WHEN TRUST MATTERS

HANDBOOK FOR HYDROGEN-FUELLED VESSELS

MarHySafe JDP Phase 1
1st Edition (2021-06)

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Foreword

Shipping faces major challenges adjusting to zero emissions over the next decades. Hydrogen is one of few zero-emission solutions with a promising potential for scalable use for the longer distances and larger energy needs in shipping.

This Handbook is an important contribution on the path to its safe and efficient introduction, as well as the use of hydrogen as marine fuel. The information in it will provide guidance on how to deal with the current safety and regulatory barriers.

The Handbook is a product of the Maritime Hydrogen Safety (MarHySafe) Joint Development Project (JDP) and developed by DNV in collaboration with all the partners and observers in Phase 1, with input from the Norwegian Maritime Authority. The Handbook provides a basis for a roadmap to hydrogen safety for the maritime industry, based on the current risk-based Alternative Design approval framework.

MarHySafe is a collaborative project involving the private business community as well as public authorities, and aims to support an increased uptake of hydrogen as an environmentally friendly solution for ships.

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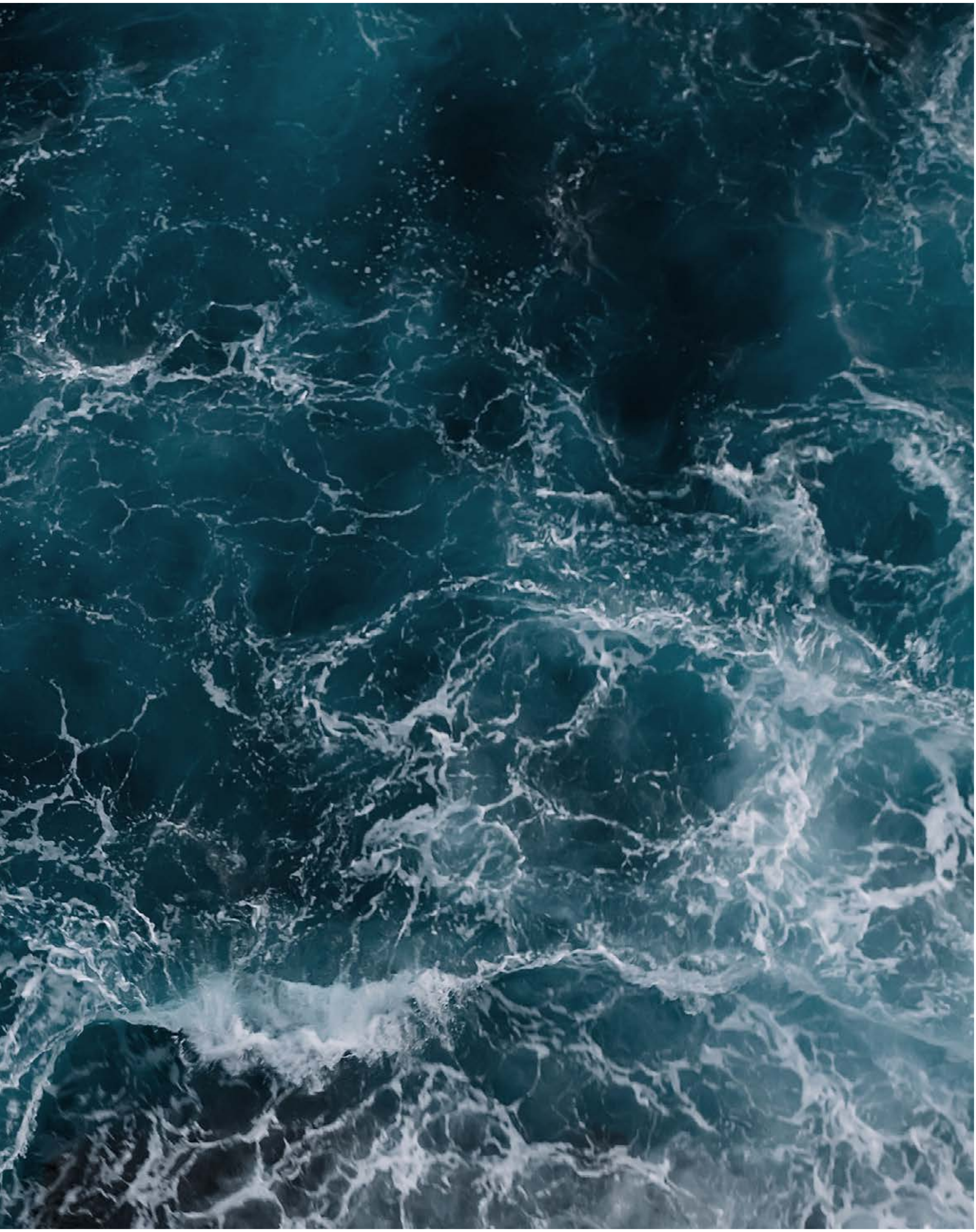

1 SUMMARY

Hydrogen is one of the few zero-emission fuels with a promising potential for scalable use for longer distances and larger energy needs in shipping.

It is therefore vital to start gathering practical onboard experience with it, without compromising on safety. The overall purpose of Handbook for Hydrogen-fuelled Vessels is to reduce safety approval costs without compromising on safety.

The first edition of this Handbook is the main deliverable of the Maritime Hydrogen Safety Joint Development Project (MarHySafe JDP) Phase 1. The development and refinement of the Handbook will continue in Phase 2 of MarHySafe, in order to contribute to and capture the knowledge and experience needed for safe and efficient introduction and use of hydrogen-fuelled ships.

The visions of the Handbook are to:
- increase the effectiveness and speed of the shift towards green shipping, without compromising on safety;
- be a knowledge accumulator and carrier; and,
- make the Alternative Design approval process more effective while developing the knowledge base for future approval according to DNV and IMO rules.

