European Maritime Safety Agency

RISK ANALYSIS OF GENERIC HYDROGEN FUEL SYSTEMS

STUDY INVESTIGATING THE SAFETY OF HYDROGEN AS FUEL ON SHIPS

DELIVERABLE D.3.2

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Abstract

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

Several generic hydrogen fuel system design concepts were identified during the hazard identification process documented in “Hazard identification of generic hydrogen fuel systems” (EMSA, 2025).

This report presents the findings from the risk analysis of two generic hydrogen fuel system designs: One utilizing compressed hydrogen (CH2) storage and the other utilizing liquefied hydrogen (LH2) storage. These systems were chosen for their advanced safety features, including secondary enclosures that facilitate rapid leak detection and prevent hydrogen ignition. The report examines hazardous events associated with hydrogen leakage for both designs, analyses leak frequencies using reliability data, and assesses potential safety implications. The bowtie technique is employed for risk analysis and barrier modelling, aiming to validate the functional and prescriptive requirements outlined in the guidance document.

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. Thus, ships using hydrogen as fuel should be built to safely handle these leaks. 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 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 second deliverable from the third task of the study (task 3.2).

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

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

What we did

Several generic hydrogen fuel system design concepts were identified during the hazard identification process documented in "Hazard identification of generic hydrogen fuel systems" (EMSA, 2025). Two of these concepts were selected as candidates for developing prescriptive guidance and, consequently, were chosen for risk analysis:

- Compressed hydrogen (CH2) fuel system with fixed fuel tanks, inerted tank connection enclosure (TCE) and secondary enclosures for the fuel distribution system.
- Liquefied hydrogen (LH2) fuel system with vacuum-insulated IMO Type C tanks, tank connection space (TCS) and secondary enclosures for the fuel distribution system.

The first design concept selected for risk analysis focuses on the storage and supply of compressed hydrogen on deck. This concept was chosen because all potential leak sources are protected by secondary enclosures, either through the use of a TCE or secondary enclosures for the fuel distribution system. This design inherently enhances the ability of gas detectors to identify leaks, leading to a reliable and fast-acting shut-down system. Additionally, the risk of hydrogen ignition after a leakage is significantly reduced by inerting the TCE and secondary enclosures.

The second design concept selected for risk analysis is liquefied hydrogen (LH2) fuel systems with vacuum-insulated IMO Type C tanks, TCS and secondary enclosures for the fuel distribution system. The concept was chosen because it has secondary enclosures for all liquefied and gaseous hydrogen piping inside the TCS. This prevents gas build-up in the TCS after a leakage, reduces excessive cooling of the TCS after LH2 leakage, and enables rapid leakage detection. Additionally, the risk of hydrogen ignition in confined spaces after a leakage is significantly reduced by preventing the hydrogen from reaching the TCS.

The secondary enclosures are arranged with vacuum for LH2 and inert gas for CH2 systems. This prevents the ignition of hydrogen in case of leakage from the inner piping.

The reasoning for excluding concepts without secondary enclosures from this analysis is the underlying difficulty in defining generally applicable safety barriers that could satisfy the functional requirements of the IGF Code when applied to hydrogen fuelled ships. Findings from previous project deliveries have shown that an explosive atmosphere can be generated quickly for hydrogen leakages, that gas detection in open environments is challenging, and that it is important to prevent leaked gas from accumulating in enclosed, semi-enclosed, and congested areas on deck.

It should be noted that the selection of the above concept designs for further risk analysis and candidates for developing prescriptive guidance does not imply that other concept designs cannot be safely developed through further analysis.

For each of the two selected concept designs, frequency analysis, consequences analysis and barrier modelling were performed for loss of containment events based on the results of the HAZID reported in “Hazard identification of generic hydrogen fuel systems” (EMSA, 2025). For the frequency analysis, the default parameters for frequency of random leaks from the HyRAM+ database were applied based on the results presented in “Reliability and safety analysis” (EMSA, 2024b). 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 performed by defining a bowtie, including 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 represented in the functional requirements and vice versa.

What we found

Risk analysis of compressed hydrogen (CH2) fuel systems

The key findings from the risk analysis of CH2 fuel systems for the selected hazardous events are presented below:

- **Leakages inside tank connection enclosure (TCE):**
    - ***Frequency analysis:*** The frequency calculations indicate that leakage events from the TCE have a high likelihood. For a fuel storage system comprising four TCEs, the total leak frequency was estimated to 9.8E-02[2], equivalent to one leak every 10 years. This is exacerbated by the high uncertainty in the generic failure values, suggesting that the actual frequency could be even higher than the calculated values.
    - ***Consequence analysis:*** If a leak is ignited inside the TCE, the consequence may be a jet fire if there is immediate ignition or a deflagration or detonation if there is delayed ignition. An explosion inside the TCE could cause its walls to blow out due to the explosion pressure, potentially impacting nearby individuals and safety-critical systems. The initial effects of such an event could range from injuries to fatalities.
    - ***Safety barrier modelling:*** The risk of leakages inside the TCE was analysed, where the top event of the bowtie was ‘Loss of integrity of TCE due to fire/explosion or overpressure’. The cause (threat) was defined as ‘H2 leakage from piping inside TCE’, while the potential consequences may endanger persons, the ship and/or safety-critical functions. The barrier functions that protect against the ‘top event’ are listed in sequential order:
        - Minimize leak frequency,
        - Minimize and stop leak,
        - Prevent ignition, and
        - Maintain TCE gas tightness.
- **Leakages in other parts of the ship’s fuel supply piping:**
    - ***Frequency analysis:*** The frequency calculations indicate that leakage events from supply piping have a relatively high likelihood. The total leak frequency was estimated to 4.4E-02, equivalent to one leak every 23 years[3]. This is exacerbated by the high uncertainty in the generic failure values, suggesting that the actual frequency could be even higher than the calculated values.

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[2] The total leak frequency was calculated by multiplying the number of equipment in each TCE by their default leak frequencies and summing the results for all TCEs.

[3] The total leak frequency was calculated by multiplying the number of equipment in the fuel supply system, excluding single-walled piping inside TCE or any Gas Valve Unit (GVU), by their default leak frequencies and summing the results.

  - ***Consequence analysis:*** Hydrogen leakages from the fuel supply piping systems may ignite and result in a fire, deflagration or detonation. Similar to the previous risk analysis case, there is also a potential for escalation, which could initiate a domino effect, sequentially affecting several hydrogen and non-hydrogen systems.

  - ***Safety barrier modelling:*** The risk of 'Leakages in the ship's fuel supply piping' was analysed by defining the top event as 'Loss of integrity of secondary enclosure'. The threat was 'H2 leakage from fuel supply piping', while the potential consequences may endanger persons, the ship and/or safety-critical functions. The bowtie is fundamentally similar to the 'leakages inside tank connection enclosure.' However, for this risk analysis, the key difference is that releases from the inner piping goes into a secondary enclosure, commonly known as a double-walled pipe.

- **Fire/explosion affecting fuel storage tanks:**

  - ***Frequency analysis:*** The hazard identification study identified that the potential fire/explosion threats to the fuel storage tanks and piping could be either a fire/explosion originating from hydrogen systems events (hydrogen-initiated events), or non-hydrogen-initiated events from ship systems/areas or outside of ship boundary. The frequency per ship year for non-hydrogen-initiated events involving fire/explosion was estimated to 9.8E-4 (one event every 1 000 years), while the frequency for hydrogen-initiated events was estimated to 1.8E-4 (one event every 5,600 years) due to the safety barrier of inert atmosphere in the TCE and double-walled supply piping.

  - ***Consequence analysis:*** A hydrogen fuel storage tank subjected to severe heat loads may experience a reduction in strength, potentially leading to rupture and subsequent explosion, deflagration, detonation, or fireball. Type IV pressure vessels are constructed from composite materials, which are more prone to heat damage than pressure vessels made of steel. Additionally, the fire may damage the safety systems needed to control the fuel system.

  - ***Safety barrier modelling:*** The risk of 'fuel storage tank rupture' due to heat ingress from fire was analysed. The barrier functions that protect against this top event are listed in sequential order:

    - Locate fuel storage tank away from high fire-risk areas,
    - Fire extinction and cooling of fuel storage tank and surroundings,
    - Passive fire protection of fuel storage tank and piping, and
    - Depressurization of fuel storage tank to maintain tank integrity.

Risk analysis of liquefied hydrogen (LH2) fuel systems

The key findings from the risk analysis of LH2 fuel systems for the selected hazardous events are presented below:

- **Leakages inside the tank connection space (TCS):**

  - ***Frequency analysis:*** The frequency calculations indicate that leakage events from piping inside the TCS have a high likelihood. The total leak frequency was estimated to 1.5 leaks per year. The major contributor for the leak frequency is the vaporizer.

  - ***Consequence analysis:*** If a leak is ignited inside the TCS, the consequence may be a jet fire if there is immediate ignition, or a deflagration or detonation if there is delayed ignition. A deflagration or detonation is a major concern due to its higher damage potential from overpressure effects. There is also a potential for escalation, which could initiate a domino effect, sequentially affecting several other tanks and hydrogen systems.

  - ***Safety barrier modelling:*** The top event of the bowtie was 'Loss of integrity of TCS due to fire/explosion or overpressure'. The threat is 'LH2 or CH2 leakage from piping inside TCS', while the potential consequences may endanger persons, the ship and/or safety-critical functions. The preventive barrier functions that protect against the 'top event' are listed in sequential order:

    - Minimize leak frequency,
    - Minimize and stop leak,

        - Prevent leakage reaching non-inert atmosphere, and
        - Maintain gas tightness in secondary enclosure.

- **Loss of vacuum insulation for tank:**

    - ***Frequency analysis:*** This risk was first introduced in “Mapping Safety Risks for Hydrogen-Fuelled Ships” (EMSA, 2024a). It was concluded that the possibility of a vacuum loss cannot be excluded. Currently, there are no available generic failure rates for vacuum loss in such systems. To obtain a specific failure rate for this safety-critical system, suitable for quantitative risk analysis, a dedicated reliability analysis would be required.

    - ***Consequence analysis:*** There are several potential consequences if the top event occurs, and these consequences may happen simultaneously:

        - Loss of structural integrity of FSHS or TCS (and/or loss of safety functions due to cryogenic effects)

        - Rapid pressure increase and excessive boil-off from the tank being discharged to open deck through the vent mast.

    - ***Safety barrier modelling:*** The top event was defined as ‘Loss of vacuum insulation on LH2 fuel tank’. The threats are leakages in the inner tank, leakages in the outer tank, leakages in primary piping systems and leakages in the secondary enclosure around piping.

      The preventive barrier function that protects against the ‘top event’ is ‘***Minimize leak frequency***’***.*** When there is only one barrier function to prevent a top event, it means that there is a single line of protection against the occurrence of that event. However, the barrier function consists of several elements that collectively contribute to its effectiveness.

      One additional barrier function is valid only for the threat ‘Leakages in primary piping systems’. This function protects against hydrogen leakages in the vacuum space by adding a secondary enclosure around the piping. The barrier function consists of the following barrier elements:

        - Secondary enclosure overpressure relief.
        - Secondary enclosure designed for pressure build-up.
        - Leakages led to a safe area.
        - Manufacturing, workmanship, and testing.

      Should all preventive measures fail and the vacuum insulation of the LH2 fuel tank be compromised, this critical event could result in a rapid and excessive boil-off from the tank, discharged onto the open deck via the vent mast. The barrier function designed to address this event is **‘Manage boil-off from the tank’,** which primarily focuses on:

        - Proper dimensioning of vent line and PRV.
        - Vent mast height and location to account for heat radiation and dispersion of unignited gases.

      A loss of tank vacuum may also compromise the structural integrity and safety functions of surrounding areas such as FSHS and TCS. Managing the resulting cooling of the surroundings should be within the ship's design capabilities. To address this risk, the mitigation barrier function ‘**Ensure structural integrity of FSHS and TCS after loss of vacuum’** has been implemented. This barrier function comprises two key elements:

        - Use of materials that can withstand low temperatures.
        - Prevent cooling of materials through heating, insulation, and drip trays.

Conclusion

With respect to the further drafting of a Guidance document, we draw the following conclusions from the findings in this report:

1. The likelihood of hydrogen leakages from piping systems cannot be excluded, meaning that ships using hydrogen as fuel should be built to safely handle these leaks. Providing secondary enclosures filled with inert gas around the primary piping systems for gaseous hydrogen and vacuum around the primary piping systems for liquefied hydrogen will enhance safety.

2. The likelihood of loss of tank vacuum insulation cannot be excluded, meaning that ships using liquefied hydrogen as fuel should be built to safely handle loss of tank vacuum insulation.

Guidance for the design and construction of secondary enclosures can be formulated as prescriptive requirements in a Guidance document based on the safety barrier modelling in this report.

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List of Abbreviations

CH2	Compressed hydrogen gas
DU	Dangerous undetected
EMSA	The European Maritime Safety Agency
ETA	Event Tree Analysis
FSHS	Fuel Storage Hold Space
FTA	Fault Tree Analysis
GHG	Greenhouse gas
H2	Gaseous hydrogen
HAZID	Hazard Identification
IGF Code	The International Code of Safety for Ships using Gases or other Low-flashpoint Fuels
IMO	The International Maritime Organization
LAC	Limiting Air Concentration
LEL	Lower Explosive Limit
LH2	Liquefied hydrogen
LOC	Limiting Oxygen Concentration
NDT	Non-destructive testing
PFD	Probability of Dangerous Failure on Demand
PRV	Pressure Relief Valve
TCE	Tank Connection Enclosure
TCS	Tank Connection Space
TPRD	Thermal Pressure Relief Device

List of general terms

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

The objective of this part of the study is to conduct a risk analysis of selected generic hydrogen fuel system configurations. These systems have been chosen based on their ability to be defined by prescriptive requirements with what is assumed to be an acceptable risk level. The assessment of the risk level is based on the findings in the previous project sub-deliveries. 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, come with safety challenges that are different from 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.

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, and this report (Deliverable D.3.2) is the second deliverable of the third task. An overview of all study tasks and deliverables are provided in Figure 1-1.

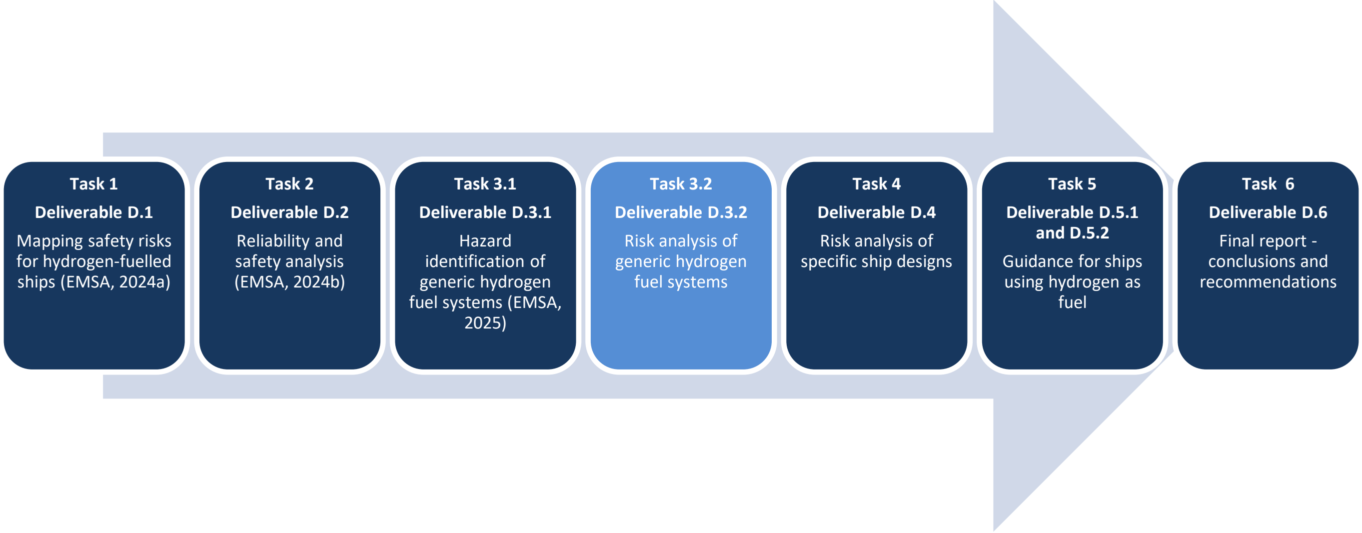

Figure 1-1 Study tasks and deliverables. This report presents the findings from the second part of the third task (Task 3.2).

