simplified versions of the detailed drawings provided by the designer, where only essential equipment and systems for hydrogen fuel systems are included.

It is important to note that while two specific ship types have been selected for assessment, the guidance document is intended to be applicable to all ship types. The bowtie diagrams and proposed safety barriers are designed to be relevant across various vessel categories. The selection of these two specific ship types serves primarily to facilitate the identification of hazards and the conduction of risk analysis.

<u>Platform Support Vessel</u>

Platform Support Vessel (PSV) with fixed compressed hydrogen (CH2) fuel storage tanks located above deck, inerted tank connection enclosure (TCE) and secondary enclosures for the fuel supply system. An illustration of the ship and fuel system arrangement is show in Figure 2-1.

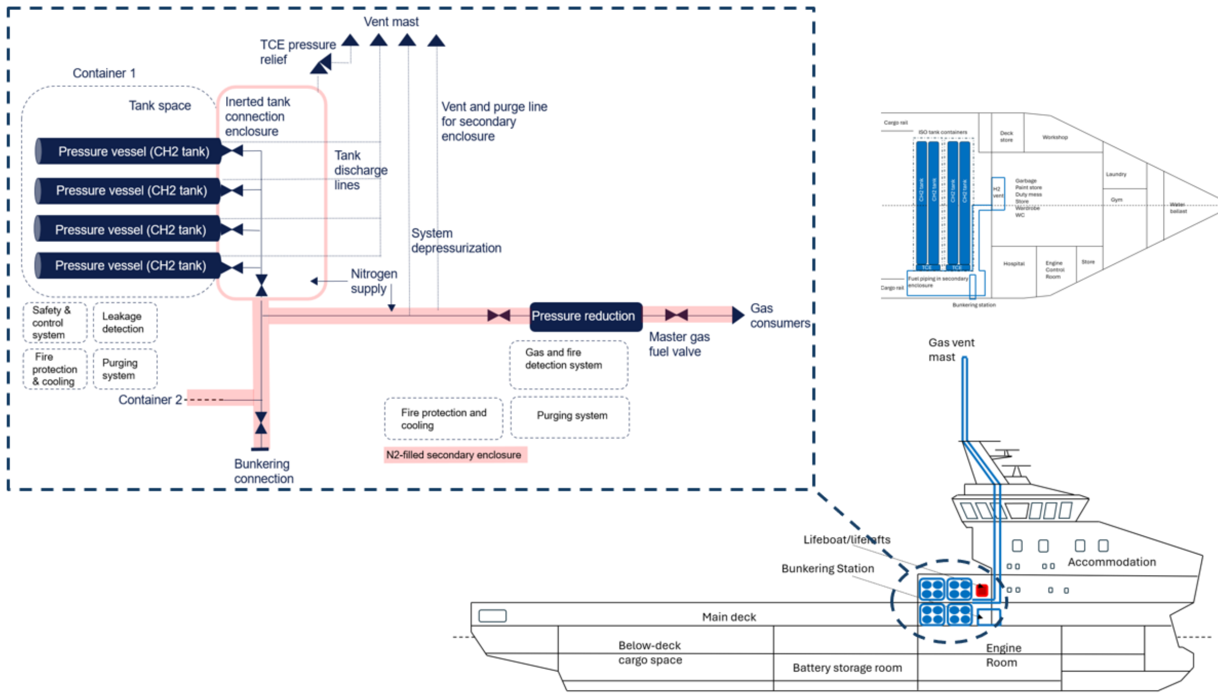

Figure 2-1 Illustration of ship and fuel system arrangement for the PSV (Source: DNV).

Service Operation Vessel

Service Operation Vessel (SOV) with liquefied hydrogen (LH2) fuel system with vacuum-insulated IMO Type C tanks stored below deck, tank connection space (TCS) and secondary enclosures for the fuel supply system. An illustration of the ship and fuel system arrangement is show in Figure 2-2.

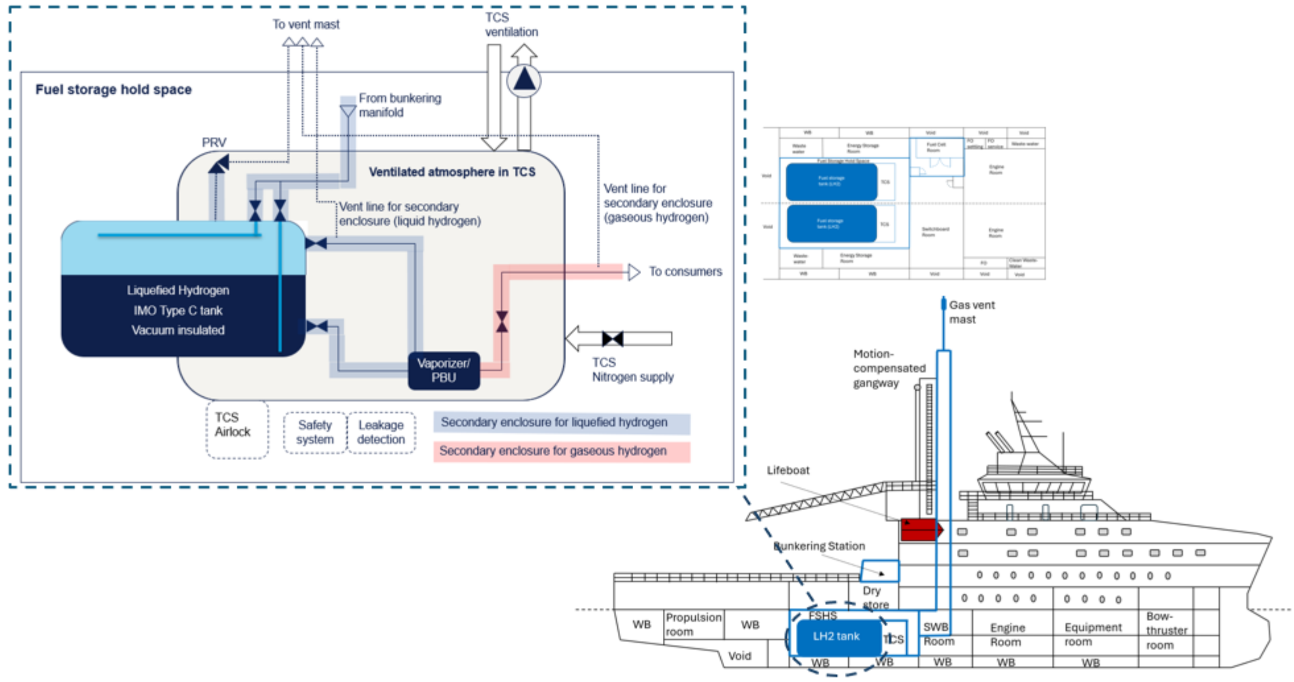

Figure 2-2 Illustration of ship and fuel system arrangement for the SOV (Source: DNV).

2.2 Selection of hazardous events

The hazardous events selected for this risk analysis build upon the work reported in "Mapping safety risks for hydrogen-fuelled ships" (EMSA, 2024a) and the results of the HAZID workshop that was held at DNV's office at Høvik on 14th -16th January 2025 (EMSA, 2025a).

The report "Mapping safety risks for hydrogen-fuelled ships" broadly divides hazardous events related to the hydrogen system into three categories:

1. *Accidental hydrogen releases* from tanks and systems (component leakages), see chapter 2.2.1

2. *Releases due to mechanical damage:* Impacts leading to hydrogen release (mainly external events), see chapter 2.2.2.

3. *Operational and emergency releases:* Events during operations and emergencies resulting in hydrogen releases, see chapter 2.2.3.In addition, we introduce a fourth category, 'occupational accidents'**,** in chapter 2.2.4, i.e. accidents as an occurrence arising out of, or in the course of, work which results in a fatal or non-fatal injury.

2.2.1 Accidental releases (component leakages)

This category of hazardous events has already been identified and analysed for generic fuel systems in "Hazard identification of generic hydrogen fuel systems" (EMSA, 2025a) and "Risk analysis of generic hydrogen fuel systems" (EMSA, 2025b), and will not be further discussed in this report. The frequency and consequences of component leakages are not specific to any ship type.

2.2.2 Releases due to mechanical damage

By mechanical damage, we refer to a forceful contact or impact to the hydrogen fuel system. While mechanical impact often refers to high-force, short-duration events, such as collisions or explosions, we also encompass environmental forces in this category, including wave loads and green seas.

This hazard identification builds on the generic assessment from the previous tasks in the study, while also considering ship-specific factors. For external impacts to fuel containment or piping systems, the following generic threats are identified:

- *Ship collision.* A ship collision involves two vessels impacting each other, which can lead to significant mechanical damage to fuel containment or piping systems. The force of the collision can cause tank puncture, ruptures, leaks, and/or structural failures.

- *Allision/contact damages*. Allision refers to the impact between a moving vessel and a stationary object, such as a dock or bridge. Similar to collision, such events can cause tank puncture, ruptures, leaks, and/or structural failures.

- *Grounding.* Grounding occurs when a vessel runs aground, impacting the seabed or underwater obstacles. This can cause severe damage to the hull and associated fuel containment systems, leading to leaks and structural integrity issues.

- *Explosions.* While blast wave overpressure and thermal effects are often the primary concerns, fragment impact can pose an equally significant risk. Explosions can propel fragments of the exploded material or nearby objects at high velocities. These high-speed fragments can strike the hydrogen fuel system, causing punctures, cracks, or other mechanical damage.

- *Mooring line snap-back.* Mooring line snap-back happens when a tensioned mooring line breaks and recoils with great force. The energy in breaking mooring lines may be sufficient to damage hydrogen fuel tanks and systems. Broken mooring lines during bunkering could also lead to a drift-off situation, with damage to the bunkering system and a resulting spill of cryogenic or high-pressure hydrogen (EMSA, 2024a).

- *Cargo operations and dropped object.* During cargo operations, the handling and movement of goods can inadvertently impact fuel containment or piping systems. Mishandling or accidents can lead to physical damage, compromising the safety and functionality of these systems. This can include dropped objects, such as heavy and/or sharp equipment or cargo, that can fall onto fuel containment or piping systems, causing punctures, dents, or fractures.

- *Shifting cargo.* During rough seas or sudden manoeuvres, cargo can shift, creating impact loads on nearby fuel containment or piping systems or the ship's structure.

- *Wave loads and green sea.* Wave loads are the forces exerted by waves on the ship's hull. These can vary significantly depending on sea conditions and can lead to structural stress and fatigue over time. Wave conditions and green sea can cause sudden and severe impacts.

- *Ice impacts.* For ships operating in polar regions, ice impacts are a significant concern. Collisions with icebergs or sea ice can cause substantial damage to the hull and other structural components, potentially threatening fuel containment and piping systems.

- *Flooded compartment causing buoyancy on fuel storage tanks.* For independent tanks, loads and impacts caused by the buoyancy of a partly or fully submerged tank (as a result of water ingress) may cause damage to the fuel containment system and ship structure.

The selection of events is based on a combination of likelihood and consequence potential. The focus has been on external hazardous events linked to the integration of hydrogen fuel systems on board. Consequently, two mechanical damage events are selected for further risk analysis:

1. *Dropped object* on fuel containment or piping due to lifting operations. This event is particularly relevant for the PSV design with frequent loading/offloading of cargo and equipment to offshore fields. The event is analysed in chapter 3.3.

2. *Ship collision and grounding* are combined into a single hazardous event (ship collision or grounding impacting fuel containment or piping system) due to their shared consequences. These events are more likely to cause penetration into containment compared to contact/allision events. The event is analysed for the SOV design in chapter 4.3 with fuel tanks located below deck.

2.2.3 Operational and emergency releases

This category addresses hydrogen releases resulting from normal operation and emergencies, which typically include the following events (EMSA, 2024a):

- *Loss of vacuum insulation for LH2 systems.* If the tank loses its vacuum-insulation capabilities, the heat input will increase significantly, and all the liquid hydrogen in the tank will boil off within a relatively short time. In this scenario, the complete tank contents will be discharged as cold vapour at the vent mast outlet. This is also relevant for a piping system that loses its vacuum-insulation capabilities. The heat input will increase significantly, and all the liquid hydrogen in the system will boil off within a relatively short time. In this scenario, the complete contents of the pipe segment will be discharged as cold vapour at the outlet of the pressure relief device.

- *Trapped volumes in LH2 systems.* Piping systems will experience a rise in pressure for trapped volumes of LH2 when the hydrogen is heated by the surroundings. Unless this pressure build-up is limited through relief devices, the pressure may exceed the design pressure of the piping system.

- *Fire and explosion.* If the hydrogen storage tank is subjected to fire loads, the tank safety valves will discharge the tank contents at the vent mast outlet when the ullage pressure reaches the safety valve set point. For CH2 fuel systems, the release to vent mast will either be caused by the automatic depressurization (Thermal Pressure Relief Device - TPRD) or manual depressurization (blowdown).

- *Leaking safety valves.* If safety valves installed to limit the tank or piping system pressure fail or develop a leak, hydrogen gas will be discharged at the vent mast outlet.

- *Gas-freeing.* During the gas-freeing of a hydrogen tank, hydrogen is displaced by an inert gas and discharged through the vent mast.

- *Bunkering incidents.* Over-pressurization may be caused by erroneous bunkering operations, leading to release to the vent mast.

The ‘fire and explosion’ and ‘bunkering incidents’ are combined into one bowtie to represent the hazard scenario of *‘gas release from the vent mast’*. The analysis is presented in chapter 3.4 and includes the following specific threats:

- Automatic depressurization (Thermal Pressure Relief Device - TPRD)

- Manual depressurization (blowdown)

- Over-pressurization during bunkering

The 'loss of vacuum-insulation for LH2 systems' is comprehensively analysed in the report 'Risk Analysis of Generic Hydrogen Fuel Systems' (EMSA, 2025b) and not further analysed here. ‘Gas-freeing’ and ‘trapped volumes’ are not selected as their consequences are significantly lower compared to the other events.

2.2.4 Occupational accidents

The International Labour Organization (ILO) defines occupational accidents as an occurrence arising out of, or in the course of, work which results in a fatal or non-fatal injury, e.g. a fall from a height or contact with moving machinery (ILO, 2015). While major accident events have the potential to cause significant harm to multiple persons, assets and the environment, occupational accidents are typically incidents resulting in injury or harm to a limited number of persons. The EMSA’s European Marine Casualty Information Platform (EMCIP) defines an occupational accident as one that affects only a person (EMSA, 2024c).

Although maritime occupational safety has improved over time, work-related death, serious injury and long-term disability remain a significant problem in the maritime sector (University of Strathclyde and HSE, 2020). The adoption of alternative fuels in shipping will introduce new occupational hazards, including increased risks associated with flammability, toxicity, cryogenic temperatures, and oxygen depletion.

Today, occupational accidents onboard ships can be quite varied due to the unique and challenging work environment. Generic incidents, not limited to hydrogen fuel systems events, include (Maritim Education, 2025):

- *Slips, trips, and falls:* These accidents often occur due to wet decks, uneven surfaces, and cluttered workspaces.

- *Machinery-related injuries:* Injuries from engines, winches, cranes, and other machinery can include hand and finger crush injuries, burns, and entanglements.

- *Burns and scalds:* Exposure to hot surfaces, steam, or chemicals in engine rooms, galleys, and maintenance areas can lead to thermal and chemical burns.

- *Musculoskeletal injuries:* Heavy lifting, awkward postures, and repetitive tasks can cause back pain, strained muscles, and joint problems.

- *Cuts, bruises, and lacerations:* Sharp tools, cables, and machinery edges can cause cuts and lacerations, ranging from minor abrasions to deep wounds.

- *Falls from heights:* Working on masts or cargo holds poses serious risks, with falls potentially resulting in broken bones and head trauma.

- *Electrical shocks:* Electrical accidents can occur during maintenance work or due to faulty wiring.

- *Enclosed space accidents:* Entering confined spaces that are not properly gas-freed can lead to exposure to toxic or flammable gases.