The interest in introducing hydrogen as a fuel in shipping is growing and several projects are planned or in the feasibility stage. However, maritime hydrogen-specific competence is very limited in the industry and among authorities worldwide, and such hydrogen-specific guidelines and rules are not yet available for ships. This was the background for initiating MarHySafe. DNV initiated the project based on the identified need to join forces with interested parties worldwide. The aim was to use MarHySafe to build national and international competence; facilitate effective processes, trust, and confidence; and start to develop the science-based foundation for future development of a regulatory framework.

The Handbook provides the basis for outlining a roadmap to hydrogen safety for the maritime industry based on the current risk-based Alternative Design approval framework (Part B, Chapter 6). The point of departure was fixed onboard fuel storage of LH_2 and compressed gaseous hydrogen (CH_2) with the energy converted by PEM fuel cells. There may be a fine balance between implementing this new technology too fast with too few safety precautions, and too slow with over-dimensioned safety systems. Further development of both the understanding and the use of criteria for equivalent risk will therefore be important for the safe, efficient introduction of hydrogen-fuelled ships (Chapter 6.3). Experience has shown that when too few safety systems are implemented, serious accidents can happen and development of a technology can stop for a long time. The alternative, overly robust systems, can drive up cost and result in slow or no implementation of the technology.

Experience from gas processing and natural gas as a fuel can provide useful insight but needs modification to be applicable for maritime use of hydrogen (Part A). Important differences in properties, related in particular to reactivity and explosion potential, make it necessary to think differently for hydrogen than for other fuels. There are also many similarities, meaning that processing and safety systems can potentially be reused with some modifications. The MarHySafe JDP has brought together the experience of industries that have used or are using hydrogen as an industrial gas and/or an energy carrier. This pooling of knowledge from maritime, oil and gas, and hydrogen systems providers, is essential for integrating hydrogen systems into a maritime setting. Experiences can be harnessed into methods and software tools that can be used for hydrogen-fuelled ship applications. Through combining a risk-based approach with digital twins tracking and indicating risks, highly qualified prototypes of hydrogen ships can be developed.

Today, it is possible to utilize advanced, digital, risk-modelling capabilities as a simulation and design tool to compare thousands of possible designs and parameter sensitivities – to find ‘the best’ solution at an acceptable cost. This way, lengthy processes with expensive laboratory trials and errors with many prototypes can be avoided. The Handbook presents and discusses the risk-based approaches and models that are available. It also covers the status of modelling capabilities for hydrogen, verification and validation of the models (Part C), and how they can be utilized to deal with the knowledge gaps in the next phase of the project (Chapter 11).

The Handbook also presents and discusses possible risk-mitigation and risk-control measures to contribute to safe design and operation (Chapter 9). Risk management and control measures to prevent, detect and isolate leaks, and to control ignition, are available. However, these measures have not been tested and validated for the use of hydrogen in maritime settings. For critical safety systems, it can therefore be necessary to perform experiments with hydrogen so that the performance can be fully understood and computer models adjusted and validated.

Phase 2 of the MarHySafe project will focus on the safe and efficient introduction of hydrogen-fuelled ships and their bunkering systems, based on the knowledge and knowledge gaps identified in Phase 1 of the project. The Alternative Design approval process, and the risk analyses required during this process, will be needed until sufficient knowledge and confidence are gained to develop rules. Therefore, the new knowledge will be used to make the Alternative Design approval process more effective and reduce approval times.

1.1 MarHySafe partners and observers

All MarHySafe partners and observers contributed to the development of the Handbook.

The MarHySafe Phase 1 project partners include:

Norwegian Maritime Authority (NMA), Norwegian Defence Materiel Agency (Naval Systems, NDMA), Equinor, Shell, Air Liquide, Linde, Kawasaki, Chart Industries, Parker, UMOE Advanced Composites, Hexagon Purus, Fincantieri, Feadship, HySeas Energy, Ballard, Cummins (previously Hydrogenics), Corvus Energy, A.V.Tchouvelev & Associates, Vancouver Fraser Port Authority, Redrock, Hydrogen Technology & Energy Corporation (HTEC), Memorial University, and DNV.

The Norwegian Public Roads Administration (NPRA), Standards Council of Canada, and Norwegian Directorate for Civil Protection (DSB) were observers in MarHySafe Phase 1.

The core team in DNV consisted of: Gerd Petra Haugom (Project Manager), Asmund Huser (Risk Assessment, QRA, CFD and modelling expert), Nathaniel Frithiof and Øyvind Sekkesæter. Narve Mjøs was the DNV Project Sponsor. In addition, several DNV internal experts and resources from different parts of the organization contributed with review, quality assurance and/or input. These include Monica Alvarez, Mike Johnson, Rolf Skjong, Magnus Lindgren, Guido Friederich, Torill Osberg, Hans Jørgen Johnsrud, Magnus Jordahl, Matthias Schmidt, Benjamin Scholz, Dalibor Bukarica and Daniel Allason.

MarHySafe Phase 1 Partners

MarHySafe Phase 1 Observers

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The Handbook is a guidance document based on current experience in a quickly developing technology, and it does not replace any official rules or guidance documents.

2 DEFINITIONS AND ABBREVIATIONS

The primary sources for the definitions are (IMO CCC7/3, 2020) and (IGF Code, 2016).

Accident – an uncontrolled event that may entail the loss of human life, personal injuries, environmental damage, or the loss of assets and financial interests.

ALARP – As Low As Reasonably Practicable

Bunkering – the transfer of liquid or gaseous fuel from land-based or floating facilities into a ship's permanent tanks or connection of portable tanks to the fuel supply system.

CFD - Computational Fluid Dynamics

CH_2 – compressed gaseous hydrogen.

CO_2 – Carbon dioxide.

DAL – Design Accidental Load.