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 reliability of safety-critical systems and presented 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, 2025).

This report presents the findings from the second part of the third task (Task 3.2), focusing on a 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.

This report has the following structure:

- Chapter 2 describes the methodology.
- Chapter 3 examines compressed hydrogen fuel systems.
- Chapter 4 examines liquefied hydrogen fuel systems.
- Chapter 5 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 fuel system designs for risk analysis.
- Chapter 2.2 presents the basis for 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 generic fuel system designs for risk analysis

Several generic hydrogen fuel system design concepts were identified as part of the hazard identification process documented in the EMSA report, ‘Hazard Identification of Generic Hydrogen Fuel Systems’ (EMSA 2024a). Based on its findings, two of these generic concepts were identified as candidates for developing prescriptive guidance and are, therefore, selected for further risk analysis.

Concepts without secondary barriers are excluded in this risk analysis due to the underlying difficulty in defining generally applicable safety barriers that could satisfy the functional requirements of the IGF Code. Findings from previous project deliveries have shown that an explosive atmosphere can be generated quickly for hydrogen leakages, that gas detection in open environments is challenging, and that it is important to prevent leaked gas from accumulating in enclosed, semi-enclosed, and congested areas on deck.

The following concepts are selected for further risk analysis:

1. Compressed hydrogen (CH2) fuel system with fixed fuel tanks, inerted tank connection enclosure (TCE) and secondary enclosures for the fuel distribution system.
2. Liquefied hydrogen (LH2) fuel system with vacuum-insulated IMO Type C tanks, tank connection space (TCS) and secondary enclosures for the fuel distribution system.

Fuel systems concepts for both CH2 and LH2 are commonly observed in the industry, and it was therefore a conscious choice to select one of each storage method concepts.

The first design concept selected for risk analysis, illustrated in Figure 2-1, focuses on the storage and supply of compressed hydrogen. A detailed description can be found in Chapter 3. This concept was chosen for the following reasons based on findings from previous project deliveries:

- The system has all leak sources protected by secondary enclosures, either by providing a TCE, or by double-walled piping for the fuel distribution system. This inherently gives gas detectors a better chance of detecting leaks, resulting in a reliable and fast-acting shut-down system.
- The secondary enclosure is arranged with inert gas, significantly reducing the risk of hydrogen ignition after a leakage.
- The secondary enclosures can be arranged with inert gas purging and vent line. This enables purging of the secondary enclosure and routing of leaked gas to a safe area in case of leakages from the inner piping.

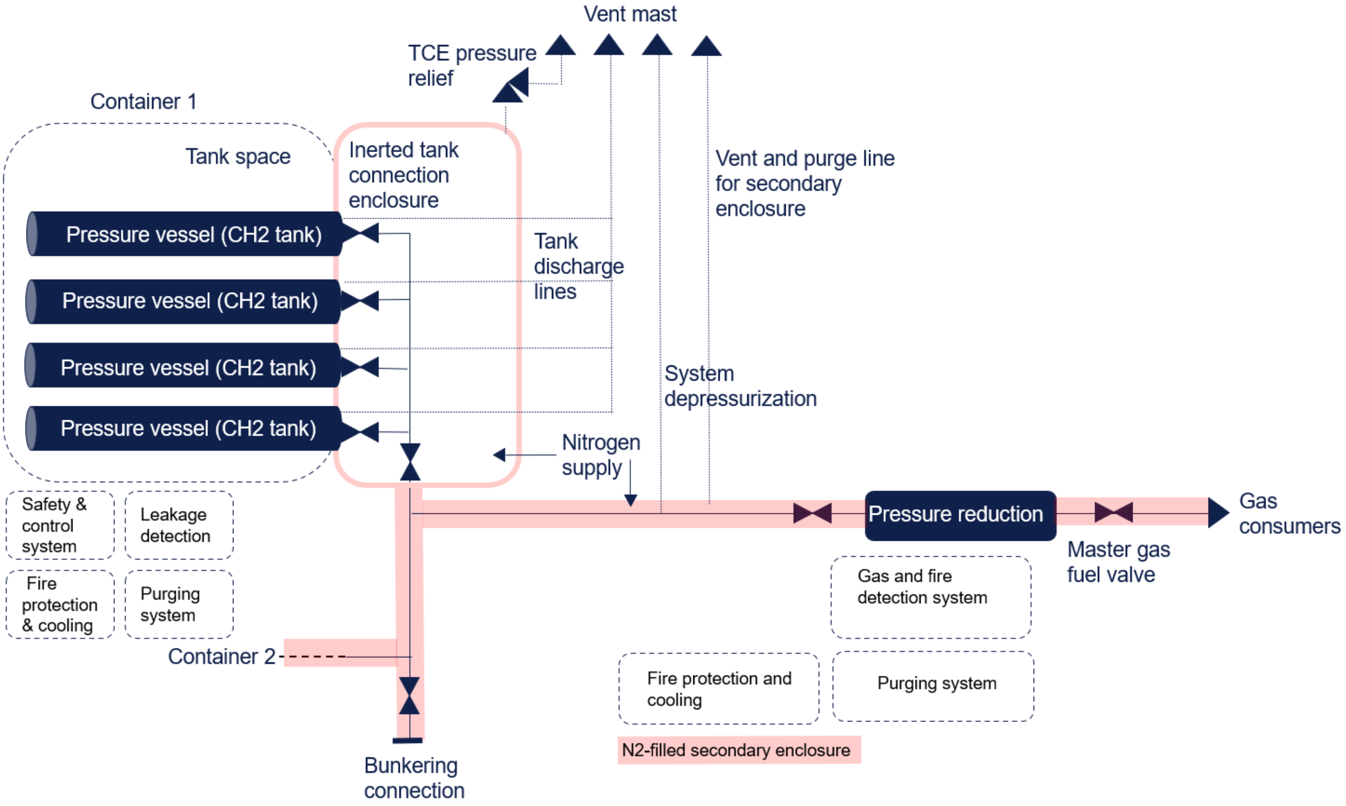

Figure 2-1 Flow diagram of the fixed CH2 fuel tank system, with inerted tank connection enclosure. (Source: DNV).

The second design concept selected for risk analysis, illustrated in Figure 2-2, is liquefied hydrogen (LH2) fuel systems with vacuum-insulated IMO Type C tanks, tank connection space and piping systems protected by secondary enclosures. A comprehensive description is available in Chapter 4. This concept was selected for reasons similar to those behind the first design concept:

- The system has secondary enclosures for all liquefied and gaseous hydrogen piping inside the TCS. This prevents rapid gas build-up in the TCS after a leakage, reduces excessive cooling of the TCS after LH2 leakage, and enables more rapid leakage detection.
- The risk of hydrogen ignition in confined spaces after a leakage is significantly reduced by preventing the hydrogen from reaching the TCS. The secondary enclosures are arranged with vacuum for pipes containing liquid hydrogen and inert gas for pipes containing gaseous hydrogen. This prevents the ignition of hydrogen in these spaces.
- The secondary enclosures can be arranged with inert gas purging and vent line. This enables purging of the secondary enclosure and routing of leaked gas to a safe area in case of leakages from the inner piping.

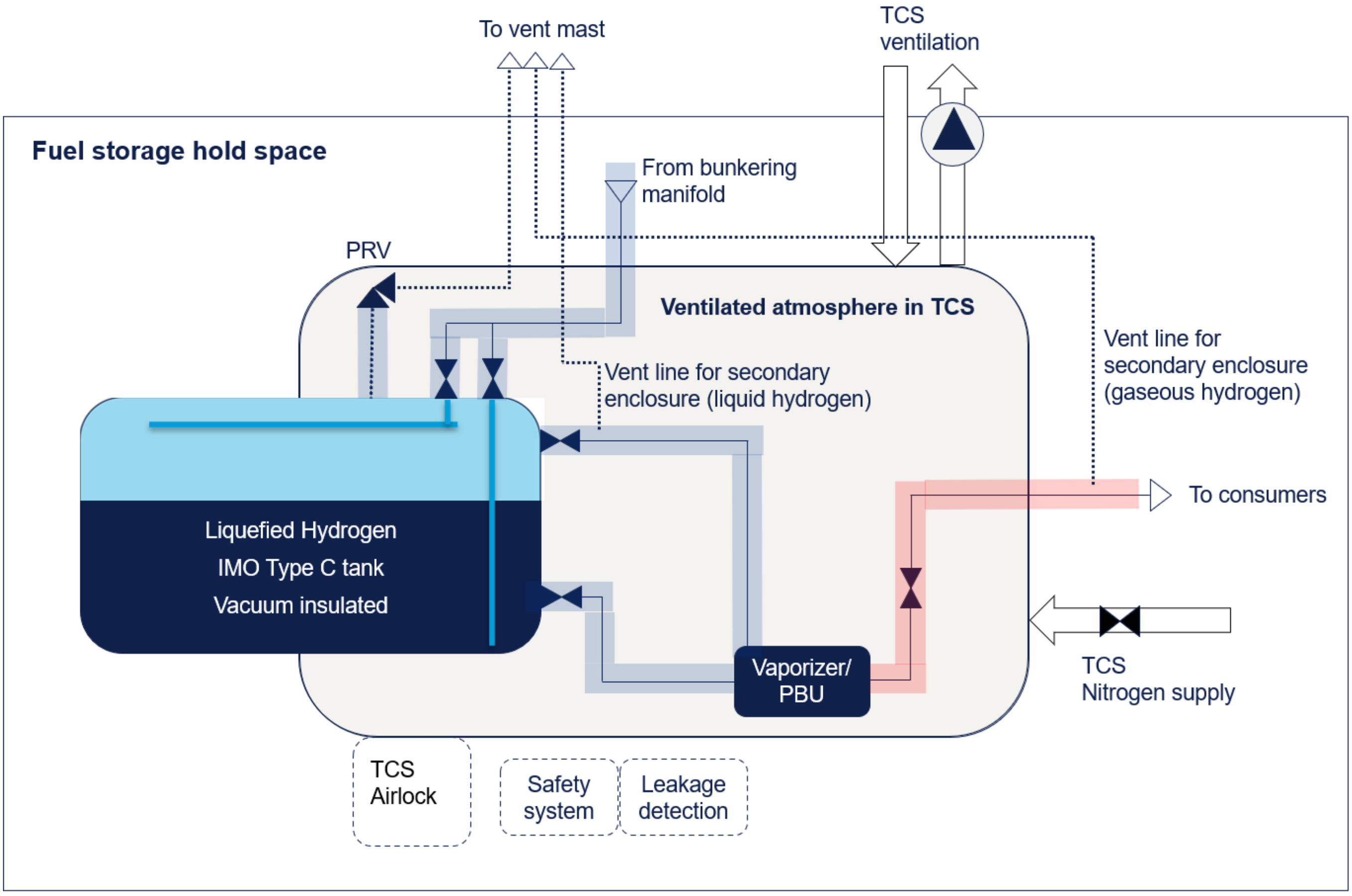

Figure 2-2 Flow diagram of the LH2 fuel system with TCS arranged with secondary enclosure for liquefied and gaseous piping, and ventilated atmosphere in TCS (Source: DNV).

It should be noted that the selection of the above concept designs for further risk analysis and candidates for developing prescriptive guidance does not imply that other concept designs cannot be safely developed through further analysis.

2.2 Selection of hazardous events

The hazardous events selected for the risk analysis build upon the results of the HAZID reported in “Hazard identification of generic hydrogen fuel systems (EMSA, 2025). The primary focus of the HAZID was on scenarios involving hydrogen leakage within the fuel system and their potential to induce flammable and cryogenic effects.

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

2.3 Risk analysis

This subchapter 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 chosen risk analysis method in this task. High-level bowties of hazardous events that pose significant risks to a hydrogen-fuelled ship and its crew were introduced in the first report from this study, “Mapping safety risks for hydrogen-fuelled ships (EMSA, 2024a). In this risk analysis the bowties have been applied on specific concepts of hydrogen fuel systems and detailed bowties have been made for selected hazardous events.

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 cheese slices. The "holes" in the cheese slices 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).

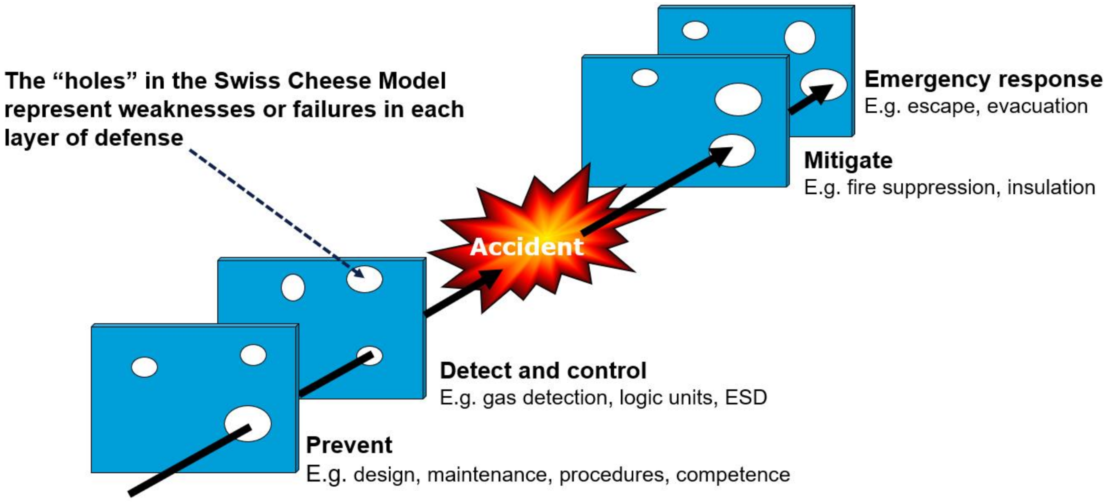

Figure 2-3 Illustration of "Swiss Cheese Model" of accident causation (Source: DNV).

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 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.