The work activities related to the hydrogen fuel system that could lead to occupational accidents, and which are selected for further risk analysis in chapter 4.4, are:

- *Entry into spaces containing hydrogen systems:* Entering such spaces may cause the crew to be exposed to gases if there is a leak of hydrogen or inert gas, or cryogenic fluids. Additionally, low surface temperatures on piping can cause frostbite, and significant hydrogen or nitrogen leaks can lead to asphyxiation due to oxygen depletion.
- *Maintenance and repair of the hydrogen system:* Release of LH2 or CH2 when the system is opened for maintenance is possible if the maintained part is insufficiently gas-freed and isolated.
- *Hydrogen bunkering:* Leakages in relation to the bunkering operation can result in a deflagration/detonation of a flammable hydrogen mixture, or jet fires, in the bunkering station. There is also potential for exposure to cryogenic temperatures.

2.3 Risk analysis

This chapter presents the risk analysis approach, including the bowtie technique, frequency analysis, consequence analysis and the overall barrier modelling principle.

2.3.1 Bowtie technique

The bowtie technique is the selected method for risk analysis in this task. High-level bowties of hazardous events that pose significant risks to a hydrogen-fuelled ship and its crew were introduced in “Mapping safety risks for hydrogen-fuelled ships” (EMSA, 2024a). In the report ”Risk analysis of generic hydrogen fuel systems” (EMSA, 2025b) bowties were applied to specific concepts of hydrogen fuel systems. In this risk analysis, the bowties are applied to specific ship types.

The bowtie approach is selected to support regulators in the rule-making process. Firstly, the technique strongly emphasizes visualisation, supporting easy understanding of risk scenarios and necessary safety barriers. Secondly, the barrier functions defined in the bowtie support the validation of the functional requirements in the Guidance by ensuring that the barrier functions are represented in the functional requirements and vice versa.

One of the most acknowledged barrier models is James Reason’s “Swiss Cheese Model” of accident causation. The model builds on the principles of “defences in depth”, with a set of successive protection layers (i.e. barriers) preventing hazards from being realized and causing accidents to happen. As revealed by its name, the Swiss Cheese model illustrates an event sequence in which barriers are presented as slices of cheese. The “holes” in the cheese represent weakened barriers, either caused by active failures or latent failures. Active failures are immediate and directly linked to the actions of operating personnel, while latent failures are underlying issues within the systems or components (e.g. dangerous undetected failures) or within the organization that create conditions for failures to occur (DNV, 2014).

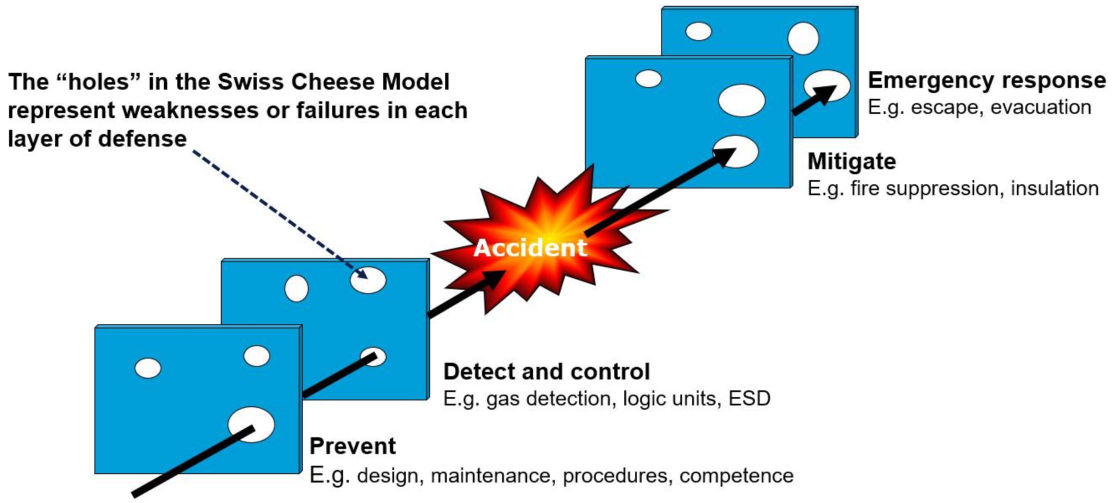

Figure 2-3 Illustration of "Swiss Cheese Model" of accident causation (Source: DNV).

The strength of the Swiss Cheese Model is how it exemplifies and promotes the following strategy for management (DNV, 2014):

- Each barrier should either prevent threats from being realised or the escalation of the event
- If one barrier fails, the subsequent barrier comes into play
- Barriers should, as far as possible, be independent of each other
- Barriers should be in place to reduce the risk as low as reasonably practicably
- No single failure should be able to cause a major accident
- "Holes", i.e. degradation in barrier performance, should be as small and few as possible

Management of major accident risk requires systems which capture complexity and reduce uncertainty. This is the main objective, or rationale, behind barrier management. It allows users to prioritize important safety measures related to technology and operation, so that the risk of major accidents can be reduced.

The bowtie model applied, illustrated in Figure 2-4, combines elements of both Fault Tree Analysis (FTA) and Event Tree Analysis (ETA) to provide a holistic view of the scenario. The central node of the bowtie represents the top event (loss of control). The left side of the bowtie (the "fault tree" side) identifies the threats leading to the top event, while the right side (the "event tree" side) maps out the potential consequences and the barriers in place to mitigate them. The bowtie focuses on the safety barriers designed to prevent an initiating occurrence from developing into the top event and the safety barriers mitigating the consequences of the top event.

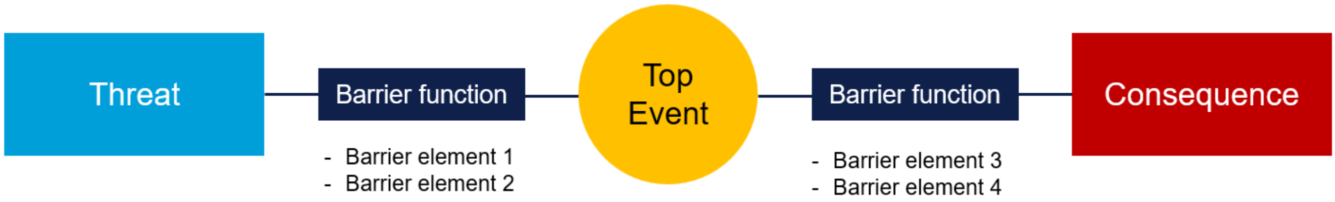

Figure 2-4 Illustration of the generic bowtie model with threat (left), top event (central), consequences (right) and safety barriers (Source: DNV).

2.3.2 Frequency analysis

It is crucial to recognize the limitations of conducting a frequency analysis on conceptual ship designs. This is mainly due to the dependence on actual operational- and detailed design input. Frequency analysis for the selected hazardous events within the categories of ‘mechanical damage’, ‘operational and emergency events’ and ‘occupational accidents’ relies heavily on specific descriptions on how the operations are conducted and what specific protection mechanisms are fitted. Conceptual ship designs lack these detailed operational descriptions and design details, making any frequency analysis potentially inaccurate.

In this task, explaining the methodology of frequency analysis has therefore been considered more appropriate than attempting to perform an exact analysis at this stage. This decision acknowledges the importance of accurate data and operational specificity.

2.3.3 Safety barrier modelling

The barriers are formulated as barrier functions and barrier elements, put in place to prevent or mitigate risks in a system. These functions are crucial in maintaining safety and ensuring that potential hazards are controlled effectively. When describing barrier functions, verbs are used to clearly convey the action being taken. For each barrier function, technical barrier elements are defined, which, alone or together, realize one or several barrier functions. Further descriptions of the bowtie methodology are detailed in the standard EN 31010:2019 “Risk assessment techniques” (IEC, 2019).

The safety barriers proposed in this report primarily focus on technical design measures. The reason is that the IGF code specifies that the Administration shall not allow operational methods or procedures to be applied as an alternative to a particular fitting, material, appliance, apparatus, item of equipment, or type thereof which is prescribed by the Code (IMO, 2015).

2.3.4 Consequence analysis

The consequence analysis is performed qualitatively and is based on the findings from the four previous reports produced in this EMSA project:

1. Mapping safety risks for hydrogen-fuelled ships (EMSA, 2024a)
2. Reliability and safety analysis (EMSA, 2024b)
3. Hazard identification of generic hydrogen fuel systems (EMSA, 2025a)
4. Risk analysis of generic hydrogen fuel systems (EMSA, 2025b)

The consequence analysis focuses on safety, i.e., the potential impacts on people and the ship. Environmental consequences are not within the scope of this study.

3. Risk analysis of Platform Support Vessel with compressed hydrogen stored above deck

This chapter presents the hazard identification and risk analysis of the Platform Support Vessel (PSV) selected in Chapter 2.1. The hydrogen fuel installation onboard includes fixed compressed hydrogen (CH2) fuel storage tanks located above deck, inerted tank connection enclosures (TCEs) and fuel piping systems protected by secondary enclosures which are inerted.

The following hazardous events are covered:

- Dropped object causing damage to fuel storage tanks or piping systems (Chapter 3.3)
- Ignition of hydrogen release through the vent mast (Chapter 3.4)

3.1 Analysis basis

The ship design selected for the risk analysis is described in this Chapter. The conceptual design serves as a starting point for identifying and analysing hydrogen-related risk factors.

A coarse general arrangement for the design is shown in Figure 3-1 and Figure 3-2. PSVs are specially designed for the logistical servicing of offshore platforms and subsea installations, from installation through the full service-life (DNV, 2025). They are primarily used to transport essential equipment, supplies, and crew to and from offshore fields (Clarksons, 2025).

The design intentions and main arrangement of the vessel is briefly presented below:

- *Fuel containment:* A collection of interconnected pressure vessels (fuel storage tanks) is secured inside four (4) ISO containers, two rows with stacking (see Figure 3-2 and Figure 3-3) on main deck. Each ISO container is arranged with a designated tank space for the pressure vessels, and a separate TCE where all tank connections, pipes, fittings, valves, and instruments are situated. The TCE is assumed gastight and filled with nitrogen at a slight overpressure. It is possible to gas-free the TCE via the inert gas purging system for access and maintenance. Each TCE is then connected to the fuel supply feeding the consumers.
- *Gas vent mast:* The gas vent pipe is fitted with secondary enclosure and routed from the fuel storage tanks' pressure relief valves, through the superstructure inside a casing, up to the gas vent mast outlet. The pressure relief system and vent mast outlet shall be arranged to safely disperse any release.
- *Fuel supply piping:* All fuel piping outside the TCEs is protected by inerted secondary enclosures (on open deck and in enclosed spaces).
- *Bunkering station:* The bunkering station is located on the main deck close to the fuel containment system. The bunkering station has an open arrangement.
- *Cargo deck and rail:* The design features a large, open deck area that can carry large quantities of cargo, such as casings, drill pipes, tubing, and other miscellaneous deck cargo. A cargo rail is fitted along each side of the main deck. It contains ventilation pipes from cargo tanks, ventilation for spaces below deck, emergency exits from below deck, escape routes in case the cargo deck is fully blocked with cargo, electrical cables, and mooring station/equipment.
- *Superstructure:* The superstructure of the PSV is in the foremost part of the vessel and includes the accommodation, bridge, and other enclosed spaces.
- *Below-deck spaces:* The engine room, arranged as a gas safe machinery space, is located below the hydrogen fuel installation on the main deck. A battery storage room and cargo tanks are located further aft.

PSVs transport a variety of cargoes, including fuel, water, drilling fluids, cement, and mud in below-deck tanks.

- *Lifesaving appliances:* Liferafts are located on the A-deck (deck above the main deck), aft of the accommodation unit.

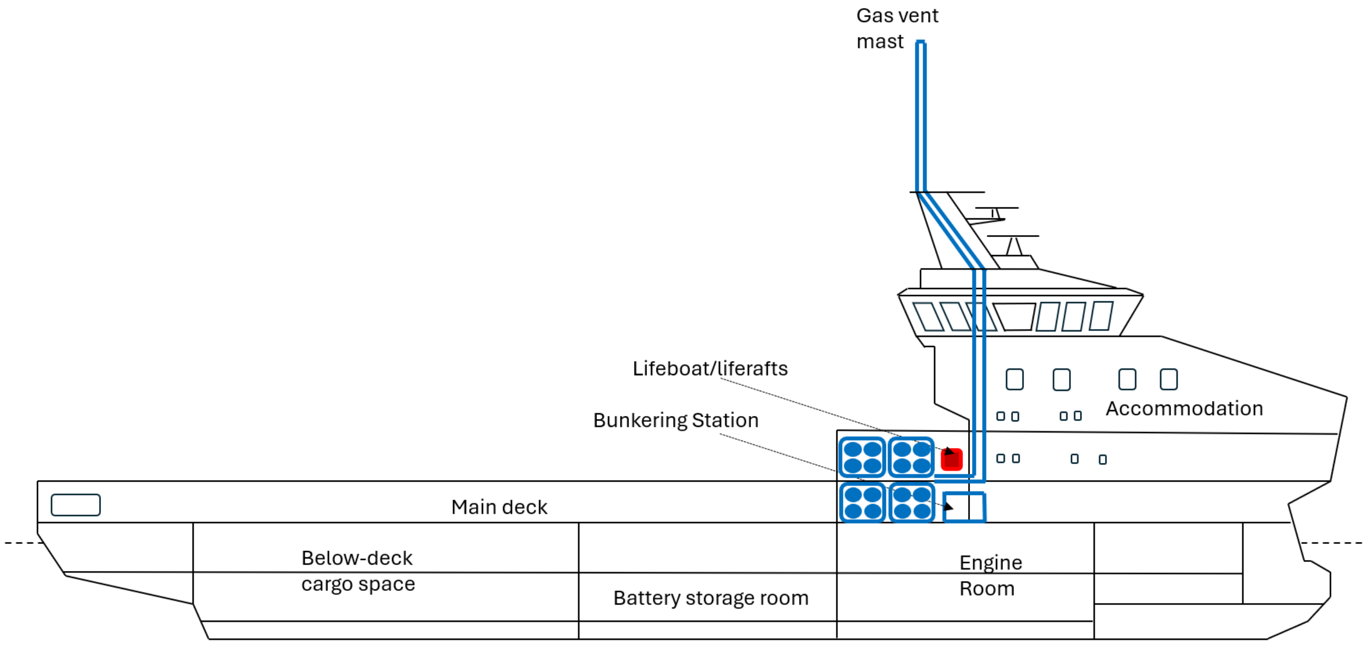

Figure 3-1 Side view of general arrangement for the PSV design (Source: DNV).

Figure 3-2 shows the general arrangement plan view for the PSV design.

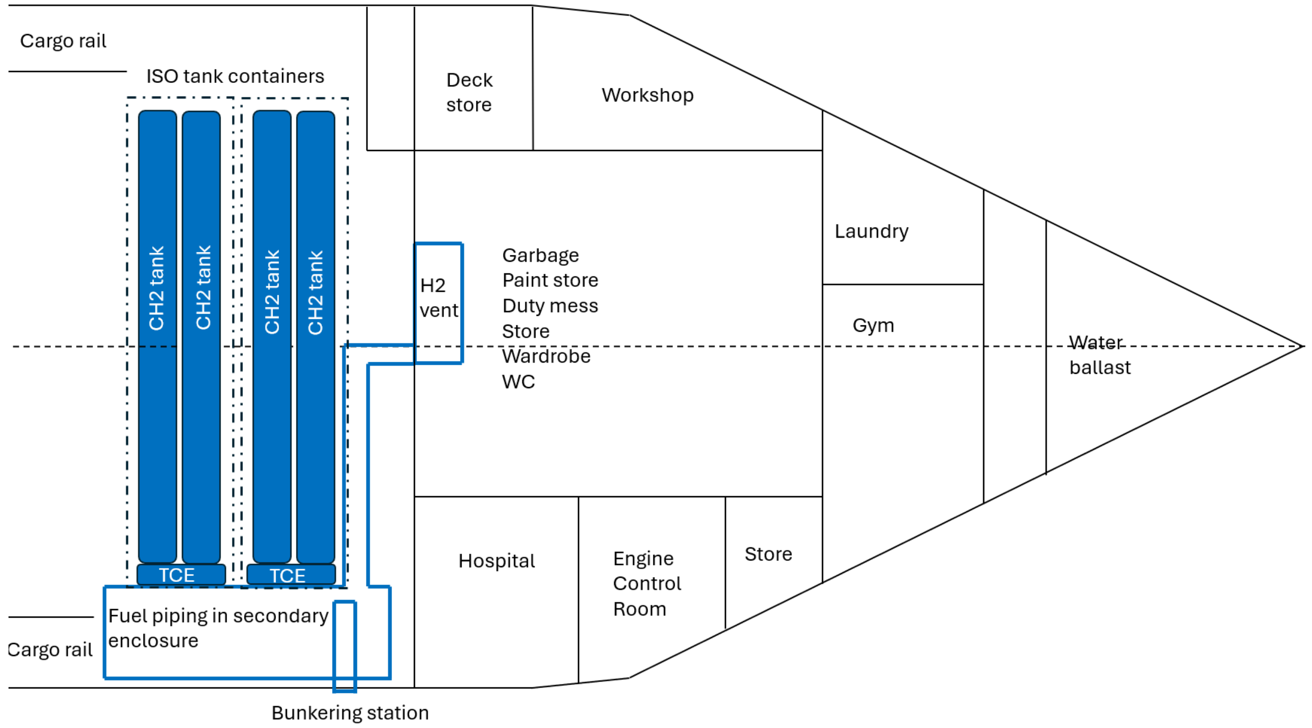

Figure 3-2 Plan view of general arrangement for the PSV design (Source: DNV).