DDT – Deflagration to Detonation Transition.

Enclosed space – a space where, in the absence of artificial ventilation, the ventilation will be limited, and any explosive atmosphere will not be dispersed naturally. 'Forced' and 'mechanical' are other terms describing artificial ventilation.

ERA – Explosion Risk Analysis.

ESD – Emergency Shutdown.

Exhaust air – exhaust from the cathode side of the fuel cell.

Exhaust gas – exhaust from the (reformer or) anode side of the fuel cell.

Explosion – a deflagration event of uncontrolled combustion.

Fuel cell (FC) – source of electrical power in which the chemical energy of a FC fuel is converted directly into electrical and thermal energy by electrochemical oxidation.

Fuel-cell module – assembly of fuel cell and necessary components for fuel supply and power output. The module typically represents the minimum equipment necessary to effectively produce electrical energy supply to the vessel from hydrogen.

Fuel-cell power installation – the FC power system and all other components and systems required to convert electrical power for the ship. It may also include ancillary systems for the fuel-cell operation, such as cooling water pumps and converters. A space containing fuel-cell power system(s) or parts of fuel-cell power system(s), providing a secondary barrier for any components containing fuel or hazardous vapours is called a fuel-cell space.

Fuel-cell power system – the group of components which contain fuel or hazardous vapours, fuel cell(s), fuel reformers, if fitted, and associated piping systems.

Fuel-cell rack – assembly of several fuel-cell modules.

Fuel-cell space – a space or enclosure containing fuel-cell power systems or parts of fuel-cell power systems.

Fuel-storage hold space – the space enclosed by the ship's structure in which a fuel tank (containment) system is situated. If tank connections are located in the fuel-storage hold space, it will also be a tank connection space.

GHG – greenhouse gases.

Hazardous area – an area in which an explosive gas atmosphere is or may be expected to be present, in quantities such as to require special precautions for the construction, installation, and use of equipment.

HAZID – Hazard Identification study.

ICE – Internal Combustion Engine

IGF code – International code of safety for ships using gases or other low-flashpoint fuels.

IMO – International Maritime Organization.

Inter-barrier space – the space between a primary and a secondary barrier around the fuel tank, whether or not completely or partially occupied by insulation or other material.

LEL – Lower explosive limit.

LH_2 – Liquefied hydrogen.

LNG – Liquefied natural gas.

LOHC – Liquid organic hydrogen carrier.

Low-flashpoint fuel – gaseous or liquid fuel having a flashpoint lower than otherwise permitted under paragraph 2.1.1 of SOLAS regulation II-2/4.

LPG – Liquefied petroleum gas.

Non-hazardous area – an area in which an explosive gas atmosphere is not expected to be present in quantities such as to require special precautions for the construction, installation, and use of equipment.

NOx – Nitrogen oxides.

NTP – @Normal Temperature and Pressure, 20oC and 101.3 kPa.

PEM – Proton-exchange membrane.

Primary fuel – fuel supplied to the fuel-cell power system.

Process air – air supply to the reformer and/or the cathode side of the fuel cell.

PRV – Pressure relief valves.

QRA – Quantitative Risk Analysis

Risk – an expression for the combination of the likelihood of a hazardous event and the severity of the consequences of this event.

RO – Recognized organization, term defined in SOLAS X-1/1.

Semi-enclosed space – a space where the natural conditions of ventilation are notably different from those on open deck due to the presence of structures such as roofs, windbreaks and bulkheads and which are so arranged that dispersion of gas may not occur (ref. IEC 60092-502:1999 Electrical installations in Ship-Tankers-Special Features).

SOLAS – Safety of Life at Sea.

SOx – Sulfur oxides.

STP – @Standard Temperature and Pressure, 0°C and 1 bar.

Tank connection space – a space surrounding all fuel-tank connections and fuel-tank valves that is required for tanks with such connections in enclosed spaces.

TQ – Technology qualification.

Ventilation air – air used to ventilate the fuel-cell space.

3 INTRODUCTION

Climate change is the greatest societal, safety, and financial risk the world is facing today. To cope with this risk, all human activities must adhere to a green transition process – driven by regulations, market requirements, and the financial sector. In this process we will see winners and losers.

3.1 Background

The shipping industry is under increasing pressure to act upon the COP 21 Paris Agreement, the new carbon dioxide (CO_2) reduction targets from the International Maritime Organization (IMO), and to reduce greenhouse gas (GHG) emissions in general. Shipping must achieve large emissions reductions over the next decades. The authorities have also increased their focus on the consequences of dangerous emissions of nitrogen and sulfur oxides (NOX, SOX) and particulate matter (PM). The European Environmental Agency claims that close to 500,000 people in Europe lose their lives prematurely every year due to local air pollution. Local and regional air pollution will in future face tougher regulations worldwide. Following reductions in air pollutants from other sources, particularly from industry and land transport, the marine sector may be expected to account for a larger percentage of emissions, and to face increased societal pressure to reduce them.

The next big deadline for the industry is 2050. The IMO's commitment to halve emissions from shipping by 2050 sets an ambitious target for the maritime world. Alternative and zero carbon fuels offer a pathway to achieve this goal, but there are still challenges with all alternative energy carriers / fuels. Liquefied natural gas (LNG) and liquefied petroleum gas (LPG) are fossil fuels. Ammonia is currently produced from fossil natural gas and is toxic. Biofuels face sustainability challenges, high costs, and limited availability. Each conversion/transport step for the alternative value chains requires energy. This influences the overall energy efficiency of the value chain while, at the same time, the necessary marine infrastructure and bunkering solutions need to be developed. All-electric solutions are limited to ferries and short distances. Within short-sea shipping, and even for transportation on urban waterways, it is considered a challenge to find zero-emission solutions for longer distances than those that can be supplied by batteries. For example, for high-speed urban sea-shuttles, batteries can become too heavy or may not be applicable due to insufficient local grid capacity for fast supply of the electricity required. Many stakeholders consider hydrogen as a viable solution for coastal and short-sea shipping. It can be a more flexible energy carrier, can facilitate onboard storage of more energy than batteries, and it is also more suitable for transport to bunkering sites. Hydrogen fuel cells might be the only zero-emission alternative given the lack of sustainable biogas. Whether hydrogen is a truly zero-emission option depends on the value chain and whether it is produced from renewable energy sources.

