European Maritime Safety Agency

MAPPING SAFETY RISKS FOR HYDROGEN-FUELLED SHIPS

STUDY INVESTIGATING THE SAFETY OF HYDROGEN AS FUEL ON SHIPS

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Document History

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1.0	21/06/2024	N/A	DNV	EMSA
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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 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 assist the industry and the regulators towards a safe and harmonised deployment of this relevant technology that could demonstrate an important step towards decarbonisation of the sector.

This report analyses hydrogen’s main characteristics to frame which safety hazards, system threats and risks to be considered and mitigated when using hydrogen as ship fuel. Natural gas – for which the IGF Code has put internationally recognised safety barriers in place to ensure its safe use – is used as a benchmark. Established principles for mitigation and control, and lessons learned from hydrogen accidents are briefly reviewed. Hydrogen modelling techniques and tools are validated. Statutory regulations and classification rules, standards, and best practices relevant to hydrogen-fuelled ships are reviewed to identify hazards and risks considered and mitigated in existing rules and regulations.

The aim of this first task in the project is to gather input for drawing up a preliminary table of contents and to establish preliminary goals and functional requirements for a Guidance document for ships using hydrogen as fuel - a live document that will be presented at the end of the project.

Executive summary

This report is developed as a part of the project “EMSA study investigating the safety of hydrogen as fuel on ships”. The project's overall objective is to 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 assist the industry and the regulators towards a safe and harmonised deployment of this relevant technology that could demonstrate an important step towards decarbonisation of the sector. This report is the result of the first part of the study.

The International Maritime Organization (IMO) updated its greenhouse gas (GHG) strategy in 2023 with a goal of achieving net-zero emissions by 2050. Together with new EU regulations, this will be 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 MSC.1/Circ.1394 and draws upon comprehensive risk assessment and reliability analysis.

What we did:

This report analyses hydrogen’s main characteristics to frame which safety hazards, system threats and risks to be considered and mitigated when using hydrogen as ship fuel. Natural gas[2] – for which the IGF Code has put internationally recognised safety barriers in place to ensure its safe use – is used as a benchmark. Established principles for mitigation and control, and lessons learned from hydrogen accidents are briefly reviewed. Hydrogen modelling techniques and tools are validated. Statutory regulations and classification rules, standards, and best practices relevant to hydrogen-fuelled ships are reviewed to identify hazards and risks considered and mitigated in existing rules and regulations.

Based on the above, this first task in the project aims to draw up a preliminary table of contents and to establish preliminary goals and functional requirements for a Guidance document for ships using hydrogen as fuel.

What we found:

Hydrogen safety hazards, threats, and risks

The primary safety hazard associated with using hydrogen as a fuel on a ship is related to the high flammability properties, which exceed those of natural gas. This is because hydrogen has a much wider flammability range and a significantly lower minimum ignition energy than methane. It is also important to note that hydrogen has a higher burning velocity than methane. This means that explosions caused by hydrogen can be more severe than natural gas explosions and may even transition into detonation. The low boiling point of hydrogen poses additional safety concerns for storage and distribution. This includes managing boil-off gas and preventing the condensation and solidification of gases with higher boiling points. Air contaminations in a liquefied hydrogen (LH2) system will solidify as nitrogen, oxygen, and frozen water. These contaminants can cause obstructions in piping or instruments, causing equipment malfunction, and presenting a possible explosion hazard when systems are heated up and the oxygen-enriched air evaporates.

Due to its low density, hydrogen gas will tend to rise and disperse in an open environment. Directional effects of high-pressure releases and releases of cryogenic hydrogen may complicate this picture. In confined spaces, hydrogen can accumulate in high spots and reach ignition sources, such as ceiling lights. Accounting for the density of any released gas is important for the proper design of many safety barriers. Examples are the location of gas detectors, the arrangement of ventilation systems, and the geometrical shape of spaces where gas leaks may occur, all of which need to account for the density of the leaking gas.

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[2] Natural gas fuel in the context of the IGF Code is either in its liquefied (LNG) or gaseous state (NG). Its composition varies, but the primary component is methane.

Damage to fuel containment systems and, to a lesser extent, piping systems has the potential to release all the hydrogen stored onboard, which would be a catastrophic event. Consequently, it is of the utmost importance that storage and distribution systems for hydrogen fuel are sufficiently protected against external events that have the potential to damage them.

When hydrogen is compressed to high storage pressures (250-700 bar), it gains significant potential energy like any other gas. Releasing this energy can cause strong pressure effects depending on the release rate, even without combustion. Sudden hydrogen releases from high-pressure hydrogen systems are also known to ignite spontaneously without any apparent ignition sources.

Hydrogen releases in confined spaces are particularly dangerous because the explosion pressure builds up rapidly after ignition, leading to potential structural damage, an increased risk of further hydrogen leakage, and the destruction of safety barriers. Leakages of LH2 in enclosed spaces will have significant cooling effects, with potential consequences for gas-tight integrity and the function of the safety equipment inside.

Upon vacuum insulation loss, or when discharging large volumes of cold gas through the vent system, the external surfaces of the LH2 containment may be cold enough to liquefy the oxygen and nitrogen in the air. Condensed air reaching ship steel and cooling of spaces could rapidly result in structural damages from low-temperature embrittlement. When air is condensed, oxygen condenses faster than nitrogen. Oxygen-enriched liquefied air increases the flammability of materials it comes into contact with.

Hydrogen can significantly degrade the mechanical properties of metals, a phenomenon known as hydrogen embrittlement.

Significant hydrogen leakages can cause asphyxiation due to oxygen depletion. Additionally, low surface temperatures and reduced flame visibility are risk factors that must be mitigated to prevent frostbites and burn injuries.

Established principles for mitigation and control of hydrogen hazards

Our review of established principles for mitigation and control highlights the greater effectiveness of technical measures over operational measures. The general principles, guidelines, and recommended practices established from knowledge acquired in other industries are vital for safely handling hydrogen. There are, however, principal differences to be considered when hydrogen technologies are moved from shore to ships. This relates to a number of conditions, including the autonomy of ships operating in the open seas, space constraints and environmental conditions. Therefore, not all land-based solutions and safety principles, such as separation distances and keeping all leakage sources in the open air, are possible to apply to ships using hydrogen as fuel.

Lessons learned from hydrogen-related accidents

Reviewing accident databases shows that hydrogen-related accidents happen. From the 575 accidents analysed in the HIAD 2.0 database, the leading causes of hydrogen-related accidents fall into two categories: system design error and failure, and human error. A combination of both was also a cause of accidents with severe consequences. The largest number of cases were linked to safety management system factors (49%). The second largest cause was errors in the material or manufacturing (35%). Many of the incidents were caused by individual human errors (29%) and system design errors (27%).

Nearly half of the incidents in the HIAD 2.0 database were related to human and organisational errors. Therefore, training the operating personnel and increasing their understanding of hydrogen hazards will be crucial to preventing future hydrogen-related incidents. Similarly, the safety management systems must properly account for hydrogen hazards in operating procedures, inspection plans and emergency response procedures.

Validation of modelling techniques and tools

In evaluating consequence scenarios involving gas leaks, ventilation, dispersion, and explosions, commercial CFD models are used to simulate these phenomena with sufficient precision. Specifically, these models can effectively capture the behaviour of hydrogen up to the point of deflagration. However, it is important to note that there is typically less validation available for hydrogen than natural gas or methane and that certain consequence types have not undergone validation. However, this does not inherently render the tools unusable. Nonetheless, careful consideration must be given to the execution of the analysis where there is limited or no validation.

While hydrogen-specific models exist for calculating leak frequency and ignition probabilities, failure data and validation are lacking to ensure their accuracy in quantitative risk analysis. Therefore, this area often has the highest uncertainty in the risk models.

Review of existing regulations and standards

We find that the existing safety barriers in the IGF Code for natural gas do not account for hydrogen's extreme flammability properties, and the need for further regulatory development is also supported by EMSA (2023) and (DNV, 2022), which identifies many required safeguards for hydrogen not found in the IGF Code.

The IMO draft Interim Guidelines for ships using hydrogen as fuel and various classification rules for hydrogen-fuelled vessels are generally based on the IGF Code safety concept for natural gas in addition to risk assessment.

In reviewing these guidelines and class rules, we have identified specific mitigation actions related to hydrogen-specific hazards, which are additional to the IGF Code regulations for natural gas. These requirements have been considered when drawing up the preliminary goals and functional requirements and will be further considered in the development of the Guidance document. The hydrogen-specific topics covered in the rules of the classification societies can generally be summarised as follows:

- Extensive guidance on risk assessment scope.
- Accumulation of released hydrogen (confined areas, enclosed, semi-enclosed spaces).
- Formation of liquefied or solidified air and water.
- Loss of vacuum insulation.
- Vent mast arrangements.
- Materials suitable for hydrogen service (hydrogen permeation and embrittlement).
- Definition of leakage sizes for various piping system components, including full bore rupture.
- Location, design, and construction of hydrogen storage tanks.
- Arrangement of secondary enclosures for hydrogen piping (vacuum, helium, nitrogen).
- Arrangement of spaces containing hydrogen systems (vacuum, helium).
- Fire safety.
- Hazardous area classification, including electrical equipment.
- Personnel safety and PPE.

Standardisation organisations provide standards for, e.g. materials, electrical equipment, and area classification, which may be applicable for reference in the final Guidance document. The EMSA study “Potential of Hydrogen as Fuel for Shipping” (EMSA, 2023) and the «Handbook for hydrogen-fuelled vessels” (MarHySafe, 2021) include comprehensive mapping of standards related to hydrogen, including standards produced for other applications that will be further considered in the development of the Guidance. Industry associations also provide best practices that may be useful in developing the Guidance.

Drawing up a preliminary Guidance

Eliminating hazards is always the best option, but it may not always be possible. In such cases, it's essential to implement a range of risk controls to reduce the risks to an acceptable level. The “Hierarchy of risk control measures" illustrated in Figure 1-1 highlights the significance of recognising the greater effectiveness of technical measures over operational measures in managing risks. The most efficient contributions to controlling risks and establishing a safe foundation for operation can be added during the design phase, utilising control measures from the top of the hierarchy. However, proper training and operating procedures will be essential for ensuring the safe operation of a ship throughout its lifespan. Finally, the design intent needs to be maintained through the full life cycle: safety measures should not degrade.

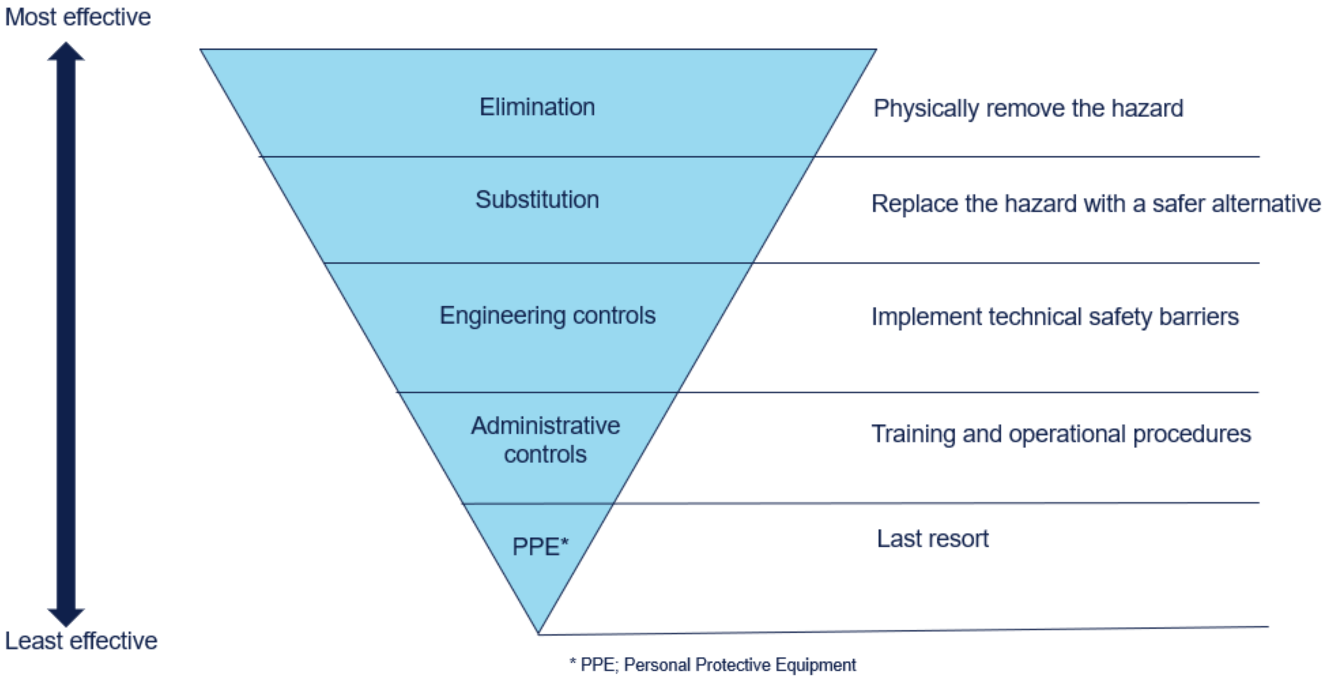

Figure 1-1The Hierarchy of Risk Control Measures (Source: DNV).

The IGF Code provides internationally recognised regulations for natural gas-fuelled ships and is a starting point and benchmark commonly used by the maritime industry when establishing new design concepts and regulations for hydrogen-fuelled ships. The safety principles illustrated in Figure 1-2, segregation, system integrity, double barriers, leakage detection, and automatic isolation of leakages are equally important for hydrogen and natural gas.

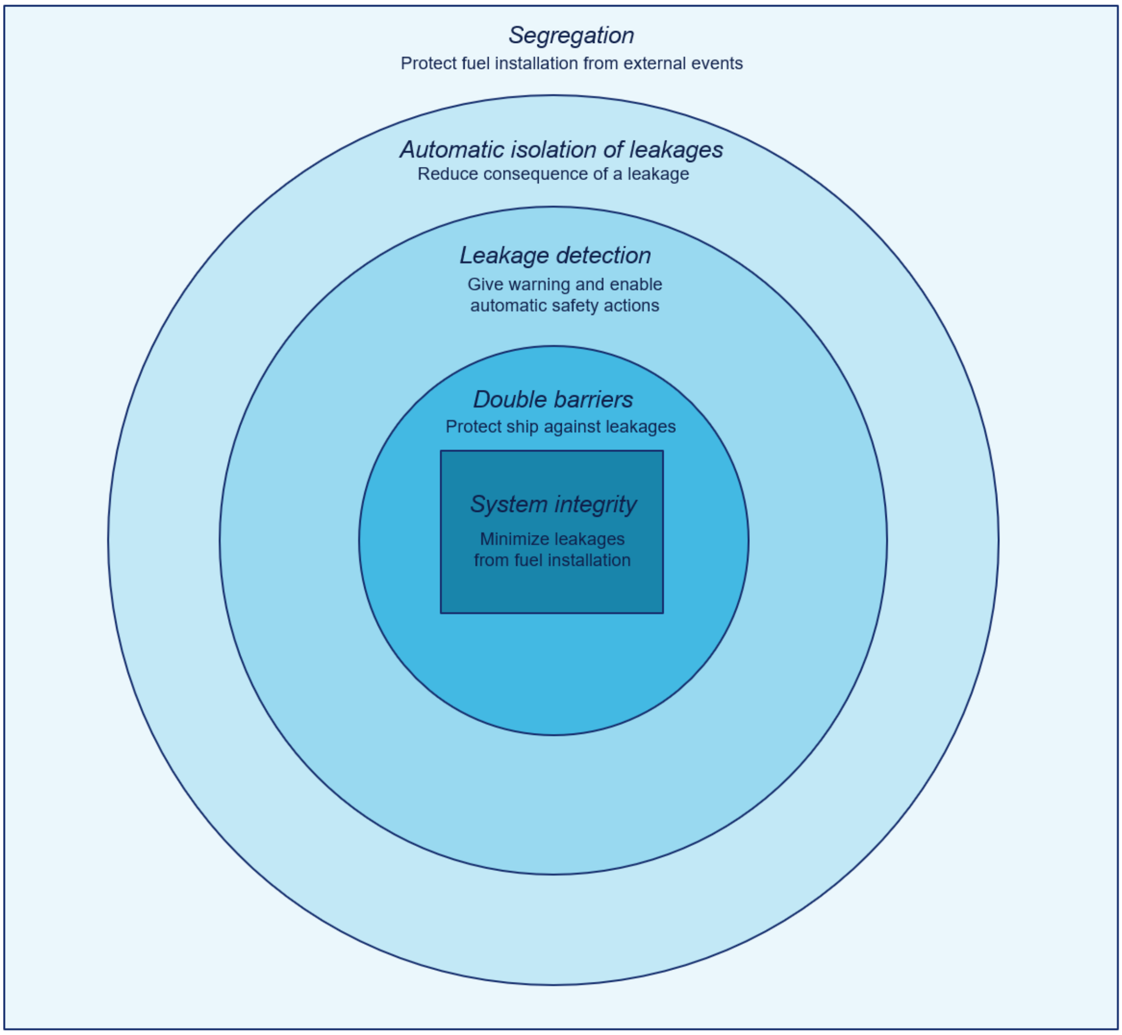

Figure 1-2 The safety concept of the current regulations in the IGF Code for natural gas fuel (Source: DNV).

However, we find that the existing safety barriers in the IGF Code for natural gas do not account for hydrogen-specific properties increasing the flammability risks.

According to (ISO, 2015) and (NASA, 1997), regulators are advised to assume an ignition source is present even when acceptable standards for certified electrical equipment are followed. This implies that the ignition of hydrogen in a release scenario should be assumed, and further measures (e.g., secondary barriers) to prevent ignition should be taken unless the ignition event is within the ship's design capabilities.

The MarHySafe project (MarHySafe, 2021) concludes that extreme explosions are more likely to happen with hydrogen than natural gas. The project notes that defining relatively small credible leak sizes in risk assessments for shore-based hydrogen applications is common. This often leads to a focus on hydrogen fires, as significant explosion events are not considered feasible due to the combination of leakage rates and safety barriers. MarHySafe recommends considering more severe leak scenarios for maritime systems due to the new and more critical application area. It is also noted that several Classification Societies have included requirements for considering leakages up to full-bore rupture in their current class rules.

Establishing the size of hydrogen leakages that a hydrogen-fuelled ship is designed to withstand is essential to determining its overall safety level. The IGF Code for natural gas refers to a “maximum probable leakage,” which can be interpreted in many ways. Another major decision that will significantly affect the ship's design is whether to follow the assumption that there is a probability of ignition even after measures like installing certified-safe electrical equipment have been taken.

From the above, we find that functional requirements ensuring the following are essential to achieve a safety level comparable to that of a conventional oil-fuelled ship:

- A substantial leakage from fuel piping systems should be considered in the design of safety barriers for a hydrogen-fuelled ship.
- The ship design should be based on the assumption that there is a probability of ignition even after measures like installing certified-safe electrical equipment have been taken.
- Hydrogen leakages should be prevented from reaching areas where combustion could be supported.

The preliminary Guidance developed in the first task of this project will be matured throughout the project as the project performs reliability analyses, formal hazard identification workshops of generic and specific ship designs, risk analyses and arranges industry-wide hearings. The final aim is to present and use the matured preliminary Guidance with hazards, goals and functional requirements as a basis to provide prescriptive requirements that fulfil the functional requirements to the degree possible.

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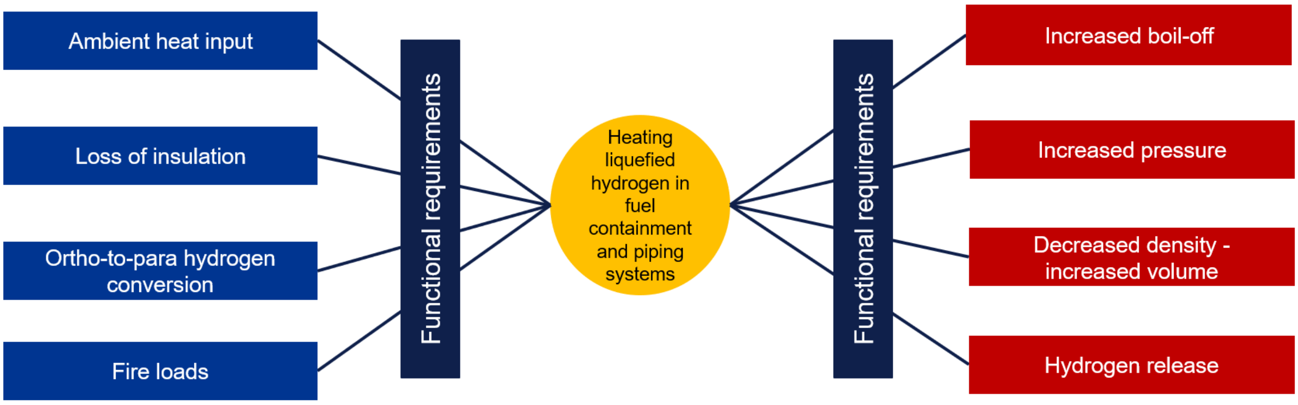
Ambient heat input
Loss of insulation
Ortho-to-para hydrogen conversion
Fire loads
Functional requirements
Heating liquefied hydrogen in fuel containment and piping systems
Functional requirements
Increased boil-off
Increased pressure
Decreased density - increased volume
Hydrogen release

List of Abbreviations

ABS	American Bureau of Shipping
BLEVE	Boiling Liquid Expanding Vapour Explosions
BV	Bureau Veritas
CCC	Sub-committee on Carriage of Cargoes and Containers (IMO)
CFD	Computational Fluid Dynamics
CH2	Compressed Hydrogen
CSA	Cryogenic Society Archive
CSB	Chemical Safety Board (USA)
DDT	Deflagration to Detonation Transition
DNV	Det Norske Veritas
DSB	The Norwegian Directorate for Civil Protection
EHSP	European Hydrogen Safety Panel
EIHP2	European Integrated Hydrogen Project Phase 2
eMARS	The Major Accident Reporting System
EMSA	European Maritime Safety Agency
ER	Expansion Ratio
ESD	Emergency Shutdown
ETA	Event Tree Analysis
EU	European Union
FCH 2 JU	Fuel Cells and Hydrogen Joint Undertaking
FLACS	Flame Acceleration Simulator
FPR	Fuel Preparation Room
FTA	Fault Tree Analysis
GHG	Greenhouse Gas
GVU	Gas Valve Unit
H2	Hydrogen
HAZID	Hazard Identification
HCRD	Hydrocarbon Release Database
HIAD	Hydrogen Incident and Accident Database
HSLC	High Speed Light Craft Vessel
IChemE	Institution of Chemical Engineers
IGC	International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IMO)
IGF	International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels (IMO)
IMO	International Maritime Organization
ISO	The international Organization for Standardization
KFX	Kameleon FireEx
KR	Korean Register

LEL	Lower Explosion Limit
LFL	Lower Flammability Limit
LH2	Liquid Hydrogen
LNG	Liquefied Natural Gas
LOC	Limiting Oxygen Concentration
LR	Lloyd's Register
LSA	Life-saving Appliances
MIE	Minimum Ignition Energy
MSC	Maritime Safety Committee (IMO)
MTF	Maritime Technical Forum
NASA	National Aeronautics and Space Administration
NBP	Normal Boiling Point
NK	ClassNK - Nippon Kaiji Kyokai
NTP	Normal Temperature and Pressure
NTSB	National Transportation Safety Board (USA)
OSHA	Occupational Safety and Health Administration
OSV	Offshore Service Vessel
PPE	Personal Protective Equipment
ppm	parts per million
QRA	Quantitative Risk Analysis
RISCAD	Relation Information System for Chemical Accidents Database
Ro-Ro	Roll-on-roll-off vessel
SOLAS	International Convention for the Safety of Life at Sea
TCS	Tank Connection Space
UEL	Upper Explosion Limit
UFL	Upper Flammability Limit
UK HSE	United Kingdom Health and Safety Executive

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 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 assist the industry and the regulators towards a safe and harmonised deployment of this relevant technology that could demonstrate an important step towards decarbonisation of the sector. This report is the result of the first part of the study.

The International Maritime Organization (IMO) updated its greenhouse gas (GHG) strategy in 2023, with the goal of achieving net-zero emissions by 2050. Together with new EU regulations, this will be critical drivers for decarbonizing international shipping. Energy efficiency measures can lower GHG emissions from ships but will not bring the industry to net-zero emissions by 2050 without a change also 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 goal-based approach provided in MSC.1/Circ.1394, and to build on extensive risk assessment and reliability analysis.

EMSA has previously published two reports related to hydrogen safety: “Use of Fuel Cells in Shipping” (EMSA, 2017) and “Potential of Hydrogen as Fuel for Shipping” (EMSA, 2023).

The latest report, “Potential of Hydrogen as Fuel for Shipping,” reviews technical issues, regulatory frameworks, and the current state of hydrogen's application as fuel for shipping. It covers topics such as production capacity, regulatory landscape, fuel storage options, supply, power generation technologies, techno-economic analyses, and risk-based case studies focusing on safety. Three HAZID studies on different ship types using hydrogen were conducted and described in the report.

Some of the preventive and mitigative recommendations and safeguards from the HAZID studies were derived from the IGF Code for methane as a marine fuel. Many safeguards identified in the studies are considered additional measures due to the inherent risks associated with hydrogen. As no regulations are available for these additional safety measures, the study concluded that further analysis and research are needed. The study has summarized the important recommendations that need further investigation and analysis.

This report will build on previous EMSA work on hydrogen safety in its efforts to characterise hydrogen as fuel and define a preliminary table of contents, preliminary goals, and functional requirements for a Guidance addressing ships using hydrogen as fuel. The report has the following structure:

- Chapter 2: Describes the methodology.
- Chapter 3: Provides characterization of hydrogen as a fuel.
- Chapter 4: Presents established safety principles for hydrogen.
- Chapter 5: Discusses lessons learned from hydrogen-related accidents.
- Chapter 6: Validates hydrogen modeling techniques and tools.
- Chapter 7: Reviews existing hydrogen requirements and standards.
- Chapter 8: Presents our findings, forming the basis for the preliminary Guidance.

2. Our approach

This chapter briefly describes the methodology used in this study to establish a preliminary table of contents and preliminary goals and functional requirements for a Guidance document addressing ships using hydrogen as fuel. Figure 2-1 illustrates the overall approach.

Firstly, we analyse hydrogen's main characteristics to frame which safety hazards, system threats and risks to be considered and mitigated in a Guidance document for ships using hydrogen as fuel (Chapter 3). Secondly, we review established principles for mitigation and control (Chapter 4), and a brief hydrogen accident review (Chapter 5). We also validate the scope and limitations of the most common explosion analysis modelling techniques and tools (Chapter 6). Thirdly, we review current statutory regulations and classification rules, standards, and best practices relevant to hydrogen-fuelled ships to identify hazards and risks considered and mitigated in existing rules and regulations (Chapter 7).

Based on this information, we summarize the hazards and risks to be considered and mitigated in the preliminary hydrogen guidance (Chapter 8), and we draw up a preliminary table of contents and establish preliminary goals and functional requirements for the Guidance.