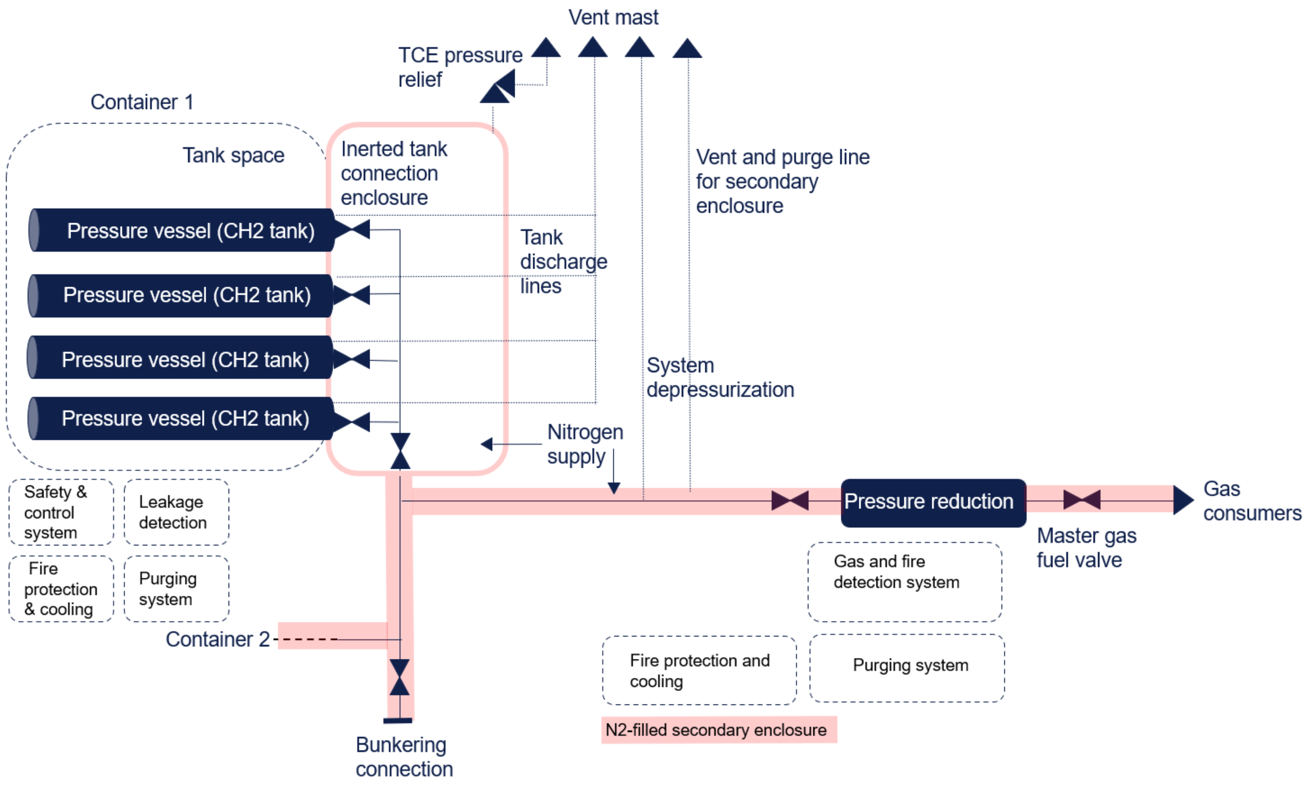

Figure 3-3 Hydrogen fuel system illustration for the PSV design (Source: DNV).

3.2 Hazard Identification

The risk analysis for the PSV with compressed hydrogen on deck focuses on *releases due to mechanical damage'* and *'operational and emergency releases'*. Occupational accidents are addressed for the SOV design in chapter 4.4.

Firstly, we assess causes that may initiate *'releases due to mechanical damage'* from the hydrogen fuel installation onboard the PSV, building on the descriptions in chapter 2.2.2:

- *Ship collision:* Another vessel may hit the fuel tanks located on the main deck of the PSV. Generally, it should be ensured that fuel tanks and piping systems are kept away from areas likely to be affected by collision damage.

- *Allision/contact damages:* PSVs frequently manoeuvre close to offshore platforms and other structures, making them susceptible to allision (contact) damage. However, vessels operating in these environments typically navigate at low speeds, which significantly reduces the kinetic energy involved in potential impacts. As a result, the likelihood of severe damage to fuel tanks is lower compared to high-speed collisions. Nevertheless, fuel tanks and piping systems should be strategically located away from areas most likely to be affected by contact to minimize the risk of damage in the event of an allision.

- *Grounding:* Being located above deck, damages caused by grounding are less of a concern for the hydrogen fuel installation onboard the PSV. For all ship types, it should be ensured that fuel tanks and piping systems are kept away from areas likely to be affected by grounding damages.

- *Explosions:* The fuel tanks and piping system may be adversely affected by explosions originating in the Engine Room or from the cargo area on the PSV. Such events can result in structural damage, compromise the integrity of fuel tanks and piping systems, and potentially lead to secondary hazards such as fuel leaks or fires. The proximity of the fuel tanks to these high fire-risk areas underscores the importance of robust protective measures, such as passive and active fire suppression systems.

- *Dropped objects:* This event is particularly relevant for the PSV design with hydrogen storage on main deck considering the frequent loading/offloading of cargo and equipment. The event is selected for further analysis in chapter 3.3.

- *Mooring line snap-back:* Fuel tanks and piping should not be located within a snap-back danger zone. Whether this is the case depends on a range of factors such as mooring line length, material, tension and deck layout and line routing. Generally, when a mooring line parts under tension, it can recoil with tremendous force and speed. The trajectory of the snap-back can be unpredictable, especially if the line hits structures or changes direction due to deck fittings.

- *Shifting cargo:* Shifting cargo presents a potential hazard in this vessel arrangement. If cargo on the main deck loses its securing mechanisms, it could become dislodged and impact critical components such as fuel tanks or associated piping systems. Such impacts may compromise the structural integrity of the fuel system, leading to leaks.

- *Wave loads and green sea:* The deck where the fuel tanks are located may be affected by wave loads and green sea, although the superstructure and the cargo railing on the PSV forms some protection. The fuel tanks and tank valves are located inside an ISO container.

- *Ice impacts:* PSVs may operate in Arctic conditions or ice-covered waters, where various forms of sea ice—including icebergs, pack ice, and multi-year ice—pose significant hazards. Collisions with these ice formations can result in substantial damage to the vessel's hull and structural components. Such impacts may compromise critical systems, including fuel containment and piping, thereby increasing the risk of leaks.

Secondly, we assess causes that may initiate *'operational and emergency releases'* from the hydrogen fuel installation onboard the PSV (ref.2.2.3) which are further analysed in chapter 3.4:

- *Fire and explosion:* For CH2 fuel storage tanks, the release to the vent mast will either be caused by the automatic depressurization (Thermal Pressure Relief Device - TPRD) or manual depressurization (blowdown).

- *Gas-freeing:* During gas-freeing of a fuel tank or piping systems, hydrogen is displaced by inert gas and discharged through the vent mast.

- *Bunkering incidents:* Over-pressurization may be caused by erroneous bunkering operations, leading to release to the vent mast.

3.3 Risk analysis of dropped object onto fuel containment systems or piping

This chapter presents the risk analysis of dropped objects on fuel storage tanks or piping due to cargo lifting operations. This event is particularly relevant for the PSV design, considering the frequency of loading and offloading of cargo and equipment to offshore fields. To protect against falling objects, the design for the PSV includes a guardrail system for mechanical protection. The protection railing extends from the accommodation unit and down to the cargo deck.

For this specific ship type, cranes on offshore units are used to lift objects to and from the vessel. However, to ensure the assessment is relevant for all ship types, dropped objects from shipboard cranes or other systems that may cause dropped objects are included in the analysis.

In addition to dropped object scenarios related to crane operations, the risk assessment should also consider potential impacts resulting from structural failures, such as the collapse of crane booms or similar components. These events, while potentially severe, are characterized by extremely low frequencies. Specifically, the estimated frequency of a crane boom collapse during lifting operations is on the order of 1×10^{-7} per lift. Given this low likelihood, the contribution of such scenarios to the overall risk profile is considered negligible and does not significantly influence the total risk estimation.

Generally, dropped objects may also penetrate a protective deck if the fuel storage tanks where to be located below deck. In such cases, strength calculations must show that the deck has sufficient strength to absorb a worst-case impact without damaging the fuel containment or piping system.

3.3.1 Frequency analysis approach

Dropped object studies are a vital component of quantitative risk assessment for offshore oil and gas operations, evaluating the risks associated with potential dropped objects during crane operations. This evaluation is typically carried out as a “Dropped Object Study” and is specific for each vessel and offshore unit.

It is important to recognise that, like collision and grounding damages, the consequences of dropped objects damaging a hydrogen fuel containment system are severe. Therefore, the emphasis should be on identifying locations where dropped objects might fall and ensuring that hydrogen tanks are not situated in those areas.

Considering the above, this subsection describes the approach for estimating the probability of a dropped object event. The explanations provided are primarily focused on detailing the methodology, as discussed in Chapter 2.3.2.

Several factors can result in objects being dropped when lifting cargo between a PSV and an offshore unit:

- Improper cargo securing
- Malfunctions or failures in lifting equipment, such as slings, hooks, or cranes
- Mistakes made by personnel, such as incorrect rigging or not following safety procedures
- Adverse weather conditions, such as high winds or rough seas destabilizing the lift
- Small items or foreign objects left on the cargo can become dislodged during the lift

There are several data sources for dropped object probabilities on offshore installations, e.g. The International Association of Oil & Gas Producers’ (OGP) - Risk Assessment Data Directory and UK Health and Safety Executive’s (HSE) accident statistics. Dropped object probabilities per lift are tabulated for mobile installations and fixed installations, for different load weights and by lifting device (main crane, drilling derrick, or other devices). Examples are provided from the OGP-data in Table 3-1 for the main crane only and consider dropped load onto the vessel.

Table 3-1: Dropped Object Probabilities for main crane on offshore mobile units per lift (Source: OGP 2010, reproduced by DNV).

Object weight	Drop onto vessel probability (per lift)
<1t	1.1E-5
1-20t	3.0E-6
20-100t	9.5E-6
>100t	0

To calculate the frequency and impact of dropped objects on fuel storage tanks and piping on the PSV from offshore units, particularly in line with DNV-RP-F107 Risk assessment of pipeline protection (DNV, 2021), the process typically involves the following steps:

1. *Categorization of dropped objects:* Objects (e.g. drill collars, casing, container, basket, etc) are classified based on weight (e.g. <2 tonnes, 2–8 tonnes, >8 tonnes) and shape (e.g. flat/long, box/round).
2. *Frequency of dropped objects:* The first step in estimating the frequency of dropped objects involves determining the lifting frequency of the identified objects. On average, a PSV can perform anywhere from hundreds to thousands of lifts per year. This frequency should encompass all relevant lifting activities over a defined operational period. Once established, the lifting frequency is multiplied by the probability of a

dropped object per lift, which is typically derived from sources mentioned in the introduction – generic accident data specific to offshore lifting operations. The result is expressed as an annual dropped object frequency (e.g. number of drops per year).

3. *Probability of drop above an object to be protected:* The likelihood of an object falling onto a protected object is usually assessed through a geometric evaluation of deck areas. This method involves assessing the spatial relationship between the crane drop zone and the layout of critical PSV components. The analysis focuses exclusively on the likelihood of impact within the defined target area, excluding potential impacts on other structures such as offshore topsides equipment, subsea pipelines, or other vessel components.

4. *Probability of damaging the protected object:* The final step involves evaluating whether the dropped object possesses sufficient kinetic energy to damage the protected object. This assessment considers both the impact energy of the object and the capacity of intervening mechanical protection or structures—such as decks, protective mechanical covers, or energy-absorbing barriers—to dissipate or mitigate that energy upon impact. If the energy absorption capacity of these structures is adequate, loss of containment can be prevented. Otherwise, the risk of puncture and subsequent release must be accounted for in the overall risk evaluation. Advanced analysis includes energy absorption factors or finite element analysis to model deformation and energy dissipation. Typical factors that will influence the energy absorption for dropped objects may be listed as follows (DNV, 1983):

    - The kinetic energy of the falling object, which is a function of its mass and the height from which it falls.
    - The contact surface during impact will be a factor determining the mode of energy absorption.
    - Location of impact on structures - generally, stiff zones result in small deflections with corresponding small energy absorption capabilities.
    - The mass of the impacted structure and the mass ratio between the structure and the dropped object may influence the dynamic behaviour of the structure and the mode of deflection.
    - The stiffness of the impacted structure and the falling object - in most cases, the main energy has been observed to be absorbed by either plastic deformation of the impacting object or the hit structure.
    - Orientation of velocity vector during impact - To simulate the most severe impact situation, the velocity vector should be normal to the plate surface through the object's centre of gravity.
    - Type and thickness of protective material: Various materials, alone or in combination, may be used for dropped object protection, e.g. steel, concrete, wood, aluminium, etc. The material thickness will affect both the local stress distribution and the material properties.

To estimate the frequency of dropped objects causing damage to fuel storage tanks or piping, the frequency of dropped objects is combined with the probabilities of them falling above and penetrating the fuel storage tanks or piping.

3.3.2 Consequence analysis

If, for example, a 500 kg vertically oriented drill pipe is dropped from the installation above and impacts the composite fuel storage tanks, it is very likely to cause a tank puncture. This will lead to a massive release of hydrogen gas, likely resulting in immediate ignition and the potential for further escalation events. This scenario represents a worst-case situation for the PSV used as the basis for this analysis, due to the severe consequences of hydrogen ignition and its proximity to the accommodation and the bridge.

Escalation events could trigger a domino effect, sequentially impacting other fuel tanks and piping systems. Heat from a fuel tank fire can cause surrounding fuel tanks to overheat, consequently opening the TPRD valves of several tanks. Furthermore, overpressure and projectiles from an explosion can damage other fuel tanks and piping systems. Escalation events could jeopardise the entire ship, increasing the risk of multiple fatalities. These events are likely to develop swiftly and may damage lifesaving equipment and/or leaving insufficient time to muster and evacuate the ship.

If the dropped object impacts hydrogen fuel piping, the consequences may be less severe compared to a tank puncture, but even this scenario can endanger the crew due to the potential for jet fire, deflagration, and detonation.

3.3.3 Safety barrier modelling

The risk of dropped object damage is analysed using the bowtie approach, and the tank puncture and piping damage resulting from a dropped object is addressed separately.

The risk of dropped object on tank is visualized in Figure 3-4. The top event is *'damage to fuel containment systems'*. The threats are described in chapter 3.4.1 and potential consequences are described in chapter 3.4.2.