It is a megatrend that the world's population increasingly lives in growing cities close to the sea. Early adopters can take advantage of this megatrend by developing zero-emission technologies and solutions for urban sea-transport, and scaling the business as new low-carbon markets emerge worldwide. For international shipping, hydrogen-based solutions might be the only zero-emission alternative. This is of special relevance for traffic in environmentally sensitive areas, such as sailing in the Arctic or in Norwegian fjords.

Hydrogen has the potential to become a popular solution for several shipping segments. Attention on hydrogen technologies is growing, and industries are increasing investment in hydrogen solutions throughout the range of foreseen hydrogen related value chains. These include hydrogen applications in transportation such as heavy trucks, rail, and maritime.

The international rule base developed by the IMO (IGF Code, 2016) (MSC.1/Circ 1455, 2013) and outlined in Chapter 6, points to a demanding approval process similar to the DNV process for Technology Qualification (TQ). This is required to demonstrate an equivalent level of safety compared with conventional solutions. Neither the IMO, Flag States, nor Class Societies have satisfactory rules and/or requirements for hydrogen-powered ships. The IMO has however initiated a process to develop rules for fuel cells in the IGF Code. DNV has Class rules, but these do not cover the storage of hydrogen.

Hydrogen gas is flammable, highly explosive, and has different safety-related properties and behaviour compared with other gases including natural gas. As experienced with other new and alternative fuel solutions, an accident may result in safety and economic consequences that put the development on hold for many years. It is therefore of utmost importance to start developing the required knowledge base for a future harmonized approach. This is a key purpose of this Tentative Handbook, and a shared motivation among all the partners and observers contributing to the work. The approach tries to utilize knowledge from all available sources, as illustrated in Figure 3.1.

Since codes and standards for maritime hydrogen are incomplete, it is necessary to apply 'first principles' where the true behaviour of systems that experience failures is discovered before measures are implemented to prevent and reduce risks. Available codes and standards for other low-flashpoint fuels are among the tools used, with the basis for these being challenged by the actual physical behaviour of hydrogen compared with conventional gases. The method used to apply first principles is risk analysis in which the physical behaviour of hydrogen in incidents is a main part of the assessment. Accelerating the large-scale roll-out of hydrogen ships can be more effectively achieved through applying information from previous accidents and, where knowledge is missing, from new experiments. Such information is used to validate and ensure that the risk-assessment models are true and representative for the situations at hand.

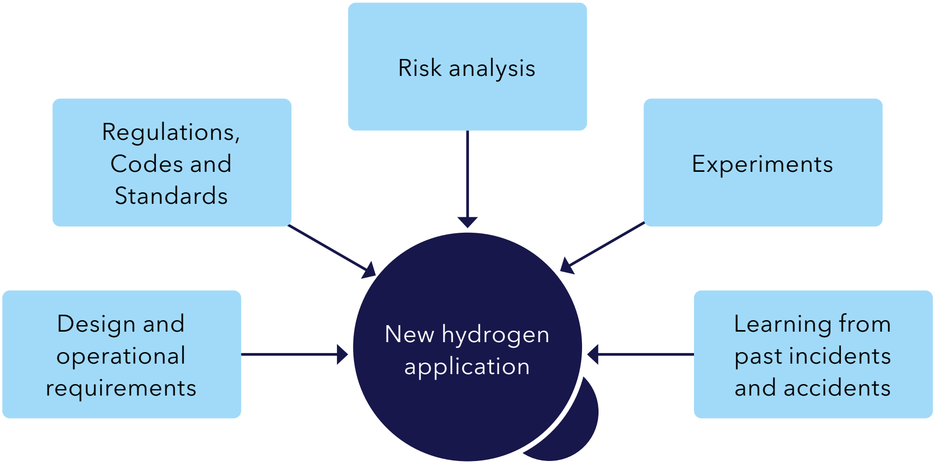
Hydrogen can be stored both as a pressurized gas and a cryogenic liquid, and the different impacts on safety are addressed in the Handbook. Indirect hydrogen storage methods such as liquid organic hydrogen carrier (LOHC) storage and ammonia are not part of the current work scope. However, the Green Shipping Programme has jointly with DNV and NMA developed a safety handbook for ammonia as a marine fuel (DNV GL, GSP, NMA, 2021).

Based on its safety-related properties, hydrogen can be considered a challenging fuel. On a ship, pure hydrogen will be stored either as a liquefied gas at very low temperature (-253 °C) and a slight overpressure (typically 1–10 bar) or as a compressed gas at very-high pressure (typically 250–700 bar). As hydrogen is the smallest of all molecules, hydrogen gas is more challenging to contain than other gases; it has a wide flammability range, ignites easily, and may self-ignite. This combination of properties may lead to increased overall risk, unless applicable safety systems and practices concerning hydrogen are implemented. Since the 'equivalent safety' regime does not tolerate increased risks, it is expected that smarter/better designs and more safety systems are needed compared with other gas fuel systems.

A key challenge is to avoid the chain of events that may lead to an accident if proper countermeasures are not in place and effective. A well-structured risk assessment process with involvement from people having the right competence is essential to identify, control, and mitigate

FIGURE 3.1

Example of input for new technologies when existing safety standards and approving bodies lack an approval basis. This often leads to delays before operation can start. Risk analyses can aid the process to identify if the risk is acceptable or if additional safety measures are required.



the potential risks related to hydrogen use as a fuel. Leaks associated with the bunkering operation and onboard fuel-storage system can potentially lead to high-risk events. Therefore, the Handbook addresses the location of the onboard fuel storage (including above or below deck).