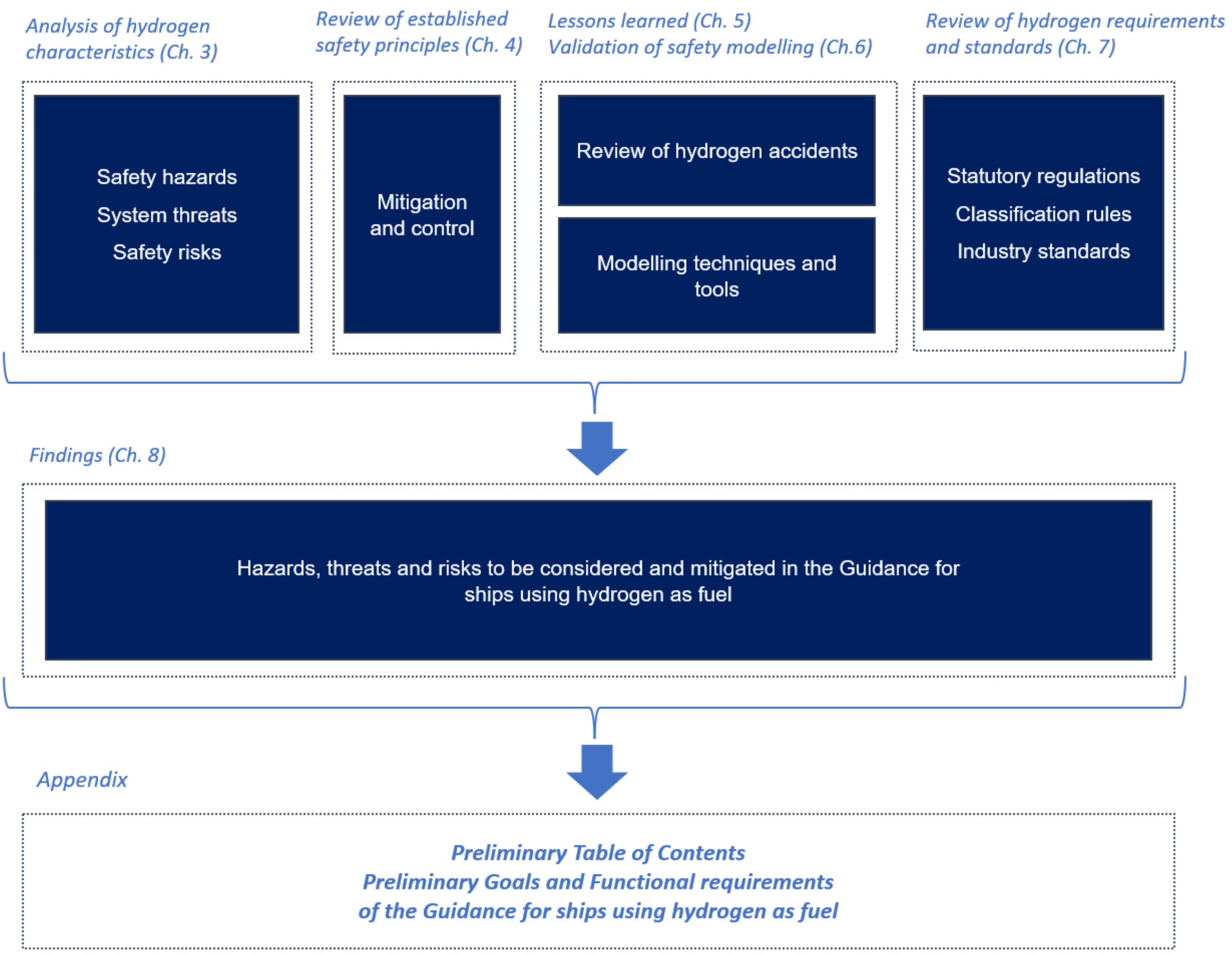

Figure 2-1 Overview of the overall approach of the study, where the outcome is a preliminary Table of contents, and preliminary Goals and Functional Requirements of a Guidance addressing ships using hydrogen as fuel.

3. Hydrogen safety hazards, threats, and risks

In this chapter, we analyse hydrogen's main characteristics. We start by evaluating physical properties influencing the flammability and storage, release, and dispersion behaviours to map the hazards related to using hydrogen as a ship fuel. We then look at typical causes that may trigger a hazardous event to frame the threats to a shipborne hydrogen installation. Lastly, we analyse the unique safety challenges of moving hydrogen from its use in industrial environments on shore to marine applications.

3.1 Hydrogen safety hazards

To address the hazards of using hydrogen as fuel on ships, we present an overview of the safety-related properties of hydrogen in Table 3-1. The corresponding properties for methane, the main component of natural gas, are included for comparison purposes. They are split into two groups: properties affecting the flammability of a fuel and properties relevant for storage, release, and dispersion phenomena, further discussed in chapter 3.1.1 and 3.1.2, respectively.

Table 3-1 Selected properties of hydrogen relevant for its safe use as a fuel compared to the corresponding properties of methane, the main component of natural gas.

Fuel properties		Hydrogen (H_2)	Methane (CH_4)
Flammability*	Lower & upper flammability limit (LFL and UFL) (% vol. fraction)	4-77	5.3-17
	Minimum ignition energy (mJ)	0.017	0.274
	Auto-ignition temperature (°C)	585	537
	Laminar burning velocity (m/s)	2.7	0.37
	Limiting oxygen concentration (% volume with nitrogen inert gas)	5	12
Storage, release, and dispersion	Normal Boiling point (°C)	-253	-162
	Expansion ratio liquid NBP/gas NTP	847	600**
	Density (kg/m3)	70.8 (L, NBP) 1.34 (G, NBP) 0.0827 (G, NTP)	422.5 (L, NBP) 1.82 (G, NBP) 0.6594 (G, NTP)
	Specific gravity (Air: 1)	0.069 (G, NTP)	0.547 (G, NTP)
	Viscosity (µPa·s)	8.81 (NTP)	11.023 (NTP)
	Heat of vaporization (J/g)	454.6 (NBP)	510.4 (NBP)
Remarks: * Ignition and combustion properties for air mixtures at 25ºC and 101.3 kPa ** varies slightly depending on LNG composition			
L – liquid, G – gas, NTP - normal temperature and pressure, NBP - normal boiling point			
Unless specified otherwise, the source of data is ISO/TR 15916 Basic considerations for the safety of hydrogen systems			

3.1.1 Hydrogen properties affecting flammability hazards

Lower and upper flammability limit

Flammability limits refer to the range of gas or vapour concentrations in air that will burn or explode in the presence of an ignition source. They are usually given as a percentage by volume of the gas or vapour in the air. The lower flammability limit (LFL) is the lowest concentration of gas or vapour which will burn or explode if ignited, while the upper flammability limit (UFL) is the highest concentration of gas or vapour which will burn or explode if ignited.

The air/gas mixture between LFL and UFL is flammable/explosive. Below LFL, the mixture is too lean to burn, and above UFL, it is too rich to burn. LFL and UFL are also referred to as the lower and upper explosion limits (LEL and UEL).

As shown in Figure 3-1 the flammable range of hydrogen in air is 4-77%, which is considerably wider than for methane. The lower flammability limits are comparable, meaning that smaller leakages of the two fuels pose similar risks of creating flammable or explosive atmospheres. However, hydrogen is ignitable in a much wider range of richer mixtures compared to methane, meaning less oxygen is required for ignition.

When hydrogen leaks from a fuel system, it is diluted from its initial concentration at the release point to a concentration that may or may not be within the flammable range, depending on conditions at the point of release.

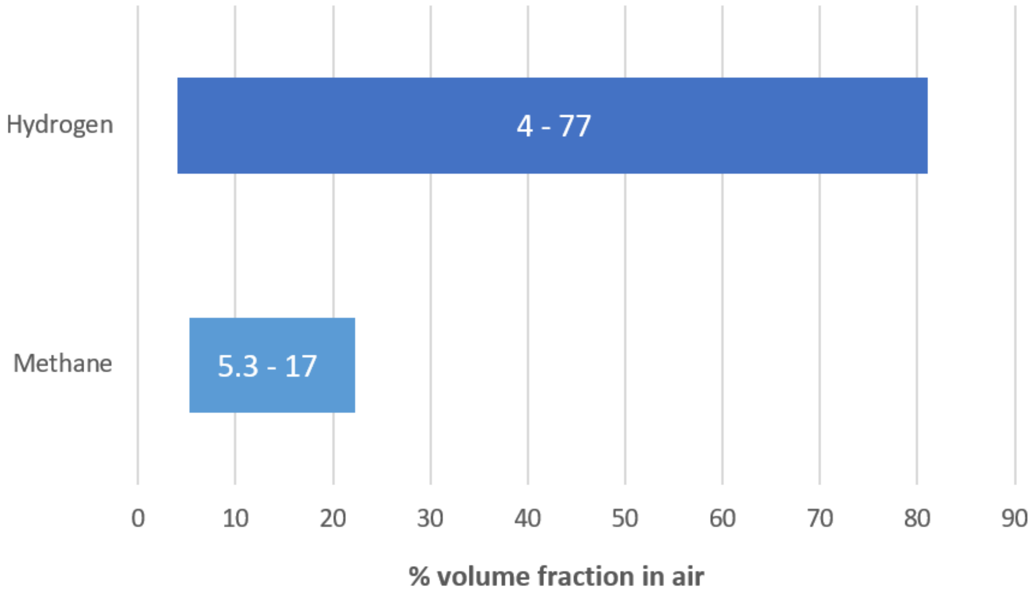

Figure 3-1 Flammability range of methane and hydrogen (Source: DNV).

Forced ventilation of an enclosed space containing hydrogen leakage sources can contribute to keeping the atmosphere in the space below LFL if the ventilation rate exceeds the leakage rate but does not eliminate the risk of ignition and resulting jet fire.

When using inerting to reduce the risk of ignition it must be noted that a hydrogen atmosphere is more sensitive to air entering than methane due to a high upper flammable limit (UFL). Hydrogen also requires less oxygen to ignite. Having hydrogen concentrations above the UFL in an inerted space is still very dangerous. If the concentrations are lowered by introducing fresh air, the atmosphere in the space can enter the flammable/explosive range.

Similarly, double-walled piping is typically fitted with ventilation to dilute the concentration in case of leaks, or inerted to keep the flammable compound-to-air ratio above the UFL. Hence, the fuel's LFL and UFL must be considered when designing the safety barriers.

Minimum ignition energy

The minimum ignition energy (MIE) determines the ignition capability of fuel-air mixtures, where the fuel may be a combustible vapour or gas. It is defined as the minimum electrical energy stored in a capacitor, which, when discharged, is sufficient to ignite the most ignitable mixture of fuel and air under specified test conditions. The MIE value is used to assess the likelihood of ignition during processing and handling.

The curve in Figure 3-2 shows within which concentrations of gas in the air, there is an explosive atmosphere. All flammable gases and vapours have their own specific “explosion curve”. If the air-gas ratio is below or above the explosion limits explained above, there will not be an explosive gas atmosphere. The lowest point of the explosion curve is the optimal ignition concentration of the gas or vapour in the air, i.e., when the minimum amount of energy is required to ignite the atmosphere.

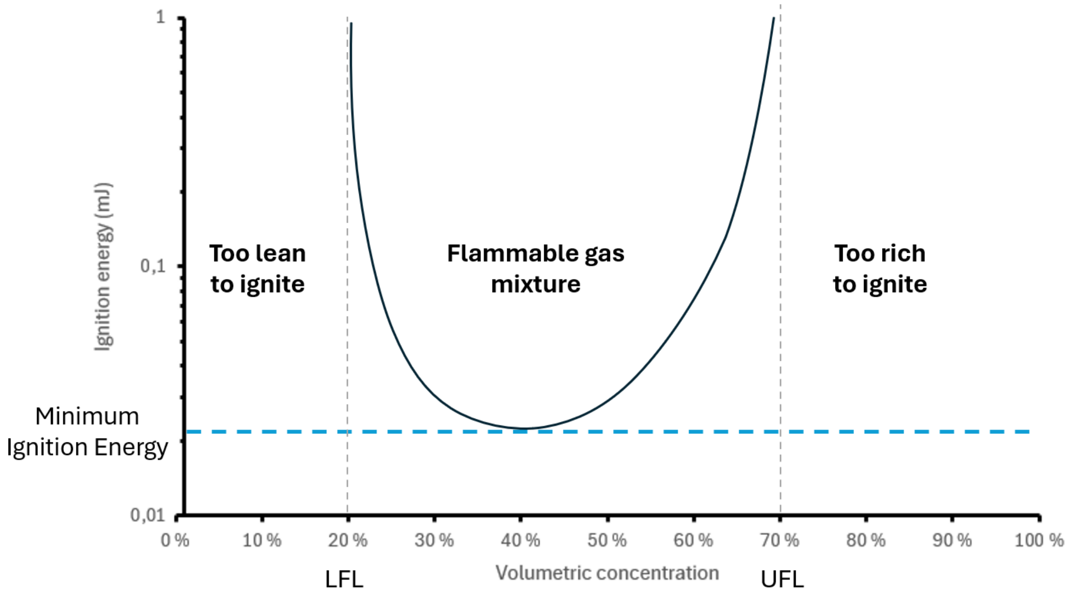

Figure 3-2 **“**Explosion curve” of a generic gas for illustration purposes (Source: DNV)

A fuel with a narrow flammability range that requires a lot of energy to ignite will pose less of a fire risk than a fuel with a wide flammability range that requires little energy to ignite.

Hydrogen requires significantly less energy to be ignited than methane (MIE for methane is 16 times that of hydrogen), and this applies over a wide range of hydrogen concentrations, as shown in Figure 3-3.

A source able to generate a spark with an energy of 1 mJ will ignite a hydrogen-air mixture with a hydrogen content ranging from 6 to 64 vol. %. At the limits of flammability, the ignition energy is similar to methane. Less energy is needed to ignite a mixture that is closer to its lowest point on the explosion curve.

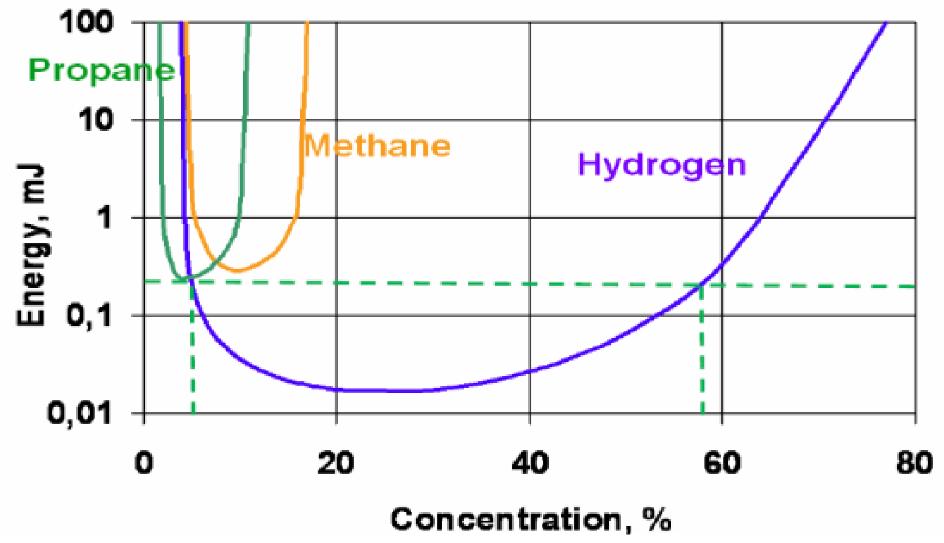

Figure 3-3 “Explosion curve” for methane, hydrogen (and propane) (HyResponse, 2015)

Electrical equipment is a potential ignition source in case of leakage and a flammable or explosive atmosphere formation. Sparks, short circuits and arches from switches or electric motors are examples of ignition mechanisms from electrical sources. Static discharges can also carry enough energy to ignite an explosive atmosphere of hydrogen.

Other relevant ignition sources reported in the literature include mechanical sparks induced from rapidly closing valves, electrostatic discharges occurring in ungrounded particulate filters, and sparks from catalyst particles (HyResponse, 2015). Hot surfaces, open flames (hot work), and exhaust are other typical sources of ignition.

Auto-ignition temperature

The auto-ignition temperature of a substance indicates the lowest temperature at which it may spontaneously ignite without the presence of an ignition source such as a flame or spark. At the auto-ignition temperature, the temperature alone provides sufficient energy to induce combustion. The auto-ignition temperature depends on pressure and oxygen availability and is typically given at standard pressure and temperature, with ideal oxygen concentration.

Between 30 and 50% of fires on merchant ships start in the engine room, and most of these fires are caused by oil leaks from pressurised systems. Oil fires usually occur when oil from a large leak (or a smaller but persistent leak) comes into contact with a nearby hot surface at a temperature that exceeds the auto-ignition temperature of the oil. The sources of heat most likely to start a fire in an engine room are hot exhaust pipe and engine surfaces, bearings of rotating machinery heating up and defunct electrical equipment (Burgoynes, 2016).

The gases and low-flashpoint liquid fuels covered by the IGF Code typically have higher auto-ignition temperatures than fuel oils. Hydrogen will be in gaseous form or rapidly vaporise upon leakage, representing a different fire and explosion hazard than liquid fuels. In a scenario where a gas fire fades out due to a lack of oxygen, materials heated by the fire could be the source of auto-ignition if oxygen is somehow reintroduced to the space.

The auto-ignition temperature for hydrogen is 585°C, which is slightly higher than for methane. In practical terms, auto-ignition risk is similar for the two fuels and significantly lower than for conventional fuel oils, with auto-ignition temperatures slightly above 200°C. Due to the high risk of fire from auto-ignited oil fuels, Class rules and SOLAS limit the acceptable surface temperature of equipment that may come into contact with oil to 220°C. This regulatory limitation will also reduce the risk of auto-ignition of leaking hydrogen.

It should be noted that most energy converters using alternative fuels are dual-fuel engines using oil as a pilot fuel, so the risks associated with the IGF Code fuels are in addition to the risk of engine room fires due to oil under pressure.

Burning velocity

The severity of an explosion will depend on many factors, but in general, the more ‘reactive’ the fuel, the worse the explosion. Reactivity, in this sense, relates to how fast a flame moves through a flammable cloud. A deflagration implies a subsonic combustion. When a flame travels very fast, going supersonic, the deflagration can transition to a detonation (Figure 3-4). A detonation is a self-sustaining explosion process with a leading shock of 20 bar that compresses the gas to a point of autoignition. The subsequent combustion provides the energy to maintain the shockwave. Detonability varies from fuel to fuel, and detonations would not occur in any realistic situation with natural gas but are entirely credible for hydrogen (DNV, 2022).

Detonation limits are the range of composition within which detonations have been observed in laboratory and field experiments. Detonation limits are a strong function of mixture composition, initial pressure and temperature but are usually considered to be narrower than the flammability limits. In addition, detonability is much more strongly dependent on the ignition source, confinement, and the physical size of the environment than flammability limits. The ability to initiate and propagate a detonation requires a set of critical conditions to be satisfied, and despite extensive research into the subject, the limits are empirical in nature.

Hydrogen's burning velocity is 265-325 cm/s, more than seven times that of methane (MarHySafe, 2021). The higher burning velocity results in greater flame acceleration in congested areas and higher pressures in confined spaces due to the resistance in venting ducts and openings through which the pressure must escape.

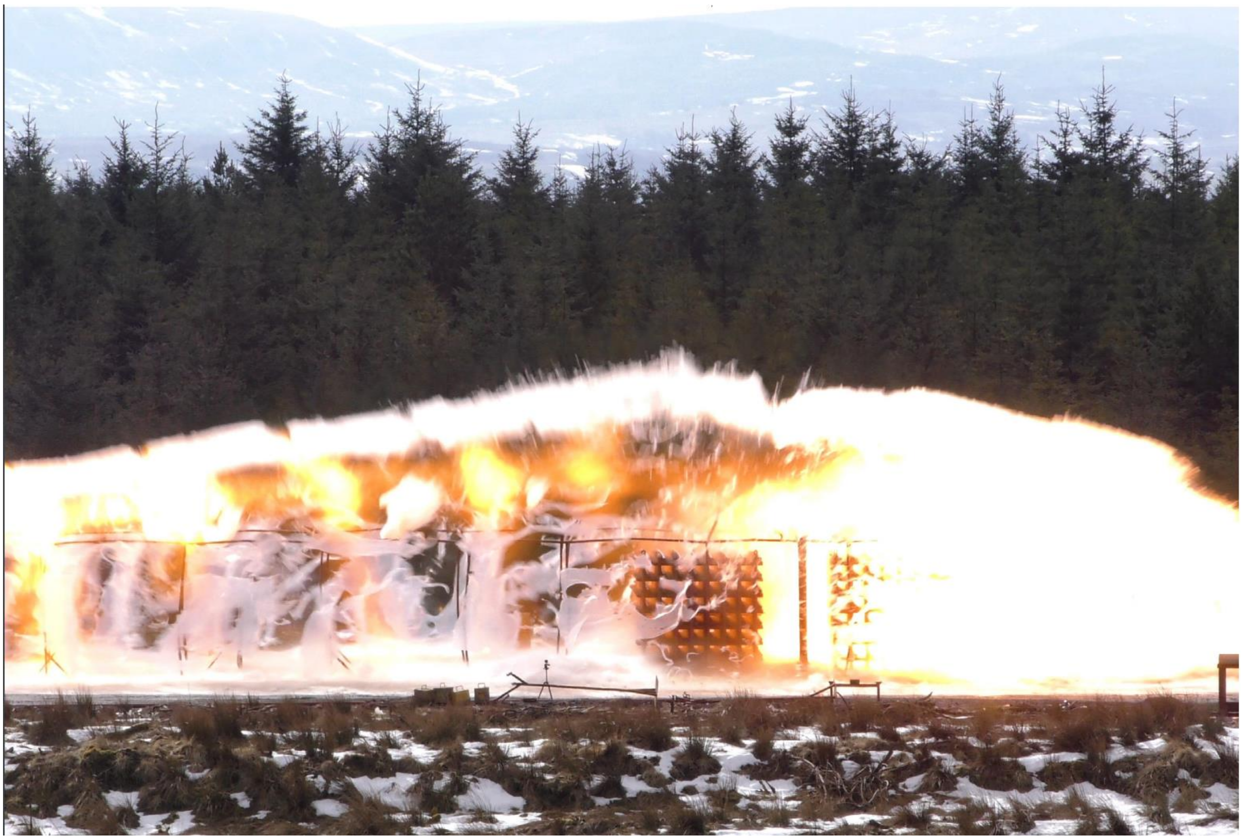

Figure 3-4 The detonation of hydrogen is entirely credible in many scenarios where traditional hydrocarbons would not pose a detonation risk. This image shows a still image from a 15 m^3 (approx. 1.3 kg) hydrogen detonation conducted as a demonstration at DNV's Spadeadam Research Centre in the UK (DNV, 2022)

Ignition of a flammable gas cloud does not always result in an explosion. Pressure is generated when either the gas cloud is confined within an enclosure or the flame accelerates to high speed (or both).

Limiting oxygen concentration

The limiting oxygen concentration (LOC) is defined as the limiting concentration of oxygen below which combustion is not possible, independent of the fuel concentration. It is expressed in units of volume per cent of oxygen. The LOC varies with pressure and temperature. It is also dependent on the type of inert gas.

The LOC has important practical implications for the safe use of hydrogen onboard ships. When tanks and systems are filled and gas freed, it is essential to avoid a flammable atmosphere. Purging with nitrogen (or another inert gas) to reduce the oxygen is a common method to achieve this. When these procedures are developed and used, it is important to be aware that hydrogen systems (LOC 5%) require more thorough purging than hydrocarbons, which have LOCs in the 11-15% range. The same issue applies if an inert gas is used as a safety barrier to prevent ignition in secondary enclosures or spaces.

3.1.2 Hydrogen properties affecting storage, release, and dispersion hazards

Other physical properties of hydrogen must also be understood to implement robust safety barriers for the storage and distribution of hydrogen onboard and to predict the hydrogen behaviour in different release scenarios.

Normal boiling point

The boiling point of a liquid is the temperature at which its vapour pressure is equal to the surrounding pressure, and the liquid changes into a vapour.

When the external pressure is:

- less than one atmosphere, the boiling point of the liquid is lower than its normal boiling point.
- equal to one atmosphere, the boiling point of a liquid is called the normal boiling point.
- greater than one atmosphere, the boiling point of the liquid is higher than its normal boiling point.

Liquids may also change to vapour at temperatures below their boiling points through evaporation. Evaporation is a surface phenomenon in which molecules near the liquid's edge escape into the surroundings as vapour, as opposed to boiling, where molecules anywhere in the liquid escape, forming vapour bubbles within the liquid.

The saturation temperature refers to the temperature at the boiling point. The liquid can be said to be saturated with thermal energy, and any addition of thermal energy results in a phase transition.

Gases are usually stored and transported in a liquid state to reduce the required storage volumes. For hydrogen, this is done by cooling the gas close to the normal boiling point. Liquefied hydrogen (LH2) has a normal boiling point of -253°C, which means it is kept at temperatures over 90°C colder than liquefied natural gas (LNG). This creates additional safety hazards related to storing and distributing hydrogen onboard.

LH2 is usually stored in vacuum-insulated pressure vessels to minimize heat input from the surroundings. Heat input causes boil-off gas to accumulate in the space above the liquid, increasing the tank pressure. It simultaneously raises the liquid's boiling point, which, combined with the tank's design pressure, allows it to be stored for extended periods. If there is a partial or complete loss of vacuum insulation, it will significantly increase the heat ingress, rate of pressure rise, and boil-off rate. When the vapour pressure reaches the set point of the tank's pressure relief valves, the hydrogen vapour is released automatically, resulting in a continuous discharge of hydrogen from the vent mast outlet on the open deck. During normal operation, boil-off gas management can compensate for the heat input, but if the tank loses its insulation properties, the contents will evaporate within hours.

Both LNG and LH2 are stored at temperatures that will cause embrittlement if normal ship steel is exposed to leakage. However, LH2 evaporates more easily and quickly, requiring less energy from its surroundings. Hence, a comparison of the two fuels' cooling effects is not straightforward. Large-scale experiments investigating and comparing the effects are limited. The cooling down to the brittle transition temperature of a structural element directly exposed to cryogenic leakages will be almost instantaneous. In a scenario where the room temperature in an enclosed space is lowered due to leakages, the cooling of the surrounding structure will be slower.

When LH2 is spilt in an enclosed space or when a hydrogen containment system or a piping system loses insulation, the ambient temperature in the affected spaces may become very low. If these spaces contain equipment or systems that are required for the safety of the ship, it is important to ensure that they remain operational after the event.

An additional safety concern with cryogenically stored hydrogen is that all gases (except for helium) will be condensed and solidified in contact with it. If air or other gases enter an LH2 system, the solidified gases can create restrictions in the piping system, interfere with the normal operation of valves and damage valve seats. 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.

In a process known as cryo-pumping the reduction in volume of condensing gases may create a vacuum that can draw in yet even more gas. Large quantities of condensed or solidified materials can accumulate if the leak persists for long periods of time. At some point, should the system be warmed for maintenance, these solidified materials will vaporise, possibly resulting in high pressures or forming explosive mixtures. These other gases might also carry heat into the liquid hydrogen and cause enhanced evaporation losses or “unexpected” pressure rises.

Expansion ratio liquid-to-gas

A liquefied gaseous fuel's expansion ratio is the volume of a given amount of that substance in liquefied form compared to the volume of the same amount of substance in gaseous form at room temperature and normal atmospheric pressure.

If liquefied gaseous fuel is spilt and vaporised within an enclosed space, the pressure inside the room will increase. Depending on the possibility of pressure relief and the vaporisation rate, the pressure increase may or may not be sufficient to damage the structure. The structure surrounding the leakage will typically be a safety barrier against further spreading of flammable gas in the ship, and maintaining the integrity and gas tightness of the bulkheads in a leakage scenario is essential.

The liquid-to-gas expansion ratio is also an important parameter when evaluating the consequences of a liquid leak regarding flammability. The volume increase associated with the phase change from liquid to gas is 847 for hydrogen. Liquefied hydrogen will rapidly boil or flash to gas when released into a room with ambient temperature and pressure and will rapidly create an explosive atmosphere.

If LH2 is released into a confined space, the pressure in the space will increase. Whether the pressure increase will be sufficient to cause structural damage depends on the leaked volume of hydrogen, the volume of the space and the availability of a sufficiently sized pressure relief arrangement.

If LH2 is released in a confined space at ambient temperature, it will quickly evaporate. This will be accompanied by a rapid reduction in temperature and displacement of the air inside, both of which will be hazardous to any persons inside the space.

Density and specific gravity

Density is defined as the amount of mass present in a given volume. For solids and liquids, this is a simple measurement. However, gases are very responsive to temperature and pressure, which can cause their densities to change quickly. Specific gravity for gases is defined as the ratio of the density of the gas to the density of air at a specified temperature and pressure. If a gas has a lower specific gravity than air (<1), it is said to be “lighter” than air, and if it has a higher specific gravity, it is said to be “heavier” than air (>1).

Gaseous hydrogen has a density of 0.0827 kg/m3 (at NTP[3]). The specific gravities of hydrogen and air at NTP are 0.07 and 1.0, respectively, meaning that hydrogen is about 14 times lighter than air at the same conditions. Therefore, it will rise and disperse in an open environment.

With a proper ship design, the significant buoyancy of hydrogen gas can be a safety asset. Where hydrogen is released into the open atmosphere, the gas is allowed to rise and disperse rapidly. However, one should be careful in applying gaseous hydrogen buoyancy observations to the releases of hydrogen vapours at cryogenic temperatures. Saturated hydrogen vapour is heavier than air and will remain close to the ground until the temperature rises. Usually, the condensation of atmospheric humidity will also add water to the mixture cloud, making it visible and increasing the mixture's molecular mass even more.