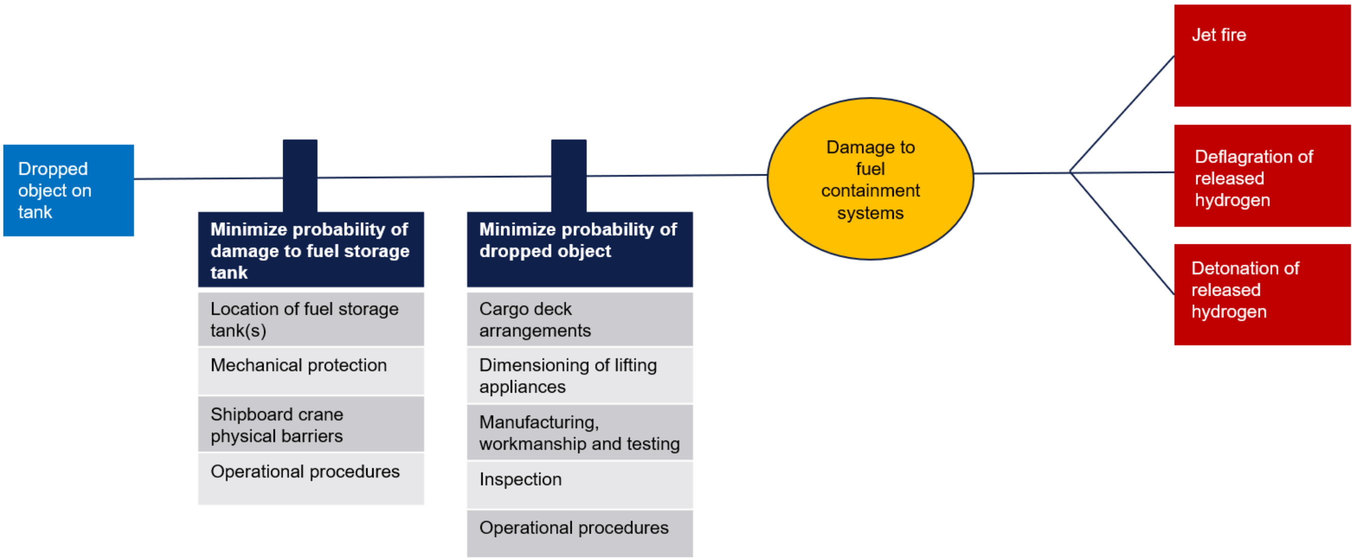

Figure 3-4 Bowtie for risk of tank puncture due to dropped object (Source: DNV).

The first barrier function aims to *Minimize the probability of damage to the fuel storage tank*. This barrier function consists of the following barrier elements:

- *Location of fuel storage tank(s):* Fuel tanks and piping systems should be kept away from areas where loading and offloading pose a damage risk.
- *Mechanical protection:* If the fuel storage tanks cannot be kept away from areas where loading and offloading pose a damage risk, they must be provided with mechanical protection strong enough to withstand worst-case damage from the cargo operation (e.g. dropped object). The mechanical protection should be designed to absorb and dissipate energy to prevent damage to the tanks.
- *Shipboard crane physical barriers:* Physical barriers around shipboard cranes can prevent accidental dropped objects and contact with fuel storage tanks. These barriers can include guardrail or other forms of containment that restrict the movement of cranes and prevent them from swinging or dropping loads onto the tanks.
- *Operational procedures:* Preventing dropped objects from impacting hydrogen containment and piping. is achieved by enforcing no-lift zones or prohibited zones around these critical areas. The IGF Code explicitly states that operational methods or procedures should not be used as substitutes for technical design measures. Therefore, implementing strict operational procedures serves as an additional risk-reducing measure to minimize the probability of damage to fuel storage tanks.

The second barrier is to *'Minimize the probability of a dropped object'.* Although this barrier function and its elements are essential in preventing dropped objects, it is only directly related to the hydrogen fuel system in cases where the fuel containment system is provided with mechanical protection. It should also be noted that some of these barriers may be external to the ship, i.e. installed on shore cranes, offshore installations etc. The barrier elements that would typically be included in this function are:

- *Cargo deck arrangements:* Proper cargo deck arrangements can significantly reduce the risk of dropped objects by ensuring that there is adequate space and a well-organized layout for manoeuvring cargo, e.g. clear pathways, adequate space, visibility and lighting, etc.

- *Dimensioning of lifting appliances:* Ensuring that lifting appliances are appropriately dimensioned for the tasks they perform is vital. This involves selecting the right size and capacity of cranes, hoists, and other lifting equipment to handle the loads safely.

- *Manufacturing, workmanship, and testing:* A rigorous regime ensuring satisfactory manufacturing, workmanship, and testing of the piping systems and other critical components should be in place. This includes adhering to high quality standards during production, conducting thorough inspections, and performing regular testing to detect any potential defects or weaknesses that could lead to dropped objects.

- *Inspection:* Regular inspection of lifting appliances and gear is essential to ensure their safe operation. This includes routine checks for wear and tear, proper maintenance of equipment, and timely replacement of any damaged or faulty parts. Inspections help in identifying and mitigating risks before they result in dropped objects.

- *Operational procedures:* Implementing and following standardized and safe lifting procedures is key to minimizing the probability of dropped objects. This involves training personnel on safe lifting practices, using appropriate lifting techniques, and ensuring that all lifting operations are conducted under controlled conditions, including assuring strict operating criteria.

If all preventive barriers fail and a tank puncture occurs due to a dropped object, the crew will need to manage the situation to the best of their ability, utilizing available resources and emergency protocols. Consequently, no credit is given to the mitigation of consequences for this event, and it is therefore omitted in the bowtie. This omission serves to emphasize that this scenario is not dimensioned for in the design and regulatory framework. All measures are aimed at ensuring that tank puncture due to dropped object does not occur.

The risk of a dropped object damaging hydrogen fuel piping is visualized in Figure 3-5. The top event is *'damage to fuel piping systems'.* The threats are described in chapter 3.4.1 and potential consequences are described in chapter 3.4.2.

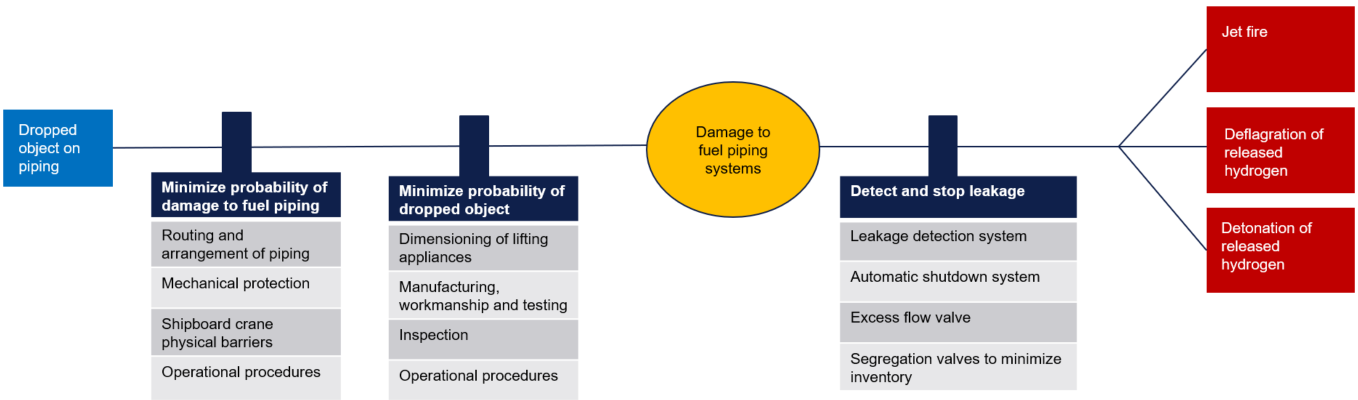

Figure 3-5 Bowtie for risk of leakages in the ship fuel supply piping (Source: DNV).

The preventive barriers are almost identical to the top event 'damage to fuel containment systems'. The main difference lies in the addition of the mitigation barrier function 'Detect and stop leak'. Since this scenario assumes the tank and safety systems remain intact, it should be possible to detect the release of hydrogen due to the dropped object, and initiate shutdown. The following barrier elements are included:

- *Leakage detection system:* Any leaks from fuel piping systems should be detectable by gas detectors, pressure differential measurements, or both.

- *Automatic shutdown system:* Similar to the gas detection system, this is a crucial safety function. The detection and shut-down safety function utilizes three subsystems: Sensor subsystem, Logic solver subsystem and Final element subsystem.

- *Excess flow valve (EFV):* EFVs are mechanical safety devices designed to automatically shut off the gas flow when it exceeds a predetermined rate.

- *Segregation valves to minimize inventory:* By isolating sections of the piping system, segregation valves reduce the volume of hazardous material that can escape in the event of a leak. This means that only the material within the isolated section can be released, rather than the entire system's contents.

3.4 Risk analysis of hydrogen release through the vent mast

A hydrogen fuel system subject to an external fire will heat up and each fuel storage tank (pressure vessel) is therefore fitted with a tank discharge line designed to safely vent the contents through the vent mast in a fire scenario. While this prevents tank rupture, it introduces other potential risks that must be managed, such as ignition of hydrogen inside the vent mast or deflagration or detonation on deck. Hence, this risk analysis covers hazardous events resulting in hydrogen releases from fuel storage tanks to the vent mast (threat) and subsequent ignition (top event).

The HAZID found several causes initiating releases from fuel storage tanks through the vent mast (EMSA, 2025a):

- *Automatic depressurization:* Thermal Pressure Relief Devices (TPRDs) are frequently used to discharge the tank contents if temperatures surpass a pre-defined threshold at the TPRD location (i.e. heat radiation monitoring). This system is designed to safely vent the pressure vessels contents before the tank walls are compromised by heat, thus preventing catastrophic failure. If a TPRD fuse is activated, the entire CH2 content will be vented through the vent line, as TPRDs remain open after triggering.

- *Manual depressurization (blowdown):* The vessel is equipped with a back-up manual remote depressurization system, enabling a controlled blow-down through the vent line to the vent mast. This procedure involves opening valves to release gas from the tanks, thereby lowering the internal pressure. Blowdown is used during emergency situations to prevent overpressure, which can lead to tank bursting.

- *Over-pressurization during bunkering:* Over-pressurization during the bunkering of compressed hydrogen can occur due to several factors:

    - *Operational error:* Incorrect handling or mismanagement during the bunkering process can lead to over-pressurization. For example, not monitoring the pressure levels properly or exceeding the agreed filling rate.

    - *Equipment malfunction:* Faulty pressure regulators, valves, or gauges can fail to control the pressure accurately, leading to over-pressurization.

- *Gas-freeing:* During gas-freeing of a fuel tank or piping systems, hydrogen is displaced by inert gas and discharged through the vent mast.

3.4.1 Frequency analysis approach

This section explores associated frequencies for the following threat scenarios:

- *Automatic depressurization (release through Thermal Pressure Relief Device - TPRD) or manual depressurization (blowdown):* Release of the TPRD or blowdown would only be needed in case of a major fire scenario. A frequency analysis for such a scenario was provided in the report “Risk analysis of generic hydrogen fuel systems” (EMSA, 2025b):

    - The analysis found that the serious fire/explosion incident frequency (non-hydrogen-initiated events) is estimated to 9.8E-4 per ship year, which equals one event every 1 000 years.

    - The fire/explosion incident frequency for hydrogen systems events (hydrogen-initiated events) was estimated to 1.8E-03 per ship year. The estimate considered TCE events only, leaving out bunkering and fuel supply events, and assuming all leaks can cause harm and a failure on demand probability (PFD) for the inert gas safety function.

- *'Gas-freeing' and 'Over-pressurization during bunkering':* There are no specific statistics available. For detailed frequency analysis of bunkering operation incidents, it is necessary to assess the contribution of the human element to system failure. The accepted way of incorporating the human element into quantitative risk analysis studies is through the use of Human Reliability Analysis (HRA) (IMO, 2018).

3.4.2 Consequence analysis

The discharge of hydrogen to the vent mast introduces potential consequences described below.

Ignition inside the vent mast

The vent mast can be subject to air ingress from the vent head, and in a venting scenario where the piping is filled with hydrogen/air mixture, it can lead to a deflagration and possibly a detonation inside the vent piping (MarHySafe, 2021).

Jet fire from the vent mast outlet

A jet fire can occur out of the vent mast of a pressurized system when certain conditions are met. First, there needs to be a release of pressurized hydrogen gas. This release creates a high-velocity jet of gas. If this gas encounters an ignition source, it will lead to a jet fire. A jet fire could also occur following a delayed ignition of an established hydrogen cloud, continuing as a jet fire from the top of the vent mast (EMSA, 2024a).

Jet fire characteristics with hydrogen were addressed in the MarHySafe JIP where it was concluded that larger hydrogen jet fires have similar properties as natural gas jet fires, though the hydrogen jet fires do have higher flame temperatures. For smaller fires, the flames are nearly invisible and a lower fraction of heat is radiated from the fire than would be the case with natural gas (MarHySafe, 2021).

The radiant heat that reaches and is absorbed by a person from a hydrogen-air flame is directly proportional to various factors, including exposure time, burning rate, hydrogen mass flow, distance from the fire and the geometry around the release point (EMSA, 2024a).

Deflagration or detonation on the open deck

Hydrogen releases on the open deck were addressed in the EMSA report "Mapping safety risks for hydrogen-fuelled ships". The consequences of igniting hydrogen released on an open deck will depend on the geometry around the release point at the top of the vent mast (EMSA, 2024a). The ignition of a gaseous hydrogen-air mixture in an unrestricted open-air environment usually results in ordinary deflagration with little pressure build-up. The direct initiation of a detonation needs much higher ignition energy than the initiation of a deflagration. Detonations of non-confined gas clouds tend to occur more easily with increasing cloud size (EMSA, 2024a).

The presence of 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 (or slow/fast deflagration). If the flame reaches a high enough speed and encounters turbulence and flame instabilities, deflagration can transition 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 (EMSA, 2024a). Blast waves from deflagrations and detonations may cause injuries or fatalities as a result of overpressure at a given location.

Gas being led inside the ship and ignited

If gas released from the vent mast reaches ventilation intakes or open doors, it could enter spaces where ignition is possible. This could endanger persons inside the ship and/or safety-critical systems (e.g. on the bridge or other internal spaces).

3.4.3 Safety barrier modelling

The risk of hydrogen release through the vent mast is analysed using the bowtie approach and visualized in Figure 3-6. The top event is 'Ignition of hydrogen release through vent mast. The threats are described in chapter 3.4.1 and potential consequences are described in chapter 3.4.2.

Note that gas-freeing event were not brought forward to the safety barrier modelling due to significantly lower consequences compared to fire and overpressurization events.

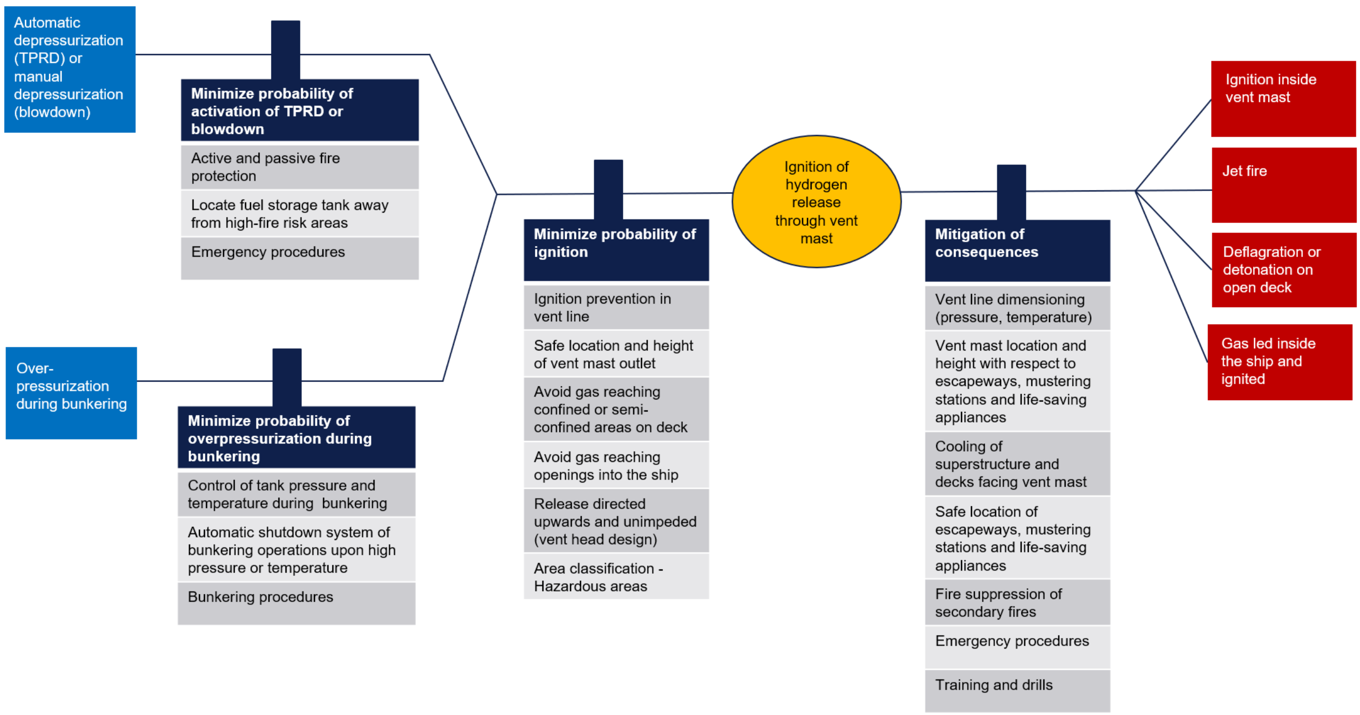

Figure 3-6 Bowtie for "ignition of hydrogen release through vent mast". (Source: DNV).