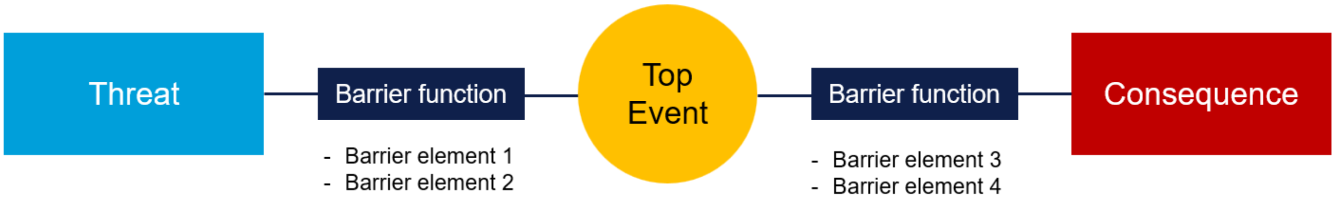

Figure 2-4 Illustration of the generic bowtie model with threat (left), top event (central), consequences (right) and safety barriers (Source: DNV).

2.3.2 Frequency analysis

Failure probabilities for hydrogen equipment were assessed and presented in “Reliability and safety analysis” (EMSA, 2024b). The report presents the results from a study investigating the reliability of selected equipment for hydrogen-fuelled ships, including assessing the suitability of various databases containing failure data. The study assessed a broad spectrum of data sources to determine which reliability data are deemed most applicable and of the highest quality. It acknowledged the lack of experience with hydrogen-fuelled ships and, consequently, of an industry-specific maritime leak database. However, the generic HCRD and/or HyRAM+ databases were considered the best alternatives when establishing leak frequencies for hydrogen-fuelled ships (EMSA, 2024b).

The generic HCRD and/or HyRAM+ databases are mainly based on failures from industries other than maritime, and only the HyRAM+ database takes into account some limited hydrogen-specific failures. With that in mind, the study noted that the following uncertainties are typically not accounted for in these databases:

- **Marine and ship environment:** Components of hydrogen-related systems onboard ships are subjected to unique loads due to the maritime environment, such as sea atmosphere/spray, green sea, thermal cycling, dynamic loads, vibrations, and inclinations.
- **Properties of hydrogen:** Differences in the properties and behaviour of hydrogen compared to the media on which the databases are based.
- **Inspection, certification, and maintenance**: The inspection, certification regime and maintenance intervals can be different for Oil & Gas and process industry installations than for ships.
- **Piping dimensions and operating pressure:** Hydrocarbon-containing equipment in the offshore industry is generally of larger dimension than hydrogen-containing equipment in, for example, hydrogen fuel systems.

Since maritime and hydrogen-specific factors are not adequately considered, the actual frequency could be higher than the calculated values in the chapters addressing leak frequencies.

For the cases in this risk analysis, the HyRAM+ was selected because it includes the equipment type “pipe joints”, which are applied for pipe connections in the CH2 system, while the HCRD database is limited to flanged joints only. The HyRAM+ failure rates are applied for all equipment for consistent and comparable results. The updated values for “default parameters for frequency of random leaks for individual components”, as per HyRAM+ Version 5.1 (HyRAM+, 2023), shown in Table 2-1, is applied in this risk analysis.

Table 2-1 Default parameters for frequency of random leaks for individual components (HyRAM+, 2023).

Equipment	Hole size (% of equipment size)	Default leak frequency per year
Valve	0.01%	2.9E-03
	0.1%	5.9E-04
	1 %	5.4E-05
	10 %	2.5E-05
	100 %	4.8E-06
Joint	0.01%	3.5E-05
	0.1%	4.7E-06
	1 %	7.9E-06
	10 %	7.5E-06
	100 %	6.4E-06
Pipe	0.01%	8.0E-06
	0.1%	3.7E-06
	1 %	9.6E-07
	10 %	4.6E-07
	100 %	1.5E-07
Instruments	0.01%	6.2E-04
	0.1%	2.0E-04
	1 %	1.1E-04
	10 %	1.0E-04
	100 %	3.7E-05
Flange	0.01%	2.0E-02
	0.1%	2.2E-03
	1 %	2.4E-04
	10 %	2.7E-05
	100 %	2.9E-06
Vaporizer	0.01%	8.1E-03
	0.1%	2.6E-02
	1 %	8.4E-02
	10 %	2.7E-01
	100 %	8.8E-01

Note that for the component type 'vaporizer', the default values for methane have been applied due to the absence of specified values for hydrogen. For all other components, the default values for hydrogen are used. The default values for gaseous piping and liquid hydrogen piping are the same for the selected components listed in Table 2-1.

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).

It should be noted that safety barriers proposed in this report mainly 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).

The selection and structure of safety barriers for ‘hydrogen leak events’ are based on the principles illustrated in Figure 2-5 and listed below (EMSA, 2024a):

1. **System integrity.** Minimize leakages from fuel installation.
2. **Double barriers (secondary enclosure).** Protect ship against leakages.
3. **Leakage detection**. Give warning and enable automatic safety actions.
4. **Automatic isolation of leakages.** Reduce consequences of a leakage.
5. **Segregation.** Protect fuel installation from external events.

For other risks addressed in this report, such as fire/explosion affecting fuel tank or loss of vacuum, the structure of the barriers would differ, and be specific for the concerned event.

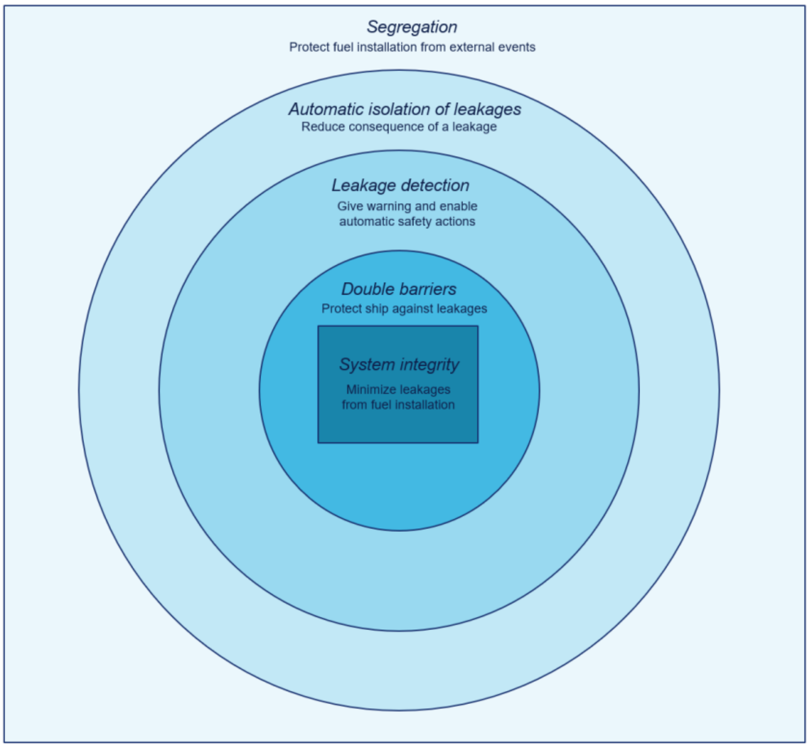

Figure 2-5 The safety concept of the current regulations in the IGF Code for natural gas fuel (Source: (EMSA, 2024a)).

2.3.4 Consequence analysis

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

- Mapping safety risks for hydrogen-fuelled ships (EMSA, 2024a)
- Reliability and safety analysis (EMSA, 2024b)
- Hazard identification of generic hydrogen fuel systems (EMSA, 2025)[4]

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

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[4] Note that this report will be cited as (EMSA, 2025a) in upcoming reports delivered as part of this study since it is the first of several reports, to be launched in 2025.

3. Risk analysis of compressed hydrogen (CH2) fuel systems

This chapter presents the risk analysis of the first generic design concept selected in Chapter 2.1.This is the compressed hydrogen (CH2) fuel system, which includes fixed fuel tanks and an inerted tank connection enclosure (TCE) and piping systems protected by secondary enclosures.

The following risk scenarios are covered:

- Leakages inside tank connection enclosure (Chapter 3.2)
- Leakages in other parts of the ship's fuel supply piping (Chapter 3.3)
- Fire/explosion affecting fuel storage tanks (Chapter 0)

3.1 Analysis basis

The concept selected for the risk analysis is described in this Chapter. The fuel system comprises fixed CH2 tanks on the open deck. A flow diagram of this concept is shown in Figure 3-1.

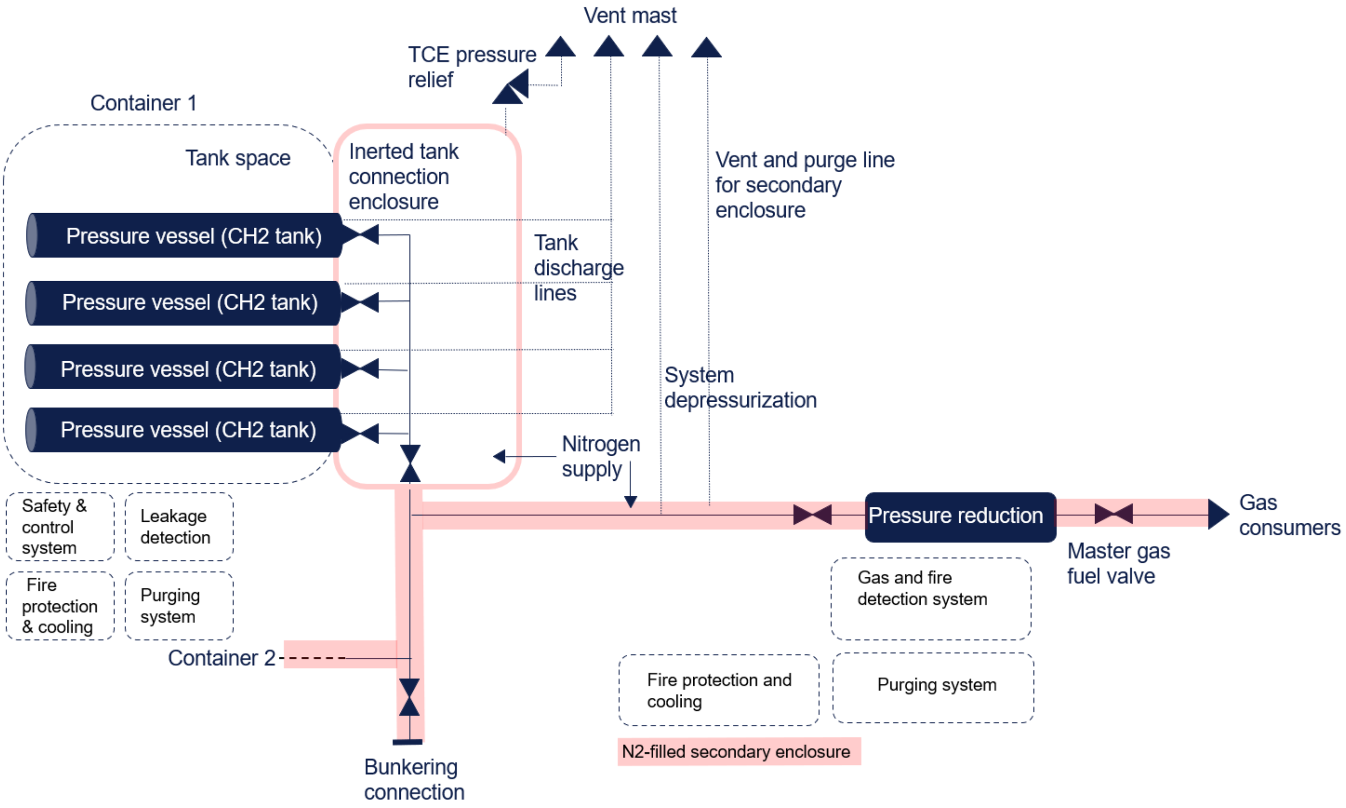

Figure 3-1 Flow diagram of the fixed CH2 fuel tank system, with inerted tank connection enclosure. (Source: DNV).

The fuel storage system:

- A collection of interconnected pressure vessels (tanks) are secured together inside an ISO container. The fuel supply from several containers are collected in a fuel manifold which is protected by a secondary enclosure.
- Each ISO container is arranged with a designated tank space for the pressure vessels, and a separate tank connection enclosure (TCE) where all tank connections, pipes, fittings, valves, and instruments are situated. The function of the TCE is to act as secondary enclosure. The tank space and the TCE are separated by a bulkhead.
- The pressure vessels are Type 4, implying that they are made from a fully wrapped carbon composite with a non-metallic liner. The pressure vessels can be mounted horizontally or vertically.
- The TCE is assumed gastight and filled with nitrogen at a slight overpressure, meaning there is no continuous inert gas consumption. The safety philosophy rests on the premise that the inert atmosphere within the enclosure will eliminate the risk of ignition of hydrogen gases inside the TCE. It is presumed that the inert condition is continuously monitored.
- The TCE is equipped with a pressure relief system designed to prevent damage to the enclosure from overpressure in the event of a leakage. This arrangement directs the leaked gas to a safe area on the open deck.
- It is possible to gas-free the TCE via the inert gas purging system for access and maintenance.
- All pipe joints in the TCE are compression fittings. These fittings use a compression nut, a compression ring (ferrule), and a compression seat. Tightening the nut compresses the ring onto the pipe, creating a seal. The tank connections (between the piping and the pressure vessels) are assumed to be threaded connections. Piping in the TCE is single-walled stainless-steel piping with an outer diameter of 10-16 mm and a 2.0 mm pipe thickness, while piping systems outside the TCE are protected by secondary enclosures.
- Each pressure vessel is fitted with a tank discharge line designed to safely vent the contents in a fire scenario.
- The fuel containment systems and associated connections and equipment are located on an open deck, protected from environmental hazards (e.g. green sea), mechanical damage (e.g. dropped object), and fire risk areas.

The bunkering system:

- A hydrogen bunkering station is located on one side of the ship and will be connected to the bunkering facility during the fuel transfer using a high-pressure hose. Initially, hydrogen gas may be transferred directly from the supplier’s storage tanks to the pressure vessel until the pressure equalises. Compressors on the shoreside may be needed to pressurise the hydrogen gas further to achieve the high pressures required (350 bar) to fill the ship's tanks.
- The bunkering station is arranged in an area on the open deck, which provides natural ventilation and unobstructed relief of leakages.
- The bunkering system consists of piping with secondary enclosures up to the bunkering connection.

The fuel supply and conditioning system:

- All piping on the ship comprises fixed piping. All piping outside the TCE is protected by inerted secondary enclosures (on open deck and in enclosed spaces).
- The regulation of the fuel supply pressure to consumers is performed by a pressure reduction and control valve, for example from 350 bar to around 10 bar. The fuel supply inlet pressure to the consumer is assumed to be around 6-7 bar. Only one container will be open towards the fuel supply system during operation. The ship control system will automate the switching of tanks to ensure a continuous fuel supply.

3.2 Risk analysis of leakages inside tank connection enclosure

The primary focus of the HAZID was on scenarios involving hydrogen leakage within the fuel system and their potential to induce flammable and cryogenic effects. In case of leakages from the piping inside the TCE, the hydrogen may ignite, causing fire or explosion. Further, a hydrogen leakage may cause over pressurization of the space. Both scenarios have the potential for structural damage and loss of integrity of the TCE.

Hence, this risk analysis covers the hazardous event of leakages inside the TCE (threat) and the potential for loss of integrity of TCE due to fire/explosion or overpressure (top event).