The positive buoyancy of hydrogen can cause a hazardous situation in (partially) confined spaces, where the hydrogen can accumulate in a layer, e.g., underneath a ceiling. However, once the leak is stopped and the air is mixed, the gases distribute uniformly throughout the room. If the gas source is small or leaks slowly, resulting in ppm[4] levels of hydrogen, the air never becomes stratified in the first place. Gases tend to diffuse and mix quickly, so even if the gas starts out stratified, it cannot stay stratified long in a small, confined space.

At its normal boiling point (NBP), liquid hydrogen has a density of 71 kg/m3. This gives it a specific gravity of 0.071, which means it is about 14 times lighter than water. When heat is added to an LH2 system from the surroundings, the volume of liquid hydrogen increases significantly. This property is indicated by the coefficient of thermal expansion, which at NBP is 23 times that of water for ambient conditions. The density decrease of heated liquefied hydrogen may result in tanks becoming liquid full, with corresponding over-pressurisation, discharge of liquid hydrogen, or both.

Gaseous hydrogen forms the smallest, lightest molecule of any gas. As a result, gaseous hydrogen better permeates through materials, passes through smaller leak paths, diffuses more rapidly in surrounding media, and has greater buoyancy than other gases. The consequences arising from these properties are that released hydrogen tends to rise and diffuse, but if confined, it can accumulate in high spots and reach ignition sources located there (e.g. ceiling lights). Hydrogen vessels and piping systems require good seals, and leaks are always a concern (ISO, 2015).

Viscosity

Viscosity is a fluid's resistance to shear motion (its internal friction). Hydrogen's low viscosity, an effect of its small molecule size, causes a comparatively high flow rate in a leakage scenario.

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[3] Normal temperature and pressure (NTP); temperature of 20°C and pressure of 1 bar

[4] ppm; parts per million

Asphyxiation

Asphyxiant gases displace and dilute oxygen from the air, causing people to suffocate. Asphyxiants with no other health effects are referred to as simple asphyxiants. Examples of simple asphyxiants include methane, hydrogen, nitrogen, helium, and carbon dioxide. Significant hydrogen leakages in enclosed spaces will cause a risk of asphyxiation due to oxygen depletion.

Most asphyxiation incidents occur when entering confined spaces, and many injuries and deaths are reported each year from such accidents. Many of the fatalities have been among rescuers trying to assist the initial casualty. Consequently, it is essential to always verify that the air quality is acceptable before entering a space with potential fuel leakages. It is worth noting that small quantities of leaked liquefied hydrogen will expand upon vaporisation and displace the oxygen inside.

Hydrogen embrittlement

Hydrogen can significantly deteriorate the mechanical properties of metals, causing hydrogen embrittlement. This effect involves many variables, such as the temperature and pressure of the environment, the purity, concentration, and exposure time of the hydrogen, the stress state, physical and mechanical properties, microstructure, surface conditions, and the nature of the crack front of the material.

Many metals absorb hydrogen, especially at high pressures. Hydrogen absorption by steel can result in embrittlement, which can lead to failures in tanks, piping systems and equipment. There is an atomic solution of hydrogen in metals. Permeated through a metal, atomic hydrogen recombines to molecules on the external storage surface to diffuse into surrounding gas afterwards. Many hydrogen material problems are related to welds or the use of improper materials.

Brittle failures of hydrogen-containing components can lead to the release of significant amounts of hydrogen with corresponding hazards from low temperatures from cryogenic releases and high pressures and temperatures from a potential ignition. The choice of materials for hydrogen systems is an important part of hydrogen safety (Molkov, 2012).

Corrosion

Hydrogen is non-corrosive, but stainless steel is a commonly used material in systems for hydrogen. The most common form of corrosion displayed by stainless steel is pitting, which occurs when the surrounding conditions overwhelm the passive film. Stainless steel also experiences crevice corrosion resulting from deposits that create crevices on metal surfaces. According to (DNV, 2021) stainless steels generally have good resistance to atmospheric corrosion, but the presence of deposits or crevices can lead to local attack. For insulated piping systems, the risk of pitting corrosion increases.

External stress corrosion cracking of stainless steel appears as cracking in areas with high tensile stresses, typically at welds, and is associated with saltwater retained on the material surface. The probability of failure increases markedly with temperature but depends on the type of stainless steel. If piping systems are exposed to seawater internally, the risk of corrosion failures increases significantly.

3.2 Hydrogen system threats

In this sub-chapter, we assess causes that may initiate hazardous events. A hydrogen fuel system on a ship faces different threats than a similar stationary system on land, and these need to be assessed and addressed in the design of a hydrogen-fuelled ship.

The nature of shipping implies that damages to a hydrogen fuel system from ship collisions and groundings must be considered. Also, dynamic loads due to ship movements, green seas on deck, vibrations, humidity, presence of chlorides, etc., are typically not design considerations in stationary shore-based systems.

Due to the relatively limited space onboard, normally applied safety distances, segregation from hazards like fires and other unrelated work (cargo handling, ship operations) cannot be observed. Additionally, a ship at sea is left to manage any emergencies with limited possibilities for escape. The special circumstances must be compensated for with appropriate preventive and mitigating safety barriers, which is why marine regulations sometimes have stricter requirements than rules and regulations governing installations on land.

3.2.1 Mechanical damage leading to hydrogen release

Damage to fuel containment systems, and to a lesser extent, piping systems, are events that have the potential to release all the hydrogen stored onboard, and it is an event a ship is not designed to survive. Consequently, it is of utmost importance that storage and distribution systems for hydrogen fuel are sufficiently protected against external events that have the potential to damage them.

Collisions and groundings

The extent of damage to a ship subject to a collision depends on factors such as speed, displacement, draft, bow shape and angle of impact of the colliding ship. Similar factors determine grounding damages. High-Speed Light Crafts and vessels in coastal trade are presumably more exposed to grounding damage. Fuel tank placement and fuel system arrangement must account for the possibility of collision and grounding.

Fire

A hydrogen fuel system subject to an external fire will heat up, promoting the opening of safety valves with subsequent hydrogen release. The fire may also damage the safety systems needed to control the fuel system, the tank and system insulation, and potentially the tank itself. Therefore, it is necessary to identify high fire-risk areas onboard and ensure that storage tanks and systems have sufficient passive and active fire protection to reduce the risk of fire damage from external events. Typical high fire-risk areas are the cargo area of tankers and container ships, cargo decks on Ro-Ro and Ro-Pax vessels, cargo holds on bulkers and engine rooms.

Explosions

Ship explosions have the potential to severely damage hydrogen fuel tanks and systems. Potential areas of explosion risk must be evaluated in relation to fuel tank location to minimize the consequences to the fuel system and avoid further escalation. Events to consider are - oil and chemical carrier cargo tank explosions, dust explosions, boiler explosions, etc. For tankers, it should also be considered that cryogenic leakages may damage cargo tanks containing toxic or flammable cargo.

Cargo operations

Cargo operations can be a significant threat to hydrogen installations, potentially damaging hydrogen storage tanks or the piping system (e.g., falling loads onto decks of OSVs, dry cargo ships, and container ships, and moving cargo on Ro-Ro vessels).

Ship operations

The energy in breaking mooring lines may be sufficient to damage hydrogen fuel tanks and systems. Broken mooring lines during bunkering could lead to a drift-off situation, with damage to the bunkering system and a resulting spill of cryogenic or high-pressure hydrogen. Crane operations on the ship, with lifting above hydrogen fuel tanks or systems, could potentially cause damage in falling load scenarios.

Environmental conditions

Bad weather conditions may result in damage to hydrogen fuel tanks and systems - e.g., from green seas on deck, loose objects on deck or due to lack of proper sea fastening of objects below deck. Equipment not designed for the marine environment may have a shorter lifespan than expected by design. The effect of exposure to the sun, sea spray, icing and snow could affect the durability of composite tanks and exposed equipment over time.

The marine environment will subject the components of a hydrogen installation to dynamic loads, vibrations, seawater, and the presence of chlorides.

3.2.2 Accidental hydrogen leakages from tanks and systems

Component leakages

Hydrogen leaks can occur within a system or as an emergency release to the surroundings. Hazards can arise when hydrogen forms an ignitable mixture with air or contaminants leak into a cold hydrogen system, such as by cryo-pumping.

Hydrogen leaks generally originate from valves, flanges, diaphragms, gaskets, and various types of seals, fittings, and hose connections. Leaks are usually caused by deformed seals or gaskets, valve misalignment, or failures of flanges or equipment. A leak may cause further failures of construction materials.

Pressure ruptures

Liquefied hydrogen will gradually heat up to the ambient temperature, and if it is trapped, as in a pipe between two valves, the pressure will increase. The resulting pressure from the trapped volume of liquefied hydrogen being vapourised and warming up to the surroundings is more than 850 bar. Heating up LH2 without a phase change will also result in a significant pressure increase (NASA, 1997). A malfunctioning pressure relief system may, therefore, lead to component damage.

Brittle fractures

System components may fail due to materials being used below their transition temperatures or by being cooled down by accidental events.

Some metallic materials used in pressure vessels and other components can significantly lose their ductility when exposed to hydrogen. This phenomenon is known as hydrogen embrittlement, and it occurs when hydrogen or hydrogen compounds permeate the material's lattice structure. Material degradation induced by embrittlement can result in catastrophic failure of containment structures. This may occur if hydrogen embrittlement is not counteracted by proper design and selection of all materials in contact with hydrogen.

Already at temperatures above 200 °C, many low-alloyed structural steels can suffer from another hydrogen-related embrittlement phenomenon known as hydrogen attack. It is a non-reversible degradation of the steel microstructure caused by a chemical reaction between diffusing hydrogen and the carbon in the steel, resulting in methane formation. The severity of the hydrogen attack increases with increasing temperature and pressure (ISO, 2015).

Corrosion failures

Hydrogen is non-corrosive, but stainless steel is a commonly used material in systems for hydrogen. The most common form of corrosion displayed by stainless steel is pitting, which occurs when the surrounding conditions overwhelm the passive film. Stainless steel also experiences crevice corrosion resulting from deposits that create crevices on metal surfaces. External stress corrosion cracking of stainless steel appears as cracking in areas with high tensile stresses, typically at welds, and is associated with saltwater retained on the material surface.

Fatigue

Hydrogen is known to significantly accelerate the initiation and propagation of fatigue cracks in a structure; components subjected to frequent load cycles can develop local fatigue failures. Due to dynamic loads and vibration, this risk is generally higher on ships than for shore-based installations. Systems for liquefied hydrogen have load cycles relating to heating and cooling, while high-pressure compressed hydrogen (CH2) systems are frequently loaded and unloaded by pressure differences.

Freezing leakage

If water or moisture is present before cooling down, fractures may occur due to the expansion of the ice formed. Therefore, it is vital to ensure dryness of the internals of fuel containment and piping systems prior to introducing LH2.

Contraction leakage

Sudden cooling down can lead to contraction and leakage from bolted flanges, which may have to be specially designed to overcome this problem.

Maintenance

Mechanical damage to the fuel containment system during maintenance could lead to leakages later on. Leakage of LH2 or CH2 when the system is opened for maintenance is possible if the maintained part is insufficiently isolated from the rest of the system. Poor workmanship during maintenance or repairs, including the use of unsuitable replacement parts, could lead to system failures. Similarly, inadequate or lack of maintenance can lead to system failures.

3.2.3 Operational and emergency events resulting in hydrogen releases

Emergency and operational releases of hydrogen from fuel containment systems

LH2 is typically stored in vacuum-insulated pressure vessels at -253°C. Due to heat input, hydrogen will boil off and accumulate in the ullage space above the liquid, increasing the tank pressure. This increases the liquid's boiling point, allowing it to be stored for extended periods. When the vapour pressure reaches the set point of the tank’s pressure relief valves, the hydrogen vapour is released automatically as cold vapour at the vent mast outlet on the open deck.

Hydrogen molecules have two energy states: ortho and para. At room temperature, 75% of hydrogen is in the ortho state, while at -253°C, it switches to the para-state. The conversion process is slow, and the transition from ortho to para releases energy and may affect the stored hydrogen boil-off rate.

If the tank loses its vacuum-insulation capabilities, the heat input will increase significantly, and all the liquid hydrogen in the tank will boil off within a relatively short time. In this scenario, the complete tank contents will be discharged as cold vapour at the vent mast outlet.

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

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

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

Emergency and operational releases of hydrogen from fuel piping systems

Similar to tanks for LH2, piping systems will experience a rise in pressure for trapped volumes of LH2 (e.g., between two valves) when the hydrogen is heated by the surroundings. Unless this pressure build-up is limited through relief devices, the pressure may exceed the design pressure of the piping system.

If the piping system loses its vacuum-insulation capabilities, the heat input will increase significantly, and all the liquid hydrogen in the system will boil off within a relatively short time. In this scenario, the complete contents of the pipe segment will be discharged as cold vapour at the outlet of the pressure relief device.

If safety devices installed to limit the piping system pressure fail or develop a leak, hydrogen gas will be discharged at the outlet of the pressure relief device.

3.2.4 Ignition sources

Fires and explosions have occurred in various components of hydrogen systems due to various ignition sources. Ignition sources have included mechanical sparks from rapidly closing valves, electrostatic discharges in ungrounded particulate filters, sparks from electrical equipment, welding and cutting operations, catalyst particles, and lightning strikes near the vent stack. In some situations, such as when hydrogen is suddenly released from a high-pressure system, it may be challenging to determine the exact source of the energy (ISO, 2015) (NASA, 1997). The table below summarises typical ignition sources to consider when evaluating hydrogen installations.

Table 3-2 Typical ignition sources to consider when evaluating hydrogen installations.

Mechanical ignition	Thermal ignition	Electrical ignition
Mechanical impact and/or friction and galling, rapidly closing valves.	Open flames and/or hot surfaces e.g., welding and cigarette smoking by personnel.	Charge accumulation leading to static discharge. Static charge is the accumulation of electrons on a surface based on a material's electrical conductivity and dielectric strength parameters. Solid particles in the flow could greatly increase the build-up of an electric charge (oxygen, carbon dioxide, nitrogen, hydrogen, sand, metal, oxide flakes from the walls of pipes, etc.). The large surface area of filters allows static charge to accumulate more readily. Lack of proper bonding and grounding can cause the buildup of static charges in piping systems. Unless anti-static clothing is used, the presence of personnel could introduce an ignition risk. Discharges of static electricity can produce high temperatures, often sufficient to cause ignition of hydrogen.
Metal fracture	Exhausts e.g., from combustion engines and exhaust stacks.	Electrical charge generated by equipment operation e.g., compressors, generators, construction equipment.
Mechanical vibration and repeated flexing.	Explosive charges e.g., construction charges, fireworks, or pyrotechnic devices.	Electric arcs can provide the energy to ignite a combustible hydrogen/air or hydrogen/oxygen mixture. Normal sources include switches, electric motors, portable phones, pagers, and radios.
	Hydrogen's interaction with catalysts or other chemical reactants can result in high temperatures.	Electrical short circuits or other electrical equipment failures can produce high surface temperatures, arcs, and sparks.
	Heating by high-velocity jets as might occur from the rupture of a tank or vessel.	Lightning strikes and their potential electrical fields can result during the approach and passing of a storm system.
	Shock waves and/or fragments as might occur from the rupture of a tank or vessel.	
	Reflected or repeated acoustic and shock waves as might occur in a flowing system.	

In a thorough review of hydrogen ignition mechanisms, (Molkov, 2012) refers to a study on hydrogen incidents, which found that hydrogen releases had more cases of unidentified ignition sources than non-hydrogen releases. Of the 81 reviewed hydrogen ignition accidents, 11 cases could identify the ignition source, while the remaining 86.3% did not have an identified source of ignition. This contrasts with data for non-hydrogen releases where 1,5% did not ignite and 65.5% had unidentifiable ignition sources. The higher percentage of unidentified ignition sources for hydrogen does prove the suggestion that there is a difference in the propensity for ignition between hydrogen and non-hydrogen gases when released.

The review also discusses spontaneous ignition caused by a sudden release of hydrogen from high-pressure systems. It is an agreed opinion that the probability of such ignition is high if mitigation measures are not undertaken, but the review notes that relevant requirements for high-pressure systems handling CH2 do not mention the problem or how to avoid it. Numerical analyses indicate that the issue does not appear in systems with operating pressures below approximately 30 bar[5] (Molkov, 2012).

3.3 Hydrogen safety risks

Hydrogen in marine applications presents unique safety challenges compared to its use in industrial environments on shore. It may also involve closer proximity to the public during port stays and is often designed, built, and operated by new entrants who may lack experience in hydrogen maritime safety engineering. In addition, the more extreme properties of hydrogen compared to natural gas are likely to make the established safety barriers of the IGF Code insufficient to provide an acceptable level of safety. This chapter will address risks introduced by installing a hydrogen fuel system onboard a ship, exemplified by uses onboard and description of potential events caused by the combination of hazards and threats discussed above.

3.3.1 Damage to fuel containment and piping systems by external events

Severe damage to fuel containment systems and, to a lesser extent, piping systems is a catastrophic event. Consequently, it is of utmost importance that storage and distribution systems for hydrogen are sufficiently protected against potentially damaging external events. Collisions, groundings, fires, and cargo and ship operations are events that have the potential to damage a storage tank.

Damage to a LH2 storage pressure vessel will result in a physical explosion referred to as a boiling liquid expanding vapour explosion (BLEVE). The energy released by a BLEVE, in combination with the likely ignition of the escaped gas, will cause considerable damage to a ship and be life-threatening to the people onboard. Gaseous hydrogen used as ship fuel is typically compressed to very high pressures (250-700 bar). Under such pressures, hydrogen tanks have considerable potential (stored) energy, like any other gas. The release of this energy can generate strong pressure effects depending on the release rate, even without the expected subsequent combustion.

3.3.2 Hydrogen releases on the open deck

According to existing guidance on hydrogen safety (ISO, 2015) (NASA, 1997), safety evaluators and others should assume an ignition source is present even when stringent measures to remove ignition sources have been taken.

The consequences of igniting hydrogen released on an open deck will depend on the circumstances. The ignition of a gaseous hydrogen-air mixture in an unrestricted open-air environment usually results in ordinary deflagration with little pressure build-up. The direct initiation of a detonation needs much higher ignition energy than the initiation of a deflagration. Detonations of non-confined gas clouds tend to occur more easily with increasing cloud size.

The presence of confining surfaces and obstacles such as pipes, tanks, and enclosure walls can significantly elevate the flame speed to hundreds of meters per second in a process known as flame acceleration (slow/fast deflagration). If the flame reaches a high enough speed and encounters turbulence and flame instabilities, deflagration can transform into a detonation. This is called a deflagration-to-detonation transition (DDT), and the potential hazards are further increased if detonation results. A deflagration can evolve into a detonation in a partially confined enclosure. The geometry and flow conditions (turbulence) strongly affect the transition from deflagration to detonation.

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[5] The inverse Joule-Thomson effect will not be the primary cause of any combustion that occurs when hydrogen is vented from a high-pressure source. The temperature increase from this effect is only a few degrees Kelvin at the most; it would not raise the gas to its ignition temperature unless it was already near the ignition temperature (NASA, 1997).

Tank discharges are significant threats to hydrogen ignition on the open deck. If a storage tank loses its vacuum insulation for some reason, the resulting boil-off could empty the entire tank in hours, and there would be no way to stop the flow of vapourised cold hydrogen out of the vent mast. A similar situation could arise if the safety valve fails or if the tank content is heated up to the safety valve's set point. If ignited, it will likely result in a constant jet fire from the vent mast outlet after the initial event described above.

Blast waves from explosions will cause injury as a result of overpressure at a given location or a combination of overpressure and duration at a given location as follows (NASA, 1997):

Table 3-3 Possible consequences of people being exposed to overpressure

Overpressure (psi)	Injury type
3 psi	1% eardrum rupture
16 psi	50% eardrum rupture
10 psi for 50 milliseconds or 20-30 psi for 3 milliseconds	Threshold of lung rupture
27 psi for 50 milliseconds or 60-70 psi for 3 milliseconds	1% mortality

The radiant heat that reaches and is absorbed by a person from a hydrogen-air flame is directly proportional to various factors, including exposure time, burning rate, heat of combustion, size of the burning surface, and atmospheric conditions (especially water vapour). Thermal radiation flux exposure levels show the following:

Table 3-4 Possible consequences of people being exposed to heat radiation

Thermal radiation flux	Injury type
0.47 W/cm^2	Pain felt in 15-30 s Skin burns in 30 s
0.95 W/cm^2	Immediate skin reactions

A worst-case scenario involving hydrogen ignition on the open deck is probably a delayed ignition of an established hydrogen plume above the ship, continuing as a jet fire from the top of the vent mast. The risk of a damaging pressure build-up from a deflagration of the initial hydrogen cloud will depend on the geometry around the release point at the top of the vent mast. The heat load from the jet fire depends on hydrogen mass flow, the height of the vent mast and the geometry around the release point.

3.3.3 Hydrogen releases in an enclosed space

Hydrogen leakages in enclosed spaces onboard a ship can develop in several ways depending on the circumstances. Various paths can lead to a deflagration or even a detonation inside the space, resulting in a rapid pressure build-up that could destroy the enclosure and other safety features required to control the hydrogen system. This has been thoroughly described in (Molkov, 2012) and in (HyResponse, 2015) as summarised below and illustrated in Figure 3-5.

An un-ignited hydrogen release will lead to the accumulation of hydrogen within the space. If the hydrogen leakage rate exceeds the ventilation rate in the space, a hydrogen concentration above LFL will be produced, creating a possibility for delayed ignition in a layer and resulting deflagration. Larger leakages can also create an overpressure in the leakage space unless proper pressure relief through ventilation is arranged. If hydrogen leaks at a lower rate than the space ventilation, not resulting in a layered hydrogen concentration above LFL, it can still result in a delayed ignition as a jet fire from the leak point.

Both types of delayed ignition can result in the deflagration of a hydrogen-air mixture with overpressure, potentially destroying the enclosure.

- For a space filled with a stochiometric hydrogen-air mixture, the flame temperature is such that a confined deflagration (excluding detonation) can cause a pressure peak of more than 800 kPa, which is more than enough to destroy the integrity of bulkheads and decks forming double barrier spaces.

- If the enclosure were only partly filled, the pressure would be less, as only the hydrogen layer would increase in temperature, not the whole volume.
- Venting of hydrogen explosions is not simple because the flame speed is high, giving a rapid rate of pressure rise. This makes it difficult to vent the combustion products fast enough. There are significant uncertainties unless venting is from very simple, mostly empty volumes.
- Pressure is governed not just by flame temperature but also by flame speed. This can produce higher pressures than quoted here. In some cases, deflagration can result in a transition to a self-sustaining detonation. Due to the higher flame propagation velocity and higher levels of overpressure, detonations present greater hazards than deflagrations.

An ignited hydrogen release can develop into a well-ventilated fire or an under-ventilated fire. In a well-ventilated fire, sufficient oxygen is present in the enclosure for complete hydrogen combustion.

- The heat load from a well-ventilated fire may damage essential safety components in the space, lead to structural failure of load-bearing construction elements due to direct flame impingement, etc.
- A well-ventilated fire may transform into an under-ventilated fire where oxygen is consumed faster than it can be replenished (e.g., if the leakage rate increases, the ventilation rate is reduced, or ventilation stops). This could lead to a scenario where the hydrogen burns out through the ventilation openings, but without sufficient air to have combustion inside the space, or to a full self-extinction within the enclosure. The self-extinguished under-ventilated fire may re-ignite when a fresh supply of air enters the enclosure. It can potentially lead to a localized deflagration and a diffusion flame in the zones containing hydrogen above LFL.

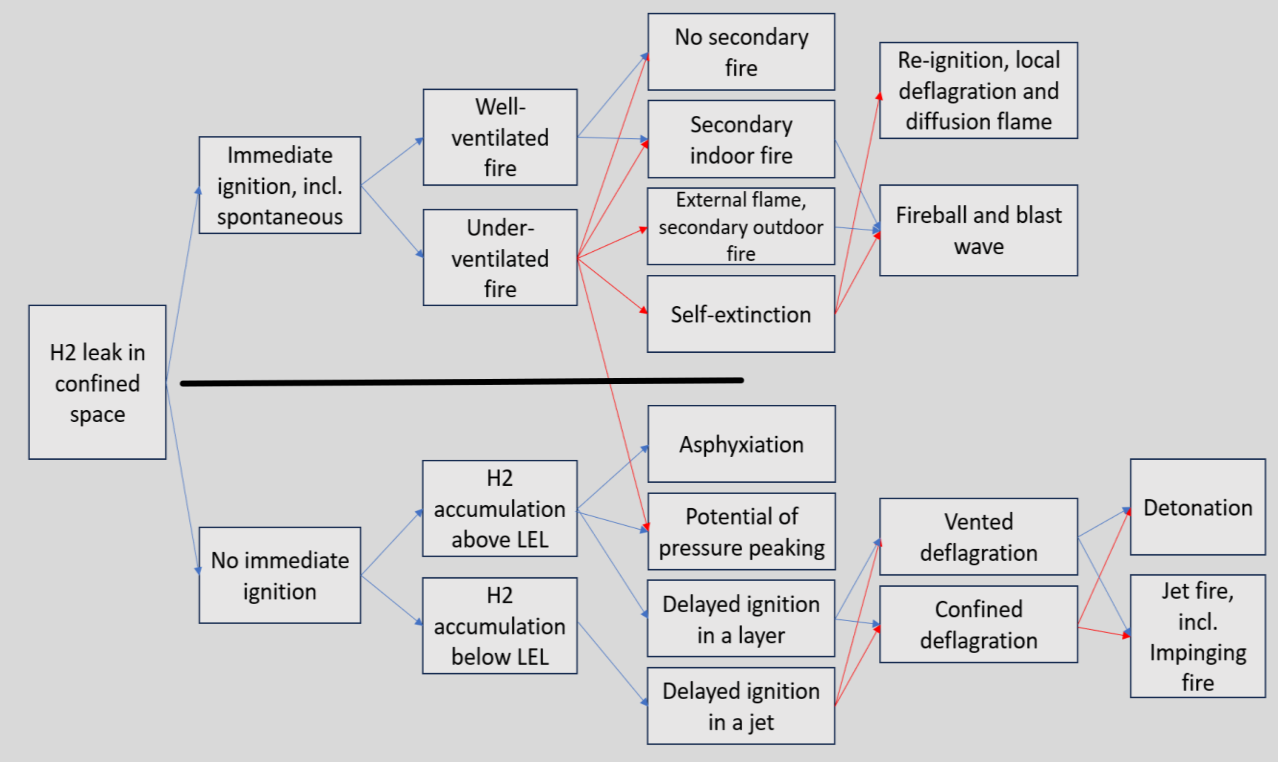

Figure 3-5 Safety-related phenomena – hydrogen leakage in confined space (inspired by (HyResponse, 2015)).

According to (ISO, 2015), deflagrations of gaseous hydrogen-air mixtures in enclosed spaces can produce pressures as much as 8 times the initial pressure, even more in special geometries. Detonation of hydrogen-air mixtures can produce pressures as much as 20 times the initial pressure (for very short durations, even more) and, with reflection, pressures 50 times the initial pressure. The spaces at risk of these explosions on a ship would typically include tank connection spaces (TCS), fuel preparation rooms (FPR), fuel reforming spaces and gas valve units (GVUs).

It is important to note that relief systems designed to protect hydrogen systems from overpressure rely on sensing pressure build-up. However, because detonation waves move faster than the speed of sound, relief systems cannot detect the approaching detonation wave in time to protect the system from rapid pressure increase. Rupture disks, relief panels, and similar systems are only effective against combustion phenomena that progress more slowly than the speed of sound (deflagrations, not detonations) (ISO, 2015).

The release of LH2 can result in significant cooling effects and may cause temperatures to drop below the ductile-to-brittle transition temperature for affected materials. This could damage load-bearing structures, compromise the gas-tightness of safety barriers, and affect the integrity and function of safety equipment.

Evaporated hydrogen expands to nearly 850 times the liquid volume, causing a pressure increase in enclosed spaces. If the space is not arranged with pressure relief and the leak is large, the resulting pressure may exceed the space's design capabilities.