The barrier function aimed to avoid automatic or manual depressurisation of individual tanks (Minimize probability of activation of TPRD or blowdown) consists of the following barrier elements:

- *Active and passive fire protection*: Fixed fire extinguishing systems on ships are essential safety measures designed to automatically detect and suppress fires. Fire insulation, cofferdams or a combination of both can be used to protect storage tanks from heat ingress in cases where it is not possible to segregate them further from surrounding spaces with high fire risk.

- *Locate fuel storage tank(s) away from high-fire risk areas*: The distance and arrangement or location of the fuel storage tank(s) in relation to high-fire-risk areas should be considered. For example, fuel storage tanks located directly above category A machinery spaces or other rooms with high fire risk would typically be a major hazard.

- *Emergency procedures*: Implementing comprehensive emergency response plans to ensure quick and efficient action in case of a fire incident.

The barrier function aimed at minimising the probability of overpressurization during bunkering (*Minimize probability of overpressurization during bunkering*) consists of the following barrier elements:

- *Control of tank pressure and temperature during bunkering*: Control and safety system should monitor for high pressure and temperature, as well as leakage detection alarms.

- *Automatic shutdown system of bunkering operations upon high pressure or temperature*: A safety system should be arranged to automatically close down the fuel supply system upon failures, leakage or abnormal situations.

- *Bunkering procedures*: Bunkering procedures, as part of "Operation manual" for vessel.

The next barrier function, relevant for all threats, is 'Minimize probability of ignition'**.** The barrier function consists of the following barrier elements:

- *Ignition prevention in vent line*: The vent mast shall be designed to minimize the risk of self-ignition internally in the vent line. In addition, vent masts shall be grounded to prevent the build-up of static electricity.

- *Safe location and height of vent mast outlet*: The vent mast outlet shall be located away from the weather deck, working areas and gangways, exhaust outlets from machinery, etc.

- *Avoid gas reaching confined or semi-confined areas on deck*: It is critical to ensure that released gases do not accumulate in confined or semi-confined areas on the deck.

- *Avoid gas reaching openings into the ship*: The vent mast outlet shall be located away from air intakes or openings to accommodation spaces, service spaces, and control stations, or other non-hazardous area.

- *Release directed upwards and unimpeded (vent head design)*: The outlet from the vent mast should be so constructed that the discharge will be unimpeded and be directed vertically upwards at the exit. The vent system and vent masts shall be designed and constructed to prevent blockage due to foreign objects, ice, etc.

- *Area classification*: Hazardous area classification around vent mast outlet.

If all the preventive barriers fail and there is an ignition of hydrogen release through the vent mast, the consequences must be thoroughly investigated to ensure that potential worst-case effects are acceptable with respect to the safety of the ship and the people onboard. Mitigation barriers listed below can reduce the effects of the event:

- *Proper vent line dimensioning*: The vent line should be designed to limit consequences of internal deflagration/detonation.

- *Ensure that the location and height of the vent mast is optimal with respect to the risk of affecting escapeways, mustering stations and life-saving appliances*: The vent mast should be located so to ensure safe dispersion of hydrogen. The height should be sufficient to prevent thermal radiation from affecting the personnel, life-saving equipment, fuel containment system and structures on board.

- *Possibility to cool down superstructure and decks* facing vent mast with water spray systems.

- *Safe location of escapeways, mustering stations and life-saving appliances*: Location of escapeways, mustering stations and life-saving appliances should be located away from the vent mast outlet.

- *Fire suppression of secondary fires*: Fire suppression systems could be used to control fires. Hydrogen fires should not be extinguished until the release has been stopped. This could result in a more hazardous second event where the escaped gas could ignite and create an explosion.

- *Emergency response plans*: Implementing comprehensive emergency response plans to ensure quick and efficient action in the event of an incident is essential.

- *Training and drills*: It will be important to conduct regular training and emergency drills to prepare crew for potential accidents and to ensure that they know how to respond effectively.

4. Risk analysis of Service Operation Vessel with liquefied hydrogen stored below deck

This chapter presents the hazard identification and risk analysis of the Service Operation Vessel (SOV) selected in Chapter 2.1. The hydrogen fuel installation onboard includes a liquefied hydrogen (LH2) fuel system with vacuum-insulated IMO Type C tank, tank connection space (TCS) and piping systems protected by secondary enclosures all located below deck.

The following hazardous events are covered in this chapter:

- Ship collision or grounding impacting fuel containment and piping systems (Chapter 4.3).
- Occupational hazards relating to fuel containment systems and piping systems (Chapter 4.4).

4.1 Analysis basis

The ship design chosen for the risk analysis is detailed in this chapter. As with the PSV, the design serves as a foundation for identifying and analysing hydrogen-related risk factors.

A general arrangement for the SOV is shown in Figure 4-1 and Figure 4-2. SOVs are specialised vessels dedicated to the operation and maintenance of offshore wind farms, although they can also serve other offshore energy sectors.

A distinct feature of SOVs is their walk-to-work functionality, equipped with a motion-compensated gangway mounted on a tall tower structure, which allows for safe personnel transfer to offshore wind turbines or platforms, even in rough seas. This system is also integrated with cranes or lifts for transferring cargo or equipment. SOVs are designed to accommodate technicians and crew for extended periods.

The design intentions and main arrangement of the vessel are briefly presented below:

- *Fuel containment:* Hydrogen will be stored onboard in two (2) vacuum-insulated pressure tanks designed in accordance with requirements for an IMO Type C fuel tank. The tanks are located in a dedicated fuel storage hold space below deck.
- *Gas vent mast:* The vent system from the tank is fitted with a secondary enclosure and routed through the superstructure inside a casing, up to the open deck above the gangway structure.
- *Fuel supply piping:* The complete fuel system is protected by secondary enclosures designed to safely contain and vent leakages.
- *Bunkering station:* The bunkering station is located above deck inside an enclosure.
- *Main deck:* The main deck is used to store equipment. Work boat(s) and side loading ramp(s) are also located on the main deck.
- *Superstructure:* The superstructure of the SOV is located in the fore part of the vessel and includes the accommodation, bridge, and other enclosed spaces.
- *Below-deck spaces*: Below-deck spaces include the engine room, switchboard room, propulsion rooms etc. The engine room is arranged as a gas-safe machinery space.
- *Lifesaving appliances:* Lifeboats/liferafts are located aft of the accommodation/bridge.

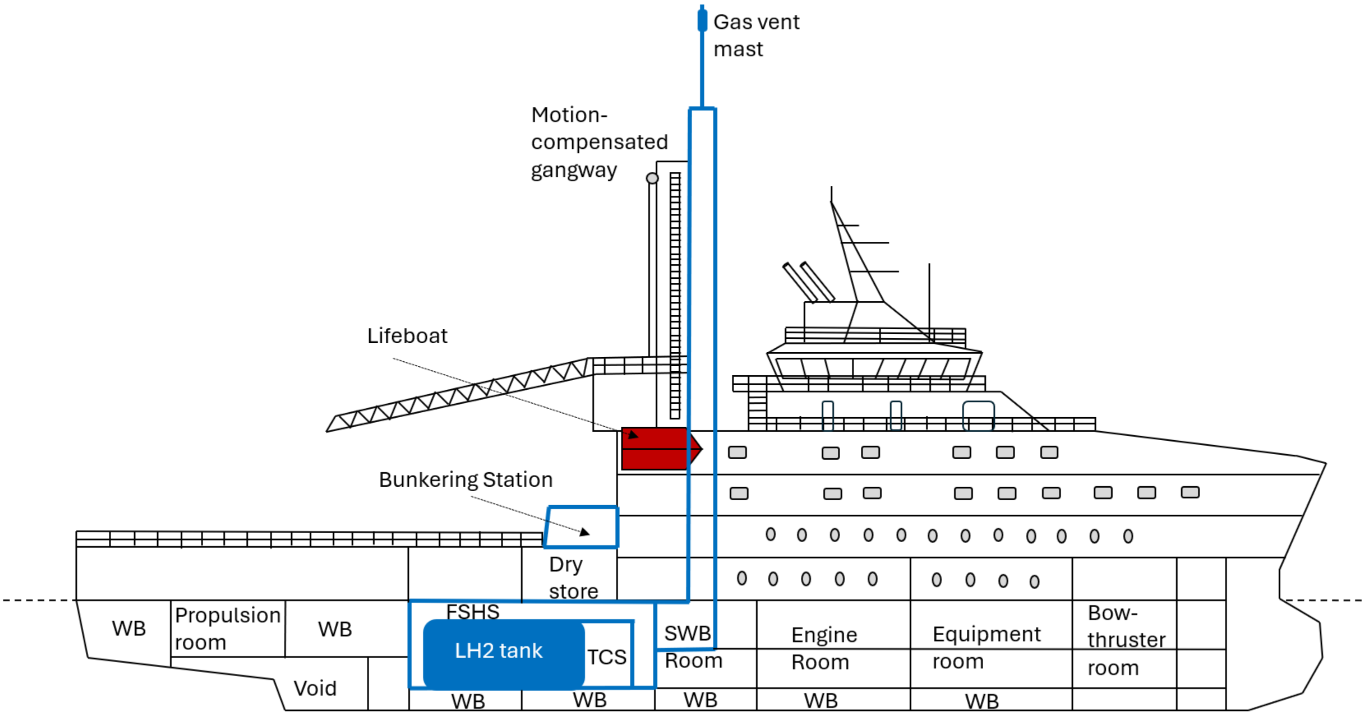

Figure 4-1 Side view of general arrangement for SOV (Source: DNV).

Figure 3-2 shows the general arrangement plan view for the SOV.

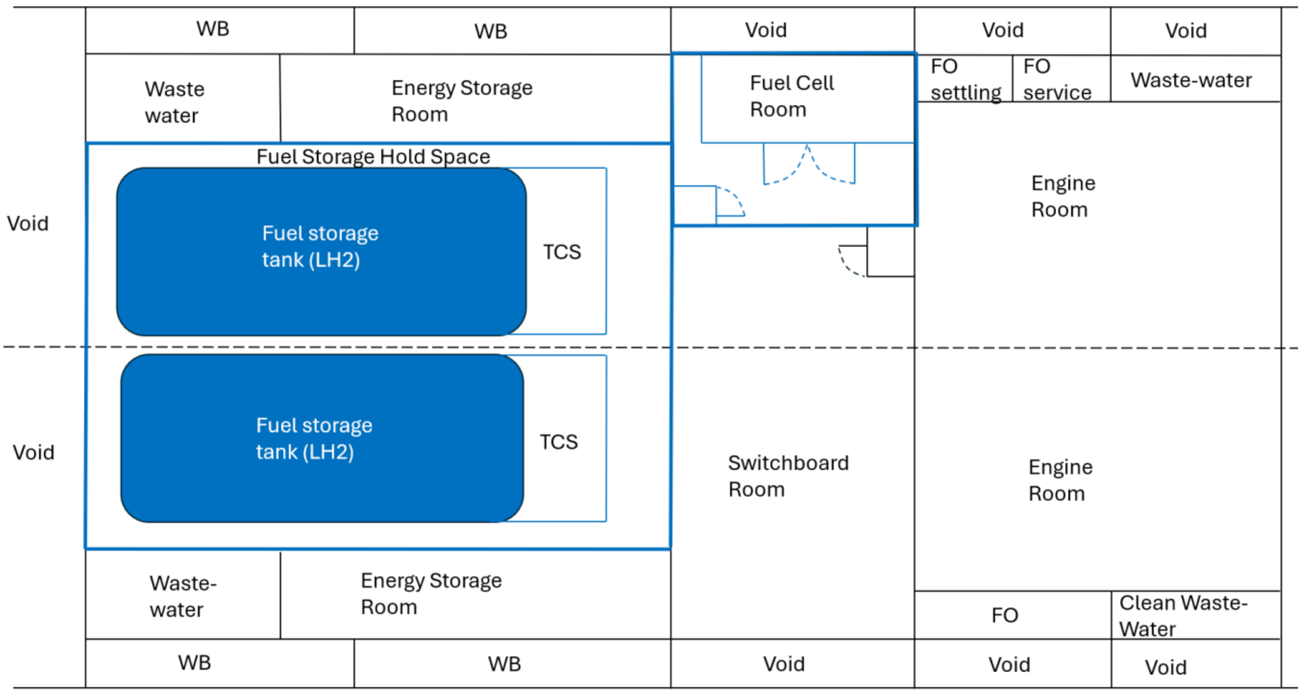

Figure 4-2 Plan view of general arrangement for the SOV (Source: DNV).

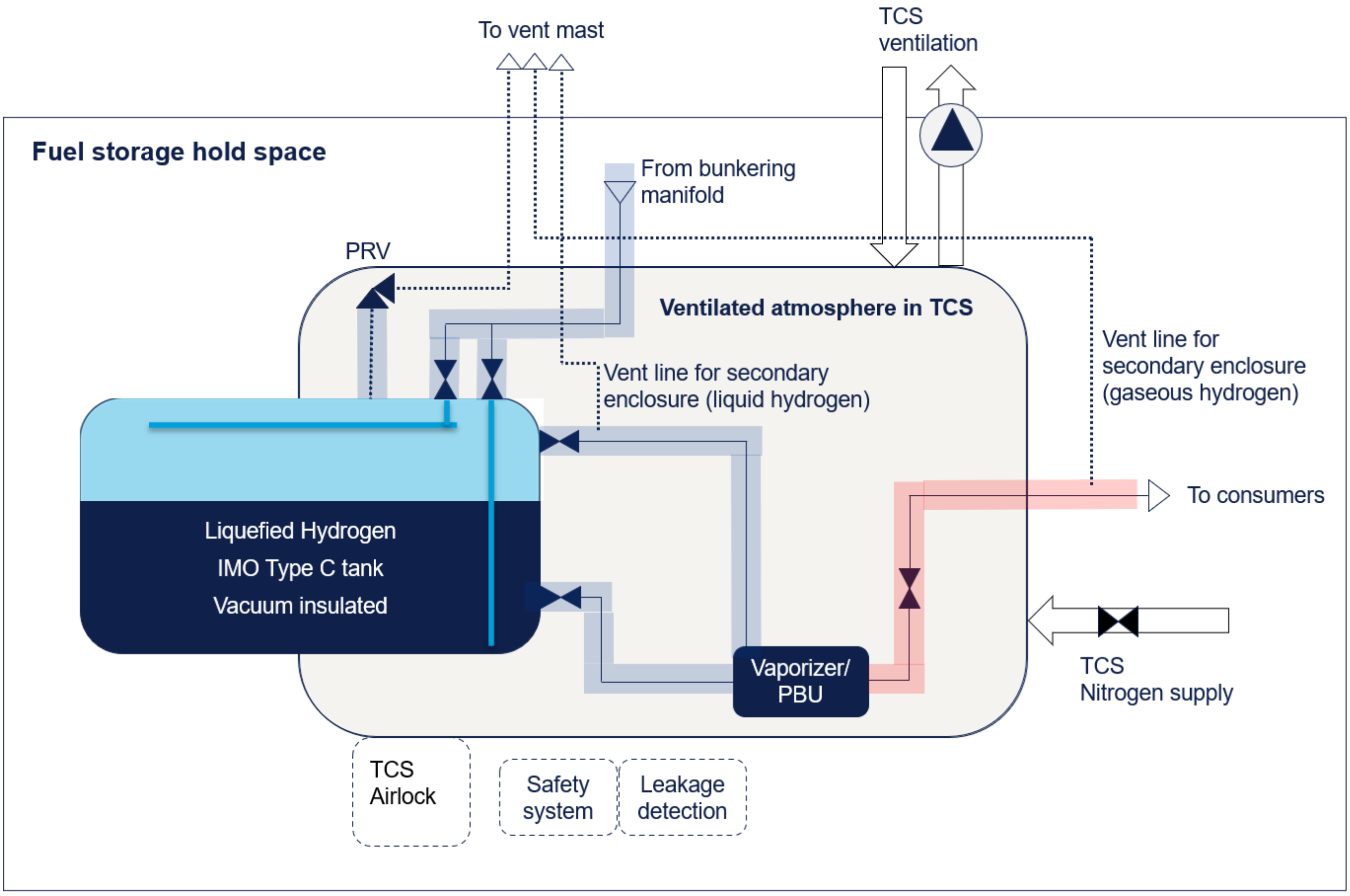

Figure 4-3 Hydrogen fuel system illustration for the SOV design (Source: DNV).