3.2.1 Frequency analysis

The HAZID study identified that there could be multiple causes for leaks, such as from welds, flanges, threaded joints and compression fittings. The underlying causes could be design errors, fabrication or installation and mounting errors, corrosion, operating conditions (e.g. vibrations) or operating outside design limits. In addition, leaks could occur due to external impacts, which is considered less likely for this case since the piping components would be protected inside an inerted enclosure.

To give an indication of the leak frequency in the TCE, the following generic equipment types and number of equipment were assumed:

- Four storage units and four pressure vessels per storage unit, which makes a total of 16 pressure vessels.
- Each storage unit has one TCE, which makes a total of four TCEs.
- Inside each TCE, there is assumed:
    - **Valves (5):** One tank/cylinder valve for each pressure vessel and one TCE manifold valve, totalling five valves.
    - **Joints (39):** 35 joints, assuming two (2) per valve, three (3) per T-joint in manifold to gas supply and vent line, in addition some for piping in general (routing etc.). One threaded connection per pressure vessel. In total, four tank connections and 35 pipe joints.
    - **Pipes (10m):** 10m piping in total.
    - **Instruments (4):** One instrument per line to each pressure vessel, in total four instruments

There is no specific failure data on threaded connections in HyRAM+. Therefore, the failure rate of joints has been applied on this equipment. Only equipment within the TCE is considered in the risk analysis.

Table 3-1 shows the total leak frequency for each TCE, calculated by multiplying the number of equipment by their default leak frequencies (from Chapter 2.3.2) and summing the results. This results in a total leak frequency of 2.5E-02, equivalent to one leak every 41 years, regardless of leak size. 91 % of the leaks are attributed to hole sizes of 0.01 % and 0.1 % of equipment size. For a fuel storage system comprising four TCEs, the total leak frequency is 9.8E-02, equivalent to one leak every 10 years.

Table 3-1 Estimated annual leak frequency from one (1) TCE, per hole size category (Source: DNV).

Hole size (% of equipment size)	Total leak frequency	Share (%)
0.01%	1.8E-02	74.7 %
0.1%	4.0E-03	16.1 %
1 %	1.0E-03	4.2 %
10 %	8.2E-04	3.3 %
100 %	4.2E-04	1.7 %
Total	**2.5E-02**	**100 %**

As pointed out in chapter 2.3.2, uncertainties and validity of the failure data for maritime applications need to be considered. In this case, the equipment is located inside an enclosure with an inerted atmosphere. The enclosure provides a controlled environment, helping to maintain consistent pressure and temperature conditions. Additionally, it offers protection against external environmental effects. However, ship-specific factors such as vibrations and dynamic motions, as well as hydrogen-specific factors, are not accounted for in the leak frequency.

While the inerted atmosphere and environmental protection may reduce leak frequency, the additional factors of vibration and motion are likely to offset these benefits. Consequently, the leak frequency could potentially be higher, though it is challenging to quantify the extent.

3.2.2 Consequence analysis

Direct effects and potential for escalation

If a leak ignites inside the TCE, it may result in a jet fire with immediate ignition or a deflagration or detonation with delayed ignition. Deflagration or detonation poses a major concern due to its higher damage potential from overpressure effects. An explosion or overpressure (unignited leak) inside the TCE could blow out its walls, potentially impacting nearby individuals, with initial effects ranging from injuries to fatalities.

There is also a potential for escalation, which could trigger a domino effect, sequentially affecting other tanks and hydrogen systems. Overpressure and projectiles from an explosion can cause damage and create larger holes in other hydrogen tanks and piping systems, leading to more significant hydrogen leaks. Escalation events could threaten the entire ship, increasing the risk of multiple fatalities. These events may develop rapidly, leaving insufficient time to muster and evacuate the ship.

Indirect effects - Damage to ship safety-critical functions

A fire/explosion or overpressure event in the TCE, as well as escalation scenarios, could potentially damage or impair ship safety-critical functions such as life-saving arrangements. The failure of these critical functions when needed could result in multiple fatalities.

Indirect effects - Structural damage to ship

A fire/explosion or overpressure event in the TCE, including escalation scenarios, could cause severe structural damage to the ship. If hydrogen is released inside confined spaces or semi-congested areas on the open deck, it can form a flammable cloud much faster than other gases. A ‘critical cloud’ capable of causing significant damage through explosion or deflagration, and posing a threat to the ship 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.

3.2.3 Safety barrier modelling

The risk of leakages inside the TCE is analysed using the bowtie approach and visualized in Figure 3-2. The top event is ‘Loss of integrity of TCE due to fire/explosion or overpressure’. The threat is ‘H2 leakage from piping inside TCE’, while the potential consequences may endanger persons, either as direct effects from hydrogen events (fire/explosion or over-pressure) or through indirect effects from ship structural damage or loss of safety-critical functions.

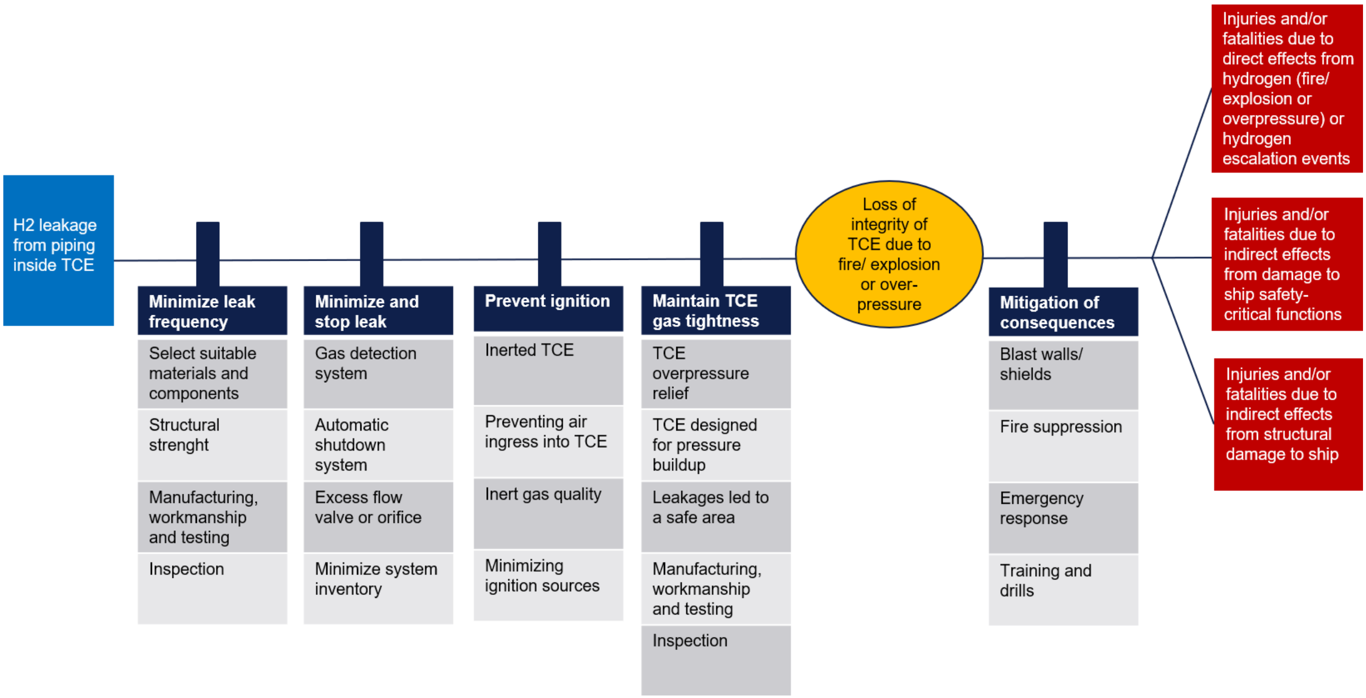

Figure 3-2 Bowtie for risk of leakages inside the tank connection enclosure. (Source: DNV).

The barrier functions to protect against the loss of integrity of TCE due to fire, explosion or overpressure are listed in sequential order:

1. Minimize leak frequency,
2. Minimize and stop leak,
3. Prevent ignition,
4. Maintain TCE gas tightness.

As described in 2.3.3, the selection and structure of safety barriers for ‘hydrogen leak events’ are based on the principles derived from the safety concept of the current regulations in the IGF Code for natural gas fuel.

The first barrier function aims to ‘**minimize leak frequency’** from components within the TCE, as it would be impossible to eliminate all sources of leakage completely. This barrier function consists of the following barrier elements:

- **Selection of suitable materials and components:**
  - **Avoid leak-prone components.** The use of leak-prone components and couplings should be minimized when designing hydrogen systems. Hydrogen piping systems should, as far as practicable, be joined by welding.
  - **Suitable materials.** All parts of the fuel system should be constructed from materials suitable for hydrogen taking into consideration the design temperature, design pressure, working stress levels and environmental conditions. Typical properties, not limited to yield stress, tensile strength, ductility,

fracture toughness, fatigue properties, hydrogen permeation properties and corrosion resistance should be considered.

- **Structural strength.** The fuel systems structural strength should be assessed against failure modes, including, but not limited to, plastic deformation, buckling, and fatigue. This should be confirmed by carrying out stress and fatigue analyses of all relevant load conditions, including operational loads, accidental loads, and internal pressure.

- **Manufacturing, workmanship and testing.** This would include measures such as putting strict requirements on pipe manufacturing, pipe joining details, tolerances, welding procedures, post-weld heat treatment, Non-Destructive Testing (NDT), pressure testing etc.

- **Inspection:** Access to the gas fuel system for inspection should be provided.

The second barrier function is to **'Minimize and stop leak'**. This barrier function consists of the following barrier elements:

- **Gas detection system.** Gas detection is a crucial safety function for any gas piping system. Detecting and stopping leaks as early as possible is essential to limit the consequences. However, the cloud build-up time for hydrogen leaks is extremely short compared to other gases. A 'critical cloud' that can cause significant damage and harm to the ship and its systems if ignited can form within seconds. Recent studies by DNV indicate that this can occur in just 5 seconds with leaks in the range of 0.1 kg/s (DNV, 2019) (DNV, 2023). A TCE will limit the gas dispersion and enable a more effective gas detection system. One should note that not all hydrogen gas detectors work effectively in an inerted space , so it's important to choose the right type of sensor for accurate and reliable measurement. While gas detection is essential for stopping leaks and isolating segments, there is significant uncertainty about whether the gas detector system can prevent a critical gas cloud and explosion from occurring, as gas detectors may not be fast enough. The inventory of the piping system may also be enough to create an explosive atmosphere inside a TCE. A thorough description and reliability analysis of a gas detection and shutdown system for a compressed hydrogen fuel system is provided in the EMSA report "Reliability and safety analysis" (EMSA, 2024b).

- **Automatic shutdown system.** The gas detection system described above should trigger a safety system designed to automatically shut down the hydrogen flow. The detection and shut-down safety function utilizes three subsystems:

  - **Sensor subsystem** (Gas detection system) – Gas detectors detect a leakage and produce an electrical signal that is sent to the logic solver.

  - **Logic solver subsystem** - detects that the electrical signal exceeds a given threshold and sends a signal to the final element subsystem.

  - **Final element subsystem** - performs the safety function by closing the tank valve(s). The gas supply from each individual tank (pressure vessel) is remotely controlled by a pneumatically actuated tank valve, acting as the final element subsystem to shut down flow in case of leak.

- **Excess flow valve (EFV) or Restrictive flow orifice (RFO).** EFVs are mechanical safety devices designed to automatically shut off the gas flow when it exceeds a predetermined rate. While EFVs are claimed to be effective in preventing large-scale gas leaks, they require a flow rate higher than normal usage to activate. This means they may not detect and prevent small to medium-sized leaks. RFOs are devices designed to control the flow of fluids by introducing a mechanical restriction of flow diameter with no moving parts. The orifice prevents flow higher than a specific rate but will not stop the flow.

- **Minimize system inventory**. Reducing system inventory through segmentation, using as small dimensions as possible, and keeping as low pressure as possible at all times can decrease the amount of hydrogen released during a leak. However, segmentation may also increase leak frequency due to the additional connections and valves required.

The third barrier function is **'Prevent ignition'**. This barrier function consists of the following barrier elements:

- **Inerted TCE.** An inerted atmosphere within the TCE, displacing oxygen, will significantly reduce the risk of hydrogen ignition. Additionally, an inerted atmosphere helps prevent oxidation of materials, which can be beneficial in maintaining the integrity of equipment and infrastructure. There will be an inlet pipe from inert generators onboard to ensure the TCE is pressurized with slight constant overpressure. There needs to be sufficient capacity onboard to inert the space and purge in case of leaks.

  The TCE should also have inert atmosphere monitoring and pressure monitoring. If there is an oxygen concentration level above the Limiting Oxygen Concentration (LOC)[5] in the TCE, which is undetected (dangerous undetected failure), the barrier function has failed. The safety system should ensure that there is always an inert atmosphere in the enclosure during operations.

- **Preventing air ingress into TCE**. The TCE should be constructed as a gas tight enclosure to prevent ingress of air compromising the inert atmosphere and to contain hydrogen in a leakage scenario. The gas-tightness of the TCE should be ensured by pressure-testing and inspection. By keeping a slight positive inert gas pressure inside the TCE, air will be prevented from entering. A reliability analysis of the inert gas system was conducted in Reliability and safety analysis (EMSA, 2024b). Air ingress can occur if there are leak paths and there is a loss of overpressure. These two are not independent events because when there is a leak, a subsequent reduction in pressure inside TCE will occur. Air leaks could occur from openings such as the inert gas inlet, ventilation ducts, cable penetrations, cracks, and pressure relief outlets. Additionally, defective hatch gaskets or access openings could also cause air leaks.

- **Inert gas quality.** The supplied inert gas must have a purity sufficient to reduce the oxygen content inside the TCE to below the LOC. Since hydrogen can ignite with less oxygen than natural gas (5% vs 12%), a hydrogen installation would have stricter requirements for inert gas quality than what is commonly provided for hydrocarbons.

- **Minimizing ignition sources.** Electrical equipment inside the TCE should be avoided as far as possible. If such equipment is needed for the performance of essential safety functions, they should be certified for safe operation in a hydrogen atmosphere. The TCE should be classified as Hazardous Zone 1.

An inerted TCE can be a robust safety barrier. However, maintaining an inert atmosphere and preventing air ingress, requires careful monitoring and control. This adds complexity to the design and operation and requires that operating personnel is familiar with all safety aspects of the installation. Nitrogen used as inert gas is non-toxic, but will displace oxygen in confined spaces, creating an asphyxiation hazard for personnel. Proper safety measures and monitoring are essential to prevent such risks, even though the risk is reduced by use of a TCE with limited volume and no possibility for entry.

The fourth barrier function, to prevent the top event from occurring, is **'Maintain TCE gas tightness'**. This barrier function consists of the following barrier elements:

- **TCE overpressure relief**. The tank connection enclosure should be protected against overpressure by a dedicated vent line to the vent mast. The inert gas inside the TCE should be prevented from escaping by a relief valve or burst disc fitted in the vent line and designed to open at a pressure setting below the design pressure of the TCE.

- **TCE designed for pressure buildup.** The tank connection enclosure should be designed to withstand the maximum possible pressure buildup during a leakage in the gaseous hydrogen piping, dictated by the leak flow rate, TCE volume and the relief capacity of the TCE overpressure relief.