Experiments have shown that evaporated hydrogen can quickly displace a breathable atmosphere and reduce the temperature to well below levels sustainable for human exposure (FFI, 2021). Personnel must be kept safe from direct contact and inhalation of cold fluids and indirectly from low surface temperatures of equipment. A leakage of cryogenically stored fuel in the vicinity of personnel could lead to cryogenic burns, internal damage due to cold vapour inhalation, and asphyxiation due to oxygen displacement. Also, the evaporation of liquids and the dispersion of low-temperature vapours might prevent personnel from accessing main escape routes and refuge areas, restricting safe evacuation.

When hydrogen is introduced to a tank or a piping system, a flammable mixture can be formed and ignited. The resulting pressure could be higher than what the systems are designed for. This can happen during gassing up and gas freeing of tanks, when gas is released through vent masts and relief systems, during bunkering operations and during normal operation of the hydrogen system. Air contaminations in LH2 systems can increase the risk of ignition. Air in an LH2 system will solidify as nitrogen, oxygen, and frozen water. These contaminants can cause obstructions in piping or instruments, causing equipment malfunction and presenting a possible explosion hazard when systems are heated up and the oxygen-enriched air evaporates.

3.3.4 Loss of vacuum insulation for fuel containment and piping systems

LH2 is stored at a temperature of -253°C, which is lower than the condensation temperature of the nitrogen and oxygen in the air. If the storage tank insulation is lost, the external surfaces of the LH2 containment may become cold enough to liquefy the oxygen and nitrogen in the air. Air is composed of 20.9% oxygen and 78% nitrogen. The liquefied gases produced by condensation on cold surfaces are not the same composition as the surrounding air. Due to the higher boiling point of oxygen (-183°C) compared to nitrogen (-196°C), oxygen condenses preferentially to nitrogen, resulting in liquid air with an oxygen concentration that could reach 50%. This oxygen-enriched liquid air poses an explosion hazard (CSA, 2015). Additionally, condensed air reaching ship steel could rapidly result in structural damage from low-temperature embrittlement. Consequently, designs must keep condensed air away from materials that can fail due to contact with liquids at cryogenic temperatures and from flammable materials.

When vacuum insulation is lost, the heat input to storage tanks and piping systems will increase rapidly. Pressure relief systems must be able to handle the quick pressure increases and hydrogen boil-off to prevent overpressure and potential failures of the tank or piping system. As mentioned in section 3.2.3, if the vacuum insulation is lost, the entire tank's contents may boil off in a matter of hours. When large volumes of cold gas are vented through the vent system and the vent mast, there is also a risk of cooling the venting system to below the condensation temperature of the air, with a similar risk as described above.

The loss of the tank’s vacuum insulation can lead to extremely low temperatures in the tank hold space, tank connection space, and areas where the vent system is located. This could potentially compromise the structural integrity of these spaces and the systems within them.

3.3.5 Heating of liquefied hydrogen in confined volumes

The density of LH2 decreases significantly with increasing temperature. If a storage tank is filled with cold LH2 without leaving enough reserve ullage space to allow for the liquid's expansion, the tank can become liquid-full when heated. Similarly, piping systems for LH2 will experience a rise in pressure for trapped volumes of LH2 (e.g., between two valves) when the hydrogen is heated by the surroundings.

4. Established principles for mitigation and control

Eliminating hazards is always the best option, but it may not always be possible. In such cases, it's essential to implement a range of risk controls to reduce the risks to an acceptable level. In this chapter, we briefly discuss established principles for mitigation and control and their applicability to ships using hydrogen as fuel.

The "Hierarchy of Risk Control Measures" illustrated in Figure 4-1 highlights the significance of recognising the greater effectiveness of technical measures over operational measures in managing risks[6]. The five layers of the inverted pyramid serve as lines of defence. Elimination and substitution are the most effective, followed by engineering controls such as designing double-walled piping systems or limiting an operation's pressure or flow rate. Administrative controls involve fitting alarms and signboards and providing training or procedures that reduce an individual's exposure to hazards. Finally, ensuring access to personal protective equipment (PPE) is the last line of defence and is the least reliable control.

Proper training and operating procedures are essential for ensuring the safe operation of a ship throughout its lifespan. However, the most efficient contributions to controlling risks and establishing a safe foundation for operation can be added during the design phase, utilising control measures from the top of the hierarchy. Finally, the design intent needs to be maintained through the full life cycle: safety measures should not degrade.

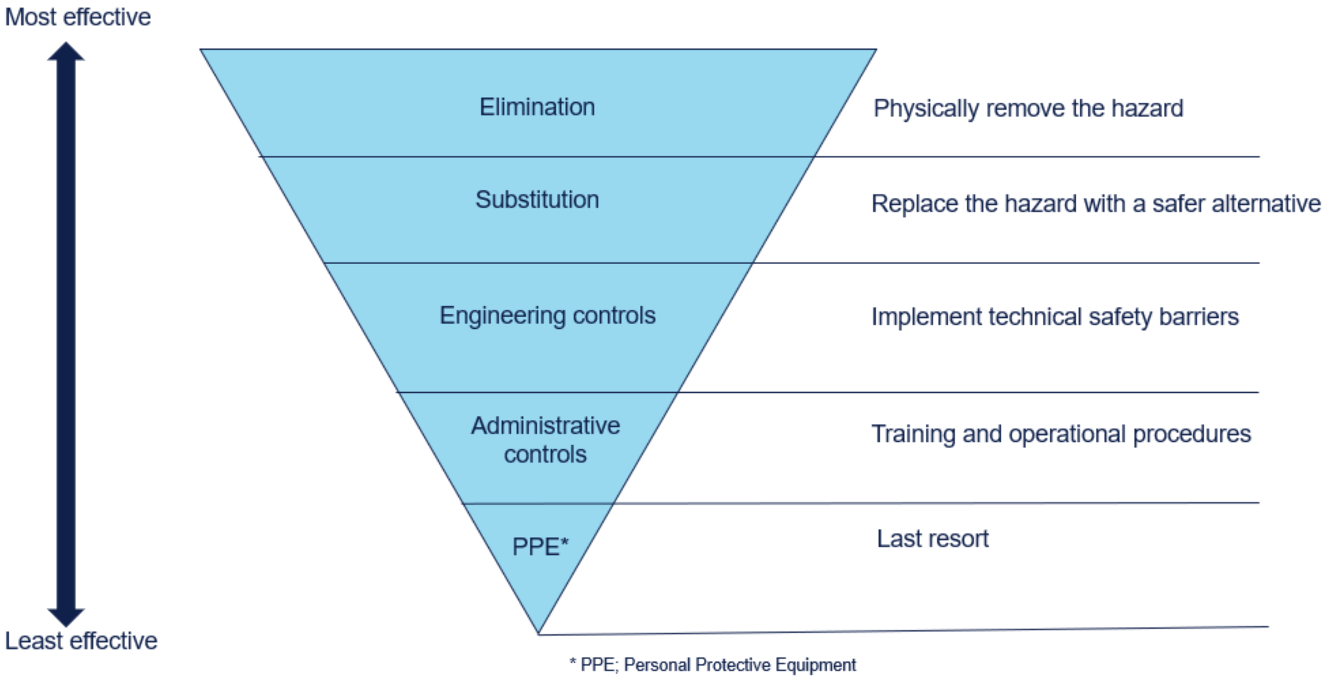

Figure 4-1 The Hierarchy of Risk Control Measures (Source: DNV).

Similar principles are reflected in established safety standards for hydrogen:

- Hazards shall be eliminated or reduced to acceptable risk levels, relocated, or isolated in that order of priority. When this is not achievable, protection shall be provided to ensure adequate safety levels, and people shall be enabled to leave the area safely (NASA, 1997).
- Recommended design principles include e.g., minimizing hydrogen quantities and flow rates, identifying and separating or eliminating potential ignition sources, preventing hydrogen accumulation in confined spaces, use of alarms and warning devices, and area control, separating people and facilities from potential effects of hazards, minimizing personnel exposure, use of PPE and safe operational procedures (ISO, 2015).

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[6] A safety system known as the “hierarchy of controls” was introduced in 1950 by the National Safety Council. The goal was to control exposures to hazards and risks as a way of protecting workers.

The general principles, guidelines, and recommended practices established based on the knowledge acquired in other industries are vital for the safe handling of hydrogen (Molkov, 2012) (NASA, 1997) (ISO, 2015). There are, however, principal differences to be considered when moving hydrogen technologies onboard ships. This relates to a variety of conditions:

- A ship operating out in the open seas is self-reliant and can, in most instances, not rely on help from outside.
- Crew and passengers cannot escape to safety in the same way as from a car or from within a building on shore.
- Due to space constraints, the safety distances are much smaller on a ship than on a comparable installation on shore.
- The environmental conditions on board ships with dynamic loads, humidity, sea spray, vibrations and inclinations are more challenging than on land.
- The power demand for a ship is typically of a different order of magnitude compared to other applications (for instance, automotive) considering similar fuel technology.
- Low-temperature materials are a necessity for LH2. Unlike supporting structures for onshore facilities, normal ship steel grades are not resistant to low temperatures.
- Shutting off the hydrogen supply may be necessary as an automatic safety action. For a ship, this may also result in loss of propulsion power and auxiliary power generation capabilities.

For the above reasons, not all land-based solutions and safety principles are directly transferable to ships but will be reflected as far as possible in the development of the Guidance for ships using hydrogen as fuel.

5. Review of hydrogen-related accidents

Using hydrogen as a ship fuel is a relatively new concept, so it is important to learn from other industries' experiences with hydrogen safety. This chapter will analyse previous accidents in different industries using hydrogen, give an overview of the most common causes of hydrogen-related accidents, and learn from the consequences of previous failures. This will help devise strategies to prevent accidents related to hydrogen systems on ships.

The European Hydrogen Safety Panel (EHSP), as part of the Fuel Cells and Hydrogen Joint Undertaking (FCH 2 JU), put together a working group to analyse over 700 incidents in the HIAD 2.0 database. The result from this work is presented in the report "Statistics, lessons learned and recommendations from analysis of HIAD 2.0 database", published in September 2019 (X. Wen, et al., 2019). The following sections will summarize the findings from this report and input from other studies on the topic. The HIAD 2.0 database includes accidents and events from the following sources:

- The French database ARIA
- The EU database eMARS
- The database IChemE
- The Japanese database RISCAD
- US CSB, NTSB and OHSA
- Other public databases
- Scientific articles
- Online news from local and technological newspapers.

5.1 Main causes

From the 575 accidents analysed in the HIAD 2.0 database, the leading causes of hydrogen-related accidents fall into two categories: system design failure and human error. A combination of both was also a cause of accidents with severe consequences. Figure 5-1 shows that the cause was related to technical issues in 422 events and human error in 532 events. The largest number of cases were linked to safety management system factors (49%). The second largest cause was errors in material or manufacturing (35%). The same figure also shows that many of the incidents were caused by individual human errors (29%) and system design errors (27%).

Figure 5-1: Number of events categorised by cause (many events had multiple causes, providing a total of more than 100%). Based on 575 events from the HIAD 2.0 Database (X. Wen, et al., 2019).

The report also found that 75% of the incidents were initiated by hydrogen systems and 25% by non-hydrogen systems (X. Wen, et al., 2019). In 46 of the cases in the ARIA database, hydrogen was generated accidentally, which can be even more dangerous as hydrogen risks would not be expected and difficult to account for. The analysis of such events showed that corrosion of steel, the reaction between water and metal, the formation of water gas, and other chemical reactions involving hydrides could lead to accidental generation of hydrogen (ARIA, 2009).

Another study investigated safety issues and accidents from hydrogen fuelling stations in Japan and the USA (Sakamoto, et al., 2016). The analysis showed that, in the USA, the main causes of hydrogen leakage in fuelling stations were design errors and inadequate fatigue planning. In Japan, leakages resulted mainly from damage and fractures in the main bodies of the equipment and pipes. From the 21 accidents in Japan between 2005 and 2014 and the 22 accidents in the USA between 2004 and 2012, the main causes are aligned with the findings from the analysis of the accidents in the HIAD 2.0 database, i.e., design error and human error. Other accidents related to hydrogen fuelling stations were fatigue, inadequate torque and sealing of screw joints in the fuelling system, and manufacturing errors of the equipment used in the system.

NASA did an analysis of 145 industrial hydrogen accidents, 125 hydrogen accidents in ammonia plants and 107 aerospace hydrogen incidents. 53% of the hydrogen accidents on industrial sites were caused by off-gassing, equipment ruptures and leaks. Most of the hydrogen-related accidents in ammonia plants were caused by gaskets and valve packing leakage, and 81% of accidents in aerospace hydrogen incidents were mainly caused by hydrogen leakage both in gaseous and liquid states. An overall grouping of the mentioned accidents identified by NASA is equipment failure. The rest of the accidents were mainly caused by human errors and lack of sufficient safety procedures (NASA, 1997). Even though the report is from 1997, the main causes of the accidents in the NASA report are similar to the accidents and events in the HIAD 2.0 database.

5.2 Consequences

Of all the events recorded in the HIAD 2.0 database, 79% involved ignited hydrogen, and of these 48% led to explosion and 31% resulted in fire. 15% of the events resulted in leakage with no ignition, and 6% were near misses. The learning from the events resulting in leakage but no ignition and near misses is that early detection and quick mitigation of a potentially larger release of hydrogen can potentially avoid escalation to fire and explosion.

The ARIA database, which is included in the HIAD 2.0 database, has 215 recorded accidents involving hydrogen that happened before 2007. 84% of events led to fire and explosion, 12% were mortal accidents, and 13% caused serious injuries, mainly to employees working at the site. Sources that led to the ignition of hydrogen were identified as hot spots, lightning, electricity, mechanical sparks and static electricity (ARIA, 2009).

5.3 Lessons learned and recommendations

To prevent future accidents, safety issues need to be identified and considered at the earliest stage possible, preferably in the design stage, but it is important to have a safety focus throughout the lifetime of the system. Lessons learned from past accidents are efficient tools for preventing future accidents. It was found that different events analysed in the HIAD 2.0 database had the same or similar causes, which proves that lessons learned from earlier accidents can help improve safety if applied.

The lessons learned from the events in the HIAD 2.0 database are divided into four main categories: (1) system design, (2) system manufacturing, installation, and modification, (3) human factors, and (4) emergency response. Overall, the main lesson learned from this study was that incidents or accidents could be caused by several minor events, and the consequences could be serious if they happen simultaneously. Consequently, small leakages and minor events should be taken seriously, and quick action should be taken to avoid potential escalation of the event.

1. System design

The lessons learned from the events in the HIAD 2.0 database under the category of system design were related to corrosion that was not detected during regular inspections, maintenance, or incompatible use of materials. Other important factors identified related to error in system design were lack of venting, fatigue, extreme weather conditions, lack of second-order redundancy on critical systems, bad design, or installation of pressure relief valves, hydrogen accumulation in confined/semi-confined spaces, hydrogen generation due to malfunction, bad equipment, and inadequate safety design for the interconnections during hydrogen transfer.

2. System manufacturing, installation, and modifications

Lessons learned with regard to system manufacturing, installation and modifications were grouped into material compatibility, venting system, and weak points. Incidents related to material compatibility led to damage or even cracks in the material used in the system, leading to leakage of hydrogen. The malfunction of hydrogen venting systems, weak points such as flange connections, welded junctions, and gauge glass for monitoring the tank level led to several incidents.

3. Human factors

However, nearly half of the incidents in the HIAD 2.0 database were related to human and organisational errors. The lessons learned related to human factors include that accidents may happen due to the following:

- Lack of regular and timely maintenance and inspection plans.
- Inadequate attention to safety devices during maintenance.
- Incorrect equipment installation after failing to follow proper procedures.
- Lack of clear instructions from supervisors.
- Insufficient control to ensure safety when restarting after a repair.
- Lack of thorough degasification and adherence to safety procedures when reusing tanks or pipes that previously contained flammable liquid or gas.

Additionally, there are lessons learned related to safety system management, including:

- Insufficient inspection plans.
- Lack of frequent inspections and safety procedures.
- Failure to check safety equipment and inspect materials for embrittlement from contact with hydrogen.

4. Emergency response

A sub-category of the above is related to emergency response. For shore-based industries, this is typically left to specially trained emergency services. On a ship, managing emergencies is the responsibility of the crew. A lack of training of emergency personnel was also identified as a contributing cause. The events studied in the HIAD 2.0 database showed that the consequence of hydrogen-related accidents/incidents can be mitigated if the first responders have sufficient knowledge about hydrogen safety and its properties when an event has occurred. The escalation of an incident could be prevented by quick action to limit inventories, which means that communication between the emergency service personnel and the technical experts must be transparent and quick. Another important lesson worth mentioning is that extinguishing fire simultaneously with hydrogen leakage could result in a more severe hydrogen explosion.

Safety issues need to be identified and considered in regulations at the design stage to prevent future accidents, but it is equally important to have a safety focus throughout the system's lifetime. Training the operating personnel and increasing their understanding of hydrogen hazards is crucial to preventing future hydrogen-related incidents. Similarly, the safety management systems must properly account for hydrogen hazards in operating procedures, inspection plans and emergency response procedures.

6. Validation of hydrogen modelling techniques and tools

This chapter presents a review of hydrogen modelling techniques and tools, discussing their use, methods, reliability, scope, and limitations in industrial sectors. While chapter 6.1 provides a general analysis of modelling tools available in the industry, chapter 6.2 offers a more detailed review of the specific consequence analysis tools that DNV plans to use in the continuation of this safety study.

6.1 General analysis of modelling techniques and tools

The "Handbook for Hydrogen-Fuelled Vessels" published in 2021 (MarHySafe, 2021), and the “Guidance on Hydrogen Safety Engineering” prepared by the European Hydrogen Safety Panel (EHSP) (EHSP, 2023), provide comprehensive descriptions of the scope and limitations of the most relevant modelling techniques and tools used for hydrogen. These range from qualitative methods to advanced Computational Fluid Dynamics (CFD) tools.

The subsequent sections offer insights into hydrogen safety modelling, categorised by various phenomena. For more detailed descriptions, we recommend referring to the reports by DNV and EHSP mentioned above.

This review does not include generic qualitative and quantitative modelling techniques, such as Fault Tree Analysis (FTA), Event Tree Analysis (ETA), and Quantitative Risk Analysis (QRA).

Leak frequencies

Hydrogen-specific failure data is essential for estimating reliable frequencies of hydrogen leaks and is a critical input for all quantitative risk analyses. Currently, estimates in maritime quantitative risk analysis for hydrogen leak frequencies must either rely on historical data from “general” onshore and offshore equipment (e.g. databases such as PLOFAM[7], HCRD/UK HSE[8], IOGP[9] and RIVM[10]), or apply failure rates for hydrogen-specific operating experience based on HyRAM leak frequency data, presented in a Sandia Report from 2022.

The general onshore and offshore equipment failure databases are based on equipment operating under different conditions compared to ship applications (MarHySafe, 2021). Sea atmosphere/spray, green sea, thermal cycling, dynamic loads, vibrations, and inclinations due to ship and wave motions are examples of unique challenges. The factors influencing the leak probability and failure on demand probability of safety-critical equipment need to be addressed. Both PLOFAM and HCRD are based on offshore leak data, which has some similarities with ship applications in terms of the marine environment, but there are also fundamental differences comparing offshore installations with ships, as mentioned above. It should also be mentioned that the RIVM and HCRD databases formed the basis for leak frequencies in HYAPPROVAL (HyApproval, 2008).

If the general onshore and offshore equipment failure data is selected as the basis for initiating leak frequency, the most practical approach to accounting for maritime-specific factors is to adjust general leak frequency data using correction factors. However, due to the limited operational experience with marine hydrogen applications, it is challenging to accurately quantify or estimate these factors. Consequently, a common practice in quantitative risk analysis for hydrogen-fuelled ships applying general leak frequencies is to perform uncertainty analyses to demonstrate how variations in leak frequency might affect the overall risk level.

HyRAM includes generic probabilities for hydrogen equipment failures, as well as probabilistic models for consequence and risk analysis. However, this data set may not be sufficiently robust due to older and limited data recorded for hydrogen leaks. In addition, over 90% of all leaks in HyRAM relate to very small and small categories, and there is a lack of diameter-dependence in the model. Despite uncertainties with HyRAM application as described above, no other hydrogen-specific alternative leak record database has been established (MarHySafe, 2021).

The HIAD database (Chapter 5.1) describes incidents with leaks, fires, and explosions from hydrogen installations, without quantifying the leak frequency. The database is a unique source of leak incidents from hydrogen installations and is used by DNV to guide hydrogen leak frequencies for specific equipment.

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[7] Process leak for offshore installations frequency assessment model (PLOFAM)
[8] Hydrocarbon Release Database (HCRD) compiled by UK HSE
[9] International Association of Oil & Gas Producers - IOGP Report 434-03 - Study frequencies of releases from a variety of storage types
[10] National Institute of Public Health and the Environment (RIVM)

Due to limited operational experience with hydrogen, the leak frequency represents a relatively high uncertainty in the risk models. In the subsequent analysis of this safety study, DNV will perform a more detailed review of failure data for relevant equipment used on hydrogen-fuelled ships, including comprehensive reliability and safety analyses, to be presented in the next deliverable (Delivery D.2). Further information about leak frequencies can also be found in Appendix C in the Handbook for Hydrogen-Fuelled Vessels.

Ignition modelling

The ignition probability is used in probabilistic risk analysis to measure the likelihood of ignition in the event of a leak. Ignition can happen immediately when the leak starts, or at some time after, causing a delayed ignition. There are no tabulated values for hydrogen in general for use in a maritime setting. Therefore, the ignition probability needs to be assessed for each case. Examples of ignition models that are commonly used in the process industry are data contained in the RIVM (the "Purple Book")[11] and IOGP[12] directories.

A limited number of models are being used in quantitative risk analyses dealing with hydrogen as a risk source. Below, the most known are briefly described:

- **HyRAM:** The ignition model in the HyRAM toolkit is unique because it is specifically designed for hydrogen. The HyRam ignition model is also called the "DNV model". This model was developed from a specific project performed by the DNV office in Kuala Lumpur in 2006 and has been adopted by the industry although it has not been developed as a general ignition model. In general, models in HyRAM are being developed at Sandia National Laboratories for the U.S. Department of Energy and provide technical data on hydrogen safety to support national and international codes and standards. As an actively developed research project, its models and data may change, and their reports will be updated periodically (SANDIA, 2021).

- **HYEX:** The HYEX ignition model is based on the HyRAM model for small leak rates, while it is improved by being made continuous as a function of leak rate and takes into account that large leaks may have a significantly higher ignition probability than the HyRAM/"DNV model" suggests (DSB, 2021).

- **EIHP2:** As Part of the EIHP2 project (European Integrated Hydrogen Project Phase 2) a set of ignition probabilities for use on hydrogen refuelling stations was developed. The probabilities were assessed based on several literature sources and experiments (EIHP2, 2003).

- **Dutch "Purple Book":** Model described in Guidelines for Quantitative Risk Assessment "Purple Book" Part 1 Establishments. The Dutch "Purple Book" method separates between direct ignition and delayed ignition. For the direct ignition probability, the method separates between low reactive gases such as ethane and propane and "average to high" reactive gases such as acetylene and benzene. It is not stated which category hydrogen falls into, but it is likely that it falls in the "average to high" reactive gas category.

The Norwegian Directorate for Civil Protection (DSB) provides a review of the HyRAM and HYEX models in their Guidelines for quantitative risk analysis of facilities handling hazardous substances published in 2021. They state that the main limitation with HyRAM is that the ignition probability is in step functions and has no refining of leaks above 6.25 kg/s, meaning that all leaks above this value have the same total ignition probability of 35 %. DSB acknowledge that the ignition probability for hydrogen can be significantly higher than what the HyRAM model states. When using the HYEX model, all leaks over 12.5 kg/s will have a total ignition probability of 1.0. DSB concludes that the HYEX model is therefore currently recommended as an ignition model for hydrogen leaks in facilities (DSB, 2021).

The ignition models are under development, meaning that there is still a high uncertainty associated with using ignition probabilities for hydrogen. Therefore, conservative values should be applied in quantitative risk analysis. Also to be noted that ignition probability models are not established for liquid hydrogen at low temperatures, as they are mainly developed for gas and for hydrocarbon liquids at normal temperatures (MarHySafe, 2021).

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[11] The Dutch National Institute for Public Health and the Environment

[12] IOGP Report 434-06, Risk assessment data directory – Ignition probabilities

Ventilation, dispersion, explosion, and fire

The different tools and methods available span from empirical tools to more advanced CFD tools. In this review we are mostly focused on the CFD tools. Several studies have aimed at validating CFD models against controlled experiments to ensure accuracy in predicting hydrogen behaviour, making these models increasingly reliable for hydrogen applications. Additionally, tool owners have conducted validations without necessarily publishing public reports or papers. These validations include assessments of hydrogen leakage and dispersion in various environments, such as confined spaces, open atmospheres, and under different conditions of pressure and temperature. Moreover, dispersion, fire and explosion models are rigorously tested to accurately predict cloud sizes, flame propagation, explosion pressure, and thermal effects. CFD tools are also validated through inter-comparison exercises, where different models and codes are benchmarked against each other and experimental results. The modelling tools are summarized in general in Table 6-1, highlighting their capabilities and limitations.

Table 6-1 Summary of risk scenarios and tool capabilities and limitations

Risk scenario	Tool capabilities and limitations
Gaseous releases and dispersion - natural and mechanical ventilation	Available CFD models are well suited for such ventilation modelling both inside a room with forced ventilation and outside with natural ventilation. The overall accuracy is sufficient, and there are known uncertainties due to turbulence models, which one needs to be aware of. These uncertainties are not new for hydrogen. Due to the uncertainties of the models, a margin is often included to evaluate how large a gas cloud is accepted; typically, 50 % of the LFL concentration can be used to represent flammable gas clouds (MarHySafe, 2021).
High pressure storage and release	Models that can simulate the dynamic behaviour of the flow inside the process equipment and pipes during a rapid leak scenario are well validated. These models are used to calculate the flowrate given a leak hole size. Specific, highly dynamic release scenarios with high pressure and speed can be resolved with dedicated CFD models that has been through validation. Due to the large differences in properties for hydrogen compared with other flammable gases, and the high-pressure storage and rapid and complex dynamic effects that can happen during a leak, it can be beneficial to use experiments to validate CFD models that are not used for hydrogen before (MarHySafe, 2021).
Jet fire	Some CFD models are validated for hydrogen fires with available experiments. Research is ongoing for further development of CFD codes for prediction of complex hydrogen fires. Phenomenological models for hydrogen jet fires are also available (e.g., Phast Miller model). These models are used for open jets where no effects of obstacles are present (MarHySafe, 2021).
Explosions – in congested areas or in enclosures.	Commercial CFD tools (e.g., FLACS and KFX) for hydrogen explosion are validated for different experiments indicating that the models are capturing the general trends up to deflagration to detonation transition (DDT). There are also indicators in the models where the onset of DDT can be predicted. Discrepancies exist for the explosion models when comparing with experiments. This is also the case for modelling of other typical gas explosions, though the amount of validation is less for hydrogen than for natural gas or methane (MarHySafe, 2021).

Risk scenario	Tool capabilities and limitations
Deflagration to Detonation Transition (DDT)	DDT is not captured by the CFD models, however work around can be applied - Explosions that reach DDT and detonation above 1 barg are critical, and it is relevant, though not essential, to be able to precisely predict how high pressures are reached (MarHySafe, 2021). In a recent project by DNV (CostFX[13]) the conditions for when DDT occurs is investigated for a full-scale congested geometry. CFD models are currently being validated against these experiments.
Other types of consequences, such as flash fire or pressure tank rupture explosions and boiling liquid expanding vapour explosions (BLEVEs)	Such phenomena are typically modelled with simplified empirical models (e.g., using the Phast tool). The flashfire is typically modelled only by gas dispersion models assuming that the flammable cloud represents the size of a potential flashfire. Empirical tank rupture models exist for pressure vessels and are validated also for hydrogen tank ruptures causing pressure waves. The BLEVE models have few or limited validations for hydrogen when it comes to realistic, larger scales. In typical risk assessments, the tank rupture scenarios are not found to be driving the risk mainly due to low probability; therefore, extensive use of the models is not normally needed, and development of models is not prioritized (MarHySafe, 2021). The same goes for flash fire.
Projectiles from explosions	Established models for this phenomenon are lacking.

6.2 Analysis of selected consequence analysis tools

This analysis has compiled the information gathered from experts within the quantitative hazard analysis domain to obtain an overview of selected tools' capabilities to model hydrogen. These are the candidate tools that DNV may use in the continuation of this safety study. Note that even though it is stated that the tool has been validated for a specific hydrogen risk scenario, it must be stressed that the amount of validation is generally less for hydrogen than for natural gas or methane.