4.2 Hazard identification

The hazards for the system threats category *'Mechanical damage'* are considered for the SOV below:

- *Ship collision:* The bow of another vessel may hit the fuel tanks located below deck on the SOV. Generally, it should be ensured that fuel tanks and piping systems are kept away from areas likely to be affected by collision damage, similar as for LNG.
- *Allision/contact damages:* SOVs frequently manoeuvre close to wind turbine installations and other structures, making them susceptible to allision (contact) damage. However, vessels operating in these environments typically navigate at low speeds, which significantly reduces the kinetic energy involved in potential impacts. As a result, the likelihood of severe damage to fuel tanks is lower compared to high-speed collisions. However, fuel tanks and piping systems should be positioned away from areas most prone to impact to reduce the risk of damage in case of an allision.
- *Grounding:* As the fuel containment system is situated below deck, damages resulting from grounding pose a risk. For all types of vessels, it is essential to ensure that fuel tanks and piping systems are kept away from areas that are likely to be affected by grounding damages.
- *Explosions or fire:* The fuel system may be adversely affected by fires or explosions originating in the engine room, battery rooms or other technical rooms on the SOV, whether located above or below deck. Such events can result in structural damage, compromise the integrity of fuel containment systems, and potentially lead to secondary hazards such as fuel leaks and explosions. The proximity of the fuel system to these high fire-risk areas highlights the importance of implementing robust protective measures, including both passive and active fire suppression systems.

- *Dropped objects:* This hazard is particularly relevant for SOV designs with equipment for loading and offloading wind turbine structures and equipment. If the energy absorption capacity of the deck structure is inadequate, breach of the deck structure and penetration into the fuel containment system may result. The ‘dropped object’ event was selected for further analysis for the PSV in chapter 3.4

- *Mooring line snap-back:* Fuel tanks and associated piping must be located outside of any snap-back danger zones. In the case of the SOV design, the risk of mooring line snap-back impacting the fuel containment system is mitigated by design: fuel tanks are installed below deck, and the bunkering station is housed within a dedicated enclosure, effectively isolating these components from potential snap-back hazards.

- *Shifting cargo:* Shifting cargo presents a potential hazard in this vessel arrangement. If cargo on the main deck loses its sea fastenings, it might shift and damage structures like the bunkering station enclosure and piping systems. These impacts can compromise the structural integrity of the fuel system, leading to leaks and subsequent explosion/fire hazard.

- *Wave loads and green sea:* In the case of the SOV design, the risk of wave loads and green sea impacting the fuel containment system is mitigated by design: Fuel tanks are installed below deck, and the bunkering station is housed within a dedicated enclosure.

- *Ice impacts:* Collisions with these ice formations can result in substantial damage to the SOV vessel’s hull and structural components. Such impacts may compromise critical systems, including fuel containment and piping, thereby increasing the risk of leaks or other safety incidents. Loads resulting from ice impacts should be taken into account for ships designed for such service.

- *Flooded compartment causing buoyancy on fuel storage tanks:* This is a general risk applicable to all vessels, with limited variation based on ship type.

The hazards for system threats category ‘Operational and emergency events resulting in hydrogen releases’ is considered for the SOV below:

- *Loss of vacuum-insulation for LH2 systems:* This hazard is relevant for all ships with LH2 stored in vacuum insulated tanks and was comprehensively analysed in the report 'Risk Analysis of Generic Hydrogen Fuel Systems'(EMSA, 2025b).

- *Trapped volumes in LH2 systems:* Piping systems will experience a rise in pressure for trapped volumes of LH2 when the hydrogen is heated by the surroundings. Unless this pressure build-up is limited through relief devices, the pressure may exceed the design pressure of the piping system.

- *Fire and explosion:* If the hydrogen storage tank is subjected to fire loads, the tank safety valves will discharge the tank contents at the vent mast outlet when the ullage pressure reaches the safety valve set point.

- *Gas-freeing:* During the gas-freeing of a hydrogen tank or piping, hydrogen is displaced by an inert gas and discharged through the vent mast on the SOV.

- *Bunkering incidents:* Leaks and over-pressurization may be caused by erroneous bunkering operations, leading to release inside the bunkering station or via vent mast.

The hazards for system threats category ‘Occupational accidents’ are covered in chapter 2.2.4 and relevant for the SOV design.

In the following sub-chapters, the risk analysis for the SOV focuses on releases due to mechanical damage due to ship collision and grounding, and occupational accidents. Operational and emergency releases are addressed for the PSV design in chapter 3.4.

4.3 Risk analysis of ship collision or grounding impacting fuel containment and piping systems

A collision is an incident resulting from a ship striking or being struck by another vessel, whereas grounding is defined as an incident in which a vessel makes contact with the seabed or shore. Damaging a hydrogen tank during a ship collision or grounding could lead to catastrophic results. Therefore, the design should aim to minimise the potential for such incidents as far as possible.

The IGF Code Part A-1 reflects the severity of LNG fuel containment damage by requiring that the fuel tank(s) should be located in such a way that the probability for the tank(s) to be damaged following a collision or grounding is reduced to a minimum. In support of this functional requirement, prescriptive requirements specify minimum distances to the ship side and bottom as a function of the width. The IGF Code also provides the option of using a probabilistic method, based on collision data, to establish minimum protective distances.

4.3.1 Frequency analysis approach

This methodology is specifically designed for Quantitative Risk Assessments (QRAs) for hydrogen-fuelled ships. It is important to note that the QRA approach is distinct from the prescriptive requirements and the probabilistic approach outlined in the IGF code. While both the QRA and the IGF probabilistic approach are based on the principle of applying damage stability statistics, they differ in their calculation methods. The explanations provided are primarily focused on detailing the methodology, as discussed in Chapter 2.3.2.

The frequency analysis presented here focuses on estimating the likelihood of puncturing a hydrogen fuel tank following a collision. This method is based on an event tree structure derived from the 'GOAL based Damage Stability project' (GOALDS), as detailed in IMO information papers[2]. It also encompasses the calculation of the probability of tank penetration, contingent upon a hull breach, based on the methodology outlined in SOLAS Chapter II-1.

To model the frequency of ship collision leading to a puncture of the fuel tank, the process typically involves estimating the following:

- *Collision frequency:* The generic collision frequency for a given ship type can be obtained from recognised maritime incident databases such as Lloyds List Intelligence or S&P Global.

- *Probability of being the struck ship vs. striking ship:* Most quantitative risk analyses consider only collisions where the hydrogen-fuelled ship is struck by another vessel. However, this may not always be accurate depending on the tank's location and situation. Probabilities of being the struck ship and the striking ship should be found using collision statistics for a given ship type.

- *Probability of tank penetration:* The current SOLAS framework for damage stability allows for calculating probabilities (denoted as p-factors) for a damage breach to occur within the limits of a defined zone in the longitudinal direction and penetrating transversally into the ship. An alternative method, fully consistent with the principles of SOLAS method but not requiring modelling of subdivision for generating damages, is known as non-zonal method. In the non-zonal method, the extents of damage breaches are sampled directly from the underlying damage statics. The probability of damaging of a specific space (e.g. LH2 tank) are estimated as a ratio of breaches overlapping (at least partially) with the space to the total number of generated breaches. The non-zonal method is more flexible than SOLAS and should give more accurate estimates of the probabilities, particularly for large samples (over 10,000 breaches) and for tank geometries deviating from an orthogonal parallelepiped.

An alternative method is to perform finite element analysis to calculate the impact energy required to overcome the structural resistance of the outer hull, internal stringers, bulkheads, and the shell of the LH2 tank, leading to puncture. While this approach provides the necessary impact energy, determining all combinations of ship sizes and impact velocities that generate this energy is feasible. However, accurately finding the probabilities of these combinations, without a significant standard deviation, can be challenging.

[2] SLF 55/INF.7, SLF 55/INF.8, SLF 55/INF.9, etc.

For grounding, the overall principle of the calculation explained above can be applied: first, determine the grounding frequency, and then estimate the likelihood of tank penetration.

4.3.2 Consequence analysis

The hydrogen fuel storage tanks contain large amounts of flammable and cryogenic material, as well as significant potential energy from boiling liquid under pressure. Damage to fuel containment systems, and to a lesser extent, piping systems, are events that have the potential to release all the hydrogen stored onboard, and it is an event a ship is not designed to survive. Consequently, it is of utmost importance that storage and distribution systems for hydrogen fuel are sufficiently protected against external events that have the potential to damage them (EMSA, 2024a).

A catastrophic event where the tank is punctured is likely to lead to the following consequences:

Deflagration or detonation

When hydrogen evaporates, it expands to nearly 850 times its liquid volume, potentially creating a significant cloud within the compromised fuel storage hold space, ballast tanks, and outside the ship's side. Ignition is highly likely due to the two colliding ships being tangled together, with metal-to-metal contact causing sparks. The confinement around the impacted area can significantly increase the flame speed to hundreds of meters per second, leading to rapid deflagrations. A hydrogen cloud capable of causing significant damage through explosion or deflagration and posing a threat to the ship structure and its systems, can develop within seconds. Severe structural damage could lead to water ingress/flooding, loss of stability, capsizing, and/or foundering, with subsequent potential for multiple fatalities.

In addition, large cloud volume, in combination with partially confined enclosures, is likely to evolve into a detonation. Detonations of non-confined gas clouds also tend to occur more easily as the cloud size increases (EMSA, 2024a). Blast waves from deflagrations and detonations may cause injuries or fatalities due to the overpressure at a given location.

There is also a potential for escalation. Gas escaping into other parts of the ship is very likely to cause secondary explosions with the potential to threaten the entire ship, increasing the risk of multiple fatalities. These events may develop rapidly, leaving insufficient time to muster and evacuate the ship in a timely manner. The scenario is likely to impair ship safety-critical and lifesaving appliances functions. The failure of these critical functions when needed could result in multiple fatalities.

Boiling Liquid Expanding Vapor Explosion (BLEVE)

When the fuel tank is punctured by the collision, the pressure inside drops very quickly. The liquid inside, which was under high pressure, now finds itself in a much lower pressure environment. The sudden drop in pressure causes the liquid to boil rapidly, which means the liquid turns into gas very quickly. This rapid vaporization leads to a significant expansion of the gas, which creates a powerful force. If the gas ignites, it will cause an explosion.

Cryogenic spill damaging ship structure and safety systems

Hydrogen spillages can cause embrittlement of normal steels and allow residual stresses to cause cracking. Due to the loss of strength of the vessel, this can lead into even further damage from the initial collision impact. Cascading events related to embrittlement is therefore a likely scenario.

4.3.3 Safety barrier modelling

The risk of fuel containment and piping system damage due to ship collision or grounding is analysed using the bowtie approach, with tank puncture and piping damage addressed separately.

The risk of tank puncture is visualized in Figure 4-4. The top event *is 'damage to fuel containment systems'*. The potential consequences are described in chapter 4.3.2.

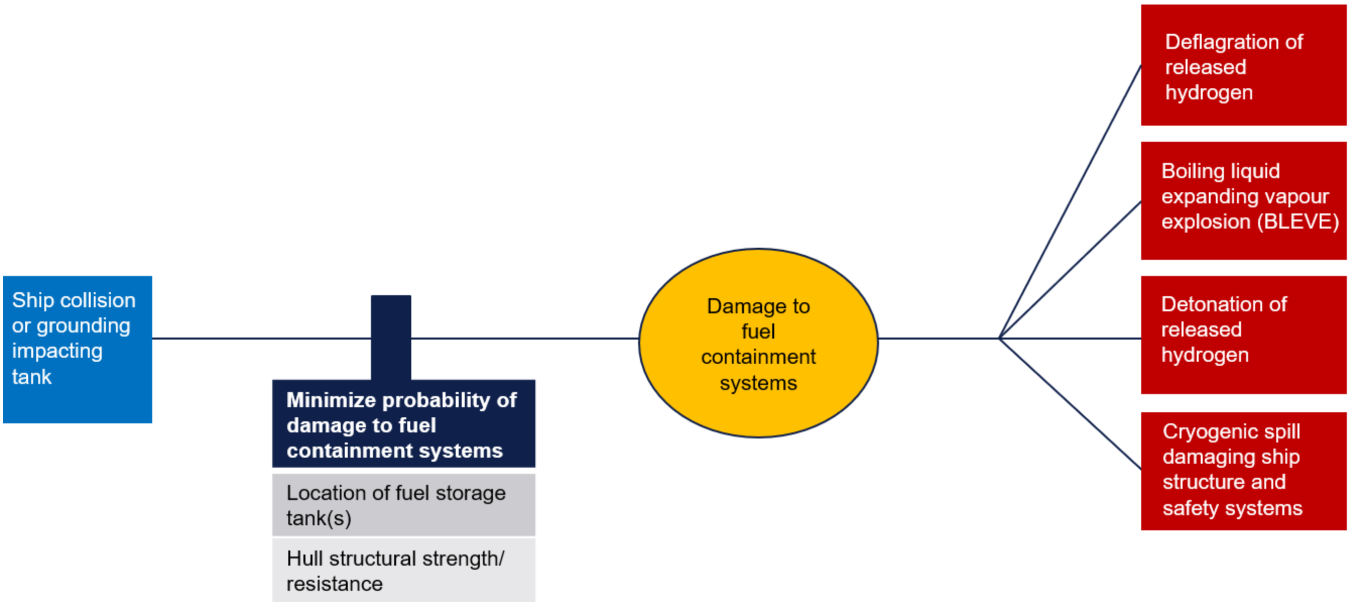

Figure 4-4 Bowtie for risk of damage to fuel containment systems due to ship collision or grounding (Source: DNV).

<u>Ship collision or grounding impacting the tank</u>

The first, and only, barrier function is to *'Minimize probability of damage to fuel containment systems'*. This barrier function consists of the following barrier elements:

- *Location of fuel storage tank(s):* The fuel storage tank(s) must be positioned to minimize the likelihood of damage in the event of an external impact. According to the IGF Code Part A-1, LNG fuel tanks should be situated at a minimum distance from the ship's side and bottom shell plating to reduce the risk of impact and ensure greater protection, and this is equally essential for hydrogen fuel systems.

- *Hull structural strength/resistance:* The hull of a ship is capable of absorbing and distributing the energy from impacts. The structure between the hull and the fuel storage tanks can also be reinforced to provide enhanced protection from impacts. However, it is important to note that while this measure may reduce the risk of damage, the structure between the ship hull and the tank cannot absorb all impacts, especially those of extreme severity.