Consequently, understanding of hydrogen and its safety-related properties in a maritime context will be key for safe and efficient introduction of hydrogen as a ship fuel. Among many important risk-related factors are: use of materials not fully compatible with hydrogen operation; the marine environment, reliable detection of process and operational deviations; ignition-source control; and, systems for maintaining safe operations.

DNV organized and led the Handbook development. The MarHySafe partners and observers have contributed actively with input, review, and feedback.

3.1.1 Moving from land-based to maritime

It is sometimes argued that experiences with hydrogen in land-based industries and transport, in submarines, and in the space industry, prove it can be safely stored on, and fuel, ships. However, there have been accidents with hydrogen onshore, and these may hold important lessons for its maritime use. Some principal differences need considering when it comes to novel hydrogen fuel systems for ships. The general lack of maritime and fuel-specific competence among suppliers and end users is recognized as a main safety hurdle for alternative fuels and their modes of operation (DNV GL, 2021). It is a well-established principle in the IMO, and for Class rules, that the level of safety requirements is increased when land-based technology is applied to ships. The required framework relates to a variety of conditions and ship motions, as illustrated in Figure 7.1:

- A ship operating out in the open seas is self-reliant and will in most instances not be able to rely on help from the outside.
- It is not possible for crew and passengers to escape to a safe external area in the same way as from a vehicle or within a building or industrial site onshore.
- Due to space constraints, the safety distances are smaller on a ship than a comparable land-based installation.
- Exposure to environmental conditions at sea is different than for land-based hydrogen applications, and may be more challenging. Humidity, sea water atmosphere/spray, thermal cycling, accelerations, vibrations and inclinations due to ship and wave motions are examples of marine challenges. The compatibility of materials, and possible consequences regarding fatigue life, for example, therefore need addressing. This involves considering the relevant marine conditions.
- Compared with a hydrogen-fuelled car, bus, or truck, the power demand for a ship is quite different. This implies that a hydrogen installation on a ship will usually be on a larger scale.

Land-based solutions are therefore not directly transferrable to ships.

3.1.2 Moving from natural gas to hydrogen

There are important differences in safety-related properties between natural gas and hydrogen gas, and also for the liquid fuels LNG and liquefied hydrogen (LH_2). Hydrogen's properties mean the criteria for selecting materials are different compared with natural gas. Hydrogen-specific factors that need addressing include, among others, the potential for embrittlement of materials, hydrogen permeation, extreme low temperature properties, and the possibility of electrostatic build-up and discharge.

A key to safe introduction of hydrogen is to consider the real properties of hydrogen and not assume that its behaviour is equal to any other gas or fuel. This means that materials, containment systems and operational practices approved and functional for compressed natural gas or LNG need to undergo additional hydrogen-specific assessments to be approved for compressed hydrogen or LH_2.

3.2 Study scope and limitations

Developing knowledge and understanding of hydrogen's safety-related properties and their potential safety implications for maritime use of hydrogen is required for its safe introduction as a ship fuel.

This Tentative Handbook for Hydrogen-fuelled Vessels takes the first necessary steps by putting in place the technical and scientific safety-related knowledge basis that is needed for a future harmonized approach. The work is undertaken as Phase 1 of the MarHySafe JDP. This Handbook is the main deliverable from MarHySafe Phase 1.

The scope covers fixed onboard fuel storage of LH_2 and compressed gaseous hydrogen (CH_2). Other hydrogen-based fuels like ammonia and LOHCs are not included in the work scope in this phase of MarHySafe. Movable hydrogen storage options, like tank swap, are not part of the present scope.

The first edition of the Handbook considers the use of fuel cells as the energy converter based on an initial focus on proton-exchange membrane (PEM) technology. Other energy converters such as internal combustion engines (ICEs), and/or H_2 blending, are not part of the present scope. Storage of hydrogen in other energy carriers, followed by the required reforming to hydrogen gas to be used in a fuel-cell power system, is principally covered in the generic fuel-cell power installation presented in Chapter 4.2.1.

Bunkering of hydrogen was not initially included; but, when the Norwegian Directorate for Civil Protection (DSB) joined, it became possible for Phase 1 to include aspects related to bunkering. While not traditionally included in Class rules, bunkering is – from a practical perspective – a critical aspect of safe operation of a hydrogen-fuelled vessel, and has been considered in Phase 1.

A range of different configurations for the use of hydrogen fuel cells and related liquid or compressed hydrogen storage in marine applications are under development. In the MarHySafe project, the basis to conduct realistic case studies was developed in a dedicated project task: 'CTR 2 Generic Ship Case Study' (DNV GL/MarHySafe, 2020). The aim of the generic ship case study was to provide relevant and realistic input for work in the other project tasks covering both CH_2 and LH_2 storage. The generic case study provided input to the activities in 'CTR 3 Alternative Design Process', and in particular to the HAZID (DNV GL/MarHySafe, 2020a). The outcome of these activities contributed important input to this Handbook.

The Handbook is organized in three main parts:

- Part A introduces the use of hydrogen in maritime.
- Part B introduces applicable regulations, codes, and standards for hydrogen as a maritime fuel.
- Part C gives an overview of relevant hydrogen safety issues and the risk-assessment methodologies needed.

The final chapter gives an overview of relevant knowledge gaps and suggests activities for Phase 2 of MarHySafe.

PART A -
INTRODUCTION TO USE OF HYDROGEN IN MARITIME

Part A of the Handbook introduces safety-related properties for hydrogen that need to be understood to be able to develop a safe hydrogen-fuelled ship concept. Part A also introduces generic system descriptions and a common terminology that can be applied in the development of maritime hydrogen systems.