- **Leakages led to safe area.** The hydrogen/nitrogen mixture in the TCE should be led to a safe area on the open deck when the pressure inside the TCE exceeds the set point of the pressure relief device. When the leakage has been stopped and the system is in equilibrium, it should be possible to purge the hydrogen inside through the vent system by supplying more nitrogen to the TCE. It should be noted that this process

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[5] The limiting oxygen concentration (LOC) is defined as the limiting concentration of oxygen below which combustion is not possible, independent of the fuel concentration.

would also have a risk of unintentionally introducing oxygen to the TCE with a corresponding risk of explosion. Another reason to lead the gas to a safe location away from the TCE is the risk of ignition of the gas released to open air.

- **Manufacturing, workmanship and testing.** A regime ensuring satisfactory manufacturing, workmanship and testing of the TCE structure should be ensured.
- **Inspection.** Access to the TCE for inspection should be provided.

If all the preventive barriers fail and there is a loss of integrity of the TCE due to fire, explosion, or overpressure, this could constitute a major accident with potential injuries and/or fatalities. Mitigation barriers can reduce the effects of the event to a certain degree, but not to a degree where the top event may be considered an acceptable event. This risk analysis has therefore focused on prevention barriers to ensure that the event does not occur. However, some possible mitigation strategies are listed below:

- **Blast walls and shields:** Strategically placed blast walls and shields could be used to protect persons and critical spaces and systems from explosions.
- **Fire suppression systems:** Fire suppression systems could be used to control fires. Hydrogen fires should not be extinguished until the leakage 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 case 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.

3.3 Risk analysis of leakages in the ship’s fuel supply piping

The primary focus of the HAZID was on scenarios involving hydrogen leakage within the fuel system and their potential to induce flammable and cryogenic effects. In case of leakages from the piping inside the secondary enclosure, the hydrogen may ignite, causing fire or explosion. Further, a hydrogen leakage may cause over pressurization of the enclosure. Both scenarios have the potential for structural damage and loss of integrity of the secondary enclosure.

Hence, this risk analysis covers the hazardous event of leakages in the ship’s fuel supply piping (threat) and the potential for loss of integrity of the secondary enclosure due to fire, explosion, or overpressure (top event).

By ship’s fuel supply piping, we mean all piping in the fuel system, excluding single-walled piping inside TCE or any Gas Valve Unit (GVU). This case is analysed on the basis of having a secondary enclosure to contain any leak.

3.3.1 Frequency analysis

To give an indication of the leak frequency in the fuel supply piping, the following generic equipment types have been analysed as an approximation of a typical installation:

- **Pipes (100m):** 100m piping in total, although this will be ship-specific.
- **Valves (10):** The supply line features 10 valves, including automatically operated isolation valves, double-block and bleed valves, pressure reduction valves, and bunkering station valves, among others.
- **Joints (50):** 50 joints; this will also be ship-specific and dependent on piping layout and arrangement.
- **Instruments (4):** Four instrument connections are assumed.

Table 3-2 shows the total leak frequency, calculated by multiplying the number of equipment units by their generic leak frequencies (failure rates) and summing the results. This results in a total leak frequency of 4.4E-02, equivalent to one leak every 23 years, regardless of leak size.

Similar to the case with leakages inside TCE, this equipment is located inside an inerted secondary enclosure. While the inerted atmosphere and environmental protection may reduce leak frequency, the additional factors of vibration and motions on a ship are likely to offset these benefits. Consequently, the leak frequency could potentially be higher, though it is challenging to quantify the extent.

Table 3-2 Estimated annual leak frequency from fuel supply piping per hole size category (Source: DNV).

Hole size (% of equipment size)	Total leak frequency	Share (%)
0.01%	3.4E-02	76.6 %
0.1%	7.3E-03	16.4 %
1 %	1.5E-03	3.3 %
10 %	1.1E-03	2.4 %
100 %	5.3E-04	1.2 %
Total	**4.4E-02**	**100 %**

3.3.2 Consequence analysis

Direct effects and potential for escalation

If a leak ignites, it may result in a jet fire with immediate ignition or a deflagration or detonation with delayed ignition. Deflagration or detonation poses a major concern due to its higher damage potential from overpressure effects, with initial effects ranging from injuries to fatalities.

There is also a potential for escalation, which could trigger a domino effect, sequentially affecting other tanks and hydrogen systems. Overpressure and projectiles from an explosion can cause damage and create larger holes in other hydrogen tanks and piping systems, leading to more significant hydrogen leaks. Escalation events could threaten the entire ship, increasing the risk of multiple fatalities. These events may develop rapidly, leaving insufficient time to muster and evacuate the ship.

Indirect effects - Damage to ship safety-critical functions

A fire/explosion event in the fuel supply system, including escalation scenarios, could potentially damage or impair ship safety-critical functions such as life-saving arrangements. The failure of these critical functions when needed could result in multiple fatalities.

Indirect effects - Structural damage to ship

A fire/explosion or overpressure event, including escalation scenarios, could cause severe structural damage to the ship. If hydrogen is released inside confined spaces or semi-congested areas on the open deck, it can form a flammable cloud much faster than other gases. A 'critical cloud' capable of causing significant damage through explosion or deflagration and posing a threat to the ship 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.

3.3.3 Safety barrier modelling

The risk of 'Leakages in the ship's fuel supply piping' is analysed using the bowtie approach, and the threats to, and consequences of, the Top Event is visualized in Figure 3-3 together with preventive and mitigating barriers. The top event is 'Loss of integrity of secondary enclosure'. The threat is 'H2 leakage from fuel supply piping', while the potential consequences may endanger persons, either as direct effects from hydrogen events (fire/explosion) or through indirect effects from ship structural damage or loss of safety-critical functions.

The bowtie is fundamentally similar to the bowtie for 'H2 leakage from piping inside TCE.' However, for this risk analysis, the key difference is that releases from the inner piping goes into a secondary enclosure, commonly known as double-walled piping.

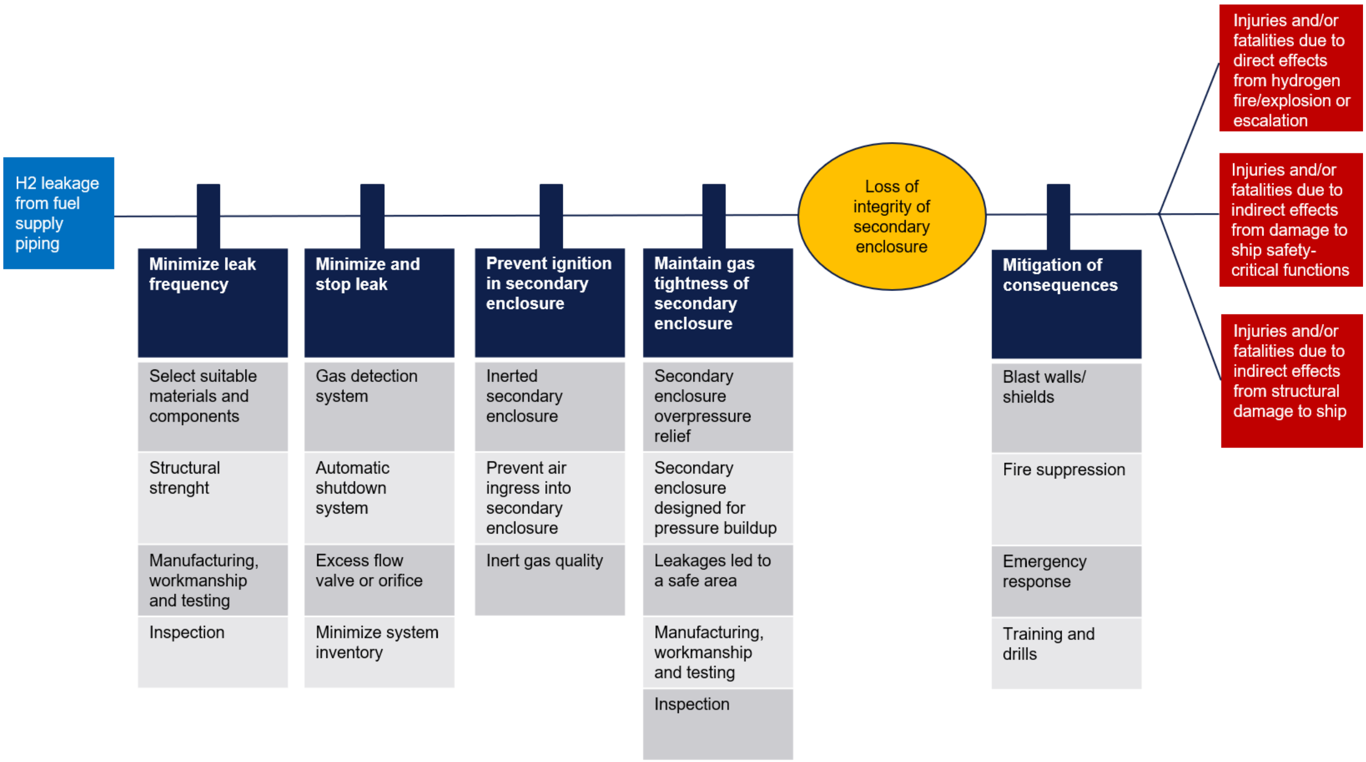

Figure 3-3 Bowtie for risk of leakages in the ship fuel supply piping (Source: DNV).

The barrier functions to protect against the loss of integrity of secondary enclosure are listed in sequential order:

1. Minimize leak frequency,
2. Minimize and stop leak,
3. Prevent ignition in secondary enclosure, and
4. Maintain gas tightness of secondary enclosure.

The first barrier is to **'Minimize leak frequency'**. This barrier function and its elements are fundamentally similar to those outlined in the risk analysis for "Leakages inside tank connection enclosure" discussed in Chapter 3.2.3.

The next barrier function aims to **'Minimize and stop leak'**. This barrier function consists of the following barrier elements:

- **Gas detection system.** A double barrier system will facilitate reliable gas detection in the secondary enclosure. Any leaks from piping systems should be detectable by gas detectors, pressure differential measurements, or both.

- **Automatic shutdown.** 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. The working principles is similar to those outlined in the risk analysis for "Leakages inside tank connection enclosure" discussed in Chapter 3.2.

- **Excess flow valve (EFV) or Restrictive flow orifice (RFO).** EFVs and RFOs would also be relevant for leaks occurring outside the TCE. The working principles is to the same as those outlined in the risk analysis for "Leakages inside tank connection enclosure" discussed in Chapter 3.2.

- **Minimize system inventory**. Piping systems supplying fuel to consumers should be designed to minimize the amount of hydrogen released after a leak has occurred by not using dimensions larger than necessary for proper system functioning and operating pressures higher than needed for sufficient mass flow of hydrogen.

The next safety barrier function is **'Prevent ignition in secondary enclosure**, which includes the following barrier elements:

- **Inerted secondary enclosure**. Inerting involves filling the secondary enclosure with an inert gas, such as nitrogen, that does not support combustion. This significantly reduces the likelihood of hydrogen igniting if a leak occurs. However, similar to TCE, if there is an oxygen concentration level above the LOC in the secondary enclosure, which is undetected (dangerous undetected failure), and a leak occurs, the consequences can be severe due to high ignition probability and subsequent fire and explosion effects. The safety system should ensure that there is always an inert atmosphere during operations. An inert atmosphere monitoring and pressure monitoring system need to be implemented. There needs to be sufficient capacity onboard to inert the secondary enclosure and purge in case of leaks.

  A constant inert gas pressure enables detection of any pressure changes:

  - Inert gas pressure higher than fuel system pressure:
    - Pressure drops to fuel system pressure; this would indicate leakage in inner pipe.
    - Pressure drops to atmospheric pressure; this would indicate leakage in outer pipe.
  - Inert gas pressure lower than fuel system pressure:
    - Pressure rises to fuel system pressure; this would indicate leakage in inner pipe.
    - Pressure dropping to atmospheric pressure; this would indicate leakage in outer pipe.

- **Gas tightness and preventing air ingress into secondary enclosure**. To ensure the integrity of secondary barrier, the same barrier elements listed for the inner pipe should be applied (ref. Chapter 3.2.3).

- **Inert gas quality.** Since hydrogen can ignite with less oxygen than natural gas (5% vs 12%), a hydrogen installation would require stricter specifications for inert gas quality than what is commonly provided for hydrocarbons.

The final safety barrier function is **'Maintain gas tightness of secondary enclosure'**, which includes the following barrier elements:

- **Secondary enclosure overpressure relief.** The secondary enclosure should be arranged with a pressure relief system designed to safely discharge hydrogen in an open-air location.
- **Secondary enclosure designed for pressure buildup.** The secondary enclosure should be designed to withstand the maximum possible pressure buildup during a leakage in the gaseous hydrogen piping.
- **Leakages led to safe area.** After a leak event, where the safety barriers have functioned as intended, the secondary enclosure will contain a hydrogen and inert gas mixture, which need to be vented safely to open air. Sufficient purging capacity will be needed onboard and number of purge cycles to be defined.
- **Manufacturing, workmanship and testing.** A regime ensuring satisfactory manufacturing, workmanship and testing of the piping systems should be ensured.
- **Inspection.** Access for inspection of secondary enclosure should be provided.

If all the preventive barriers fail and there is a loss of integrity of the secondary enclosure, this could constitute a major accident with potential injuries and/or fatalities. Mitigation barriers can reduce the effects of the event to a certain degree, but they cannot completely eliminate the risks. This risk analysis has focused on prevention barriers to ensure that the event does not occur. However, some mitigation strategies are listed below, including but not limited to:

- **Fire suppression systems:** Fire suppression systems to control and extinguish fires rapidly.
- **Emergency response plans:** Implementing comprehensive emergency response plans to ensure quick and efficient action in case of an incident.
- **Training and drills:** Conducting regular training and emergency drills to prepare crew for potential accidents and ensure they know how to respond effectively.

3.4 Risk analysis of fire/explosion affecting fuel storage tanks

The primary focus of the HAZID was on scenarios involving fire or explosion affecting the fuel storage tank (threat) and the potential for fuel storage tank rupture (top event). A hydrogen fuel system subject to an external fire will heat up and may experience a reduction in strength, with subsequent rupture as a result. Hence, this risk analysis covers the hazardous event of onboard fires (threat) and the potential for loss of integrity of the storage tank (top event).

3.4.1 Frequency analysis

The hazard identification study identified that potential fire and explosion threats to the fuel storage tanks and piping could include:

- Fire/explosion originating from hydrogen systems events (hydrogen-initiated events), e.g., hydrogen leak, explosion and/or jet fire. A hydrogen jet fire may impinge on other parts of the hydrogen system, causing an escalation.
- Non-hydrogen-initiated fire events from ship systems/areas. Typical high fire-risk areas are the cargo area, engine rooms, switchboard room, battery storage spaces, etc.

Non-hydrogen-initiated events:

An approximate estimate of the fire frequency for non-hydrogen-initiated events can be derived from the S&P Global Market Intelligence database for ship casualties (formerly IHS Fairplay). The database has records for serious and non-serious casualties for tankers since 1976, and serious incidents have been recorded for other vessel types since 1978 (S&P Global, 2025).