If the preventive barrier function fails and a tank puncture occurs, it is important to note that all measures in the ship's design or regulatory standards are aimed at ensuring that a tank puncture due to a ship collision or grounding does not occur. Consequently, no significant credit is given to the mitigation of consequences for this event, and it is therefore omitted in the bowtie.

The risk of piping damage due to ship collision or grounding is visualized in Figure 4-5. The top event is 'damage to piping systems'. The potential consequences are described in chapter 4.3.2.

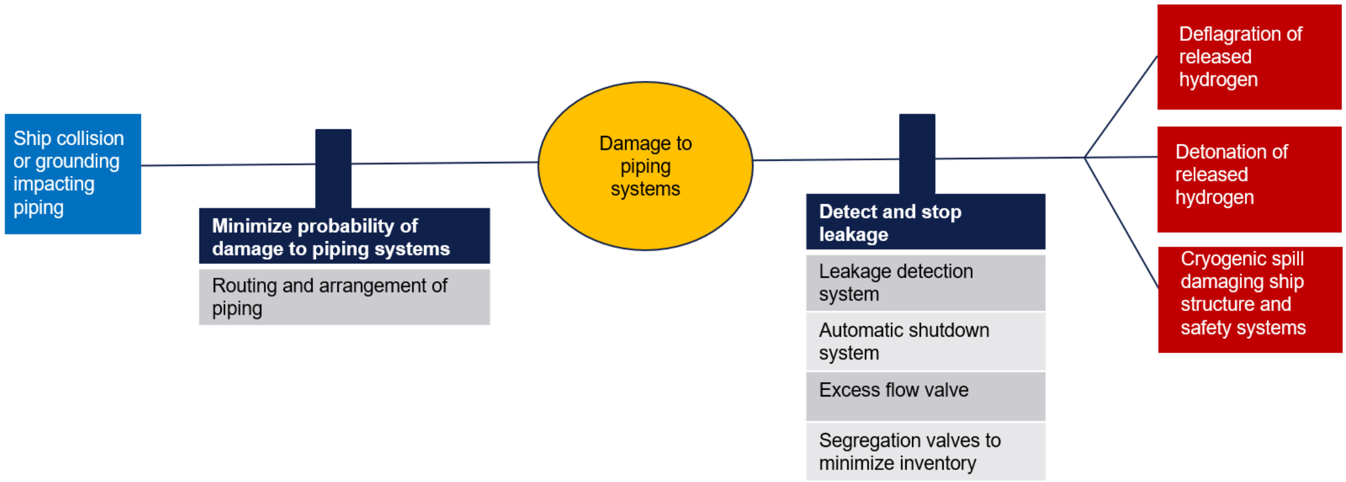

Figure 4-5 Bowtie for risk of damage to piping systems due to ship collision or grounding (Source: DNV).

The preventive barriers are almost similar to the top event 'damage to fuel containment systems' see Figure 4-4. The key barrier element for this safety function is 'routing and arrangement of piping'. Piping systems should preferably be routed out of harm's way and where this is not possible, be protected against mechanical damage by physical barriers.

Since this scenario assumes the fuel tank and safety systems remain intact, it should be possible to detect the release of hydrogen and initiate shutdown. The following barrier elements are included:

- *Leakage detection system:* Any leaks from fuel piping systems should be detectable by gas detectors, pressure differential measurements, or both.
- *Automatic shutdown system:* Similar to the gas detection system, this is a crucial safety function. The detection and shut-down safety function utilizes three subsystems: Sensor subsystem, Logic solver subsystem and Final element subsystem.
- *Excess flow valve (EFV):* EFVs are mechanical safety devices designed to automatically shut off the gas flow when it exceeds a predetermined rate.
- *Segregation valves to minimize inventory:* By isolating sections of the piping system, segregation valves reduce the volume of hydrogen that can escape in the event of a leak. This means that only the volume within the isolated section can be released, rather than the entire system's contents.

4.4 Risk analysis of occupational accidents

The properties of hydrogen introduced new safety challenges that must be understood and observed in the onboard work activities. For occupational hazards, the work activities relating to the hydrogen fuel system that are selected for further risk analysis in this chapter are:

- *Entry into spaces containing hydrogen piping:* Entering such spaces may cause the crew to be exposed to gases if there is a leak of hydrogen, inert gas, or cryogenic fluids. In addition, low surface temperatures on piping may cause frost burns, and hydrogen or nitrogen leakages can lead to asphyxiation due to oxygen depletion.
- *Maintenance and repair (opening hydrogen piping):* Release of LH2 or CH2 when the system is opened for maintenance is possible if the maintained part is insufficiently gas-freed and isolated.
- *Hydrogen bunkering:* Leakages in relation to the bunkering operation can result in a deflagration/detonation of a flammable hydrogen mixture or jet fires in the bunkering station. There is also potential for exposure to cryogenic temperatures.

4.4.1 Frequency analysis approach

A comprehensive review of major data sources for marine occupational accidents was presented in a report prepared for Lloyd's Register by the University of Strathclyde and the UK Health and Safety Executive (HSE). This review included databases such as: IMO Global Integrated Shipping Information System (IMO-GISIS), Accident databases of flag and maritime administrations, EMCIP, P&I Clubs and commercial maritime intelligence data providers like Lloyd's List Intelligence and S&P Global. The study indicated that the maritime industry suffers from significant under-reporting of occupational accidents (University of Strathclyde and HSE, 2020).

Consequently, the above statistics cannot be fully trusted for use in quantitative risk analysis, although they do provide valuable information for learning and improvements. An alternative approach is to model the risk and estimate the frequency of occurrence. This requires detailed descriptions of work tasks and their frequency. Methods such as Human Reliability Analysis (HRA), introduced in chapter 3.4.1, can be used to model these frequencies.

4.4.2 Consequence analysis

There are several potential consequences of occupational accidents, as described below.

Injury/fatality due to asphyxiation

Experiments have shown that evaporated hydrogen can quickly displace a breathable atmosphere and reduce the temperature to well below levels sustainable for human exposure (FFI, 2021). Since hydrogen expands 850 times in the liquid-to-gas transition, even small amounts of liquefied hydrogen can vaporize and displace oxygen, creating a hazardous environment (DNV, 2022). It is important to note that many of the injuries and fatalities of confined space entries involve rescuers attempting to assist the initial victim.

Exposure to inert gases like nitrogen can also lead to asphyxiation, as these gases can displace oxygen in confined spaces.

Injury/fatality due to cryogenic burns (struck by release or touching surfaces)

Cryogenic burns are a significant hazard associated with liquid hydrogen spills. Personnel must be protected from direct contact and inhalation of cold fluids, as well as indirectly from low surface temperatures of equipment. A leakage of cryogenically stored fuel in the vicinity of personnel could lead to cryogenic burns or internal damage due to cold vapour inhalation. Also, the evaporation of liquids and the dispersion of low-temperature vapours might prevent personnel from accessing main escape routes and refuge areas (DNV, 2022).

Injury/fatality due to high pressure hydrogen release and jet fire

A jet fire can occur from a compressed hydrogen system. A leak generates a high-velocity jet of gas and if ignited it will lead to a jet fire. Jet fires could also occur following a delayed ignition of a continuous leak which has established a hydrogen cloud, continuing as a jet fire (EMSA, 2024a). The radiant heat that reaches and is absorbed by a person from a jet fire is directly proportional to factors, such as exposure time, burning rate, and hydrogen mass flow (EMSA, 2024a).

Injury/fatality due to deflagration or detonation of released hydrogen

A deflagration or detonation event can be extremely dangerous to individuals. During a hydrogen deflagration, the flame front moves through the hydrogen-air mixture at subsonic speeds, generating heat and pressure. The resulting pressure wave can cause significant damage to surrounding equipment, structures, and personnel. Additionally, the intense heat generated during a deflagration can cause severe burns to anyone in close proximity.

4.4.3 Safety barrier modelling

The risk of occupational accidents due to hydrogen-related work activities is analysed using the bowtie approach, and each of the threats is addressed separately.

The risk of entering enclosed spaces containing hydrogen or inert gas piping is visualized in Figure 4-6. The top event is '*exposure to hydrogen or inert gases'*. The potential consequences are described in chapter 4.4.2.

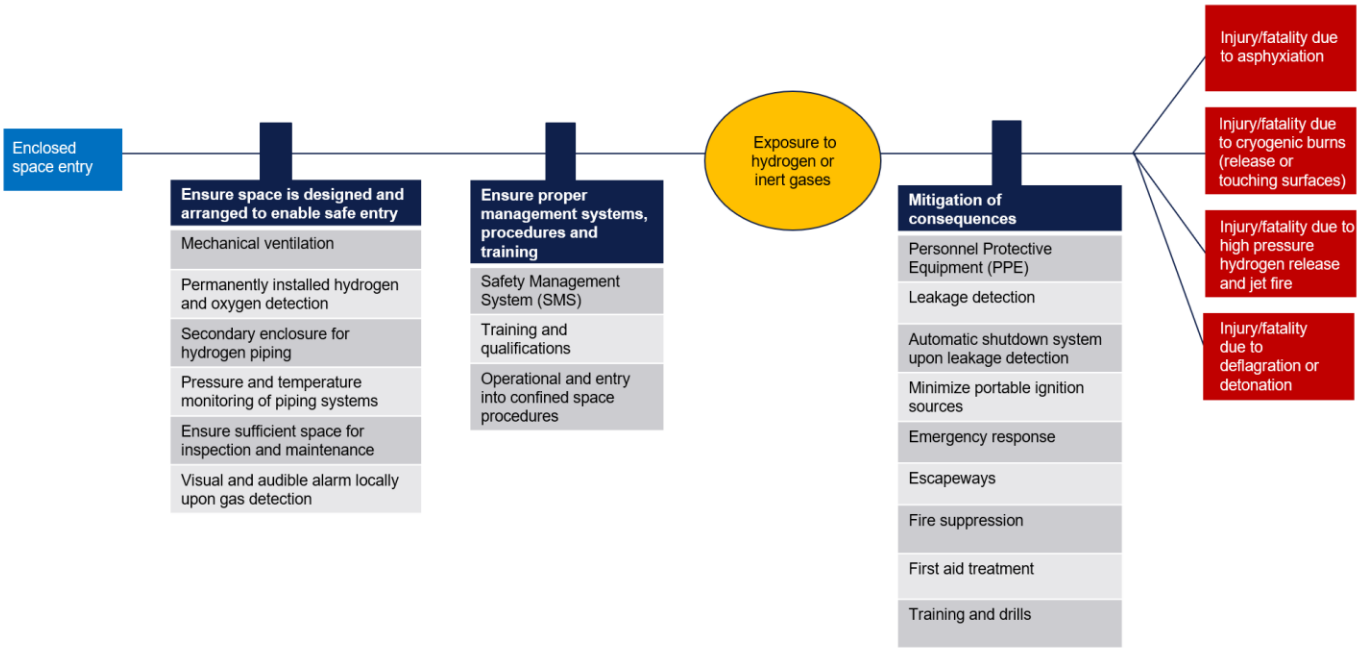

Figure 4-6 Bowtie for risk of exposure to hydrogen or inert gases due to entering enclosed spaces (Source: DNV).

The bowtie includes two preventive barrier functions, one addressing "technical design measures" and the other addressing "soft factors". The logic of the barrier function setup is that the first barrier should ensure that the space is designed and arranged to enable safe entry. Although this alone could, in theory, be sufficient to prevent an accident, the next barrier, considering soft factors such as management systems, procedures and training, is considered an essential barrier to avoid accidents.

The first barrier function to protect against the hazards of entering enclosed spaces is '*Ensure space is designed and arranged to enable safe entry.* The barrier functions consist of the following barrier elements:

- *Mechanical ventilation:* Mechanical ventilation is crucial for ensuring safe entry into enclosed spaces. It helps to maintain a continuous flow of fresh air, ensuring that oxygen levels remain safe for personnel. Proper ventilation systems reduce the risk of asphyxiation and explosion from small leakages by diluting and removing potentially dangerous gases.

- *Permanently installed hydrogen and oxygen detection:* Permanently installed hydrogen and oxygen detectors continuously monitoring the atmosphere in the space are essential for early detection of gas leaks. If hydrogen or oxygen levels deviate from safe thresholds, the system triggers alarms, warning people not to enter and allowing for immediate corrective actions.

- *Secondary enclosure for hydrogen piping:* A secondary enclosure for hydrogen piping adds a layer of protection against leaks. The secondary enclosure prevents any escaping hydrogen from entering the workspace and reducing the risk of fire or explosion. It also facilitates easier detection of leaks.

- *Pressure and temperature monitoring of piping systems:* Monitoring the pressure and temperature of piping systems help detect anomalies that could indicate potential failures or leaks. By continuously tracking these metrics, and with support by alarm functionality, crew can take proactive measures to address issues before they escalate into hazardous situations.

- *Ensure sufficient space for inspection and maintenance:* Adequate space for inspection and maintenance is necessary to ensure that crew can safely access and work on equipment. Sufficient clearance around piping and other components allows for thorough inspections, routine maintenance, and repairs without compromising safety.

- *Visual and audible alarm locally upon gas detection:* Local visual and audible alarms provide immediate alerts to personnel in the vicinity of a gas leak. These alarms ensure that crew are quickly informed of potential dangers, warning about dangers inside the space prior to entry, and allowing them to evacuate from spaces or take appropriate actions to mitigate the risk. The combination of visual and audible signals enhances the likelihood of prompt and effective responses.

The next barrier function is *'Ensure proper management systems, procedures and training'*. The barrier functions consist of the following barrier elements:

- *Safety Management System (SMS):* The SMS mandated by the International Safety Management (ISM) Code is a structured and documented system enabling shipping companies to effectively manage safety and environmental protection. It includes procedures for safe operation, emergency preparedness, and continuous improvement.

- *Training and qualifications:* Proper training and qualifications are essential for ensuring that crew members are competent to safely execute daily work tasks and are aware of the unique hazards associated with hydrogen. Proper training is needed to ensure that all personnel is familiar with the SMS to ensure the personnel are aware of their roles and responsibilities, promoting a culture of safety and compliance.

- *Operational and entry into confined space procedures:* This includes detailed protocols for the safe entry into confined spaces, where hazards such as flammability, toxicity, and oxygen depletion are more pronounced. These procedures should outline the steps for assessing risks, using appropriate PPE, and ensuring proper ventilation and monitoring before and during entry.

Should all the preventive barriers fail and the top event occurs, the barrier function *'Mitigation of consequences'* comes into play:

- *Personnel Protective Equipment (PPE):* PPE is essential for safeguarding workers from the hazards associated with hydrogen. Proper PPE minimizes the risk of burns, asphyxiation, and other injuries during routine operations and emergencies.

- *Leakage detection:* Any leaks from piping systems should be detectable by gas detectors, pressure differential measurements, or both.

- *Automatic shutdown system upon leakage detection:* This is a crucial safety function. The detection and shut-down safety function utilizes three subsystems: Sensor subsystem, Logic solver subsystem and Final element subsystem.

- *Minimize portable ignition sources:* Minimizing ignition sources is crucial in environments where flammable fuels are present. This involves strict control over the use of fixed and mobile equipment that can cause ignition.

- *Emergency response:* The emergency response plan should include clear procedures for evacuation, communication, and coordination with emergency services. Appropriate training of personnel should be provided.

- *Escapeways:* Escapeways provide safe routes for crew to exit hazardous areas quickly. These routes should be clearly marked, unobstructed, and regularly inspected to ensure they are accessible at all times.

- *Fire suppression:* Fire suppression systems are essential for controlling and extinguishing fires involving hydrogen.

- *First aid treatment:* First aid treatment provides immediate care to individuals injured by exposure to hydrogen. This includes having trained first aid responders on-site, as well as accessible first aid kits and medical supplies.

- *Training and drills:* Regular training and drills are essential for preparing crew to handle the unique hazards of hydrogen.

The risk of maintenance and repair when opening hydrogen piping is visualized in Figure 4-7. The top event is *'exposure to hydrogen or inert gases'*. The potential consequences are described in chapter 4.4.2.