4 INTRODUCTION TO MARITIME HYDROGEN SYSTEMS

Many different vessel types may be relevant for using hydrogen as fuel. These represent a range of dimensions, operational patterns, and constraints, and it is impossible to cover all in one study. It was therefore necessary to select one vessel type as the basis for the Alternative Design case study explored as part of the Handbook development.

In this study, a passenger vessel was selected as the generic vessel type, specifically a car ferry in compliance with the SOLAS convention for passenger vessels. There are multiple reasons for this choice, the main consensus being that ferries are likely to have the most onerous requirements, and are expected to be among the first vessels using hydrogen as a fuel. The generic vessel case was used as input to the Alternative Design evaluations including the HAZID study (DNV GL/MarHySafe, 2020a) undertaken as part of MarHySafe Phase 1.

The generic ship case represents a case where both liquid and compressed hydrogen storage may be feasible. This way, we had a basis for comparison between LH_2 and CH_2 storage, unlike what may be achievable with two distinctly different ships or ship types. The approach is feasible for the current (early) stage of hydrogen technologies for maritime use and for this first-phase iteration in MarHySafe. It provides a basis for moving forward to gain improved understanding regarding risks and uncertainties, and at the same time provides a 'fair' basis for risk comparison. This input is described in the Generic Ship Case study (DNV /MarHySafe, 2020).

4.1 Safety-related properties

Some safety-related hydrogen properties require special attention. They include its low density, low ignition energy, wide flammability range, and potential explosiveness. Table 4.1 summarizes hydrogen parameters that can influence safety, and compares them with those for methane. For each parameter, the impact on safety is described. For completeness, this table also includes parameters that are relatively similar to methane.

Hydrogen gas is a lot lighter than methane. Hydrogen's high buoyancy can be both an advantage and a challenge, and it needs to be considered in designing hydrogen systems. It is often argued that due to the lower density of hydrogen, an outdoor hydrogen gas release will disperse quickly. The buoyancy has a good effect in lifting the gas in the passive zone of the hydrogen gas cloud. However, for a high momentum jet with a release rate above a certain size, as long as the gas velocity in the plume is above the ambient air velocity, then the gas is driven by its momentum, and not by buoyancy. During this phase, it can build a large gas cloud in a similar manner to what happens in natural gas leaks. This momentum effect is also valid inside enclosed rooms, and the gas cloud can build up at all locations before it moves upwards to the ceiling.

A stoichiometric mixture is one where there is exactly the amount of fuel to completely use up all the oxygen with no excess fuel remaining. It is when the maximum combustion energy can be released. A stoichiometric mixture of hydrogen in air contains 29.5 volume percent (vol%) hydrogen, whereas for natural gas, the stoichiometric mixture is around 10 vol%. To get to this richer concentration with hydrogen, it is necessary to have a larger leak rate. This larger leak rate comes naturally for hydrogen since an equal hole size gives about three times the volumetric flow of natural gas in a like-for-like situation. Due to the wide flammability range of hydrogen, it can build a much larger flammable cloud with a smaller amount of gas compared with methane. An example of the amount of hydrogen that is needed to generate a critical cloud size and explosion pressure is given in the subsection on 'Simplified assessments of explosion consequences' in Appendix C.

The autoignition temperatures for hydrogen and methane are comparable; hence, there are similar ignition probabilities from hot surfaces. The minimum (spark) ignition energy for hydrogen concentrations below 15% is similar to that for methane. For higher hydrogen concentrations, the ignition energy can be more than an order of magnitude lower than the minimum for methane. Therefore, for richer hydrogen clouds, a higher ignition probability is possible if there are ignition sources with energies that will not ignite methane but will ignite hydrogen.

When selecting materials that will be in contact with hydrogen, it is critical to consider its properties to ensure that all materials used are compatible with hydrogen. This approach is needed to avoid hydrogen embrittlement and minimize the frequency of leaks.

When hydrogen burns, the only combustion product is water vapour. Clean hydrogen/air mixtures burn with a non-luminous, almost invisible, pale-blue hot flame liberating the chemically bound energy as heat (gross heat of combustion). The theoretical maximum flame temperature of a premixed stoichiometric mixture of hydrogen in air is as high as 2130 °C. Hydrogen flames can reach higher temperatures than other gases, but at the same time the radiation heat transfer out from the flame is normally lower. When the size of the fire increases, the radiation level also increases. For a large hydrogen fire, the radiation levels are comparable with those from hydrocarbon fires, and the flame becomes more visible.

A hydrogen explosion could be a serious consequence from a hydrogen leak (and ignition) in an enclosed or semi-open space, and this scenario might for certain conditions lead to high explosion overpressures. Estimation of hydrogen explosion risk is therefore a key element in hydrogen risk analyses, and extensive risk analyses may be required to understand and mitigate the risks associated with hydrogen efficiently. That is also why we have dedicated several of the following Handbook chapters to the topics associated with hydrogen risk assessments.

4.1.1 Risk comparison for gaseous hydrogen and methane

When comparing all safety-related properties for hydrogen and methane in gaseous form, and considering two otherwise equal systems, it is assessed that the properties of hydrogen result in a higher explosion risk. This is the case when hydrogen concentration is above 15%. Considering all effects in Table 4.1, it is seen that there are more negative than positive effects. The most important reasons are:

- hydrogen's larger flammability range, which means that a larger part of the gas can be ignited;
- hydrogen's lower ignition energy (for the high concentrations);
- shorter burning distances needed to initiate deflagration to detonation transition (DDT); and,
- higher explosion pressures in a hydrogen explosion.

Fire consequences are also different, but the fire severity is similar for natural gas and hydrogen. In addition, hydrogen storage tanks may be at higher pressures, potentially causing higher leak frequencies. The foreseen rapid increase in hydrogen appliances can lead to an unwanted increase in serious hydrogen explosion incidents if the risk is not addressed properly.