The selected tools are:

- Phast and Safeti
- Kameleon FireEx (KFX) and EXSIM
- FLACS and FLACS Fire

Noting other tools that are not part of this analysis: OpenFOAM, HyFOAM, EFFECTS, RISKCURVES, Shell FRED, Shell Shepard, Shell PIPA, ANSYS, CFX and GASFLOW.

Table 6-2 shows the validation categorisation of the selected tools while

Table 6-3 shows the results of the review.

Table 6-2 Categorisation of tools

Validation category	Abbreviation
Validated for hydrogen	Validated (V+)
Validated for hydrogen, but may require some parameter adjustments or workarounds to achieve results comparable to experimental research	Validated (V-)
Not validated for hydrogen, but general models exist and can be used	General (G)
Not applicable/ not recommended/ no model available, incl. unknown	(N/A)

Table 6-3 Validation overview of the selected tools

Hydrogen risk scenario and consequences	Phast and Safeti	Kameleon FireEx (KFX) and EXSIM	FLACS and FLACS fire
Gaseous horizontal releases and dispersion - natural ventilation above deck (unobstructed jet)	V(+)	V(+)	V(+)
Gaseous vertical releases and dispersion (vent release) - natural ventilation above deck (unobstructed jet)	V(-)	V(-)	V(-)
Gaseous releases and dispersion - Mechanical ventilation below deck (impinged jet inside vented spaces)	N	V(+)	V(+)
Gaseous releases and dispersion - Naturally vented areas, above deck (impinged jet in congested areas)	N	G*	G*
Liquid release (pool formation and evaporating pool)	V(-)	G**	V(-)
Pool fire (large spill, e.g. tank puncture after collision)	G	G	G
Jet fire***	V(+)	V(+)	V(-)
Explosion/ Deflagration in enclosures/confined spaces	V(-)	V(+)	V(+)
Explosion/ Deflagration in congested areas (partly open)	V(-)	V(+)	V(+)
Deflagration to Detonation Transition (DDT)	N	N/A	V(-)
Detonation	N	N	V(-)
Boiling liquid expanding vapour explosions (BLEVE)	N	G	Unknown

Noting:

* The performance for dispersion in unconfined, congested regions for both KFX and FLACS is rated “G” as the CostFX[13] experiments will be the first to assess this. Comparison and validation are ongoing.

** Liquid hydrogen release experiments are available, and a process is ongoing to validate KFX for this. KFX has an extensive multiphase CFD model that is validated for LNG, CO2 and other complex multiphase releases with dispersion and fire.

*** There are currently several sub-categories for dispersion, but performance for jet fires is grouped into one over-arching category. For information, KFX validation statuses for each of the sub-categories have been provided: Semi-confined enclosures, G; Impinged jets, V(-); Vertical jets, V(+); and Horizontal jets: V(+). It is noted that KFX is well suited and validated for fires inside engine rooms and semi-confined fires in general for hydrocarbon fires, and it is expected that this will also work fine for hydrogen fires since it is validated for hydrogen jet fires.

The following risk scenarios were not included in the review but are described briefly below:

- **Ventilation:** Air flow in natural (above deck) or mechanically ventilated areas is in general validated for CFD tools. This is usually run to obtain the initial conditions before a gas dispersion/fire scenario is started. It is further used to assess the effectiveness of the ventilation design in a room or open space.
- **Flash fire**: In general, explosions are more likely to happen with hydrogen compared with natural gas, due to the higher flame speed. A flash fire can harm people inside the cloud. Therefore, the capability to model flash fire is directly linked to gas dispersion (see gaseous releases).

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[13] CostFX JIP investigating cost-efficient explosion load descriptions for process areas.

- **Structural response:** There are tools developed to conduct dynamic response analysis of structures subjected to explosion/blast-induced shock waves, as well as consequences of heating of structures due to fires. There are no known validations of such tools considering hydrogen explosions or fire loads. As long as one selects a structure response tool that can capture nonlinear rapid dynamics, the loads from hydrogen are not, in principle, different than loads from other gases that they have been validated for. Hence, it is assessed that such tools can also be applied to hydrogen loads. The explosion pressure and thermal radiation may typically be derived from other tools (e.g. CFD), and such response tools can be used to further assess structural consequences. Validation of ABACUS is performed in the CostFX project with rapid, dynamic explosion loading on piping systems, indicating that this tool is capable of handling structure response to explosion loads. Similarly, the FAHTS/USFOS tools are validated for fire response analyses due to hydrocarbon fires and are expected to perform well also for hydrogen fire loads.

- **Cryogenic flow and consequences:** The phenomenon is investigated with testing and experiments, though modelling capabilities of special effects due to hydrogen are limited (MarHySafe, 2021). The MarHySafe handbook states that it is possible to undertake modelling with a special version of KFX (called KFX-LNG). It is then possible to model spray leaks and possible pools, including cooling effects when the cryogenic spray hits structural beams. However, such models are not yet validated for liquid hydrogen cryogenic loads and consequences.

6.3 Summary of tool validation

In evaluating consequence scenarios involving gas leaks, ventilation, dispersion, explosions, and fires, commercial CFD models are used to simulate these phenomena, and it is found that, in general, sufficient precision is obtained also for hydrogen. However, it requires that the user is familiar with the possible uncertainties. Specifically, these models can effectively capture the behaviour of hydrogen explosions up to the point of deflagration. However, it is important to note that there is typically less validation available for hydrogen compared to natural gas or methane. Also, note that certain consequence types (ref. chapter 6.2) have not undergone validation. However, this does not inherently render the tools unusable. Nonetheless, careful consideration must be given to the execution of the analysis where there is limited or no validation.

Several ongoing activities and projects are increasing the knowledge of realistic, full-scale hydrogen consequences, including a close collaboration between experimentalists and modellers. Such developments are underway to improve the commercial codes.

The CFD codes are also well suited in design and rule development to investigate the effects of design improvements where the consequences can be compared, and the relative differences obtained. The codes may have uncertainties in the absolute values obtained; however, when two solutions are compared, these codes are well suited to capture the optimal solution. In the development of maritime rules, the CFD codes are therefore well suited to investigate design options for hydrogen systems and select options which has both acceptable risk levels and are cost-effective[14].

While hydrogen-specific models exist for calculating leak frequency and ignition probabilities, failure data and validation are lacking to ensure their accuracy in quantitative risk analysis. Therefore, it is often here that we find the highest uncertainty in the risk models. The ignition models are under development, meaning that there is still a high uncertainty associated with using ignition probabilities for hydrogen. Therefore, conservative values should be applied in quantitative risk analysis. Also to be noted that ignition probability models are not established for liquid hydrogen at low temperatures, as they are mainly developed for gas and for hydrocarbon liquids at normal temperatures (MarHySafe, 2021).

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[14] MarHySafe Phase II is currently utilizing CFD explosion tools to develop guidance for compressed hydrogen storage above deck.

7. Review of existing hydrogen regulations and standards

In this chapter, we review current statutory regulations, classification rules, standards, and best practices relevant to hydrogen-fuelled ships to identify hydrogen-specific hazards and risks considered and mitigated in existing rules and regulations.

7.1 International regulations

The IGF Code

The IMO has provided an international mandatory regulatory framework for alternative fuels through the International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels (IGF Code). This code establishes internationally recognised safety barriers to ensure the safe use of natural gas (LNG) as a fuel. However, the Code does not currently include detailed technical requirements for hydrogen.

The IGF Code applies to ships to which Part G of the International Convention for the Safety of Life at Sea, 1974, as amended (SOLAS) Chapter II-1 is applicable. The purpose of the IGF Code is to provide an international standard for ships operating with gas or low-flashpoint liquids as fuel. It does not apply to gas carriers, which are covered by the IGC Code.[15] The current version of the IGF Code includes prescriptive regulations only for natural gas. Regulations for other fuels will be added to the Code as and when the IMO develops them.

The IGF Code's basic philosophy considers the goal-based approach (MSC.1/Circ.1394/Rev.2). Therefore, goals and functional requirements are specified for each section, forming the basis for the design, construction, and operation. The IGF Code Part A includes goals and functional requirements applicable to all gaseous and low-flashpoint fuels.

The IGF Code Part A-1/B-1/C-1 includes specific requirements for ships using natural gas as fuel to meet the functional requirements. They have a complete scope, covering system design, arrangement, manufacture, workmanship, testing and operational requirements for all system parts from the bunkering connection to the fuel consumer, including the exhaust outlet.

For fuels not covered by specific requirements, e.g., hydrogen, compliance with the goal and functional requirements of Part A of the Code must be demonstrated through a risk-based approval process referred to as the alternative design approval process.

DNV has studied the challenges of applying the IGF Code regulations for natural gas fuel also for hydrogen (DNV, 2022). In Appendix A, we present our findings related to the applicability of existing safety barriers to hydrogen based on a comparison of the physical properties and related safety risks of natural gas and hydrogen.

As summarized in Figure 7-1, we find that the existing safety barriers in the IGF Code do not account for hydrogen's extreme flammability properties. This illustrates the need for further regulatory development, also supported by EMSA (2023), which identifies many required safeguards for hydrogen not found in the IGF Code.

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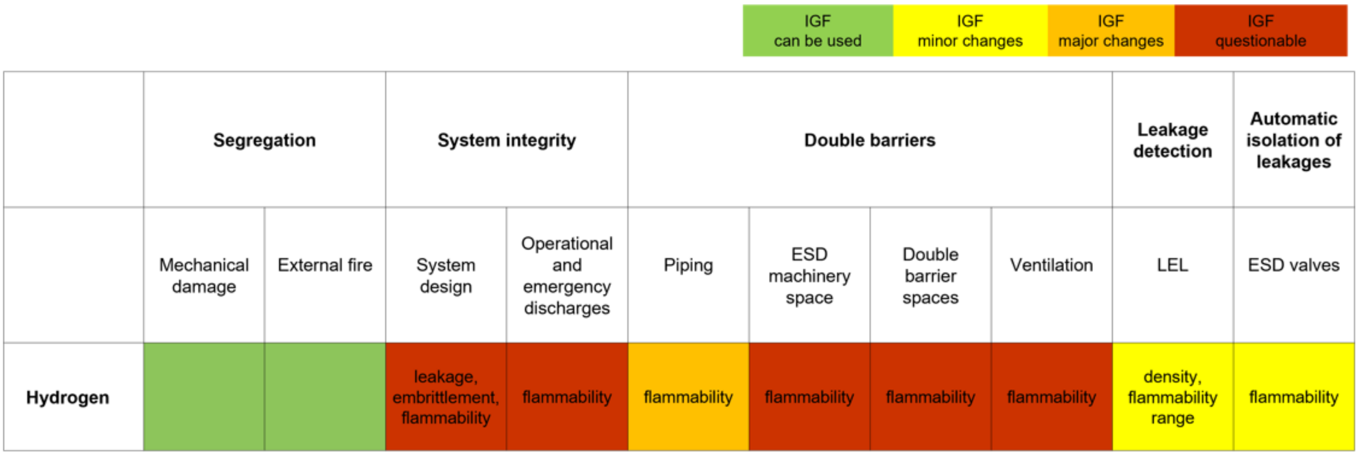
[15] IGC Code – The International Code of the Construction of Equipment of Ships Carrying Liquefied Gases in Bulk.



🟩	🟨	🟧	🟥
IGF can be used	IGF minor changes	IGF major changes	IGF questionable

	Segregation		**System integrity**		**Double barriers**				**Leakage detection**	**Automatic isolation of leakages**
	Mechanical damage	External fire	System design	Operational and emergency discharges	Piping	ESD machinery space	Double barrier spaces	Ventilation	LEL	ESD valves
Hydrogen	🟩	🟩	🟥 leakage, embrittlement, flammability	🟥 flammability	🟧 flammability	🟥 flammability	🟥 flammability	🟥 flammability	🟨 density, flammability range	🟨 flammability

Figure 7-1 Suitability of using the safety concept of the current regulations in the IGF Code for natural gas also for hydrogen when used as fuel onboard (DNV, 2022).

<u>The draft IMO Interim Guidelines for the safety of ships using hydrogen as fuel</u>

The IMO Sub-Committee on Carriage of Cargoes and Containers (CCC) has a working group dedicated to amendments to the IGF Code and developing guidelines for alternative fuels and related technologies. Provisions for new fuels are initially developed as non-mandatory interim guidelines to gain experience with their application before the guidelines are included as mandatory regulations through IGF Code amendments. The development of interim guidelines for the safety of ships using hydrogen was added to the work plan in 2021, with a targeted completion date in 2024.

The latest version of the draft Interim Guidelines for the safety of ships using hydrogen as fuel (CCC 9/WP.3) includes the following text in 1.6: “These Interim Guidelines have been closely aligned with the International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels (IGF Code), adopted by resolution MSC 391(95), as amended, in particular section 3 which is mainly text taken from chapter 3 of the IGF Code, albeit modified to reflect the recommendatory nature of these Interim Guidelines.”

With reference to Appendix A, our analysis indicates that a close alignment with the requirements in Part A-1 does not provide a sufficient safety standard for hydrogen as fuel because of the differences in physical properties between hydrogen and natural gas. The main challenge is that it is more difficult to prevent the ignition of hydrogen after a leakage.

<u>Other hydrogen-related IMO provisions</u>

IMO has developed Interim Guidelines for the Safety of Ships using Fuel Cell Power Installations (MSC.1/Circ.1647). However, the guidelines are limited to the fuel cell power installation and do not cover the onboard storage and distribution of hydrogen fuel.

IMO has developed the Interim Recommendations for Carriage of Liquefied Hydrogen in Bulk, the Maritime Safety Committee (MSC) Resolution MSC.420(97) for carriage of liquefied hydrogen as cargo. The Interim Recommendations were initiated by and developed for a liquid hydrogen supply pilot project and are currently under revision.

7.2 Classification rules and guidelines

Several classification societies have issued requirements for hydrogen-fuelled vessels, listed in Table 7-1.

Table 7-1 Classification rules and guidelines for hydrogen as fuel.

Classification Society	Document reference
ABS	Requirements for Hydrogen Fueled Vessels
BV	Hydrogen-fuelled ships Rule Note NR678
DNV	Pt.6 Ch.2 Sec.16 Gas fuelled ship installations – Gas fuelled hydrogen
LR	Classification of Ships Using Gases or Other Low-Flashpoint Fuels, Appendix LR3 Requirements for Ships Using Hydrogen as Fuel

Class rules and guidelines also exist for fuel cell installations, and for the carriage of hydrogen as cargo.

Table 7-2 Classification rules and guidelines for fuel cells and hydrogen carriage.

Classification Society	Document reference
ABS	Requirements for Fuel Cell Power Systems for Marine and Offshore Applications
ABS	Requirements for Liquefied Hydrogen Carriers
BV	Ships Using Fuel Cells. Rule Note NR547
DNV	Pt.6 Ch.2 Sec.3 Fuel Cell Installations (FC)
DNV	Pt.5 Ch.7 Liquefied gas tanker Sec.17 [12] Hydrogen
KR	Guidance for fuel cell systems on board of ships
NK	Guidelines for Liquefied Hydrogen Carriers

The classification rules for hydrogen-fuelled vessels are generally based on the IGF Code safety concept discussed in Appendix A and the Code's specific requirements for natural gas, in addition to risk assessment.

In reviewing these guidelines and class rules, we have identified specific mitigation actions related to hydrogen-specific hazards, which are additional to the IGF Code regulations for natural gas. These requirements have been considered when drawing up the preliminary goals and functional requirements and will be further considered in the development of the Guidance document. The hydrogen-specific topics covered in the rules of the classification societies can generally be summarised as follows:

- Accumulation of released hydrogen (confined areas, enclosed, semi-enclosed spaces).
- Formation of liquefied or solidified air and water.
- Loss of vacuum insulation.
- Vent mast arrangements.
- Materials suitable for hydrogen service (hydrogen permeation and embrittlement).
- Definition of leakage sizes for various piping system components, including full bore rupture.
- Location, design, and construction of hydrogen storage tanks.
- Arrangement of secondary enclosures for hydrogen piping (vacuum, helium, nitrogen).
- Arrangement of spaces containing hydrogen systems (vacuum, helium).
- Fire safety
- Hazardous area classification including electrical equipment.
- Personnel safety and PPE.

Additionally, the classification requirements include specifics on what to cover in the risk assessment for a hydrogen-fuelled ship.

Appendix B contains requirements to be considered in developing a Guidance for ships using hydrogen as fuel based on a review of current classification rules from ABS, BV, DNV, and LR. The presentation structure is aligned with the IGF Code Contents structure, which is the same as used for the draft IMO Interim Guidelines for hydrogen-fuelled ships.

7.3 Standards and best practices

Standardisation organisations provide standards for materials, electrical equipment, and area classification. These standards may be applicable as references in the final Guidance document.

The EMSA study “Potential of Hydrogen as Fuel for Shipping” (EMSA, 2023) and the «Handbook for hydrogen-fuelled vessels” (MarHySafe, 2021) include comprehensive mapping of standards related to hydrogen, including standards produced for other applications that will be further considered in the development of the Guidance. Industry associations provide best practices that also may be useful in the development of the Guidance.

8. Drawing up a Preliminary Guidance

In this chapter, we summarize the hazards and risks to be considered and mitigated in the preliminary hydrogen guidance based on the information gathered in the previous chapters:

- hazards and risks introduced by installing a hydrogen fuel system onboard a ship (Chapter 3).
- established principles for mitigation and control (Chapter 4).
- lessons learned from hydrogen accident review (Chapter 5).
- scope and limitations of the most common explosion analysis modelling techniques and tools (Chapter 6).
- hazards and risks considered and mitigated in existing rules and regulations (Chapter 7).

The aim is to define a preliminary table of contents, preliminary goals, and functional requirements for a Guidance document addressing ships using hydrogen as fuel. Some of the gathered information (e.g., Chapter 6) is at a level of detail which is not applicable to the definition of preliminary goals and functional requirements but will be used when further developing the Guidance document throughout the study.

8.1 Hazards and risks introduced by installing a hydrogen fuel system onboard a ship

In this sub-chapter, we will address preventive and mitigating safety barriers required to reduce the risks identified in Chapter 3.3. The writing of this report precedes the HAZID workshops planned for later in the project. Therefore, the evaluation is based on a high-level assessment of hazardous events that pose significant risks to the ship and its crew.

8.1.1 Damage to fuel containment and piping systems by external events

From a risk perspective, the consequence of damaging an LH2 tank or a tank containing CH2 could be a catastrophic event, and the design should make the likelihood of such an event as low as possible.

Figure 8-1 illustrates tank and system damage as the top event in a high-level bow tie, where potential threats are listed on the left side and potential consequences on the right side. Functional requirements must be added as preventive barrier functions on the left side because it will not be technically feasible to reliably mitigate the consequences of a tank rupture.

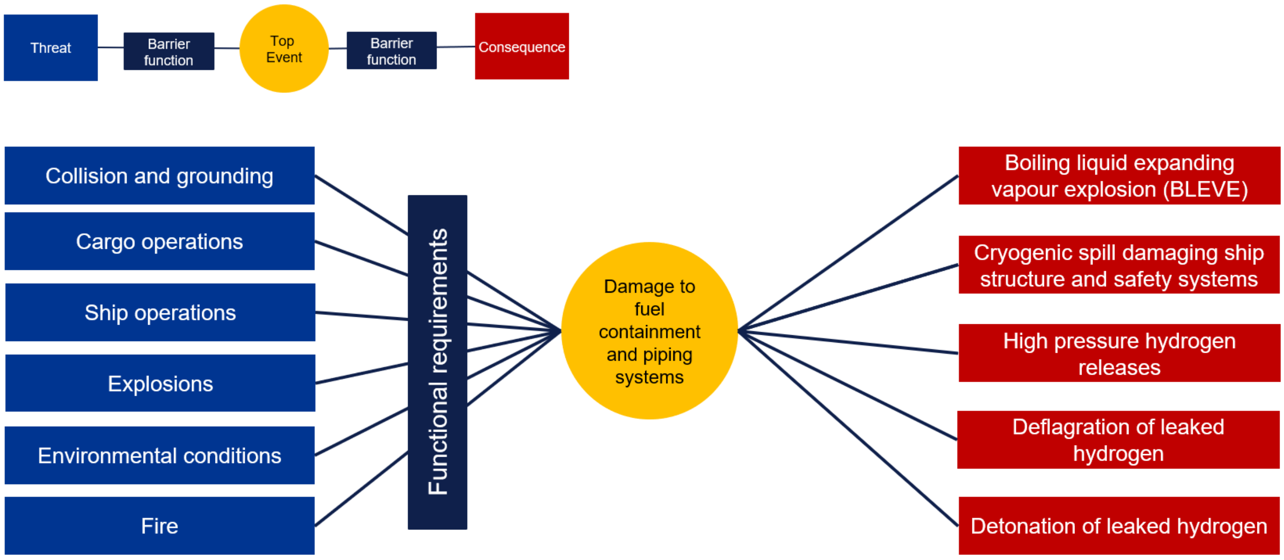


Figure 8-1 Mechanical damage threats may lead to loss of containment and corresponding consequences for stored hydrogen in liquefied and compressed form (High-level bow tie illustration).

Functional requirements aimed at minimizing the probability of mechanical damage to hydrogen containment systems must address the following:

- Fuel tanks and piping systems must be kept away from areas likely to be affected by collision and grounding damages.
- Fuel tanks and piping systems must be kept away from areas where loading and offloading pose a damage risk or be provided with some form of mechanical protection strong enough to withstand worst-case damage from the cargo operation.
- Fuel tanks and piping systems must be kept away from areas where ship operations pose a damage risk or be provided with some form of mechanical protection strong enough to withstand worst-case damage from ship operations.
- Fuel tanks and piping systems must be kept away from areas on the ship with a high risk of fire.
- Fuel tanks and piping systems must be kept away from areas on the ship with a risk of explosion not related to the hydrogen installation.
- Fuel tanks and piping systems must be suitable for the marine environment with dynamic loads, vibrations, sea spray and sun radiation and protected against mechanical damage from green seas, snow, and ice loads.

8.1.2 Hydrogen releases on the open deck

The consequences of igniting hydrogen released on an open deck will depend on the circumstances. In an unrestricted open-air environment, this usually results in ordinary deflagration with little pressure build-up, but the presence of confining surfaces and obstacles can lead to a more severe explosion. A fuel tank releasing significant amounts of hydrogen to the open deck through the vent system is a scenario where the consequences of ignition could be the most severe.

Figure 8-2 illustrates hydrogen releases on open deck as the top event in a high-level bow tie, where potential threats are listed on the left side and potential consequences on the right side. Functional requirements must be added as preventive barriers on the left side and mitigative barriers on the right side.

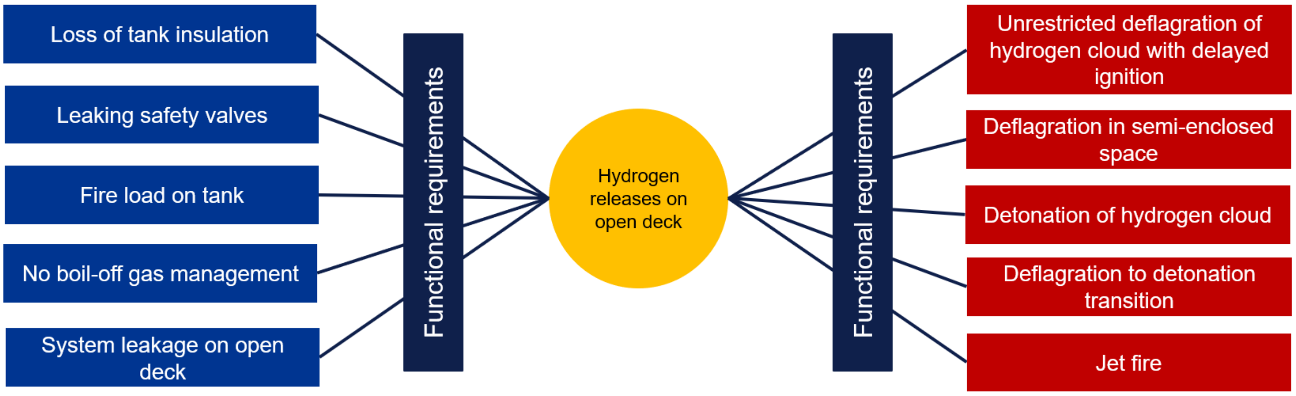


Figure 8-2 Releases from liquefied or compressed fuel containment systems on open deck with corresponding threats and consequences (High-level bow tie illustration).

Preventing all large releases of hydrogen from, e.g. the containment systems is not technically feasible. Consequently, mitigating barriers and consequence analyses must be in focus to ensure safety. Risk-reducing measures should focus on making detonations and confined deflagrations as unlikely as possible and keeping heat radiation from jet fires at acceptable levels.

Functional requirements aimed at minimizing the probability and mitigating the consequences of hydrogen being ignited on the open deck must address the following:

Preventive measures

- The fuel containment system should be designed to minimize operational discharges by preventing LH2 from heating up too quickly through effective tank insulation and providing the means to manage the boil-off gas in normal operation.

Mitigating measures

- The fuel containment system and the system providing pressure relief should be arranged to ensure that any hydrogen being discharged accidentally or through normal operation is routed to open air at the safest possible location onboard.
- The fuel containment system, pressure relief system, and deck layout should be arranged to prevent discharged hydrogen from accumulating in confined and congested areas.
- 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.
- Any leaks from tanks and piping systems should be detectable and automatically isolated from the source of the hydrogen supply. Segregation valves should be arranged to limit the amount of hydrogen being discharged after a leakage is detected and stopped.
- LH2 piping systems on the open deck should be protected within a secondary enclosure that can contain any leakage and vent the evaporated hydrogen to the safest location possible onboard.

8.1.3 Hydrogen releases in enclosed spaces

Ignited hydrogen releases in confined spaces can lead to the deflagration or detonation of a flammable hydrogen mixture, destroying the enclosure and other safety features required to control the hydrogen system. On a ship, the spaces at risk of these explosions would typically include tank connection spaces (TCS), fuel preparation rooms (FPR), and fuel reforming spaces. Regulations and guidelines for other flammable fuels, like natural gas and methanol, require such spaces as safety barriers designed to limit the extent of any fuel leaks, assuming that any consequences can be controlled (i.e., prevent ignition, protect against cryogenic damages, etc.).

Hydrogen safety guidance advises against designs introducing the risk of leakages in enclosed and semi-enclosed spaces and advises designing for the possibility of ignition of released hydrogen. This indicates the need for further development of safety barriers for hydrogen handling in enclosed spaces like TCS and FPR if those concepts are to be used in some form also for hydrogen as fuel.

The leakage of LH2 can also cause significant cooling effects and subject materials to temperatures below the ductile-to-brittle transition temperature. This could damage load-bearing structures and compromise the gas-tightness of safety barriers, as well as affect the integrity and function of safety equipment. Experiments have demonstrated that evaporated hydrogen can quickly displace a breathable atmosphere. The evaporation of hydrogen can lead to expansion and potentially cause a pressure increase in enclosed spaces.

Figure 8-3 illustrates hydrogen releases in enclosed spaces as the top event in a high-level bow tie, where potential threats are listed on the left side and potential consequences on the right side. Functional requirements must be added as preventive barriers on the left side and mitigative barriers on the right side.

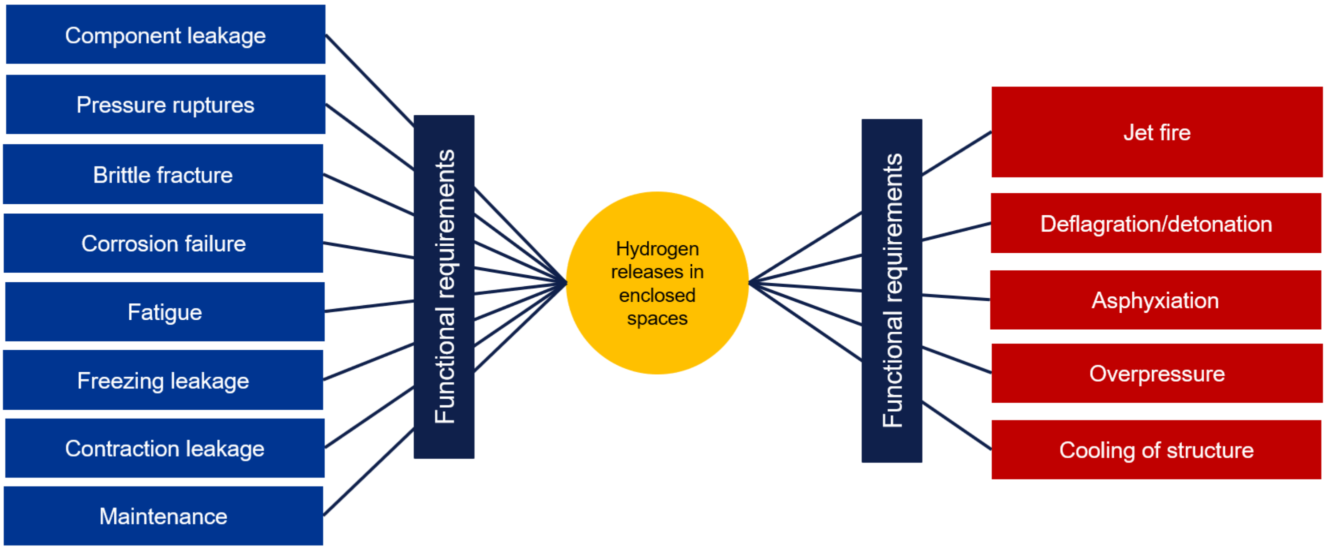


Figure 8-3 Liquefied or compressed hydrogen released in enclosed spaces can have serious safety implications (High-level bow tie illustration).