In this frequency calculation, a serious casualty involving the casualty type ‘fire/explosion’ is applied. A serious casualty is where there is structural damage, breakdown or total loss which renders the ship unseaworthy. Furthermore, all types of ships related to tankers, bulkers, dry cargo, passenger vessels, and fishing are included. The total serious incident frequency per ship year involving fire/explosion for this categorization is 9.8E-4, which equals to one event every 1 000 years. The statistics is based on ships using conventional fuels.

Fire/explosion originating from hydrogen systems events (hydrogen-initiated events):

For hydrogen-initiated events, an approximate estimate is performed. Note that the estimate considers the TCE events only, leaving out bunkering and fuel supply events. A ship specific analysis would be needed to assess if ignited leaks from bunkering and fuel supply could also impact the tanks.

By conservatively applying the total leak frequency from the four TCEs (found in Chapter 3.2), we get a value of 9.8E-2, assuming all leaks can cause harm, even minor ones. A reliability analysis of an inert gas system for tank connection spaces was conducted in the EMSA report “Reliability and Safety Analysis” (EMSA, 2024b). It was found that the failure on demand probability (PFD) for a basic inert gas configuration, with no additional redundancy of gas monitoring, was estimated at 1.8E-03, meaning it would fail in every 552 demands.

To obtain the ignited hydrogen leak frequency, the initial leak frequency is multiplied by the PFD. This results in a frequency of 1.8E-4, which equals to one event every 5,600 years. The calculation shows that, due to the safety barrier of inert atmosphere in the TCE and double-walled supply piping, a non-hydrogen-initiated fire in the vicinity of fuel storge tanks is more likely than a hydrogen-initiated fire. Without the inert system, and conservatively assuming ignition upon leakage, the event frequency would increase by three orders of magnitude (based on the success rate of the inert system, which is the inverse of its Probability of Failure on Demand, or PFD).

However, as pointed out previously, there is high uncertainty in the generic failure values for hydrogen leaks, suggesting that the actual frequency could be higher than the calculated values.

Note that while the above calculations gives an approximate frequency estimate sufficient for this “Layer of Protection” type of risk analysis, the event tree for consequence and risk analysis, as produced in the EMSA report “Reliability and Safety Analysis” (EMSA, 2024b), can be applied for Quantitative Risk Analysis (QRAs).

3.4.2 Consequence analysis

Direct effects and potential for escalation

A hydrogen fuel storage tank subjected to severe heat loads may experience a reduction in strength, potentially leading to rupture and subsequent explosion, deflagration, detonation, or fireball. This could lead to multiple fatalities.

There is also a potential for escalation, which could trigger a domino effect, sequentially affecting other tanks and hydrogen systems. Overpressure or projectiles from an explosion can cause damage and create larger holes in other hydrogen tanks and piping systems, leading to more significant hydrogen leaks. Escalation events could threaten the entire ship, increasing the risk of multiple fatalities. These events may develop rapidly, leaving insufficient time to muster and evacuate the ship.

Indirect effects - Damage to ship safety-critical functions

A fire/explosion event in the fuel tanks could potentially damage or impair ship safety-critical functions. The fire may damage the safety systems needed to control the fuel system, preventing it from performing mitigating actions designed to reduce the consequences of the event. The effects of non-functioning ship safety-critical functions, when needed, could lead to multiple fatalities.

Indirect effects - Structural damage to ship

A fire/explosion event in the fuel tanks could cause severe structural damage to the ship. If hydrogen is released inside confined spaces or semi-congested areas on the open deck, it can form a flammable cloud much faster than other gases. A ‘critical cloud’ capable of causing significant damage through explosion or deflagration and posing a threat to the ship 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.

Additionally, it is also important to emphasize that the activation of pressure relief devices, resulting in the release of hydrogen through the vent mast during a severe fire scenario, can also pose a significant hazard, even if the tank maintains its integrity. A large gas cloud would be released from the vent mast and could be ignited by the fires onboard, causing an explosion. Additionally, if hydrogen is discharged through the vent mast and ignited, the resulting jet fire may generate dangerous heat radiation levels.

3.4.3 Safety barrier modelling

The risk of ‘fuel storage tank rupture’ due to heat ingress from fire or explosion is analysed using the bowtie approach, and the threats to, and consequences of, the Top Event is visualized in Figure 3-4 together with preventive and mitigating barriers. The top event is ‘Fuel Storage Tank Rupture. The threat is ‘Fire/explosion affecting fuel storage tank’, while the potential consequences may endanger persons, either as direct effects from hydrogen events (deflagration, detonation, fireball, etc.) or through indirect effects from ship structural damage or loss of safety-critical functions

One barrier not included in the analysis involves fire prevention and protection in high-risk areas, as it does not directly relate to hydrogen systems. The analysis presumes this barrier has already failed, resulting in fire or explosion affecting the fuel storage tank.

It should also be noted that type IV pressure vessels are constructed from composite materials, which are more prone to heat damage than pressure vessels made of steel[6]. Consequently, an arrangement that reduces the pressure in the tank when it is in danger of being engulfed by a fire will be necessary. Thermal Pressure Relief Devices (TPRDs) are commonly used in shore-based industries to discharge the tank contents if temperatures exceeding a certain threshold are detected. This system is designed to safely vent the vessel’s contents before the walls are compromised by heat, thus preventing catastrophic failure. The positioning of fuse sensors is crucial, as there is a risk of fire impingement without the fuse reaching the release temperature.

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[6] Relevant standard is ISO 11119-3:2020 Gas cylinders — Design, construction and testing of refillable composite gas cylinders and tubes Part 3: Fully wrapped fibre reinforced composite gas cylinders and tubes up to 450 l with non-load-sharing metallic or non-metallic liners or without liners.

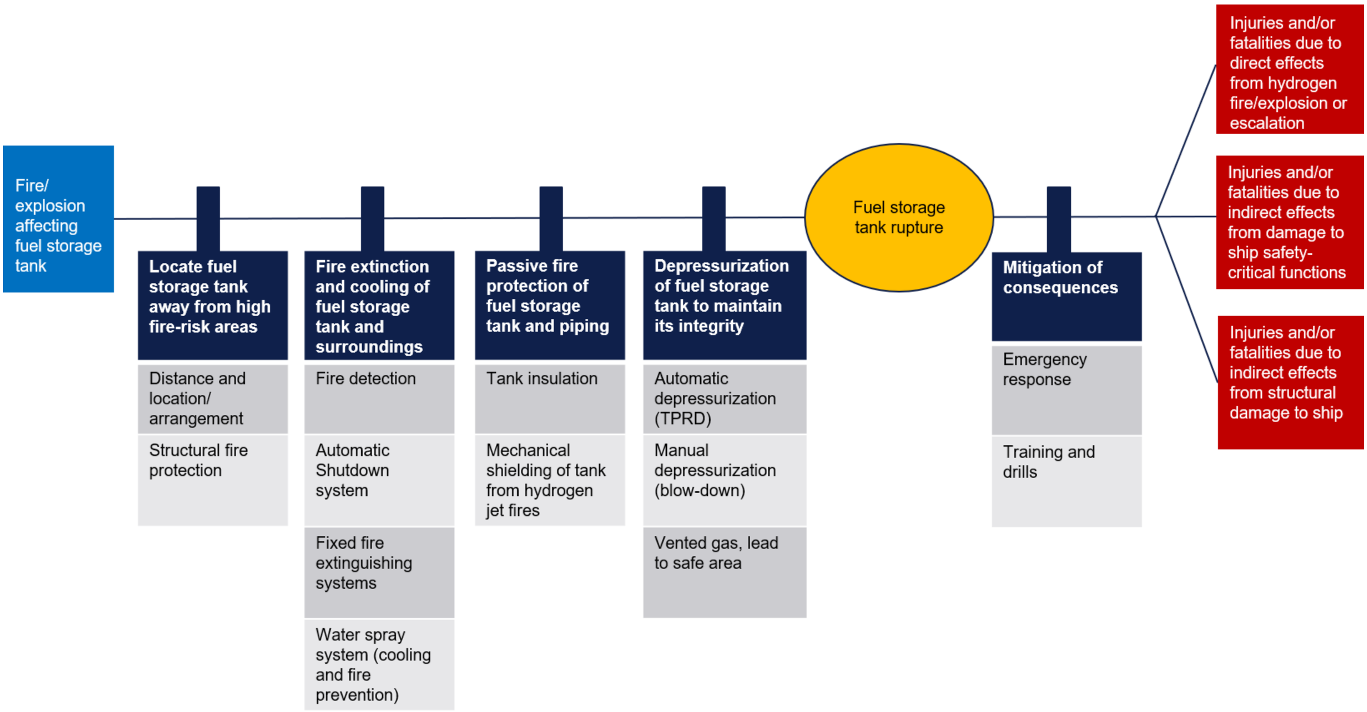

Figure 3-4 Bowtie for risk of fire/explosion affecting fuel storage tanks by heat ingress (Source: DNV).

The barrier functions to protect against fuel storage tank rupture are listed in sequential order:

1. Locate the fuel storage tanks away from high fire-risk areas when designing the ship,
2. Fire extinction and cooling of fuel storage tank and surroundings,
3. Passive fire protection of fuel storage tank and piping, and
4. Depressurization of fuel storage tank to maintain tank integrity.

The first three barrier functions aim to preserve the structural integrity of hydrogen tanks and piping by minimising heat transfer from fires. This reduces the likelihood of the materials weakening and potentially rupturing, and also the likelihood of pressure relief device activation and subsequent hydrogen release. These barriers would also grant extra time for emergency response teams to manage the fire before it can inflict significant damage on the hydrogen storage system. The final barrier function, ‘Depressurization of fuel storage tank to maintain tank integrity’, aims to safely vent the fuel storage tank contents before the tank structure is compromised by heat, and to prevent catastrophic failure. The following sections examine the barrier functions in greater detail.

The first barrier function is to **‘Locate the fuel storage tanks away from high fire-risk areas when designing the ship**’. Generally, the fuel containment systems should be located and arranged to minimize the risk of excessive heat input from a fire. The barrier function consists of the following elements:

- **Distance and location/arrangement.** 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.
- **Structural fire protection.** 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.

The second barrier function is **‘Fire extinction and cooling of fuel storage tank and surroundings’**. The barrier function consists of the following elements:

- **Fire detection.** Fire detection and alarm systems (detection of both hydrogen and non-hydrogen fires). A fire detection system needs to consider the properties of hydrogen flames and use appropriate flame detectors, such as IR detectors (MarHySafe, 2021).
- **Automatic shutdown.** Hydrogen fire extinguishing should be based on the isolation and shut-down of the hydrogen supply to the fire by automatic action by the hydrogen safety system.
- **Fixed fire extinguishing systems.** Fixed fire extinguishing systems on ships are essential safety measures designed to automatically detect and suppress fires.
- **Water spray system** for cooling and fire suppression for exposed parts of fuel storage tanks located on open deck.

Should the two first barrier functions fail, the aim of the third barrier is to protect the tank and piping by passive fire protection. Larger hydrogen jet fires exhibit properties similar to those of natural gas jet fires, although hydrogen jet fires have higher flame temperatures. In the case of smaller fires, the flames are nearly invisible, and a lower fraction of heat is radiated compared to natural gas fires (MarHySafe, 2021).

The barrier function includes the following elements:

- **Tank insulation.** Designed to protect the tanks from the heat and potential damage caused by fires, particularly hydrogen jet fires.
- **Mechanical shielding of tank from hydrogen jet fires.** Separating the hydrogen piping systems from the tanks with a physical barrier helps protect the tank from direct exposure to the flames, reducing the risk of tank rupture or explosion.

The final barrier function to prevent the top event, is the **‘Depressurization’ of the fuel storage tank to maintain its integrity**. Reaching the last barrier indicates that the situation has become severe or critical onboard. This barrier function includes the following elements:

- **Automatic depressurization system.** 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 vessel’s 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. The positioning of fuse sensors is crucial, as there is a risk of pressure vessel impingement from jet fire without the fuse reaching the opening threshold.
- **Manual depressurization system (controlled blow-down).** Due to the possible reliability issues with TPRDs, a back-up manual remote depressurisation system should be considered, able to perform a controlled blow-down through the fuel line to the vent mast. With lower pressure, the tanks will last longer (reduced pressure increases survivability). It must be ensured that the controlled blow-down option is not affected by any safety shut-down functions.
- **Vent system** should be dimensioned for automatic and manual depressurization scenarios.

If all the preventive barriers fail and there is a fuel storage tank rupture, this could constitute a major accident with potential injuries and/or fatalities. Mitigation barriers can reduce the effects of the event to a certain degree, but they cannot completely eliminate the risks. This risk analysis has focused on prevention barriers to ensure that the event does not occur. However, some mitigation strategies are listed below, including but not limited to:

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

- **Training and drills:** Conducting regular training and emergency drills to prepare crew for potential accidents and ensure they know how to respond effectively.

4. Risk analysis of liquefied hydrogen (LH2) fuel systems

This chapter presents the risk analysis of the liquefied hydrogen (LH2) fuel system with vacuum-insulated IMO Type C tanks, tank connection space (TCS) and piping systems protected by secondary enclosures as selected in Chapter 2.1.

The following risk scenarios are covered:

- Leakages inside tank connection space (Chapter 4.2)
- Loss of vacuum insulation for the tank (Chapter 0)

4.1 Analysis basis

The fuel system concept selected comprises an LH2 fuel tank with Tank Connection Space (TCS), where liquefied and gaseous fuel piping are protected by secondary enclosures. The tank is located below the deck, surrounded by a dedicated Fuel Storage Hold Space (FSHS). A flow diagram illustrating this concept is shown in Figure 4-1.