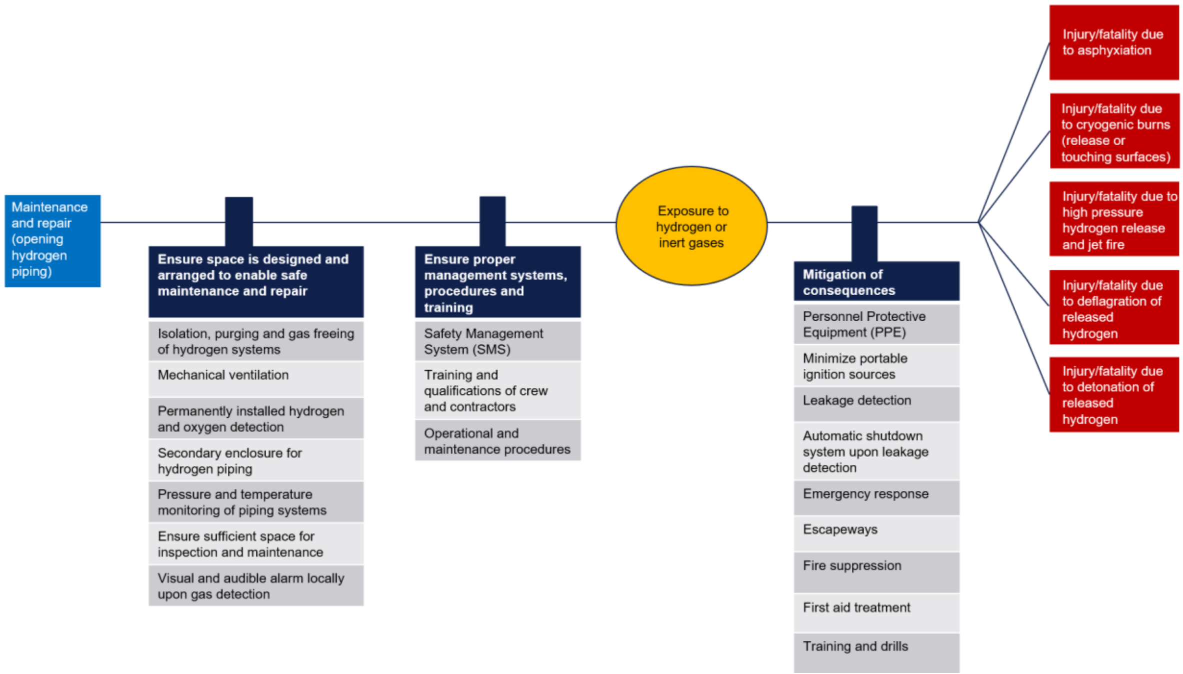

Figure 4-7 Bowtie for risk of exposure to hydrogen or inert gases due to maintenance and repair (opening hydrogen piping) (Source: DNV).

The structure of the bowtie is almost similar to the previous event *'enclosed space entry'*. The descriptions will therefore focus on the key difference in the technical barrier function:

- *Isolation, purging and gas freeing of hydrogen systems:* Procedures should describe how isolation is performed, depressurization of the system, purging hydrogen out of the system and testing for residual hydrogen before declaring the equipment fit for maintenance (Hydrogen Tools, 2025).

The risk related to bunkering operations is visualized in Figure 4-8. The top event is *'exposure to hydrogen'* The potential consequences are described in chapter 4.4.2.

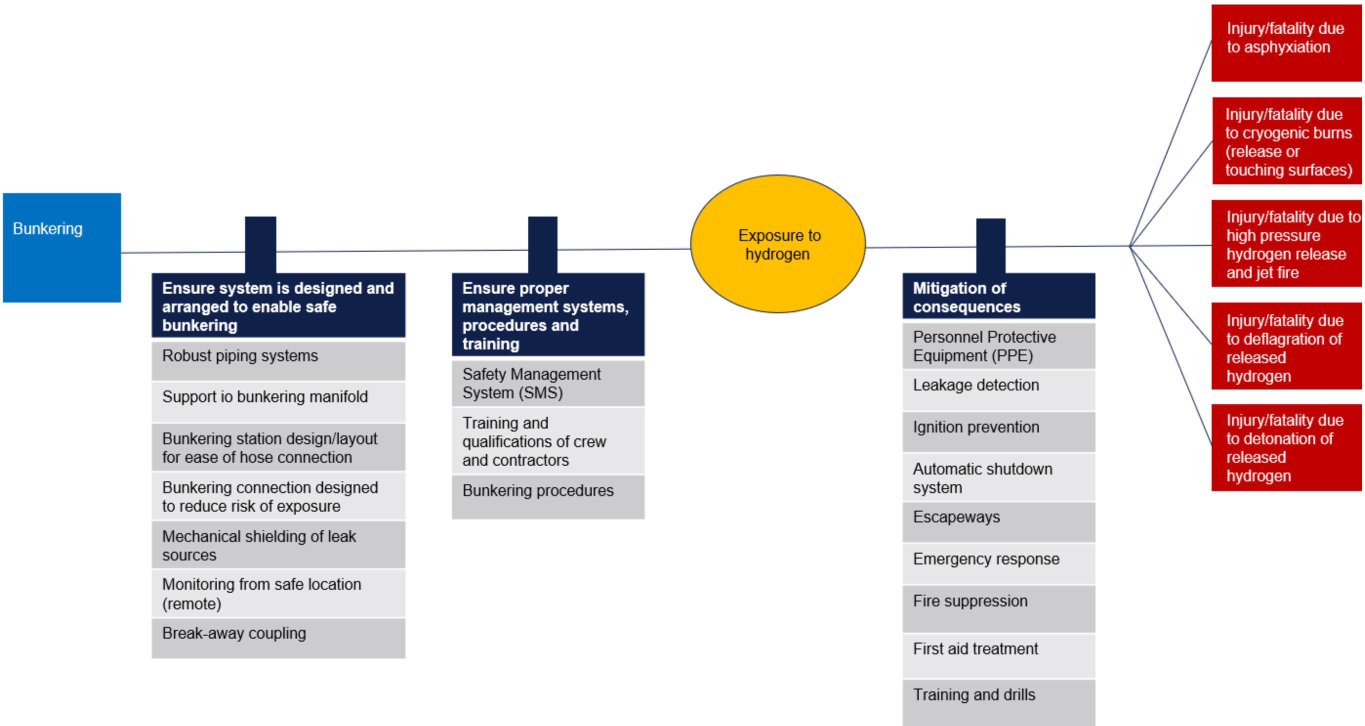

Figure 4-8 Bowtie for risk of exposure to hydrogen in bunkering operations (Source: DNV).

The consequences of hydrogen leakages, and particularly the ignition of hydrogen in a semi-enclosed bunkering station, were analysed in the report “Reliability and safety analysis”, and are severe and must be avoided (EMSA, 2024b). Consequently, safety barriers should be designed to prevent the release of hydrogen, avoid the formation of flammable mixtures and limit ignition sources as far as possible. Safety barriers and safety systems that may be exposed to low temperatures from leakages (EMSA, 2024a).

The first barrier function ‘Ensure system is designed and arranged to enable safe bunkering’ consists of the following barrier elements:

- *Robust piping systems:* Piping systems used for bunkering of hydrogen should be designed to minimize the probability of leakages, contain leakages if they occur, and avoid cold surfaces where air can condense.
- *Support of bunkering manifold:* 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 connected to the bunkering facility.
- *Bunkering station design/layout for ease of hose connection:* The design and layout of the bunkering station should facilitate easy and secure connection of hoses.
- *Bunkering connection designed to reduce risk of exposure:* The connections used for bunkering should be designed to minimize the risk of hydrogen leaks.
- *Mechanical shielding of leak sources:* Mechanical shields should be installed around potential leak sources to contain any accidental releases of hydrogen. This helps to protect personnel from exposure to hydrogen.
- *Monitoring from a safe location:* Monitoring systems should be set up to allow for remote observation of the bunkering process.
- *Break-away coupling:* Break-away couplings are designed to disconnect automatically if excessive force is applied, such as in the event of a drift-off. This prevents damage to the system and reduces the risk of hydrogen leaks.

The mitigation barriers are identical to the previous bowties for occupational accidents. However, what is specifically relevant for bunkering are:

- *PPE:* Personnel involved in bunkering operations should be outfitted with appropriate personal protective equipment.
- *Leak detection and Automatic shutdown system:* The bunkering system should be arranged with means to detect leakage and systems to automatically stop the bunkering process. The bunkering system should be arranged with a shut-down valve in the bunkering station to facilitate emergency closing of the bunkering supply. Additionally, an emergency shutdown communication system should be arranged between the ship and the bunkering facility.
- *Training and drill:* Regular training and drills are essential for preparing crew to handle the unique hazards of hydrogen.
- *Emergency response:* The emergency response plan should include clear procedures for evacuation, communication, and coordination with emergency services. Appropriate training of personnel should be provided.

5. Conclusion

This study has performed a risk analysis of two specific ship types: a PSV with compressed hydrogen stored above deck and a SOV with liquefied hydrogen stored below deck. The aim has been to provide insights and recommendations for enhancing the reliability and safety of hydrogen technologies, contributing to the wider goal of developing a guidance document concerning ships utilising hydrogen as fuel. Regarding the further drafting of a guidance document, we draw the following conclusions from the findings in this report:

1. Hydrogen may be released from compressed hydrogen tanks through the vent mast and may ignite inside the vent mast or on the open deck. Ships with this type of fuel system must be capable of handling any foreseeable consequences of this event.

While having a vent mast arranged to safely disperse any release of hydrogen from fuel storage tanks and piping systems is an important safety function, e.g. in a fire scenario or during bunkering, the risk of ignition of released hydrogen must be managed.

This necessitates a case-by-case evaluation of the consequences of an event in which the preventive barriers fail, leading to the ignition of hydrogen released through the vent mast. It must be ensured that the potential worst-case scenario regarding heat loads and pressure effects is acceptable in terms of the safety of the ship and its crew. Access to muster stations, escape routes, and life-saving appliances should remain unrestricted.

2. Dropped objects damaging compressed hydrogen tanks or fuel piping may result in rapid release of large quantities of hydrogen, with a corresponding risk of severe explosions and fires.

The consequences of a compromised hydrogen containment system can result in considerable material damage as well as injuries and fatalities for individuals on board. The hydrogen fuel storage tanks contain large amounts of flammable material, as well as significant potential energy from gas under pressure. Damage to fuel containment systems, and to a lesser extent, piping systems, are events that have the potential to release all the hydrogen stored onboard, and it is an event a ship is not designed to survive. Consequently, it is of utmost importance that storage and distribution systems for hydrogen fuel are sufficiently protected against external events that have the potential to damage them (EMSA, 2024a).

Established principles for risk control state that the removal of hazards is the most effective measure. In this case, it implies that the first line of defence should be to avoid locating tanks in areas where they can be impacted by dropped objects. A second, less effective measure would be to implement engineering controls, such as mechanical protection, designed to absorb the impact of falling objects before they can damage the tank.

In conclusion, recognising areas where dropped objects might land is crucial. Just as the segregation principle is used to prevent damage from collisions and groundings, priority must be given to positioning hydrogen tanks away from such locations. This is equally important for liquified hydrogen fuel systems.

3. Ship collision and grounding damaging liquefied hydrogen tanks is an event where it is difficult to apply mitigating measures to prevent severe consequences.

Liquefied hydrogen tanks contain large amounts of flammable and cryogenic material, as well as significant potential energy from boiling liquid under pressure. Damage to fuel containment systems, and to a lesser extent, piping systems, are events that have the potential to release all the hydrogen stored onboard, and it is an event a ship is not designed to survive. Consequently, it is of utmost importance that storage and distribution systems for hydrogen fuel are sufficiently protected against external events that have the potential to damage them (EMSA, 2024a).

The IMO conducted a similar evaluation when developing regulations for LNG fuel tanks, reaching the same conclusion. Therefore, it is reasonable to assume that the protective measures specified in the IGF Code for tank safeguarding can also be applied to hydrogen as a fuel.

If it is deemed necessary to include stricter requirements for probabilistic evaluation of the tank location for hydrogen, it should be considered to revisit the acceptance criteria defining the acceptable distance from the ship side. Applying stricter acceptance criteria in the probabilistic method for tank location in the IGF Code enables use of an established procedure for finding acceptable tank locations.

4. New fuels introduce new occupational hazards.

The work activities related to the onboard hydrogen fuel system, such as entering spaces containing hydrogen piping, maintenance and repair, and bunkering operations, introduce new occupational hazards associated with direct exposure to hydrogen and its flammable and cryogenic properties, as well as asphyxiation effects.

To safely operate a hydrogen-fuelled ship, the crew must thoroughly understand the hazards associated with handling the fuel. They must also be aware of the safety features integrated into the design and their purpose, operation, and maintenance requirements. It is, therefore, vital to establish comprehensive training, operating procedures, and a robust safety culture to ensure the safe operation of the ship.

This emphasizes the need for regulatory guidance regarding training of crew and procedures for normal operation, maintenance and emergency drills.

6. References

Clarksons. (2025). *What are platform supply vessels (PSVs)?* Retrieved from https://www.clarksons.com/glossary/what-are-platform-supply-vessels-psvs/

DNV. (1983). *Dropped objects - A summary report on damage assessment and energy absorption. Report no. 82-0959.*

DNV. (2014). *Barrier management in operation for rig industry - Good practices.*

DNV. (2021). *RP-F107 Risk assessment of pipeline protection.*

DNV. (2022). *Fuel properties and their consequence for safety and operability. DNV report no. 2022-1163, Nordic Roadmap publication no.1-B/2/2022. .*

DNV. (2024). *Rules for Classification - Part 6 Additional class notations - Chapter 2 Propulsion, power generation and auxiliary. December 2024.*

DNV. (2025). *Offshore service vessels (OSV)*. Retrieved from https://www.dnv.com/maritime/Offshore/vessels/osv/

EMSA. (2024a). *Mapping safety risks for hydrogen-fuelled ships.* Lisbon: European Maritime Safety Agency.

EMSA. (2024b). *Reliability and safety analysis.* Lisbon: European Maritime Safety Agency.

EMSA. (2024c). *Annual overview of marine casualties and incidents 2024 - Appendix 1 Definitions from the IMO Casualty Investigation Code and the Directive 2009/18/EC.*

EMSA. (2025a). *Hazard identification of generic hydrogen fuel systems.* Lisbon: European Maritime Safety Agency.

EMSA. (2025b). *Risk analysis of generic hydrogen fuel systems.* Lisbon.

FFI. (2021). *Large scale leakage of liquid hydrogen - - tests related to bunkering and maritime use of liquid hydrogen.*

Hydrogen Tools. (2025). *Maintenance Procedures.*

HyRAM+. (2023). *Hydrogen Plus Other Alternative Fuels Risk Assessment Models (HyRAM+) Version 5.1 Technical Reference Manual.*

IEC. (1999). *IEC 60092-502:1999 Electrical installations in ships - Part 502: Tankers - Special features.*

IEC. (2010). *IEC 61508:2010 Functional safety of electrical/electronic/programmable electronic safety-related systems.*

IEC. (2019). *31010:2019 Risk management — Risk assessment techniques.*

ILO. (2015). *Investigation of Occupational Accidents and Diseases - A Practical Guide for Labour Inspectors.*

IMO. (2015). *International Code of Safety for Ships using Gases or other Low-flashpoint Fuels. Resolution MSC.391(95) adopted 2015.*

IMO. (2018). *REVISED GUIDELINES FOR FORMAL SAFETY ASSESSMENT (FSA) - MSC-MEPC.2/Circ.12/Rev.2.*

IMO. (2019). *Generic guidelines for the development of goal-based standards. MSC.1/Circ.1394/Rev.2.*

ISO. (1999). *ISO/IEC Guide 51:1999 Safety aspects.*

MarHySafe. (2021). *Handbook for hydrogen-fuelled vessels. MarHySafe JDP Phase 1. DNV, 1st edition (2021- 06).*

Maritim Education. (2025). *The Most Common Injuries Onboard Ships: Prevention and Response*. Retrieved from https://maritimeducation.com/the-most-common-injuries-onboard-ships-prevention-and-response/

OGP. (2010). *Risk Assessment Data Directory - Mechanical lifting failures.*

S&P Global. (2025). *Casualty and Events Database.*

University of Strathclyde and HSE. (2020). *Safety challenges at sea: Data and evidence.*

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