The consequences of hydrogen ignition in enclosed spaces are severe and must be avoided. Consequently, safety barriers should be designed to prevent hydrogen release and avoid flammable mixtures forming if leaks do occur. Ignition sources should be limited as far as possible. Safety barriers and safety systems that may be exposed to low temperatures from leakages must be designed accordingly.

Functional requirements aimed at minimizing the probability of hydrogen releases, the consequence of hydrogen ignition in enclosed spaces, and the consequences of un-ignited hydrogen releases must address the following:

Preventive measures

- All fuel piping systems located in enclosed spaces should be protected within a secondary enclosure that can contain any leakage and vent the evaporated hydrogen to open air at the safest location possible.
- All fuel piping systems should be designed and arranged to minimize the probability of leakages. This implies using materials that are not deteriorated by hydrogen, are suitable for the system's design temperature, are arranged and supported to ensure that operational conditions do not cause undue stresses and are connected by welding as far as possible. Where welding is not possible, joining methods are chosen to minimize the probability of leakage.
- All fuel piping systems for LH2 should be arranged with a system to manage the heating up and corresponding pressure increase of trapped volumes of LH2 and vent it to open air at the safest location possible.

Mitigating measures

- The fuel containment and piping systems should be designed to ensure that the operational releases from purging, gas freeing and pressure relief are managed safely. This is also applicable for emergency releases due to system leaks and loss of vacuum insulation on tanks and systems.
- The potential for low temperatures in a space or area due to cryogenic leakage or vacuum loss should not compromise the integrity of structural materials, the functionality of safety systems or components necessary for the ship's safety.
- Any leaks from tanks and piping systems should be detectable and automatically isolated from the source of the hydrogen supply. Segregation valves should be arranged to limit the amount of hydrogen being discharged after a leakage is detected and stopped.
- The number of ignition sources should be minimized in areas where there is a risk of having a flammable hydrogen mixture while still ensuring that the design can manage an ignition of the released hydrogen.
- Fuel piping systems should be designed to minimize the consequences of leakage by limiting the inventory of hydrogen in the system to what is necessary for operation. This implies limiting the pipe diameter and operating pressure to what is necessary at all points, arranging segregations to prevent the discharge of larger hydrogen volumes, and introducing flow restrictions and excess flow devices.

- Spaces containing hydrogen installations should be arranged to manage any pressure build-up caused by hydrogen leakage and to ensure that flammable hydrogen mixtures cannot spread to other spaces.
- A deflagration or detonation of hydrogen on the open deck or in a space containing a hydrogen release source should not:

  - disrupt the function of equipment or systems located in other spaces.
  - cause flooding of water below the main deck.
  - cause damage to work areas or accommodation, injuring people staying in these areas under normal operating conditions.
  - disrupt the proper functioning of control stations and switchboard rooms necessary for power distribution.
  - damage life-saving equipment or associated launching arrangements.
  - disrupt the proper functioning of fire-fighting equipment located outside the explosion-damaged space.
  - affect other areas of the ship so that chain reactions involving, inter alia, cargo, gas and bunker oil may arise.
  - prevent access to life-saving appliances or impede escape routes.

8.1.4 Loss of vacuum insulation for fuel containment and piping systems

Liquefied hydrogen is stored at a temperature of -253°C, which is lower than the condensation temperature of the nitrogen and oxygen in the air. If the storage tank vacuum insulation is lost, the external surfaces of the LH2 containment may become cold enough to liquefy the oxygen and nitrogen in the air. This oxygen-enriched liquid air poses an explosive hazard. Additionally, condensed air reaching ship steel could rapidly result in structural damage from low-temperature embrittlement. Also, the heat input to storage tanks and piping systems will increase rapidly.

Another consequence of losing tank insulation is the possibility of extreme cooling of the tank hold space surrounding the tank.

Figure 8-4 illustrates the loss of vacuum insulation as the top event in a high-level bow tie, where potential threats are listed on the left side and potential consequences on the right side. Functional requirements must be added as preventive barriers on the left side and mitigative barriers on the right side.

Figure 8-4 Loss of vacuum insulation for liquefied fuel containment and piping systems (High-level bow tie illustration).

It is not possible to exclude the possibility of a vacuum loss. Consequently, designs must be arranged to keep condensed air away from materials that can fail due to contact with liquids at cryogenic temperatures and from flammable materials. Pressure relief systems must be able to handle the quick pressure increases and hydrogen boil-off to prevent overpressure and potential failures of the tank or piping system. Pressure relief systems must be able to manage the thermal loads and flow resulting from such an event.

Functional requirements aimed at minimizing the probability and the consequence of insulation loss of the fuel containment and piping systems must address the following:

Preventive measures

- The outer tank of a vacuum-insulated fuel containment system and the piping systems connecting the inner tanks to the tank exterior should be designed to minimize the probability of air entering the vacuum space from outside and hydrogen leaking into the vacuum space from the tank side, compromising the vacuum insulation.
- Primary piping systems should be designed to minimize the probability of hydrogen leaking into the vacuum space and compromising the vacuum insulation. Pressure relief systems fitted to relieve pressure in the vacuum space should also be arranged to avoid air entering the vacuum space from the outside.

Mitigating measures

- The design and capacity of the pressure relief arrangements should be suitable for situations in which LH2 containment systems or piping lose insulation properties.
- If the fuel containment systems or piping systems for LH2 lose insulation through vacuum loss, managing the resulting cooling of the surroundings should be within the ship's design capabilities.
- The fuel containment and piping systems should be designed to avoid ice formation on cold surfaces from moisture in the air under normal operating conditions.
- The fuel containment and piping systems, including the piping for the pressure relief arrangements from the tank and systems, should be designed to safely manage the possibility of air condensing on cold surfaces upon loss of insulation.
- The ship is arranged to manage the resulting lower temperatures in tank hold spaces, tank connection spaces, and other spaces that may be affected. Issues to cover include:
    - using materials able to withstand the lowest temperature they may be subjected to.
    - ensure that all components of safety systems required to mitigate hydrogen safety events can continue to operate at the lower temperature after a leakage event or a loss of tank or system vacuum insulation.
- Vent mast surface temperature remains above the condensation temperature of the air or arrangements are made to collect the condensed air safely. The vent system must also be designed to manage the contraction of the piping system when it is cooled down to approximately the storage temperature of the hydrogen.

8.1.5 Heating of liquefied hydrogen in fuel containment and piping systems

The density of LH2 decreases significantly with increasing temperature. If a storage tank is filled with cold LH2 without leaving enough reserve ullage space to allow for the liquid's expansion, the tank can become liquid-full when heated. Similarly, piping systems for LH2 will experience a rise in pressure for trapped volumes of LH2 (e.g., between two valves) when the hydrogen is heated by the surroundings.

Figure 8- illustrates the heating of LH2 in fuel containment and piping systems as the top event in a high-level bow tie, where potential threats are listed on the left side and potential consequences on the right side. Functional requirements must be added as preventive barriers on the left side and mitigative barriers on the right side.

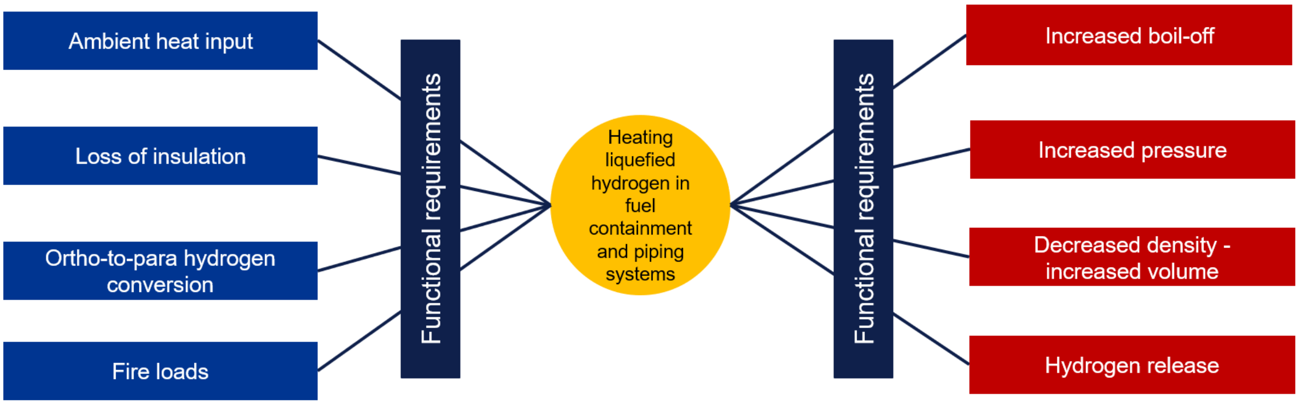


Figure 8-5 Heating liquefied hydrogen in fuel containment and piping systems (High-level bow-tie illustration).

Controlling the tank filling level will be necessary, considering that pressure relief devices are typically designed to operate with gaseous hydrogen. For LH2 piping systems, all pipe segments and components that can be isolated by valves or other devices must be arranged to sustain the increase in pressure due to heat input.

Functional requirements aimed at minimizing the probability of excessive heat input and the consequence of insulation loss of hydrogen containment and piping systems must address the following:

Preventive measures

- Fuel containment and piping systems should be provided with effective insulation to avoid unnecessary boil-off under normal operating conditions.
- Fuel tanks and piping systems must be kept away from areas on the ship with a high fire risk.
- Bunkering procedures should ensure that bunkering of fuel with a high percentage of ortho-hydrogen is avoided.

Mitigating measures

- Fuel containment systems for LH2 should be arranged with the means to ascertain the tank pressure, temperature, and filling level.
- Fuel containment systems for LH2 should be arranged with information on acceptable filling levels to prevent a liquid-full tank. Alarms and shut-down systems should be arranged to prevent overfilling during bunkering or transfer between tanks.
- Fuel piping systems for LH2 should be arranged to prevent overpressure when fuel is heating up in the system under normal and abnormal operating conditions.

8.1.6 Leakages during bunkering

Leakages in relation to the bunkering operation can result in a deflagration/detonation of a flammable hydrogen mixture in the bunkering station, which could lead to structural damage and be dangerous to personnel.

Figure 8-6 illustrates leakages during bunkering as the top event in a high-level bow tie, where potential threats are listed on the left side and potential consequences on the right side. Functional requirements must be added as preventive barriers on the left side and mitigative barriers on the right side.

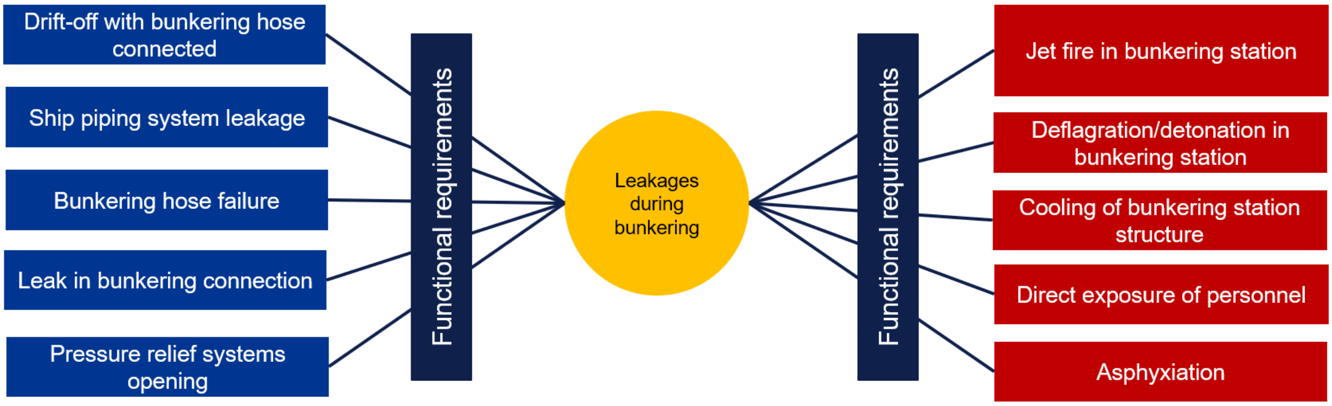


Figure 8-6 Leakages during bunkering (High-level bow tie illustration).

The consequences of hydrogen leakages, and particularly the ignition of hydrogen in a semi-enclosed bunkering station, are severe and must be avoided. Consequently, safety barriers should be designed to prevent the release of hydrogen and to avoid the formation of flammable mixtures as far as possible. Ignition sources should be limited as far as possible. Safety barriers and safety systems that may be exposed to low temperatures from leakages must be designed accordingly.

Functional requirements aimed at minimizing the probability of hydrogen releases, the consequence of hydrogen ignition, and the consequences of un-ignited hydrogen releases in the bunkering station must address the following:

Preventive measures

- Piping systems used for bunkering of hydrogen should be designed to minimize the probability of leakages, contain leakages if they occur, and avoid cold surfaces where air can condense.
- The construction and support of the ship bunkering manifold should be strong enough to prevent damage to the bunkering system in a drift-off, where the bunkering hose is the only point connecting the ship to the bunkering facility.

Mitigating measures

- The ship bunkering station should be arranged to reduce the consequences of an ignition event as far as possible. This implies preferably locating the bunkering station on the open deck. In case having the bunkering station on the open deck is not possible, the volume of the bunkering station subjected to potential leakage should be minimized, and openings should be arranged to optimise the relief of explosion pressure. The fitting of equipment and items causing congestion increases the risk of deflagrations and detonations and should be avoided in bunkering stations.
- The ship bunkering station should be arranged to withstand the consequences of cryogenic leakages from the bunkering arrangements.
- Personnel involved in bunkering operations should be outfitted with appropriate personal protective equipment.
- The bunkering hose should be arranged to separate the ship and the bunkering facility without releasing hydrogen or overloading the ship or bunkering facility manifolds.
- The bunkering system should be arranged with means to detect leakage and systems to automatically stop the bunkering process.
- The bunkering system should be arranged with a shut-down valve in the bunkering station to facilitate emergency closing of the bunkering supply.
- An emergency shut-down communication system should be arranged between the ship and the bunkering facility.

8.1.7 Contamination of liquefied hydrogen

Air contaminations in the LH2 system will solidify as nitrogen, oxygen, and frozen water. These contaminants can cause obstructions in piping or instruments, causing equipment malfunction, and presenting a possible explosion hazard when systems are heated up and the oxygen-enriched air evaporates. Contaminants like air and inert gas should consequently be avoided as far as possible in tanks and systems for LH2. Contamination can typically happen during bunkering operations or when tanks cool down after gas-freeing. If inert gas systems are connected to the fuel system for purging purposes, there is a risk of transferring nitrogen to a cold hydrogen system.

From the above, we find that functional requirements should ensure the following:

- Operational procedures should be guiding the crew in how to avoid contaminations of LH2 systems.
- Systems for LH2 should always be kept at a higher pressure than the surroundings to prevent the ingress of contaminants.
- Procedures for heating and purging LH2 tanks periodically to remove accumulated oxygen may be necessary.

8.2 Established principles for mitigation and control

Established principles for mitigation and control of risks related to hydrogen as described in Chapter 4 are in line with the principles laid down in the “Hierarchy of Risk Control Measures " highlighting the significance of recognising the greater effectiveness of technical measures over operational measures in managing risks.

According to (ISO, 2015) and (NASA, 1997), regulators are advised to assume an ignition source is present even when acceptable standards for certified electrical equipment are followed. This implies that the ignition of hydrogen in a release scenario should be assumed, and further measures (e.g., secondary barriers) to prevent ignition should be taken unless the ignition event is within the ship's design capabilities.

The MarHySafe project (MarHySafe, 2021) concludes that extreme explosions are more likely to happen with hydrogen than natural gas. The project notes that defining relatively small credible leak sizes in risk assessments for shore-based hydrogen applications is common. This often leads to a focus on hydrogen fires, as significant explosion events are not considered feasible due to the combination of leakage rates and safety barriers. MarHySafe recommends considering more severe leak scenarios for maritime systems due to the new and more critical application area. It is also noted that several Classification Societies have included requirements for considering leakages up to full-bore rupture in their current class rules.

Hydrogen-fuelled ships are subject to compliance with the IGF Code and, therefore, must comply with the Code’s fundamental requirement that the overall safety level shall be equivalent to a conventionally fuelled ship. This must also be the basis for any specific guidance or regulation setting requirements for hydrogen used as a ship fuel.

Establishing the size of hydrogen leakages that a hydrogen-fuelled ship is designed to withstand is essential to determining its overall safety level. The IGF Code for natural gas refers to a “maximum probable leakage,” which can be interpreted in many ways. Another major decision that will significantly affect the ship's design is whether to follow the assumption that there is a probability of ignition even after measures like installing certified-safe electrical equipment have been taken.

From the above, we find that functional requirements must ensure the following to achieve a safety level comparable to that of a conventional ship:

- A substantial leakage from fuel piping systems should be considered in the design of safety barriers for a hydrogen-fuelled ship.
- The ship design should be based on the assumption that there is a probability of ignition even after measures like installing certified-safe electrical equipment have been taken.
- Hydrogen leakages should be prevented from reaching areas where combustion could be supported.

8.3 Lessons learned from hydrogen-related accidents

From the review of accident databases, we found that hydrogen-related accidents do happen, and the main causes are human error, system design error and failure, or a combination of both. Incidents or accidents could be caused by several minor events, and the consequences could be serious if they happen simultaneously. Small leakages and minor events should be taken seriously, and quick action should be taken to avoid potential escalation of the event. The above underscores the importance of having a reliable and sensitive means to detect anomalies at an early stage.

Over half of the hydrogen accidents on industrial sites were caused by off-gassing, equipment ruptures and leaks. Most of the hydrogen-related accidents in ammonia plants were caused by gaskets and valve packing leakage, and 81% of accidents in aerospace hydrogen incidents were mainly caused by hydrogen leakage in gaseous and liquid states.

Many incidents and accidents were related to human and organisational errors, including poor maintenance, incorrect equipment installation, failure to follow procedures, and lack of instructions and safety procedures. This finding supports the IGF Code requirement preventing the acceptance of operational measures in lieu of safe engineering solutions.

A lack of training of emergency personnel was also identified as a contributing cause. For shore-based industries, this is typically left to specially trained emergency services, but on a ship, managing emergencies is the responsibility of the crew. The study of the HIAD 2.0 database showed that the consequence of hydrogen-related accidents/incidents can be mitigated if the first responders have sufficient knowledge about hydrogen safety and its properties when an event has occurred (X. Wen, et al., 2019).

Safety issues need to be identified and considered in regulations at the design stage to prevent future accidents, but it is equally important to have a safety focus throughout the system's lifetime. Training the operating personnel and increasing their understanding of hydrogen hazards is crucial to preventing future hydrogen-related incidents.

Similarly, the safety management systems must properly account for hydrogen hazards in operating procedures, inspection plans and emergency response procedures.

From the above, we find that functional requirements should ensure the following:

- Hydrogen installations should be equipped with appropriate systems to detect leakages at an early stage, and the systems should be arranged to automatically isolate the leakage so that the risk is minimized.
- The use of leak-prone components and couplings should be minimized when designing hydrogen systems.
- Substantial leaks should be accounted for in the design of hydrogen-fuelled ships.
- Maintenance procedures and information for all hydrogen-related installations should be available onboard.
- Operational procedures to support trained personnel in safely operating the fuel bunkering, storage, and transfer systems should be available onboard.
- The ship-operating company should employ seafarers who have completed training to attain the abilities appropriate to the capacity to be filled and the duties and responsibilities to be undertaken.
- Emergency procedures accounting for any hazardous situation that may arise should be available onboard, special training for first responders should be provided, and drills and emergency exercises should be conducted at regular intervals.

8.4 Application of the IGF Code safety principles

As described in Chapter 7.1, the IGF Code provides internationally recognised regulations for natural gas-fuelled ships and is a starting point and benchmark commonly used by the maritime industry when establishing new design concepts and regulations for hydrogen-fuelled ships. The safety principles illustrated in Figure 8-7, segregation, system integrity, double barriers, leakage detection, and automatic isolation of leakages are equally important for hydrogen and natural gas.

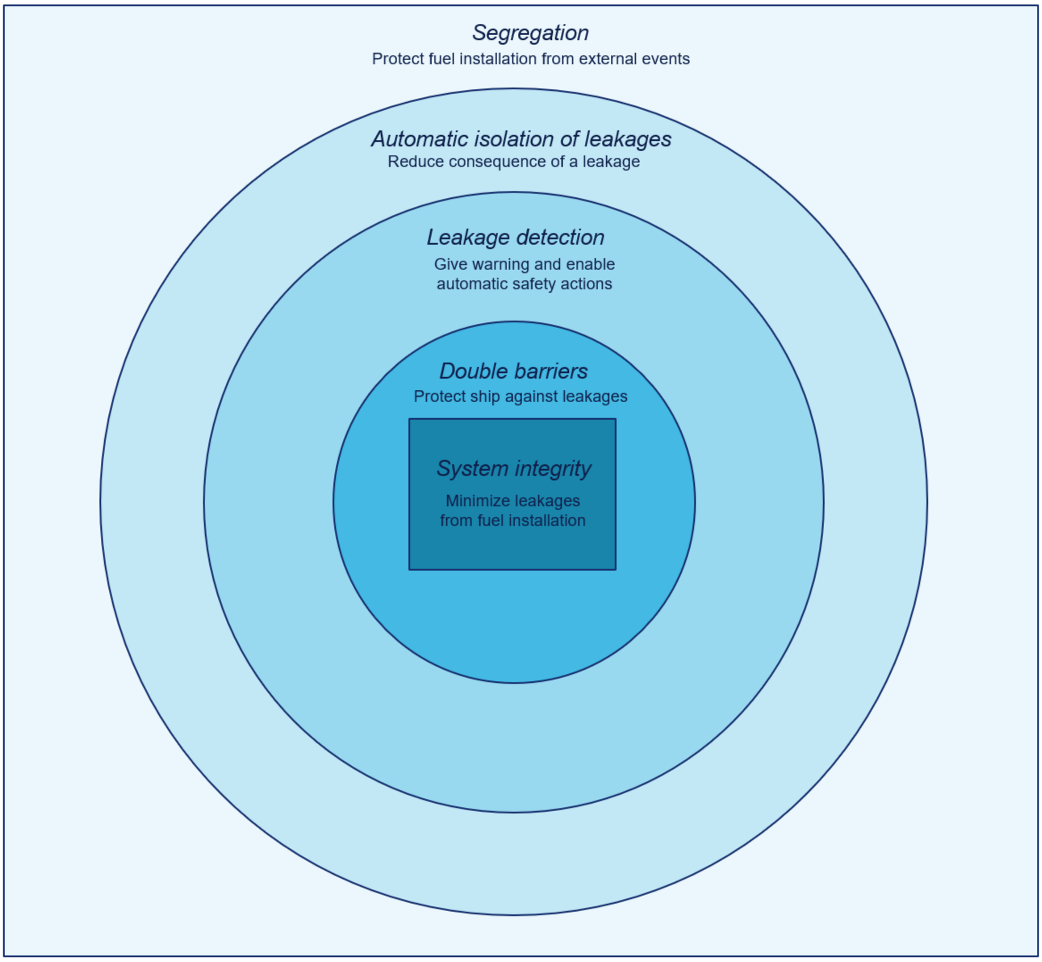


Figure 8-7 The safety concept of the current regulations in the IGF Code for natural gas fuel

However, as summarised in Figure 7-1 and discussed in more detail in Appendix A, we find that the existing safety barriers in the IGF Code for natural gas do not account for hydrogen-specific properties increasing the flammability risks. This illustrates the need for further regulatory development, which is also supported by EMSA (2023) and (DNV, 2022), which identifies many required safeguards for hydrogen not found in the IGF Code. In the following, we will discuss the implications when drawing up an EMSA preliminary Guidance for ships using hydrogen as fuel.

8.4.1 System Integrity

As illustrated in Figure 8-7, the primary safety barrier is to minimize leakages through the design of the fuel containment and piping systems.

Using system design to reduce the probability of leakages

To ensure that the fuel systems are fit for purpose, the IGF Code requires suitable materials (e.g., for cryogenic temperatures), design to minimize leakage sources (e.g., using welded connections with a minimum of flanged connections and prohibiting the use of leak-prone components like bellows), and set requirements for manufacture, workmanship, and testing. The principles of ensuring fit-for-purpose design and minimizing leakage sources are especially relevant for hydrogen fuel systems where the consequence of a leak is more difficult to control. Because gaseous hydrogen consists of very small molecules, smaller leaks are common.

Hydrogen can significantly deteriorate the mechanical properties of metals, a process known as hydrogen embrittlement. Many metals absorb hydrogen, especially at high pressures. Hydrogen absorption by steel can result in embrittlement, leading to equipment failures. The choice of material for hydrogen systems is an important part of hydrogen safety, and specific requirements are needed for materials such as piping and components, gaskets, packaging materials, etc.

Control of operational and emergency discharges from the fuel system

Liquefied hydrogen is stored in vacuum-insulated tanks at -253°C. The extreme temperature difference from ambient temperatures and the relatively small volumes may cause challenges with holding times, potentially leading to operational releases from the storage tank.

When hydrogen is compressed to high storage pressures (250-700 bar), it gains significant potential energy like any other gas. Releasing this energy can cause strong pressure effects depending on the release rate, even without combustion. Sudden hydrogen releases from high-pressure hydrogen systems are also known to ignite spontaneously without any apparent ignition sources. Tanks for CH2 are often proposed with composite materials, protected against pressure increase from fire load with temperature-activated pressure relief devices, which will release all hydrogen if activated.

Swappable hydrogen storage units

Bunkering high-pressure hydrogen from shore has challenges, including the time needed for the bunkering process. Consequently, several projects are looking towards swappable CH2 storage units that can be recharged at shore facilities. This concept is not in line with current shipbuilding practice, where gas fuel storage tanks are permanently onboard and are certified in accordance with the requirements of the IGF Code. Control over such tanks, when they are not onboard, will be a challenge, and they will require disconnection and connection of numerous non-permanent connections to the piping system for each bunkering. Lifting hydrogen tanks on and off the ship will introduce an additional risk.

From the above, we find that functional requirements should ensure the following:

- Leakage sources in hydrogen piping systems should be minimized by avoiding detachable pipe connections and reducing the number of valves and other leakage sources as much as possible.
- All parts of an installation in direct contact with hydrogen should be constructed from materials suitable for hydrogen service.
- Fuel tank holding time requirement adequate to prevent operational hydrogen releases as far as possible.
- Proper requirements for fire resistance, possibilities of pressure relief, and possibilities for isolation of each composite tank.
- Swappable hydrogen storage units are certified for use onboard hydrogen-fuelled ships with the same safety level as hydrogen storage tanks permanently installed onboard.

8.4.2 Double barriers

Acknowledging that leakages do occur despite a high focus on system integrity, double barriers to protect the ship against leakages is the second safety principle illustrated in Figure 8-7. This will typically be to provide a secondary enclosure around any leakage point in the fuel system.

Safe containment of gas fuel leakages, ensuring that such leakages do not reach non-hazardous spaces and areas not designed for gas, is a fundamental principle in the IGF Code. This principle has mandated the great location flexibility for LNG fuel tanks and systems in the IGF Code. This is ensured through the arrangement of tank connection spaces, fuel preparation rooms, secondary enclosures for pipes, and GVU enclosures.