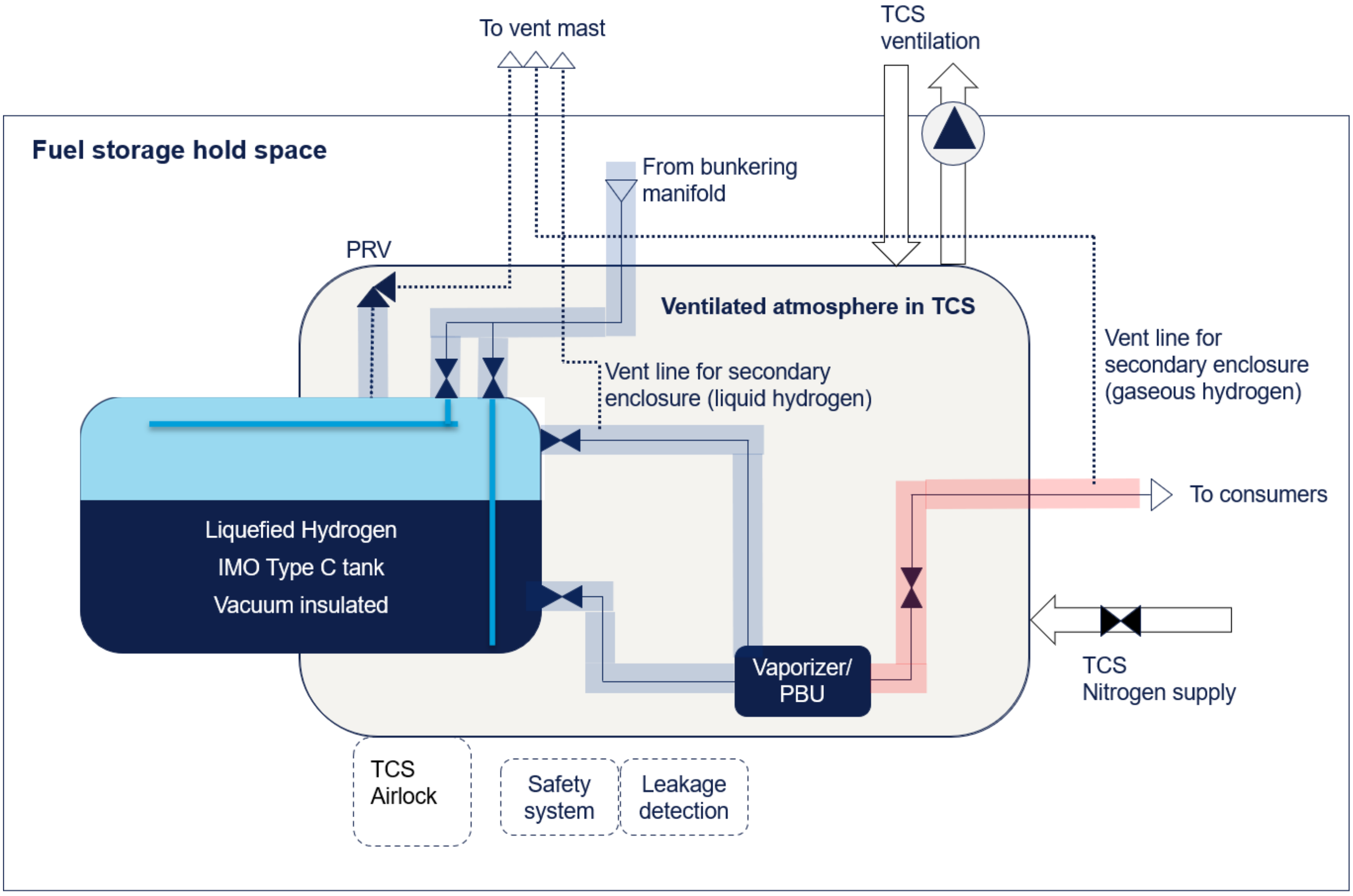

Figure 4-1 Flow diagram of the LH2 fuel system with TCS arranged with secondary enclosure for liquefied and gaseous piping, and ventilated atmosphere in TCS (Source: DNV).

The concept is assumed to have the following features:

- Hydrogen will be stored onboard in a vacuum-insulated pressure vessel designed in accordance with requirements for an IMO Type C fuel tank.
- The tank is located in a dedicated fuel storage hold space.
- The piping connecting the inner tank to the piping system in the TCS is routed through the outer tank (vacuum space). The piping is protected by a secondary enclosure. All tank connections are arranged in a dedicated TCS.
- The fuel system is designed with secondary barriers around all leak sources, i.e. around piping and piping components inside the TCS and from the TCS to consumers and the bunkering station.
- Design pressure of the fuel containment system is 10 bar.
- The TCS is arranged with:
    - Leak detection.
    - Vaporizer/pressure build-up unit (PBU).
    - Inlets and outlets for mechanical ventilation.
    - Instruments (pressure and temperature)
    - Airlock access

4.2 Risk analysis of leakages inside the tank connection space

The primary focus of the HAZID was on scenarios involving hydrogen leakage within the fuel system and their potential to induce flammable and cryogenic effects. In case of leakages from the piping inside the TCS, the hydrogen may ignite, causing fire or explosion. Further, a hydrogen leakage may cause over pressurization of the space. Leakages of liquefied hydrogen would generate rapid pressure build-up as LH2 expands 850 times in the transition from liquid to vapour. Additionally, the cooling effect inside the TCS would be significant. Both scenarios have the potential for structural damage and loss of integrity of the TCS.

Hence, this risk analysis covers the hazardous event of leakages from piping inside the TCS (threat) and the potential for loss of integrity of TCS due to fire/explosion or overpressure (top event).

4.2.1 Frequency analysis

Leakages could occur from pipes, pipe connections or components in liquefied or gaseous piping. The underlying causes could typically be design errors, fabrication or installation and mounting errors, corrosion, operating conditions (e.g. vibrations) or operating outside design limits. In addition, leaks could occur due to external impacts, which is considered less likely for this case since the piping components will be protected inside a TCS.

To give an indication about the leak frequency from piping inside the TCS, the following generic equipment types and number of equipment are assumed:

- **Valves (5):** Tank valves and valve downstream vaporizer.
- **Pipes (10m):** Liquid and gaseous piping.
- **Instruments (5):** Pressure and temperature transmitters

- **Vaporizer (1):** The component type ‘vaporizer’ was applied since this is usually the generic term used to describe any device that converts a liquid into a vapor.
- **Flange (10):** Two flanges per valve is assumed.

Table 4-1 shows the total leak frequency for the TCS, calculated by multiplying the number of equipment by their generic leak frequencies (failure rates) and summing the results. This results in a total leak frequency of 1.5 per year, regardless of leak size. The major contributor for the leak frequency is the vaporizer, with a share of 84%.

Note that there is high uncertainty in the generic failure values, which are derived from generic industry databases primarily focused on the oil, gas, and chemical industries. Consequently, maritime and hydrogen-specific factors are not adequately considered, suggesting that the actual frequency could be even higher than the calculated values in the Table 4-1.

Table 4-1 Estimated annual leak frequency from TCS, per hole size category (Source: DNV).

Hole size (% of equipment size)	Total leak frequency	Share (%)
0.01%	2.3E-01	14.9 %
0.1%	5.2E-02	3.4 %
1 %	8.7E-02	5.8 %
10 %	2.7E-01	17.9 %
100 %	8.8E-01	58.1 %
Total	1.5	100 %

4.2.2 Consequence analysis

Direct effects and potential for escalation

If a leak is ignited inside the TCS, the consequence may be a jet fire if there is immediate ignition, or a deflagration or detonation if there is delayed ignition. A deflagration or detonation is a major concern due to its higher damage potential from overpressure effects. An explosion inside the TCS would likely compromise the structural integrity of the TCS, potentially impacting nearby individuals and safety-critical systems, and allow leaking gas to escape to other parts of the vessel. The initial effects of such an event could range from injuries to fatalities.

There is also a potential for escalation. The initial explosion may damage the TCS, piping systems and systems designed to isolate the leakage (valve actuators etc). 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.

Indirect effects - Damage to ship safety-critical functions

A fire/explosion event in the TCS could potentially damage or impair ship safety-critical functions. The failure of these critical functions when needed could result in multiple fatalities.

Indirect effects - Structural damage to ship

A fire/explosion event in the TCS could cause severe structural damage to the ship. Hydrogen can form a flammable cloud much faster than other gases. A ‘critical cloud’ capable of causing significant damage through explosion or deflagration and posing a threat to the ship 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.

4.2.3 Safety barrier modelling

The risk of ‘leakages inside the Tank Connection Space’ is analysed applying the bowtie approach and the threats to, and consequences of, the Top Event is visualized in Figure 4-2. The top event is ‘Loss of integrity of TCS due to fire/ explosion or overpressure. The threat is ‘LH2 or CH2 leakage from piping inside TCS’, while the potential consequences may endanger safety-critical functions, persons, and the ship.

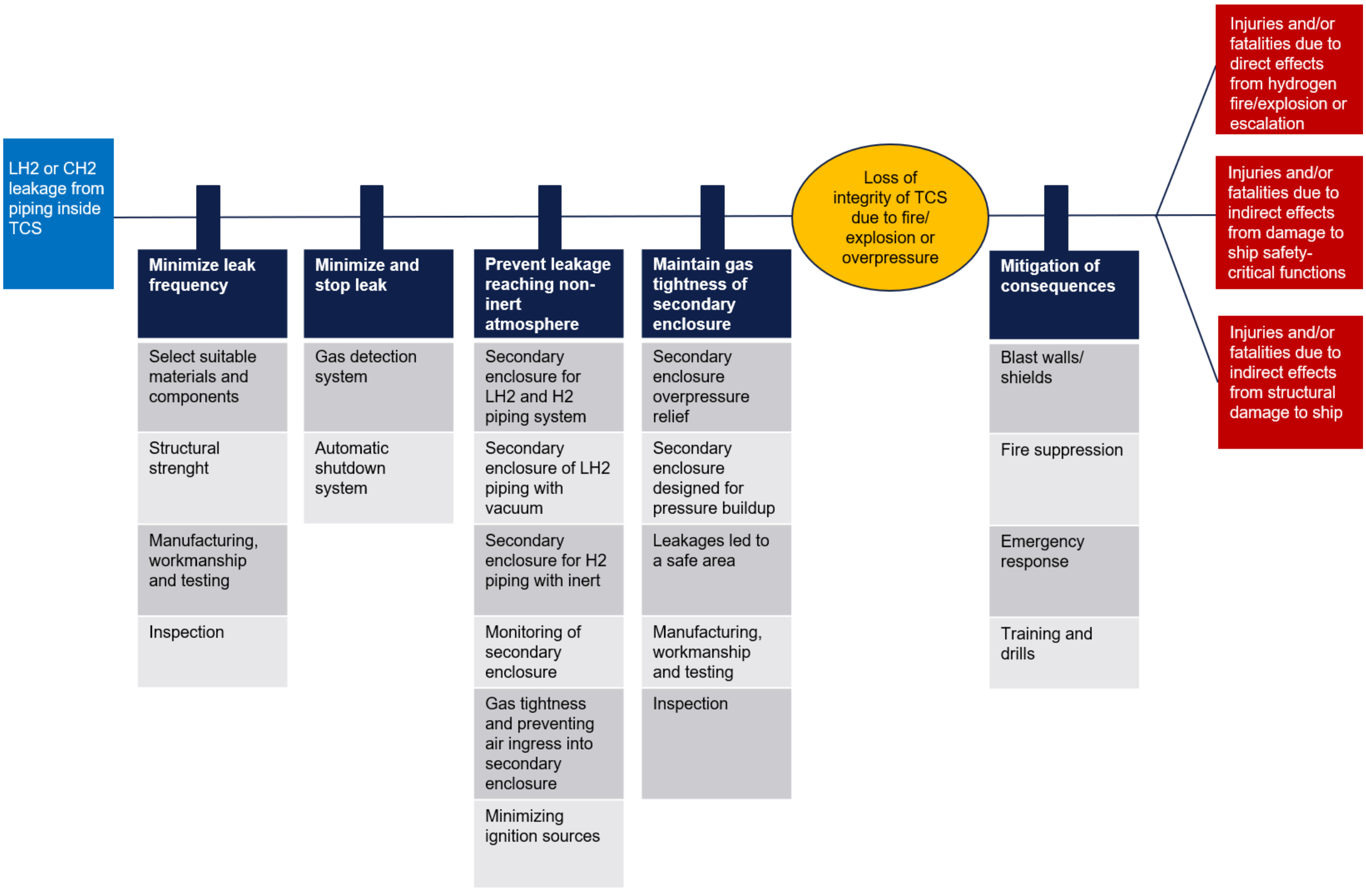

Figure 4-2 Bowtie for risk of leakages inside TCS in LH2 fuel system. (Source: DNV).

The preventive barrier functions to protect against the loss of integrity of TCS due to fire, explosion or overpressure are listed in sequential order:

1. Minimize leak frequency,
2. Minimize and stop leak,
3. Prevent leakage reaching non-inert atmosphere, and
4. Maintain gas tightness of secondary enclosure.

The structure of the preventive barriers is similar to the CH2 case, which involves leakages within the TCE as described in Chapter 3.2. The key difference here is the presence of a secondary enclosure (double-walled piping) within the TCS. All four of the preventive barrier functions aim to prevent hydrogen from leaking into the TCS, thereby preventing the possibility of ignition and a following deflagration/detonation inside the TCS.

The first barrier function aims to **‘Minimize leak frequency’**. This barrier function consists of the following elements:

- **Selection of suitable materials and components:**
    - **Avoid leak-prone components.** The use of leak-prone components and couplings should be minimized when designing hydrogen systems. Hydrogen piping systems should, as far as practicable, be joined by welding.
    - **Suitable materials.** All fuel system parts should be constructed from materials suitable for hydrogen, considering the design temperature, design pressure, working stress levels and environmental conditions. Typical properties, including yield stress, tensile strength, ductility, fracture toughness, fatigue properties, hydrogen permeation properties, and corrosion resistance, should be considered.
- **Structural strength.** The fuel systems structural strength should be assessed against failure modes, including, but not limited to, plastic deformation, buckling, and fatigue. This should be confirmed by carrying out stress and fatigue analyses of all relevant loads, including operational loads, accidental loads, and internal pressure.
- **Manufacturing, workmanship and testing.** This would include measures such as putting strict requirements on piping fabrication and joining detail requirements, tolerances, welding procedures, post-weld heat treatment and Non-Destructive Testing (NDT) requirements, pressure testing etc.
- **Inspection:** Access for the inspection of the gas fuel system should be provided.

The second barrier function is to **‘Minimize and stop leak’**. This barrier function consists of the following barrier elements:

- **Leakage detection system.** It is essential to detect and stop leaks as early as possible to limit their consequences as far as possible. As pointed out in Chapter 3.2.2, the cloud build-up time for hydrogen leaks is extremely short compared to other gases.
- **Automatic shutdown system.** The gas detection system described above should trigger a safety system that automatically shuts down the hydrogen flow. The detection and shut-down safety function utilizes three subsystems:
    - **Sensor subsystem** (Gas detection system) – Gas detectors detect a leakage and produce an electrical signal that is sent to the logic solver.
    - **Logic solver subsystem** - detects that the electrical signal exceeds a given threshold and sends a signal to the final element subsystem.
    - **Final element subsystem** - performs the safety function by closing the tank valve(s). The gas supply from each individual tank (pressure vessel) is remotely controlled by a pneumatically actuated tank valve, acting as the final element subsystem to shut down flow in case of leak.

The third barrier function aims to **‘Prevent leakage reaching non-inert atmosphere**, and consists of the following barrier elements:

- **Secondary enclosure for liquid and gaseous piping.**
    - The piping system for liquefied hydrogen should be arranged with a secondary enclosure to prevent hydrogen leaks from dispersing to the surroundings. The secondary enclosure should be designed to safely contain any leakages. To limit the probability of leaked hydrogen igniting in the secondary enclosure, it should be protected with a vacuum atmosphere (the low boiling temperature of liquefied hydrogen prevents the use of nitrogen as an inert gas)

  - The piping system for gaseous hydrogen should be arranged with a secondary enclosure to prevent hydrogen leaks from dispersing to the surroundings. The secondary enclosure should be designed to safely contain any leakages. To limit the probability of leaked hydrogen igniting in the secondary enclosure, it should be protected with an inert atmosphere at all times.

The vacuum/inert atmosphere in the secondary enclosure should be monitored.

- **Preventing air ingress into secondary enclosure**. To ensure the integrity of the secondary barrier, the same barrier elements listed under the first barrier function for the inner pipe should be applied.

- **Inert gas quality.** Since hydrogen can ignite with less oxygen than natural gas (5% vs 12%), a hydrogen installation would have stricter requirements for inert gas quality than what is commonly provided for hydrocarbons.

- **Minimizing ignition sources.** Electrical equipment inside the secondary enclosure should be avoided as far as possible. If such equipment is needed to perform essential safety functions, it should be certified for safe operation in a hydrogen atmosphere. The secondary enclosure should be classified as Hazardous Zone 1.