Hydrogen systems can still be made as safe as natural gas systems. However, the adverse effects of hydrogen mean that different, inherently safe designs, and a higher level of safety precautions with preventive and mitigating measures, might be needed in order to obtain a system whose safety level is equivalent to those of conventional hydrocarbon systems. A more thorough discussion of this is provided in Chapter 8.3.1. The document (ISO/TR 15916, 2015) is a relevant reference source for further information regarding hydrogen safety properties.

FIGURE 4.1

Ignition energy (Miranda, 2019) and laminar burning velocity of gases as a function of the gas concentration in air.

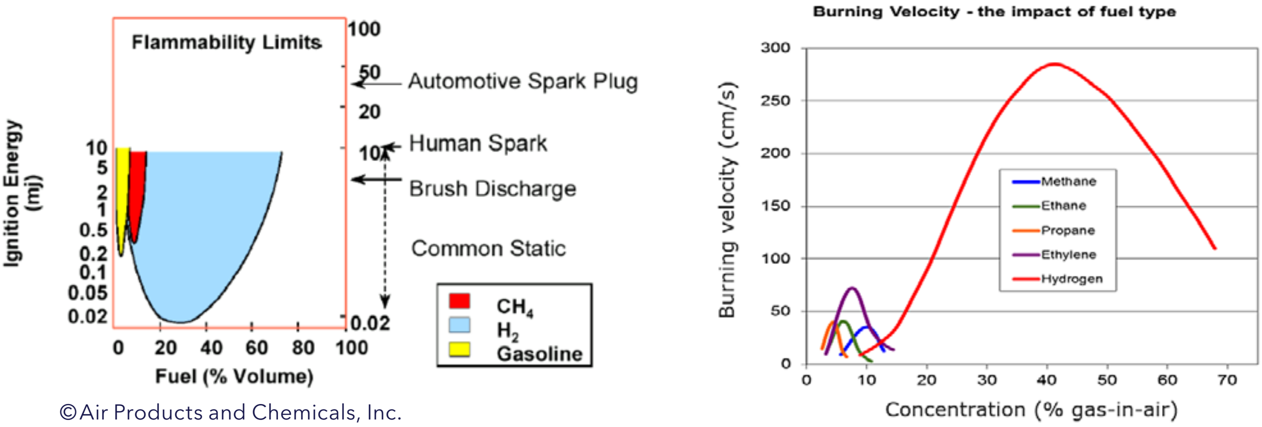


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TABLE 4.1

Comparison of safety-related properties for hydrogen and methane (ISO/TR 15916 , 2015), (Rigas, 2012).

Property	Hydrogen	Methane	Consequences for hydrogen safety
Gas density at NTP	0.0827 kg/m^3	0.659 kg/m^3	Can be positive for outdoor dispersion due to buoyancy, but only for passive clouds. High-pressure jet dispersion is dominated by momentum not buoyancy. Also negative because LFL may extend further for hydrogen jet than for methane.
Flammability range (25 °C, 101.3 kPa)	4–75 vol%	5–17 vol%	Negative, causing larger flammable cloud volume. LFL = 4% only for upward propagating H_2 flames, 8% is the lean limit of hydrogen combustion for practical applications.
Autoignition temperature	585 °C	537 °C	Neutral.
Minimum ignition energy	0.017 mJ	0.27 mJ	Negative. The ignition energy varies significantly with gas concentration (see Figure 4.1). For hydrogen concentrations up to 60%, the ignition energy is less than that of methane, with the absolute minimum being more than an order of magnitude less.
Boiling point	-253 °C	-161 °C	More challenging than CH_4. LH_2 can condense oxygen in air and cause unknown effects due to concentrated oxygen. Cryogenic effects different from LNG.
Amount of energy, heat of combustion (lower heating value)	120 kJ/g	50 kJ/g	For high-pressure gas releases at the same pressure and through the same hole size, the energy released for hydrogen is about 85% of that for methane.
Maximum burning velocity in NTP air (cm/s)	265–325	37–45	Negative. Results in much greater flame acceleration in congested areas and higher pressures in confined spaces due to the greater difficulty in venting the explosion fast enough. Rapid flame acceleration will give high explosion pressures in small clouds.
Detonability measured in minimum mass of tetryl (Bull, 1979)	0.8 g	16 000 g	Negative. Given greater flame acceleration with hydrogen (see above), DDT is a realistic if unlikely possibility. This is not the case for methane. A hydrogen detonation can propagate through the full cloud and increase the explosion severity significantly.
Laminar diffusion coefficient at NTP (cm2/s)	0.61	0.16	Negligible effect on dispersion which is dominated by turbulent diffusion. Other effects are more important, such as flow speed and low density causing longer momentum jets.
Speed of sound at NTP (m/s)	1 294	446	Negative, contributes to larger volumetric flowrates from leaks. Hydrogen has higher speed of sound and lower density. These cancel eachother out, resulting in similar jet momentum for releases with the same pressure and hole size.
Compressibility factor Z average 0 to 300 barg	01. Jan	0.9	Minor effect of non-ideal gas. Causes a reduced mass leak rate for H_2 compared to using ideal gas law. For higher pressure, real gas effects are larger.
Joule-Thomson effect when pressure is relieved	Causes a small temperature increase	Causes a temperature decrease	Negligible since the temperature increase effect on hydrogen is only a few Kelvins. Requirement to limit CH_2 temperature in storage tanks restricts filling rates (relevant for CH_2 bunkering).
Adiabatic flame temperature	2 045 °C	1 875 °C	Hydrogen flames can be hotter.
Heat radiated from flame to surroundings	17–25%	23-33%	These ranges are indicative and vary with release rate. Smaller hydrogen flames are invisible. At large release rates, a hydrogen fire can have the same radiation level as methane. There is very limited large-scale hydrogen data.