However, as discussed below, this double barrier principle does not account for hydrogen's high flammability, necessitating further regulatory development.

Ventilation

The IGF Code sets requirements for ventilation arrangements for secondary enclosures, tank connection spaces and fuel preparation rooms to control fuel leakages and protect against overpressure. The ventilation system shall dilute gas leakages and transfer them to a safe discharge in the open air, maintain a pressure differential between spaces to ensure that any change of atmosphere goes from a non-hazardous to a hazardous space, and ventilation ducts may serve as pressure relief in the event of LNG releases in enclosed spaces.

Ventilation as a possible risk mitigation measure for hydrogen installations has been discussed and analysed in (MarHySafe, 2021). CFD analyses of hydrogen releases in enclosed spaces indicate that a release of 220 g hydrogen over a 30-second period in a typically sized maritime room (80 m^3) with a ventilation rate of 100 air changes per hour (more than 3 times what is required in the IGF Code for natural gas) can generate an explosive atmosphere. As a safety barrier, ventilation could be used to prevent small leakages from building up an ignitable hydrogen atmosphere but would not prevent possible ignition and jet fire. For more significant hydrogen releases in enclosed spaces, forced ventilation should not be considered as a reliable safety barrier. It should be noted that the main safety barrier applied in other industries is to exclude the possibility of hydrogen leakages in enclosed spaces.

This should be considered when developing functional requirements for double barriers, as discussed below.

Piping systems with secondary enclosures

The IGF Code concept of ventilated secondary enclosures is unsuitable for hydrogen piping systems due to the risk of ignition and deflagration/detonation of leaked hydrogen in the outer pipe. In a piping system for gaseous hydrogen, an inert gas filling may be used to prevent flammable mixtures in the outer pipe. This is not an alternative for LH2, as nitrogen may condense due to the low temperature in a leak scenario. Vacuum (or helium) in the outer pipe may be used.

Pressure relief of the outer pipe must be arranged with closed secondary enclosures. For vacuum-protected systems, the relief system must not compromise the vacuum inside.

From the above, we find that functional requirements should ensure the following:

- The concept of ventilated secondary enclosures should not be accepted due to the risk of ignition and deflagration/detonation of leaked hydrogen in the outer pipe.
- Piping systems for LH2 should require a vacuum in the outer pipe to prevent flammable mixtures, as nitrogen may condense due to the low temperature in a leak scenario.
- Piping systems for gaseous hydrogen could use an inert gas to prevent an ignitable atmosphere in the outer pipe.
- Pressure relief of the outer pipe must be arranged with closed double barrier systems. For vacuum-protected systems, the relief system must not compromise the vacuum inside.

Double barrier spaces

Where the need for many piping components makes fitting a secondary enclosure around piping inconvenient, the IGF Code accepts that these components be placed in dedicated gas-tight spaces where it is possible to control the ignition sources for a natural gas atmosphere. Examples of such spaces are tank connection spaces, fuel preparation rooms, and gas valve units. As discussed above, relying on ignition control to manage hydrogen leakage does not provide a reliable safety barrier. The explosion pressure from a deflagration in an enclosed space may damage bulkheads and possibly other safety barriers and allow the leak to spread further, escalating the situation.

To make hydrogen storage in enclosed spaces/below deck a viable alternative, additional safety barriers must be implemented in tank connection spaces and fuel preparation rooms to reduce the likelihood of a hydrogen explosion to a minimum.

As discussed above, dilution ventilation is not a suitable mitigation strategy for hydrogen. An alternative could be to operate with an inert atmosphere in the space to prevent leaking hydrogen from mixing with an oxidiser. However, this strategy would raise several design- and operational issues related to access for inspection and maintenance, pressure release and cooling of the space in case of LH2 leakages and inert gas quality:

- An inert atmosphere prevents access for inspection and maintenance. Gas-freeing for entrance would remove the primary safeguard that prevents an explosion.
- Maintaining an inert atmosphere would require that ventilation arrangements are closed off to prevent the inert gas from escaping. This implies that the protected space is vulnerable to pressure increases due to leaks. A pressure relief system with sufficient capacity would have to be arranged to prevent damage due to pressure rise from rapidly evaporating LH2 or CH2.
- Hydrogen can ignite with less oxygen than the ignition of natural gas would require (5% vs 12%). This would put stricter requirements on inert gas quality. The presence of ventilation systems could introduce air into the inert space.
- A leakage of LH2 can cool down the space below the condensation temperature of nitrogen in seconds, as demonstrated at DNV’s Spadeadam facility in the UK (FFI, 2021).

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

A way forward is to require secondary enclosures for hydrogen piping systems also inside tank connection spaces, fuel preparation rooms, and other spaces where hydrogen leakages are possible. A working double barrier around piping systems for liquefied and gaseous hydrogen could reduce the possibility of generating an explosive atmosphere in enclosed spaces to a level where the significant consequences of an explosion would be justified. Also, with the limited volumes available for catching releases resulting from leakages in the primary barrier, the discussion regarding likely leakage rates becomes less relevant, as the protective secondary enclosure would have to manage a leakage filling up the annular space safely, whether this occurs after a small or medium-sized leakage or a full-bore rupture.

From the above, we find that functional requirements should ensure the following:

- The likelihood of a hydrogen explosion in enclosed spaces is reduced to a minimum by proving secondary enclosures able to safely contain any leakage that may arise for hydrogen piping systems in tank connection spaces, fuel preparation spaces and other spaces where hydrogen leakages are possible.

ESD machinery spaces

The ESD-protected machinery space concept from the IGF Code implies that high ventilation rates, early detection, isolation of leakages, and disconnection of non-certified safe electrical equipment will prevent leakages from generating gas mixtures above the lower explosion limit range and being ignited. Considering the extreme flammability of hydrogen, this concept should not be considered a suitable machinery space concept when hydrogen is used as a fuel for internal combustion engines.

8.4.3 Leakage detection and automatic isolation of leakages

As illustrated in Figure 8-7, leakage detection and automatic isolation of leakages are important parts of the IGF Code safety principles. They enable early warning and initiate automatic safety actions to reduce the consequences of a leakage.

From a safety point of view, early gas detection is essential to quickly respond to a leakage, which must be alarmed and isolated as rapidly as possible. In enclosed spaces, the location of gas detectors and the geometrical shape of spaces where gas leaks may occur need to account for the density of the leaking gas. In confined spaces, hydrogen will typically mix quite fast but can initially accumulate in layers in high spots.

Hydrogen gas tends to rise and disperse in an open environment, which is better for the ship's safety but may make reliable leakage detection difficult. The directional effects of high-pressure releases and releases of cryogenic hydrogen may complicate the issue of optimal gas detector locations.

As discussed in 8.3, small leakages and minor events should be taken seriously, and quick action should be taken to avoid potential escalation.

Functional requirements should ensure that:

- Quick and reliable gas detection is arranged and automatically triggers a safety system to isolate leakages at a point where the remaining hydrogen inventory is minimized.

8.4.4 Segregation

The last safety principle illustrated in Figure 8-7 is segregation, to protect the fuel installation from external events causing mechanical damage and instigating leakages, is equally essential for hydrogen as for natural gas.

Functional requirements should ensure that:

- Fuel containment and piping systems are located with sufficient protection against damages from external events.

8.5 The Preliminary Guidance for ships using hydrogen as fuel

The Preliminary Guidance for ships using hydrogen as fuel follows the IGF Code structure. The first four chapters of the Guidance follow the IGF Code Part A, which applies to all SOLAS ships using gaseous or low-flashpoint fuels. The remaining chapter headings follow the IGF Code Part A-1, B-1 C-1 and D structure, which contains goals, functional requirements, and prescriptive regulations applicable to ships using natural gas as fuel. This is the same structure used by IMO in developing Interim Guidelines for ships using hydrogen as fuel.

The goal of the IGF Code is to ensure that ships using gas as a fuel are as safe as those using conventional oil fuel. This should also be the main objective of any guidelines providing design requirements to ships using hydrogen as fuel. Chapter 3 of the IGF Code outlines several high-level functional requirements. Compliance with these requirements should ensure that a ship powered by gas or low-flashpoint fuels is as safe as a conventionally fuelled ship. Given the mandatory nature of IGF Code Part A, these high-level functional requirements are also reflected in the preliminary Guidance.

From Chapter 5 onwards, each chapter in the Guidance starts by listing the hazards related to its subject. It should be noted that this work precedes hazard identification and risk ranking, which will follow later in this project. They are regarded as prerequisites for developing any functional requirements in the Guidelines for Developing IMO Goal-Based Standards. Consequently, the relevant hazard selection used to develop preliminary risk-mitigating functions is based on the findings in this report and previous DNV HAZID work for clients and joint industry projects.

Further, from Chapter 5 onwards, each chapter of the Guidance has a sub-goal supporting the main goal of providing a safe hydrogen-fuelled ship, followed by functional requirements on the chapter subject matter intended to achieve the defined sub-goal. The structure is built up by first defining which of the high-level functional requirements in Chapter 3 are relevant to the chapter's subject matter and then defining more specific functional requirements considered necessary to achieve the overall goal of providing a safe ship. The functional requirements are derived through several methods and sources, including:

- The analysis of hazards, threats, and risks in Chapter 0 of this report.
- The review of established principles for mitigation and control of hydrogen hazards in Chapter 4 of this report.
- The review of previous hydrogen-related incidents in Chapter 5 of this report.
- The review and analysis of existing regulations as described in Chapter 7 and Appendix A of this report.

The preliminary Guidance will be a live document throughout the project, maturing as the project performs reliability analyses, formal hazard identification workshops of generic and specific ship designs, risk analyses and arranges industry-wide hearings. The final aim is to use and present the matured preliminary Guidance with hazards, goals, and functional requirements as a basis to provide prescriptive requirements fulfilling the functional requirements to the degree possible.

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Appendix A Suitability of the IGF Code safety principles for natural gas when applied to hydrogen

DNV has studied the challenges of adopting the safety concept of the current regulations in the IGF Code for natural gas fuel also for hydrogen (DNV, 2022). In the following, we present our findings related to the applicability of existing safety barriers to hydrogen based on comparing the physical properties and related safety risks of natural gas and hydrogen.

A.1 IGF Code safety principles for natural gas

The IGF Code provides internationally recognised regulations for natural gas (LNG) fuelled ships and is a starting point and benchmark commonly used by the maritime industry when establishing new design concepts and regulations for hydrogen-fuelled ships. As illustrated in Figure 9-1the safety principles applied in the current regulations in the IGF Code for natural gas fuel can broadly be divided into five categories: segregation, system integrity, double barriers, leakage detection, and automatic isolation of leakages.

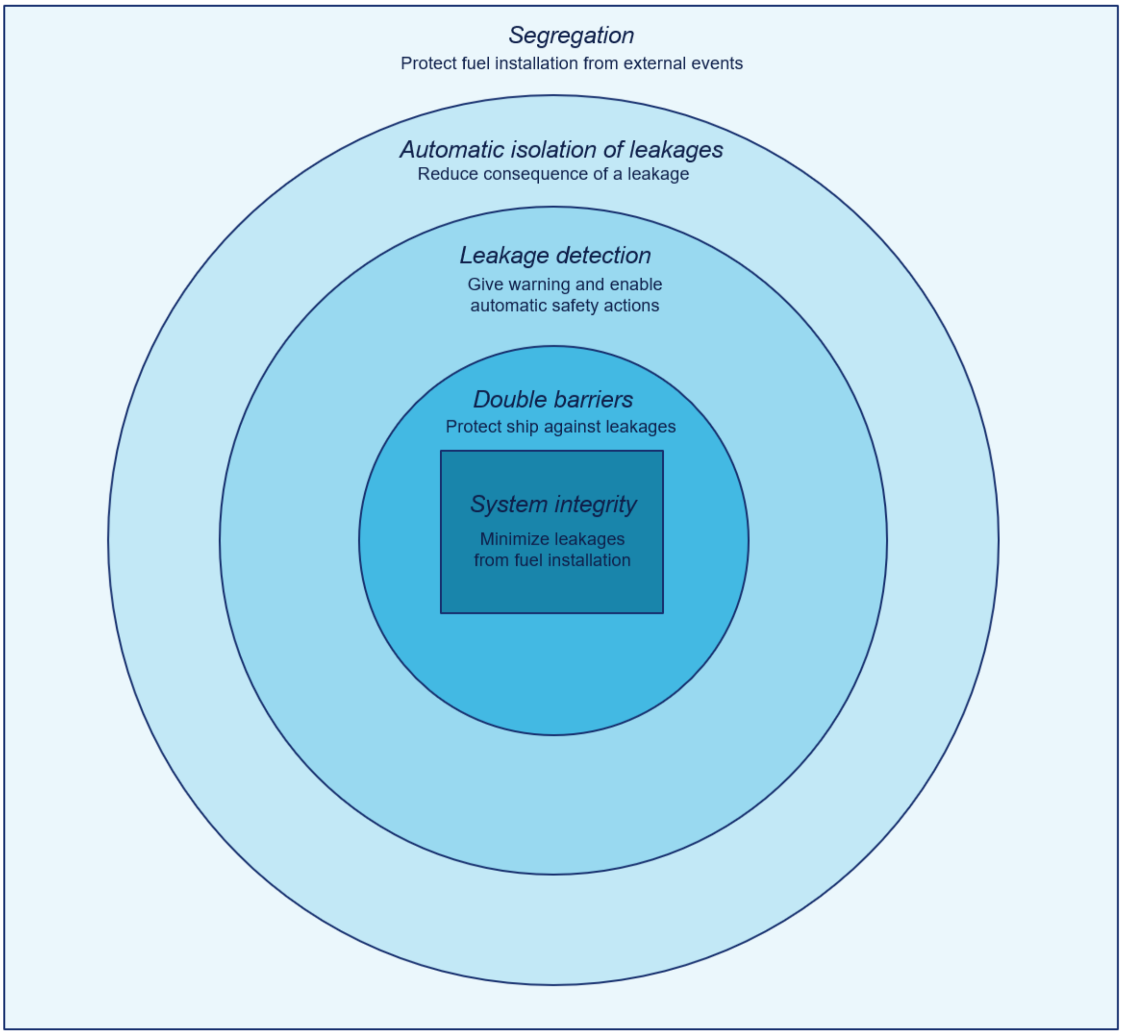


Figure 9-1 The safety concept of the current regulations in the IGF Code for natural gas fuel.

The five main safety principles can be summarized as follows:

1. Segregation:

The fuel installation, particularly the LNG fuel storage tanks, contains large amounts of flammable and cryogenic material and, in the case of pressurised tanks, also a huge amount of potential energy from boiling liquid under pressure. Consequently, sufficient protection from external events causing mechanical damage and instigating leakages is essential for the ship's survival.

The IGF Code establishes limitations regarding the location of fuel-containing equipment to provide sufficient protection from collisions and grounding, heat exposure from an external fire, and damage from ship and cargo operations. Area classification is applied to prevent fuel leak ignition and enable safe access, ventilation arrangements, and LSA locations.

2. System integrity:

Considering that LNG is a flammable and cryogenic gas, the fuel storage tank and systems must be designed to minimize leakages from the fuel installation.

System design requirements to reduce the risk of leakages

To ensure that LNG fuel systems are fit for purpose, the IGF Code requires suitable materials (e.g., for cryogenic temperatures), design to minimize leakage sources (e.g., using welded connections with a minimum of flanged connections and prohibiting the use of leak-prone components like bellows), and set requirements for manufacture, workmanship, and testing.

Control of operational and emergency discharges from the fuel system

The IGF Code requires arrangements to control the tank pressure to avoid discharges from the tank for a period of 15 days. Venting fuel vapour to control the tank pressure is not acceptable, except in emergency situations. Activating the safety system (emergency shutdown - ESD) is not considered an emergency in this context. A worst-case scenario with respect to discharges from the vent mast is a fire surrounding the LNG fuel tank, causing full-capacity discharge from the tank's pressure relief valves.

The IGF Code also requires that no gas be discharged into the atmosphere during bunkering. However, operational discharges from vents in the fuel piping system are not limited.

The Code sets requirements for the location of the vent mast, surrounding safety zone, and hazardous area to limit the consequences of a gas discharge from tanks/systems for the ship and crew.

3. Double barriers:

Fuel leakages reaching ignition sources may cause fires or explosions, and cryogenic leakages may damage ship structures and safety barriers. Consequently, all fuel system parts must have double barriers to protect the ship against leakages. This will typically be to provide a secondary enclosure around any leakage point.

The IGF Code requires that fuel piping routed through enclosed spaces be protected by a secondary enclosure capable of containing any gas that may leak from the primary piping system. Where the need for many piping components makes it difficult to fit a secondary enclosure around piping, the IGF Code requires that these components be placed in dedicated gas-tight spaces where it is possible to control the ignition sources. Examples of such spaces are tank connection spaces, fuel preparation rooms, and gas valve units.

Ventilation arrangements to control fuel leakages and protect against overpressure

The IGF Code sets requirements for ventilation arrangements for secondary enclosures, tank connection spaces and fuel preparation rooms to control fuel leakages and protect against overpressure. The ventilation system shall dilute gas leakages and transfer them to a safe discharge in the open air, maintain a pressure differential between spaces, ensuring that any change of atmosphere goes from a non-hazardous to a hazardous space, and ventilation ducts may serve as pressure relief in the event of LNG releases in enclosed spaces.

Access openings between hazardous and non-hazardous spaces

Where double barriers are arranged as rooms, they must be provided with some form of access for inspection and maintenance. Access openings can compromise the gas-tightness of tank connection spaces, fuel preparation rooms, and gas valve unit enclosures.

The IGF Code includes several approaches to ensure that access openings to hazardous spaces do not allow gas leakages to spread to non-hazardous spaces where potential ignition sources are not controlled.

One solution is accessing a hazardous space from the open deck in an area where potential gas release through the door will be manageable and safe. Where this is not possible due to the ship arrangement, one can arrange access via a double door arrangement, creating a new room between the two doors where a gas leakage can be handled safely (airlock). In cases where the consequence of leakage is deemed unacceptable, the arrangement of accessways between two spaces is prohibited (e.g., between tank connection space and engine room). In some instances, it can be feasible to gas-free the complete system before opening, like for gas valve units arranged in the engine room, thereby not needing any other precautions to prevent gas leakages.

4. Leakage detection:

System leakage must be detected to give a warning and enable automatic safety actions. The detection methods depend on arrangements but normally include gas detection systems, low-temperature measurements, and changes in pressure and temperature.

As opposed to a leakage from the tank containment system, a leakage in the fuel piping system can be isolated to limit the amount of fuel being released to the surroundings. To achieve this, it must be possible to detect that there is a leakage in the system, and the system must be arranged in such a way that strategically located valves can close and segregate the leakage point from large reservoirs of fuel. The IGF Code has applied the above safety barrier to limit the consequences of an LNG leakage. It requires that leakage detection devices are arranged everywhere there is a possibility for fuel leakages, such as in the bunkering station, annular space of double-walled piping systems, tank connection spaces, fuel preparation rooms, and in GVUs in the engine room.

5. Automatic isolation of leakages:

When a leakage is detected, the fuel supply system must be automatically shut down to reduce its consequences. This requires systems and arrangements to isolate the leakage from the source when the detection systems find something wrong with the fuel system. To achieve this, a number of isolation devices are required in the system, enabling the automatic shut-down of the fuel supply to the damaged system.

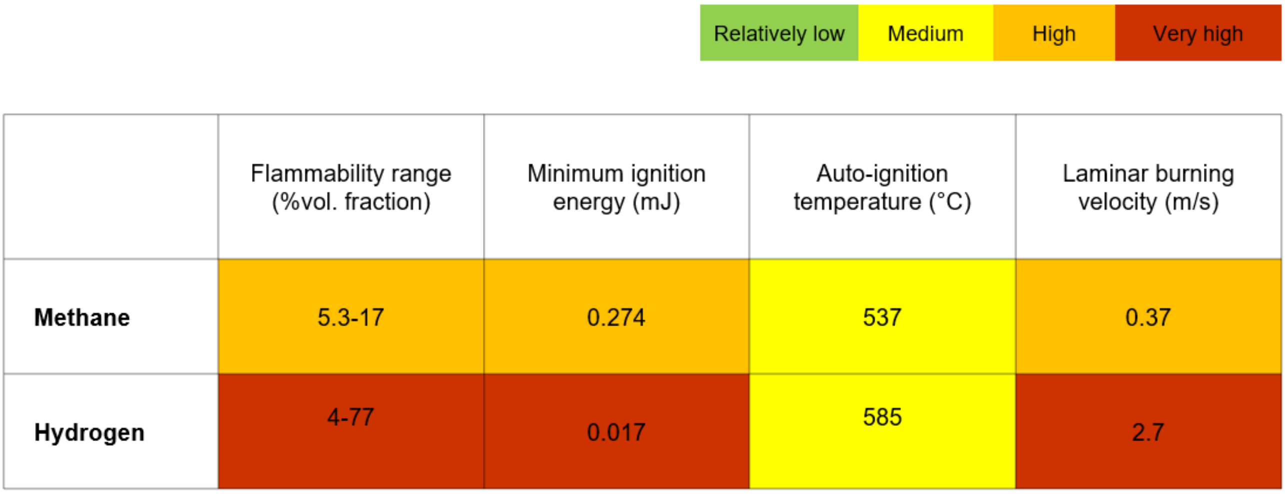
Further, these detectors shall send signals to emergency shut-down valves placed on tank connections and in the fuel system, stopping the fuel supply to the leakage point. This type of shut-down will necessarily also stop the fuel supply to the engine, and therefore, the Code requires redundancy in the fuel supply or some other arrangement to prevent an unacceptable loss of power generation and propulsion power.

A.2 Comparison of physical properties and related safety risks

A comparison of their physical properties and associated safety risks is necessary to determine if the same safety principles and regulations can be applied to hydrogen as they are to natural gas. We divide them into two groups: safety risks related to fuel flammability and safety risks related to storage, release, and dispersion. These groups are illustrated in Figure 9-2 and Figure 9-3 respectively.

When it comes to flammability, hydrogen poses a greater risk than methane. This is because hydrogen has a wider flammability range (6-7 times wider) and significantly lower minimum ignition energy than methane. In other words, a hydrogen leak is more likely to ignite than a methane leak. Additionally, hydrogen's higher burning velocity means that explosions caused by hydrogen can be more severe and even transition into detonation. Figure 9-2 highlights the extreme flammability properties and safety risks associated with hydrogen compared to methane.

Any hydrogen discharge on the open deck or in semi-enclosed or enclosed spaces onboard poses an additional safety risk compared to methane. If hydrogen is released in confined spaces, it can be especially dangerous because the pressure can build up rapidly after ignition, leading to potential structural damage, a higher risk of further hydrogen leakage, and the destruction of safety barriers.



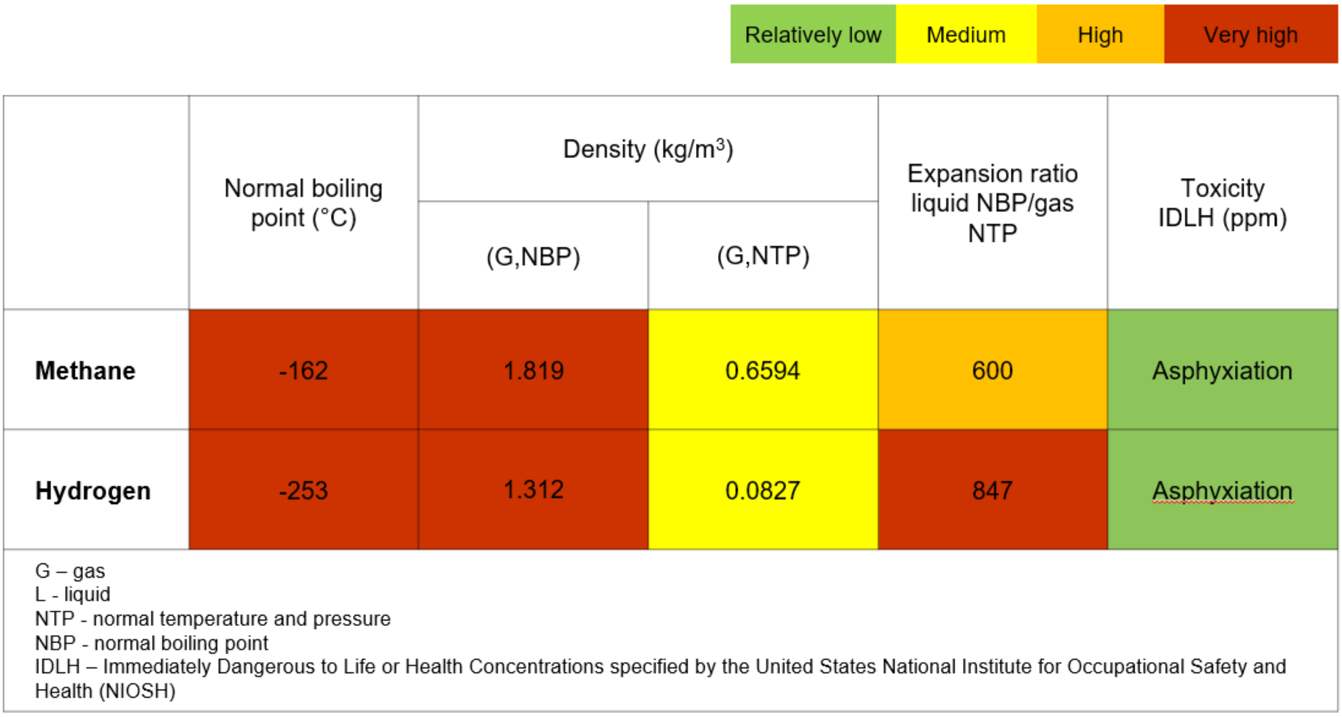
Relatively low | Medium | High | Very high

	Flammability range (%vol. fraction)	Minimum ignition energy (mJ)	Auto-ignition temperature (°C)	Laminar burning velocity (m/s)
Methane	5.3-17	0.274	537	0.37
Hydrogen	4-77	0.017	585	2.7

Figure 9-2 Safety risks related to flammability properties of methane and hydrogen when used as fuel onboard (DNV, 2022).

Liquefied hydrogen has a normal boiling point of -253°C and is stored at temperatures over 90°C lower than LNG. This creates extra safety concerns for onboard hydrogen storage and distribution, including managing boil-off gas and preventing the condensation and solidification of other gases with higher boiling points, such as oxygen and nitrogen.

When hydrogen is compressed to high pressures (250-700 bar), it gains significant potential energy, just like any other gas. Releasing this energy can cause strong pressure effects depending on the release rate, even without combustion. It's important to note that sudden hydrogen releases from high-pressure systems into the air can ignite spontaneously without any apparent ignition sources like a spark, hot surface, or fire. Additionally, hydrogen can lead to a significant reduction in the mechanical properties of metals, which is known as hydrogen embrittlement. Therefore, selecting appropriate materials for hydrogen systems is crucial to ensuring hydrogen safety. Figure 9-3 illustrates that hydrogen has similar but more extreme storage, release, and dispersion properties than methane.



Relatively low | Medium | High | Very high

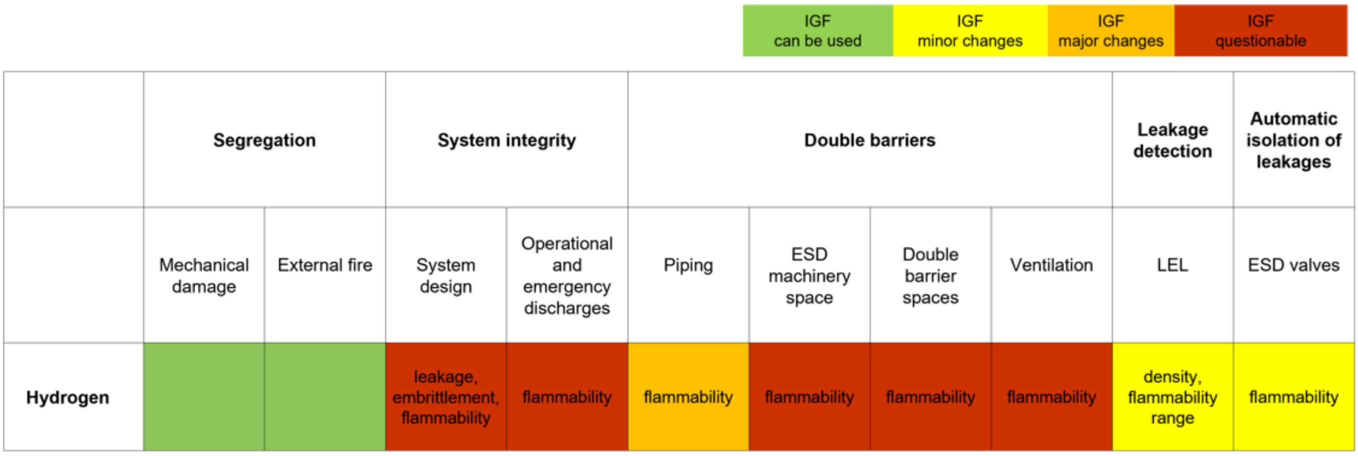
	Normal boiling point (°C)	Density (kg/m^3)		Expansion ratio liquid NBP/gas NTP	Toxicity IDLH (ppm)
		(G,NBP)	(G,NTP)		
Methane	-162	1.819	0.6594	600	Asphyxiation
Hydrogen	-253	1.312	0.0827	847	Asphyxiation

G – gas
L - liquid
NTP - normal temperature and pressure
NBP - normal boiling point
IDLH – Immediately Dangerous to Life or Health Concentrations specified by the United States National Institute for Occupational Safety and Health (NIOSH)

Figure 9-3 Safety risks related to storage, release and dispersion properties of methane, and hydrogen when used as fuel onboard (DNV, 2022).