The fourth barrier function, to prevent the top event from occurring, is **'Maintain gas tightness of secondary enclosure**. This barrier function consists of the following barrier elements:

- **Secondary enclosure overpressure relief**. The secondary enclosure should be arranged with a pressure relief system designed to prevent overstressing the enclosure.

- **Secondary enclosure designed for pressure build up.** The secondary enclosure should be designed to withstand the maximum possible pressure buildup during a leakage in the hydrogen piping.

- **Leakages led to safe area.** The overpressure relief system protecting the secondary enclosures should vent the hydrogen to a safe area in open air.

Manufacturing, workmanship and testing. A regime ensuring satisfactory manufacturing, workmanship and testing of the piping systems and their secondary enclosures should be ensured. If all the preventive barriers fail and there is a loss of integrity of the TCS due to fire, explosion, or overpressure, this could constitute a major accident with potential injuries and/or fatalities. Mitigation barriers may reduce the effects of the event to a certain degree, but the ship safety depends on the preventive barriers.

This risk analysis has focused on prevention barriers to ensure that the event does not occur. However, some mitigation strategies are listed below, including but not limited to:

- **Blast walls and shields:** Using blast walls and shields to protect persons and critical spaces and systems from explosions.

- **Fire suppression systems:** Fire suppression systems to control and extinguish fires rapidly.

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

- **Training and drills:** Conducting regular training and emergency drills to prepare crew for potential accidents and ensure they know how to respond effectively.

4.3 Risk analysis of loss of vacuum insulation for tank

The HAZID addressed the loss of vacuum insulation on LH2 tanks or LH2 piping systems. Liquefied hydrogen is stored at a temperature of -253 °C. If the storage tank vacuum insulation is lost, heat from the surroundings would reach the inner tank, causing the hydrogen to warm up quickly. As the hydrogen warms, it will boil off, increasing the pressure inside the tank. When the pressure reaches the safety valve set point, the tank content will be discharged at the vent mast to prevent over-pressurization. The spaces and ship structures surrounding the tank will experience low temperatures. Moist air in the fuel storage hold space can condense on the tank's surface, leading to ice formation. An additional safety concern with cryogenically stored hydrogen is that all gases (except helium) will condense and solidify in contact with it. Surfaces not properly insulated can be cooled to below the normal boiling point of oxygen (-183°C), thus condensing the air around it. This condensed air will be enriched with oxygen and can significantly increase the flammability of any organic materials it comes into contact with or embrittle materials.

To investigate this scenario further, this risk analysis covers the hazardous event of leakages in the inner tank, outer tank, or piping in the vacuum space (threat) and their potential to cause loss of vacuum insulation for the LH2 fuel tank (top event).

4.3.1 **Frequency analysis**

This risk was described in “Mapping Safety Risks for Hydrogen-Fuelled Ships” (EMSA, 2024a). It was concluded that the possibility of a vacuum loss cannot be excluded. Currently, there are no available generic failure rates for vacuum loss in such systems. To obtain a specific failure rate for this safety-critical system, suitable for quantitative risk analysis, a dedicated reliability analysis for loss of vacuum insulation for LH2 fuel tanks would be required.

4.3.2 **Consequence analysis**

There are several potential consequences in the event of loss of vacuum insulation for the LH2 fuel tank, and these consequences may happen simultaneously:

- When the vacuum insulation is compromised, the tank's pressure will rapidly increase due to the excessive boiling of the liquid hydrogen. The tank pressure will almost immediately exceed the opening pressure of the safety valves, and the boil-off will be discharged through the vent mast. This process will continue until the tank is empty. The continuous hydrogen venting through the vent mast to the open deck could ignite and cause a deflagration or detonation. The hydrogen will likely continue to burn as jet fire from the vent mast outlet.

- An additional effect of the loss of vacuum insulation is that the surface of the outer tank, which is normally at ambient temperature, drops to a temperature closer to the hydrogen inside. This will have a significant cooling effect on the surrounding spaces (TCS and FSHS). Therefore, the following consequences must be avoided:

    - Loss of structural integrity of surrounding spaces such as FSHS or TCS due to low-temperature embrittlement caused by extremely cold ambient temperatures.

    - Air condensation on the tank surface and impinging on ship structures, causing local damage.

    - Severe under pressure due to air condensation causing structural failure in surrounding spaces (FSHS).

    - Safety systems not functioning due to low ambient temperatures.

4.3.3 Safety barrier modelling

The risk is analysed using the bowtie approach, and the threats to, and consequences of, the top event are visualized in Figure 4-3.

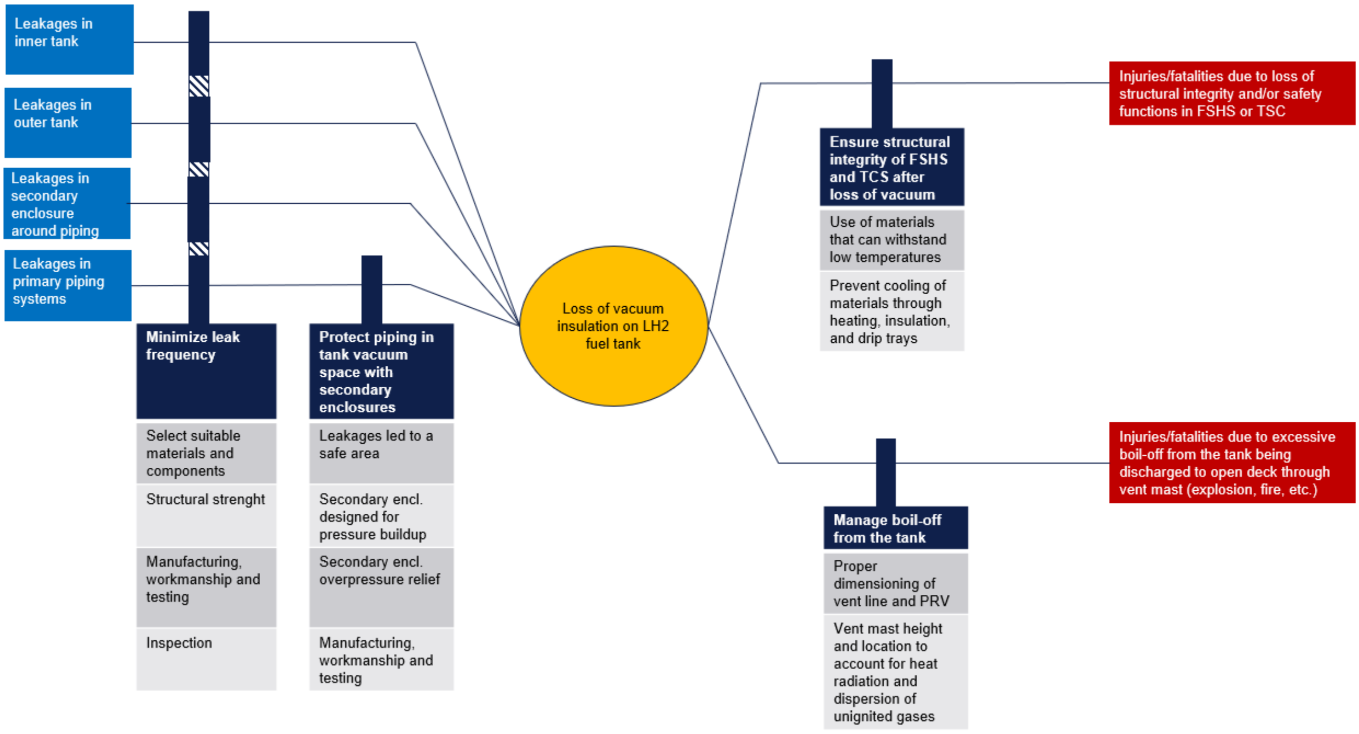

Figure 4-3 Bowtie for risk of loss of vacuum insulation on LH2 fuel tank (Source: DNV).

The top event is ‘Loss of vacuum insulation on LH2 fuel tank.’ The threats with the potential to initiate the top event are:

- Leakages in inner tank.
- Leakages in outer tank.
- Leakages in primary piping systems connecting the inner tank to the piping system in the TCS routed through the outer tank (vacuum space).
- Leakages in secondary enclosure around piping connecting the inner tank to the piping system in the TCS routed through the outer tank (vacuum space).

The consequences are related to increased boil-off in the tanks, which leads to the release of large volumes of hydrogen gas on deck (the whole tank content) and the effects of the tank surface becoming very cold.

The primary barrier function protects against the ‘top event’ by **'minimising leak frequency’**. This is the only barrier function applicable for leakages in inner tank, outer tank or secondary enclosure around piping. When only one barrier function is in place to prevent a top event, it indicates a single line of defence against its occurrence. This can render the system vulnerable; if that one barrier function fails, no additional safeguards exist to prevent the top event. The barrier function comprises several barrier elements, which together enhance its effectiveness.

These elements include:

- **Selection of suitable materials and components:**
    - **Avoid leak-prone components.** The use of components and couplings that are prone to leaks should be minimised when designing hydrogen piping systems. Hydrogen piping systems should be joined by welding wherever practicable.

    - **Suitable materials.** The fuel tank and piping systems must be made from materials suitable for hydrogen, taking into account the design temperature, design pressure, working stress levels, and environmental conditions. Typical properties should be evaluated, including yield stress, tensile strength, ductility, fracture toughness, fatigue characteristics, hydrogen permeation resistance, and corrosion resistance.

- **Structural strength.** The fuel tank and piping system's structural strength should be evaluated against potential failure modes, including, but not limited to, plastic deformation, buckling, and fatigue. This should be verified by conducting stress and fatigue analyses of all pertinent loads, including operational and accidental loads and internal pressure.

- **Manufacturing, workmanship and testing.** This would include measures such as imposing strict requirements on tank and piping fabrication and joining details, tolerances, welding procedures, post-weld heat treatment, Non-Destructive Testing (NDT), pressure testing, and so forth.

- **Inspection:** Access to the fuel tank system for inspection should be provided.

One more preventive barrier function is applicable specifically to the threat of 'Leakages in primary piping systems'. This function protects against hydrogen leakages into the vacuum space by **adding a secondary enclosure around the piping routed through the vacuum space**. The barrier function includes the following essential elements:

- **Leakages led to safe area.** After a leak event, the secondary enclosure will contain a mix of hydrogen and inert gas, which need to be vented safely to open air.

- **Secondary enclosure designed for pressure build up.** The secondary enclosure should be designed to withstand the maximum possible pressure buildup during a leakage.

- **Secondary enclosure overpressure relief**. The secondary enclosure should have pressure relief to vent mast.

- **Manufacturing, workmanship and testing.** A regime ensuring satisfactory manufacturing, workmanship and testing of the piping systems and their secondary enclosures should be ensured.

Should all preventive measures fail and the vacuum insulation of the LH2 fuel tank be compromised, this critical event could result in a rapid and excessive boil-off from the tank, discharged onto the open deck via the vent mast. The barrier function designed to address this event is **'Manage boil-off from the tank'**, which primarily focuses on:

- **Proper dimensioning of vent line and PRV.** The design and capacity of the pressure relief arrangements should be suitable for situations in which LH2 containment systems lose their insulation properties.

- **Vent mast height and location to account for heat radiation and dispersion of unignited gas.** If hydrogen discharged to the open deck is ignited, **the consequences for the ship with respect to pressure effects and heat load should be manageable**. This includes scenarios with flash fire, jet fire, and deflagrations. Deflagration-to-detonation and detonation should be avoided by design. Manageable implies that heat loads and pressure shocks should be at a level that allows people to evacuate the area without injuries and that access to muster stations, escape routes, and life-saving appliances is not restricted.

  Calculations estimating maximum boil-off rates and the consequences of delayed ignition and a subsequent jet fire from the top of the vent mast must likely be performed on a case-by-case basis.

A loss of tank vacuum may also compromise the structural integrity and safety functions of surrounding areas such as FSHS and TCS. Managing the resulting cooling of the surroundings should be within the ship's design capabilities. The cooling of surrounding structures and equipment could be a result of:

- Direct contact with the outer tank.
- If the vacuum is lost, the temperature in the spaces surrounding the tank will drop. This also applies to spaces surrounding the tank vent line routed from the tank PRV to the vent mast. The effect of the vacuum loss will likely have to be calculated on a case-by-case basis.
- If the vacuum is lost, the surface temperature of the tank and the tank vent system may fall below the condensation temperature of the gases in the air. Condensed air may drip onto structures below, cooling them to below their brittle transition temperature.

To address this risk, the mitigation barrier function ‘**Ensure structural integrity of FSHS and TCS after loss of vacuum’** has been implemented. This barrier function comprises two key elements: selecting materials that can withstand the lowest temperatures that may arise from a tank vacuum loss and preventing the structures from cooling below their transition temperature.

- **Use of materials that can withstand low temperatures** – Materials in direct contact with the tank’s outer shell, such as the structure of the TCS (which is welded to the tank's outer shell) and the tank supports, should be made from a material that remains ductile at the relevant temperatures.

- **Prevent cooling of materials through heating, insulation and drip trays -** Heat balance calculations must likely be performed on a case-by-case basis to evaluate the vacuum loss thermal effects on fuel storage hold space, TCS and tank vent line surroundings. Inerted spaces without air circulation would likely become colder than mechanically ventilated spaces. Mitigating design measures may include mechanical ventilation to warm the space, insulation to prevent the cooling of critical structures, and drip trays to collect condensed air, thereby preventing contact with ship structures.

5. Conclusion

This study has focused on a 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. The aim has been to offer insights and recommendations for enhancing the reliability and safety of hydrogen technologies and to contribute to the wider goal of developing a Guidance document concerning ships utilising hydrogen as fuel. With respect to the further drafting of a Guidance document, we draw the following conclusions from the findings in this report:

1. The likelihood of hydrogen leakages from piping systems cannot be excluded, meaning that ships using hydrogen as fuel should be built to safely handle such leaks.

Providing secondary enclosures filled with inert gas around the primary piping systems for gaseous hydrogen will:

- Significantly reduce the risk of ignition after a hydrogen leakage.
- Enhance gas detection, enabling a dependable and quick-acting shutdown system.
- Enable purging of the secondary enclosure and routing of leaked hydrogen to a safe area in the event of leaks from the primary piping.

Providing secondary enclosures with a vacuum around the primary piping systems for liquefied hydrogen will:

- Prevent rapid pressure build-up in the TCS and reduce excessive cooling of the TCS after a hydrogen leak, enabling more rapid detection of leaks.
- Significantly reduce the risk of ignition in confined spaces after a leakage by preventing the hydrogen from reaching the TCS. The secondary enclosures are arranged with a vacuum, which prevents the ignition of hydrogen in these spaces.
- Enable the purging and routing of leaked hydrogen to a safe area in the event of leaks from the inner piping.

Guidance for the design and construction of secondary enclosures can be formulated as prescriptive requirements in a Guidance document based on the safety barrier modelling in this report.

2. The likelihood of loss of tank vacuum insulation cannot be excluded, meaning that ships using liquefied hydrogen as fuel should be built to safely handle loss of tank vacuum insulation.

A loss of vacuum insulation will cause a rapid boil-off of the hydrogen in the tank with a corresponding discharge of hydrogen through the vent mast on the open deck. The consequences of igniting the boil-off gas should be evaluated on a case-by-case basis.

A loss of vacuum insulation will lead to a substantial cooling of the tank's surroundings. The consequences should be assessed on a case-by-case basis.

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