A.3 Applicability of existing safety barriers to hydrogen

As illustrated in Figure 9-1, the safety barriers applied to LNG systems by the IGF Code can broadly be divided into five categories: segregation, system integrity, double barriers, leakage detection, and automatic isolation of leakages. The suitability of these safety barriers for hydrogen is summarized in Figure 9-4. We find that the existing safety barriers in the IGF Code do not account for hydrogen's extreme flammability properties. This illustrates the need for further regulatory development. Our findings are summarised in the following sub-chapter.



🟩	🟨	🟧	🟥
IGF can be used	IGF minor changes	IGF major changes	IGF questionable

	Segregation		**System integrity**		**Double barriers**				**Leakage detection**	**Automatic isolation of leakages**
	Mechanical damage	External fire	System design	Operational and emergency discharges	Piping	ESD machinery space	Double barrier spaces	Ventilation	LEL	ESD valves
Hydrogen	🟩	🟩	🟥 leakage, embrittlement, flammability	🟥 flammability	🟧 flammability	🟥 flammability	🟥 flammability	🟥 flammability	🟨 density, flammability range	🟨 flammability

Figure 9-4 Suitability of using the safety concept of the current regulations in the IGF Code for natural gas also for hydrogen when used as fuel onboard (DNV, 2022).

The applicability of the five main safety barriers for hydrogen can be summarized as follows:

1. Segregation

Segregation from mechanical damage

Significant damage to an LNG storage tank would be a catastrophic event that the ship is not designed to handle, and the same applies to liquefied and CH2 storage tanks. Therefore, it is logical to presume that the protective measures outlined in the IGF Code for tank safeguarding can be utilised for hydrogen as a fuel.

If it is deemed necessary to include stricter requirements for tank location for hydrogen, it should be considered to revisit the acceptance criteria defining the acceptable distance from the ship side in the probabilistic method for tank location in the IGF Code.

Segregation from external fire loads

Similar to the argument above on protection from mechanical damage, it is reasonable to assume that the regulations in the IGF Code to safeguard LNG systems from fire damage are appropriate for hydrogen systems.

One exception should be made for composite tanks. High-pressure tanks made of composite materials are commonly used to store CH2, as they are lightweight. However, it is necessary to analyse and understand the behaviour of these tanks in fire scenarios to determine if the current fire protection regulations outlined in the IGF Code provide adequate protection for this type of tank. Additionally, the ability of composite tanks to withstand impacts and dynamic loads must be assessed to ensure their suitability in an environment where accidental loads from cargo and ship operations are possible.

Hazardous zones to control ignition sources

Given the significant differences between hydrogen and methane with respect to densities and flammability/reactivity, one should probably be careful in adapting the IGF approach for methane to hydrogen fuel installations. The Code considers enclosed and semi-enclosed spaces safe if the equipment inside is certified accordingly. The ignition mechanisms for hydrogen are less well understood, the flammable range is significantly wider, and the energy required to ignite a hydrogen/air mixture is an order of magnitude lower.

2. System integrity

System design requirements to reduce the risk of leakages

The principles of ensuring fit-for-purpose design and minimizing leakage sources are especially relevant for hydrogen fuel systems. Because gaseous hydrogen consists of very small molecules, smaller leaks are common. Consequently, one should consider having strict requirements for leakage sources in hydrogen piping systems, avoiding detachable pipe connections, and reducing the number of valves and other leakage sources to the extent possible.

Hydrogen can significantly deteriorate the mechanical properties of metals, a process known as hydrogen embrittlement. Many metals absorb hydrogen, especially at high pressures. Hydrogen absorption by steel can result in embrittlement, leading to equipment failures. The choice of material for hydrogen systems is an important part of hydrogen safety, and specific requirements are needed.

Control of operational and emergency discharges from the fuel system

Operational releases from the tanks should not be an issue for hydrogen stored under pressure. However, tanks for CH2 are often protected against pressure increase from fire load with temperature activated pressure relief devices which will release all hydrogen if activated, resulting in a significant gas cloud. Considering the ignition sensitivity and significantly higher reactivity, including the propensity for detonation, it is clear that hydrogen releases are more hazardous compared to releases of LNG.

Liquefied hydrogen is stored in vacuum-insulated tanks at -253°C. The extreme temperature difference from ambient temperatures and the relatively small volumes may cause challenges with holding times, potentially leading to operational releases from the storage tank.

3. Double barriers

Piping

The double barrier principle applied for LNG systems to prevent leakages from reaching ignition sources can also be applied to prevent leakages of hydrogen pipes. However, the degree to which the higher flammability of hydrogen will require additional safety measures to prevent ignition in annular spaces of double-walled piping systems needs to be investigated.

ESD-protected machinery space concept

The early 4-stroke gas-fuelled engines were not available with a double-barrier fuel system. To facilitate the use of these engines, the IGF Code allows the use of fuel systems without double barriers if this is compensated for with extended requirements for ventilation, engine room arrangement, gas detection, and automatic shut-down of fuel supply to the engine room. The philosophy is that high ventilation rates, early detection, and isolation of leakages will prevent leakages from generating gas mixtures above the lower explosion limit range. Considering the extreme flammability of hydrogen, the ESD Machinery concept is not considered suitable.

Double barrier spaces (e.g., tank connection space, fuel preparation room)

The extreme flammability of hydrogen will require additional safety barriers to enable storage of hydrogen in liquefied or compressed form in enclosed spaces.

Ventilation

Ventilation as a possible risk mitigation measure has been discussed and analysed in (MarHySafe, 2021). CFD analyses of hydrogen releases in enclosed spaces indicate that a typically sized maritime room (80 m3) can only survive a leak below 220 g hydrogen in total for a short-duration gas leak (assuming ignition). As a safety barrier, ventilation could be used to prevent small leakages from building up an ignitable hydrogen atmosphere but would not prevent possible ignition and jet fire. For more significant hydrogen releases in enclosed spaces, forced ventilation should not be considered as a reliable safety barrier. It should be noted that the main safety barrier applied in other industries is to ensure that hydrogen leakages occur in the open air, using its buoyancy to keep leakages out of harm’s way.

Access openings between hazardous and non-hazardous spaces

The applicability of the various requirements in the IGF Code with regard to safe access arrangements to hazardous areas such as tank connection spaces, fuel preparation rooms and gas valve unit enclosures while preventing spreading of gases to non-hazardous areas needs further consideration.

4. Leakage detection

An arrangement enabling the detection of leakages, which communicates with a system designed to stop the system flow and thereby reduce the amount of fuel that can escape, will be equally important for hydrogen fuel systems. The detector alarm level and detector location must be adjusted for the specific properties of hydrogen.

5. Automatic isolation of leakages

Automatic closing of valves and other safety actions upon detection of leakages or loss of safety barriers to reduce the consequence is equally important for hydrogen as for natural gas. In order to achieve this, a dedicated safety system is required.

Appendix B Review of classification rules for hydrogen-fuelled ships

The table below contains requirements to be considered in the development of a Guidance for hydrogen as fuel on ships based on a review of current classification rules from ABS, BV, DNV and LR. The structure is based on the IGF Code Contents, the same structure as for the IMO draft Interim Guidelines.

IGF Code Contents		Classification requirements
Part A	Goal and functional requirements	Some classification societies have modified wording in the functional requirements (marked by underlined text): ■ The probability and consequences of fuel-related hazards shall be limited to a minimum through arrangement and system design, such as materials, ventilation, detection, and safety actions. In the event of leakage or failure of the safeguards, necessary safety actions shall be initiated. ■ The design philosophy shall ensure that safeguards and safety actions for the fuel installation do not lead to an unacceptable loss of power. ■ Commissioning, trials and maintenance of fuel systems and machinery shall satisfy the goal in terms of safety, availability, reliability, and maintainability. ■ A single failure in a technical system or component shall not lead to an unsafe or unreliable situation, including a failure which prevents the safety system from operating on demand.
	General requirements	Some classification societies have included additional goals under general requirements: ■ When hazards cannot be eliminated, inherently safer features shall be designed, arranged, and managed throughout the life of the ship. Inherent safety features are to primarily focus on passive means, such as the applicability of materials, physical barriers, containment, separation, natural ventilation, and absence of ignition sources; and secondly, active means, such as detection, isolation, ventilation, inerting and extinguishment. ■ Hazards shall be managed for all hydrogen systems regardless of the inventory of hydrogen. Most classification societies have included various requirements to the risk assessment and its scope (HAZID, HAZOP, risk analysis, explosion analysis).
Part A-1	Ship design and arrangement	Functional requirements/design principles required by classification societies additional to IMO regulations: ■ The fuel containment systems and associated connections and equipment shall be located on an open deck with sufficient natural ventilation and unobstructed relief of leakages to prevent the accumulation of escaped gas and shall be protected from environmental hazards (e.g. green sea), mechanical damage (e.g. dropped object), and fire risk areas.

		■ Other locations and arrangements of the fuel containment system and associated connections and equipment, e.g. semi-enclosed spaces, enclosed spaces below deck, swappable container arrangement, etc., may be accepted if proven to have an equivalent level of safety through a risk assessment. ■ The fuel containment system and piping system for liquefied gas fuel shall be able to contain cryogenic leakages without damaging other structures due to the low temperature of the leaked fuel or related condensed atmosphere. ■ Areas with piping systems for gaseous fuel shall be arranged to prevent gas spreading to non-hazardous spaces. ■ All components of the hydrogen installation shall have safe access for inspection and maintenance. ■ Defined leakage sizes shall be considered for the various piping system components, including full bore rupture. ■ Fuel piping systems shall be located in such a way that the risk of mechanical damage from ship operations, cargo operations and green seas is minimized, either by locating the fuel piping systems away from such hazards, or by providing mechanical protection. Classification societies have added specific requirements to Ship design and arrangement related to: ■ Arrangements to avoid the accumulation of hydrogen on open deck and in semi-enclosed and enclosed spaces. ■ Means to purge and gas free spaces where fuel release is reasonably foreseeable after release. ■ Minimum volume of enclosed and semi-enclosed bunkering stations and tank connection spaces. ■ Gas safe machinery space concept required (ESD protected machinery space concept excluded). ■ Mustering stations and lifesaving equipment shall not be located in hazardous areas, and evacuation routes shall not be impacted by potential jet fires and/or heat radiation. ■ High-pressure hydrogen systems shall be located in an inerted enclosure. ■ Lines and equipment for liquid hydrogen shall be protected with vacuum insulated enclosures.

	Fuel containment system	Functional requirements/design principles required by classification societies additional to IMO regulations:
		■ Potential dangers to be avoided include:
		  ■ Fuel containment systems shall be designed to avoid formation of ice or frozen air.
		  ■ Fuel leaking to form a flammable or explosive atmosphere.
		■ The fuel containment system shall be designed to avoid the formation of liquefied and solidified air and water.
		■ Loss of vacuum is not to lead to an unsafe condition.
		■ The materials used for the fuel containment system are to be compatible with the fuel stored. The fuel containment system is to be resistant to hydrogen embrittlement.
		■ Fuel containment systems shall be located in such a way that the risk of excessive heat input from a fire is minimized.

		■ Fuel containment systems shall be located in such a way that the risk of mechanical damage from explosions is minimized, either by locating the fuel tanks away from areas of explosion risks by providing mechanical protection, or by reducing the risk of explosions. ■ Fuel containment systems shall be designed and arranged not to cause damage to other structures due to low temperature leakages. ■ Fuel containment systems shall be designed and arranged to minimize, as far as practicable, the extent of hazardous areas and potential sources of release. Classification societies have added specific requirements to Fuel containment system related to: ■ Design and construction requirements for storage tanks for liquefied hydrogen limited to IMO type C tanks. ■ Design and construction requirements for compressed hydrogen tanks (cylinders, compressed hydrogen tanks other than cylinders, and Multiple-element gas containers (MEGC)). ■ An automatic, fail-safe, shut-off valve shall be mounted directly on or within each hydrogen cylinder where the shutdown system is integrated in the ship’s safety system. ■ Cylinders, connections, fittings, and valves shall be suitable for operation in the environmental conditions in which they are expected to operate taking account of the specific characteristics of the marine environment. Justification of the suitability of their design, construction and testing shall be submitted. ■ Means are to be provided to verify the loading condition (fuel temperature, pressure, and filling level) of the portable storage tank and cylinders before connection to the ships fuel system. ■ The requirements for liquefied gas fuel containment are applicable to IMO type C tanks only; all other tank types shall be considered on a case-by-case basis. ■ Secondary barriers and thermal insulation shall prevent liquefaction and solidification of ambient air i.e., oxygen, nitrogen etc. ■ Secondary barrier shall provide for tank pressure and boil-off to rates which are compatible with anticipated hydrogen consumption on board under all operational conditions for the intended life-/operation cycles of the tank. ■ When the inner insulating space is blanketed with hydrogen gas in order to prevent liquefaction and solidification of air against the inner barrier. Safety measures for preventing leakage of gas from the inner insulation space are to be considered to ensure the reliability of the insulation structure. ■ Specific requirements related to thermal insulation and protection considering extremely low temperatures, prevention of liquefaction and solidification of air, and resistance to the effects of high oxygen concentrations caused by air condensation and subsequent evaporation at low temperatures. ■ Relief valve sizing shall include loss of vacuum. ■ The vent mast shall have a design pressure not less than 20 barg. ■ Vent mast exits shall be arranged to safely disperse any release, to prevent its ignition, and limit the consequences of ignited gas (i.e., thermal radiation and fire impingement). Safe distances shall be

		determined from gas dispersion analysis and heat radiation analysis according to EIGA 211/17 *Hydrogen Vent Systems for Customer Applications* or other relevant standards, where the boundary is determined by the greater of the LEL or 6 kW/m2, which shall not be less than B/3 or 6 m above the weather deck…Extension of hazardous areas and safety distances shall be considered based on the result of the analysis. ■ The vent mast height shall be sufficient to prevent thermal radiation from affecting the personnel, life-saving equipment, fuel containment system and structures on board. ■ Vent masts are to be equipped with fixed hydrogen gas detection and monitored in accordance with Section 15. ■ Design of venting systems with regard to potential ignition inside vent line, extremely cold temperature, oxygen rich liquid air and ice formation and condensed liquid air. ■ Flammable concentrations may lead to DDT in vent masts of sufficient length. The ratio diameter/ length shall be designed to prevent that occurrence by design. ■ The vent mast shall be designed to minimize the risk of self-ignition internally in the vent line. Guidance note: Molecular seals in combination with inert gas supply to prevent air ingress at the vent mast outlet may be considered. ---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e--- ■ Vent masts shall be grounded to prevent build-up of static electricity. ■ The vent system shall be designed in such a way that no liquid hydrogen is vented. ■ Nitrogen inert gas generators shall produce inert gas with an oxygen content which does not exceed 4,4 per cent by volume. ■ If inert gas generators are provided, they shall be capable of producing inert gas with oxygen content less than 3% by volume. A continuous-reading oxygen content meter shall be fitted to the inert gas supply from the equipment and shall be fitted with an alarm set at a maximum of 3% oxygen content by volume. ■ At liquefied hydrogen temperature, only Helium can be used as an inert medium. ■ Appropriate inert gas is to be chosen according to the expected operating temperature ranges of the hydrogen fuel contained in the systems to be inerted. For example, for hydrogen systems operating above the liquefication temperature of nitrogen, -196°C (-320°F), nitrogen gas may be used as an inerting gas. For temperatures below the liquefication point of nitrogen, helium may be considered. ■ Fuel tanks are to have maximum temperature of no more than 85 °C (185 °F) during bunkering operations.
	Material and general pipe design	Functional requirements/design principles required by classification societies additional to IMO regulations: ■ The design and arrangement of liquid hydrogen piping systems, including components and equipment, shall be insulated as necessary to avoid condensation and freezing of air constituent gases in normal operation. ■ Cryogenic condensates, in case of any single failure, shall be handled by suitable spill protection systems and the design shall prevent concentrated constituent gases, and hydrogen, spreading to non-hazardous spaces. Classification societies have added specific requirements to Material and general ship design related to:

		■ Materials compatible with hydrogen use, in particular with respect to hydrogen-specific metallurgical phenomena such as hydrogen permeation, hydrogen-induced cracking, stress corrosion cracking, hydrogen embrittlement and hydrogen attack. ■ Material of construction and ancillary equipment such as insulation is to be resistant to the effect of high oxygen concentrations caused by condensation and enrichment at the low temperatures attained in parts of the cryogenic hydrogen containment system. ■ Fuel piping lengths shall be minimized to reduce the likelihood of failure and inventory. ■ Hydrogen piping systems, where appropriate, shall be designed such that the fuel mass flow does not significantly exceed the maximum demand of the consumer(s). ■ Piping systems, including piping and components, for liquefied fuel shall be protected by a secondary enclosure able to contain leakages and protect the surfaces from exposure to atmosphere or other gases with higher boiling point than hydrogen. The secondary enclosure shall be arranged with vacuum. ■ Secondary enclosures protecting liquefied hydrogen piping shall be vacuum insulated or helium inerted and have a vapour tight seal in the outer covering to prevent the condensation of air and subsequent oxygen enrichment within the insulation. ■ The outer surface of the secondary enclosures shall in normal operation not cause condensation of air constituent gases and shall be arranged for collection and drainage of such condensation, or equivalent solutions, in case of any single failure. ■ Liquefied hydrogen and cold hydrogen vapours piping systems are to be provided with a thermal insulation system as required to minimize heat leak during bunkering and transfer operations and to protect personnel from direct contact with cold surfaces. ■ Gaseous fuel piping systems shall be arranged with a secondary enclosure. Single walled low-pressure piping located in an area on the open deck providing natural ventilation and unobstructed relief of leakages, may be accepted based on results from CFD analysis. ■ The secondary enclosure for high pressure piping systems, including bunkering line, shall be inerted or arranged with vacuum. ■ The secondary enclosure for low pressure fuel piping shall be inerted or arranged with vacuum. Arrangements with redundant mechanical ventilation system, can be accepted based on satisfactory results from CFD analysis. ■ The use of expansion bellows is not allowed for installation in hydrogen systems.
	Bunkering	Functional requirements/design principles required by classification societies additional to IMO regulations: ■ Formation of oxygen enriched environments shall be prevented or at least mitigated; and

		■ For liquefied and compressed hydrogen bunkering stations, accumulation of gas is to be prevented and non-essential machinery and equipment is to be eliminated to reduce congestion. Classification societies have added specific requirements to Bunkering related to: ■ Bunkering manifold surfaces shall be insulated to prevent condensation and/or solidification of gases (e.g. nitrogen, oxygen, etc.) caused by the low temperature. ■ Bunkering systems shall be designed and arranged to minimize the need for crew in the vicinity by minimizing local intervention required in normal operation. ■ The bunkering system shall include means to remove contaminants condensed at low temperature, such as a filter. ■ For compressed hydrogen, the connections at the bunkering station shall be self-sealing in case of disconnection.
	Fuel supply to consumers	Functional requirements/design principles required by classification societies additional to IMO regulations: ■ Leakages in the fuel piping system shall not cause damage to other structures due to the low temperature. ■ The design and arrangement of high pressure compressed hydrogen systems shall take into account self-ignition and delayed ignition of the released gases, by arranging secondary barriers with inerting or other equivalent means. ■ Fuel piping systems shall be designed and arranged to minimize as far as practicable the extent of hazardous areas and potential sources of release. ■ It shall be possible to detect leakages in a fuel piping system, and automatically isolate the leakage from the source. ■ It shall be possible to automatically isolate the piping systems for fuel at the tank boundary. ■ Fuel systems shall be arranged to minimize the size, pressure, and duration of a leak, by active or passive means, or a combination thereof. Classification societies have added specific requirements Fuel supply to consumers related to: ■ Use of materials reactive to contact with liquefied air or liquid oxygen (e.g. lubricants, grease) is to be avoided. ■ Appropriate means for the filtration of contaminants from the fuel is to be provided. The filtration system is to be fitted with means to indicate at all times whether the filter is becoming blocked or experiencing other loss of functionality. ■ The quantity and location of fuel filters shall be sufficient to ensure the quality of the fuel supplied is in accordance with required fuel quality standard of the consumer(s), if necessary. ■ The fuel filters shall be accessible, isolatable, and capable of being purgeable for cleaning, and fitted with instrumentation as necessary for safe, effective and reliable function.
	Power generation including propulsion	Classification societies have added specific requirements to Power generation including propulsion related to:

	and other gas consumers	■ When hydrogen is intended to be used for propulsion or essential services, a combination of separated sources of power distributed in several spaces is required. This requirement may be waived upon consideration by the Society when hydrogen is not essential to the proper functioning (e.g.: dual-fuel engines)
	Fire safety	Functional requirements/design principles required by classification societies additional to IMO regulations: ■ Fixed-fire extinguishing systems shall be installed having due regard to the fire growth potential of the protected spaces; and ■ Fire extinguishing appliances shall be readily available. Classification societies have added specific requirements to Fire safety related to: ■ Hydrogen fire-extinguishing shall not be initiated until the fuel source has been isolated. ■ Additional coverage of water spray system for exposed fuel piping on open deck, escape routes, exposed lifeboats, life rafts and muster stations. ■ If a water spray system is installed for cooling and fire prevention for exposed parts of fuel tanks located on open deck this system shall not interfere with the function of the heat radiation monitoring as given for vent masts. Release of the water spray systems shall not be possible before the heat radiation monitoring (e.g. TPRD) is activated. ■ Prevention of condensation and/or solidification of water caused by the water spray system contacting low-temperature areas of the pressure relief system. ■ Those areas covered with water spray shall permit safe transit along escape routes and exit of personnel from those spaces (e.g. secure walkways, necessary gratings etc.) ■ The fire detection systems are to detect hydrogen flames. ■ Dry powder or carbon dioxide fire extinguishing medium.
	Explosion prevention	Functional requirements/design principles required by classification societies additional to IMO regulations: ■ The design and arrangement shall minimize the inventory of hydrogen. ■ Hazardous areas and safety distances shall be reduced to a minimum. Classification societies have added specific requirements to Explosion prevention related to: ■ Explosion analysis and gas dispersion analysis ■ Anti-static clothing and footwear, and a portable hydrogen detector for each crew member working in the fuel area. ■ Explosion relief devices are to be designed so that if an explosion occurs the pressure will be relieved without creating projectiles.
	Ventilation	Classification societies have added specific requirements to Ventilation related to: ■ Hazardous spaces shall in general be inerted or arranged with vacuum. Hazardous spaces containing only fuel gas piping with design pressure below 20 bar can be protected with dilution ventilation.

		■ Application of mechanical forced ventilation of hazardous spaces where a cryogenic liquid or vapour can occur is not allowed. ■ The ventilated hazardous spaces are to be provided with a continuous operating mechanical forced ventilation system of the extraction type, and the ventilation capacity shall be sufficient to dilute the gas/ vapour concentration below 25% of the LEL in all reasonably foreseeable leakage scenarios. The ventilation system is to provide effective ventilation of the complete space, also taking into consideration the density of the leaking fuel gases and any internal obstructions, e.g. piping, equipment, valves, etc. ■ The hydrogen leakage rate in normal operation for each space is to be determined by measures or estimation based on manufacturer values for calculating the ventilation needs. This leakage rate is to be included when considering a leakage scenario due to technical failure. ■ The ventilation arrangements are to take account of the density of any potential releases of hydrogen. Commentary: Cryogenic hydrogen is denser than hydrogen at ambient temperatures and can be reactive with the surrounding atmosphere. Hydrogen releases in the air may react to form other vapours that are heavier than air. End of Commentary ■ Fuel preparation rooms shall be provided with an increased mechanical type of gas evacuation system to quickly dissipate a catastrophic leak of hydrogen to reduce the risk of fire and explosion. ■ Arrangement of the ventilation system that eliminate or at least minimize areas where gas may accumulate. ■ Localised ventilation at locations where fuel release is reasonably foreseeable (e.g. flange, valve, seal, etc.) or where gas may accumulate (e.g. structural beams, cable gates and pipe racks). ■ 100 per cent redundancy of ventilation fans. ■ Ventilation rates sufficient to prevent flammable atmospheres for the reasonably foreseeable leakage scenario. ■ Inerting of tank connection spaces for liquefied hydrogen as alternative to ventilation.
	Electrical installations	Functional requirements/design principles required by classification societies additional to IMO regulations: ■ Electrical generation and distribution systems, and associated control systems, shall be designed such that a single fault will not result in the loss of ability to maintain the safety of the hydrogen-fuelled installation. ■ Electrical equipment shall function as intended for all normal and reasonably foreseeable abnormal environments (e.g. oxygen deficient/enriched environment). Classification societies have added specific requirements to Electrical installations related to: ■ The temperature class T1 and equipment group IIC (or IIB H2) are to be used for potential flammable atmosphere for certified safe equipment.
	Control, monitoring and safety systems	Functional requirements/design principles required by classification societies additional to IMO regulations: ■ Control, monitoring and safety systems shall be arranged to ensure safe and reliable operation of the fuel installation. ■ A fuel safety system shall be arranged to automatically close down the fuel supply system upon failures in accordance with these rules and the installations safety philosophy. ■ Leakages of cryogenic and gaseous fuel shall be detected and alarmed.

		■ The fuel system is to remain safe in the event that the safety system fails to operate as a result of a single failure. The behaviour and status on failure and fault detection are to be defined. ■ The probability of failure on demand of safety functions and any associated safety sub-systems shall be minimized through design. ■ The fuel safety system and fuel control system shall be provided with a) visual and audible alerts of failure; b) fault tolerance of sensor inputs, e.g. range checking, wire breaking monitoring; c) self-monitoring capabilities to detect both functional and hardware failures; d) proportional control valves with position feedback; e) manual control of remotely controlled equipment (where appropriate); f) instrumentation devices to allow local and remote reading of essential parameters associated with storage, processing and bunkering; g) redundant data communication (where redundancy is required); and h) safeguards to prevent unauthorised modification of process related parameters. Classification societies have added specific requirements to Control, monitoring and safety systems related to: ■ A hydrogen vapour detection and alarm system are to be provided to warn of the release of hydrogen at the following locations: i) Fuel storage hold spaces ii) The vent mast ■ An audible and visible alarm shall be activated at overpressure and, if required, underpressure of each gaseous hydrogen cylinder on the navigation bridge and in a continuously manned central control station or safety centre as well as locally. ■ The vacuum pressure shall be monitored where loss of vacuum shall result in an audible and visual alarm.
Part B-1	Manufacture, workmanship and testing	-
Part C-1	Drills and emergency exercises	-
	Operation	Classification societies have added specific requirements to Operation related to: ■ The operational procedures are to include the limitations for machinery space entry and personnel protective equipment
		Classification societies have added specific requirements to Personnel Safety and PPE related to: Systems and arrangements are to be designed so personnel do not enter spaces expected to have hazardous or flammable gas concentrations. When entry is necessary, spaces are to be hydrogen-free prior to personnel entry. Regarding introduction of potential sources of ignition into spaces unless certified gas-free, special consideration for suitable protective equipment should be given to the low ignition energy of hydrogen and static electricity. Anti-static

		tools are to be provided for use where necessary suitable for hydrogen service. Personal protective equipment (PPE) for use in potential hydrogen environments includes anti-static protective clothing, including boots and gloves. When handling liquid hydrogen, PPE for potential leaks or splashes should be considered for eye/face protection and other skin protection.

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