Comments give positive or negative safety effects for hydrogen compared with methane or natural gas systems. (NTP = Normal Temperature and Pressure, 20 °C and 101.3 kPa.)

4.1.2 Hydrogen in liquid (cryogenic) form

Compared with methane, hydrogen's extremely low boiling point makes it more challenging (and energy consuming) to store as a liquid. Since hydrogen has a narrow 20 °C temperature range for its liquid-phase it is more demanding to maintain hydrogen in the cryogenic liquid phase and to minimize boil-off compared with natural gas.

LNG is quite often mentioned as a good and reasonable starting point for the introduction of LH_2. Since LH_2 needs to be stored at a much lower temperature than LNG to be kept in the liquid form, there are some potentially serious pitfalls associated with this approach. The actual properties of LH_2 must be considered when designing LH_2 systems.

The potential cryogenic effects of a LH_2 release need to be considered. Common gases such as oxygen and nitrogen may liquefy or even solidify in contact with LH_2. During recent experiments with LH_2 releases it was observed that liquid and solid oxygen was formed at the ground and temperatures as low as 85 K were observed. It is believed that a pre-cooled ground from the previous test contributed to this happening in this specific case, and that the liquefaction and solidification of oxygen contributed to the ignition and serious explosion event that was observed (Jordan, 2020).

Because hydrogen needs less energy to evaporate than LNG, a LH_2 spray is expected to vaporize more easily and result in less cooling of – for example – surrounding steel than a comparable LNG spray. A pool from a larger spill of LH_2 is cooler than a similar LNG pool. However, the LH_2 would evaporate quicker, hence the resulting cooling effect can be either higher or lower. Large-scale experiments where these effects are investigated for hydrogen are limited. Fast evaporation of leaking LH_2 may lead to fast pressure build-up in confined spaces if venting is insufficient or ineffective. This needs to be considered in the dimensioning of LH_2 storage-tank hold space enclosures and related vent systems. Recent reports on LH_2 testing undertaken as input to the Norwegian Public Roads Administration hydrogen ferry development project may illustrate the potential challenges related to the use of LH_2 (DNV, 2020), (DNV , 2020a), (FFI, 2021). Some key learnings from this work and associated scenarios can be summarized as follows.

FIGURE 4.2

Snapshot of a horizontal release video showing the neutral plume with wind direction aligned with jet direction; left, seen from the side; right, fisheye fixed wide-angle camera view. Test 13. Visible plume is due to water vapour. The frosting on the pad to the right is due to the vertical impinging test that was performed prior to this.

FIGURE 4.3

Three different video snapshots of the same release from top of the vent mast. Almost all the released hydrogen is exiting the top of the vent mast. Wind is shifting partly from the side and towards the viewer. The release is bending over with the wind and in the passive phase it behaves more like a neutral plume. Test 14.

Outdoor releases:

- Outdoor releases were performed with liquid hydrogen from a LH_2 truck with 10 bar reservoir pressure, a flexible hose, and a nozzle up to 1-inch. Downward-facing vertical releases with release rates up to 0.8 kg/s resulted in a pool size of at most 1 m diameter on the concrete pad. This pool disappeared rapidly when the release was finished.
- Temperature measurements indicated the presence of liquid or solid constituents of air at a maximum of 1 m from the release point on the concrete surface.
- As hydrogen evaporates quickly, the consequences of cryogenic spill on steel plates seem to be less than for spills with LNG, as indicated by (Klebanoff, Pratt, & LaFleur, 2017). At some larger release rates, also cryogenic effects of LH_2 spills is expected to be critical for structural integrity, and more research can be needed to investigate this.
- The flammable hydrogen plume spread along the ground with a neutral buoyancy (Figure 4.2). It is expected that the cooling effect of the liquid hydrogen is cooling the air/hydrogen mixture so that the plume does not become buoyant.
- Flammable concentrations of hydrogen/air mixtures were observed at 50 m, but not 100 m downwind of the release when this was in the horizontal direction.
- Ignition of the fully developed hydrogen cloud caused a flash fire with no observation of fast deflagration or detonation from the outdoor release. It is noted that there were no obstacles in the path of the cloud.
- It should be noted that if the gas cloud became trapped in a congested or confined region such as under a quay, or a truck or skid on the quay, it could potentially result in severe explosion pressures. This severity would need to be evaluated throught experiments and modelling.

Enclosed-room releases simulating a tank connection space with a vent mast:

- Release of LH_2 was also performed inside a 24 m^3 room with a 10 m tall vent mast connected to it. The diameter of the vent pipe was 450 mm. The release rates were up to 0.67 kg/s LH_2. Tests were performed without and with ignition at the top of the mast. The test that had the smallest release rate and was ignited at the top of the vent had a release rate of 0.37 kg/s.
- Results showed that the room was typically filled with 100% hydrogen gas within 30 s.
- The cool hydrogen gas spread from the vent mast with neutral buoyancy (Figure 4.3).
- No clogging of the vent mast due to condensation or freezing of components in air was observed.
- The tests where hydrogen was ignited at the top of the vent mast showed a slow burn back to the room with a low-severity explosion. It is noted that the low severity in this case can have been due to incomplete combustion caused by lack of oxygen and a too-rich cloud. The release rate was relatively large for the room, and it is expected that with a lower release rate, a more severe explosion could have happened.

4.2 Generic hydrogen system configuration

A generic ship case (DNV /MarHySafe, 2020) was developed to provide relevant input cases to the Alternative Design (HAZID) study. The generic ship case was 'built' into a vessel by adding the main building blocks. This gives the opportunity to 'build' a generic vessel concept based on input from a variety of sources for different parts of the vessel. This way, IPR/confidentiality challenges can be reduced as the resulting generic vessel will not be a real vessel. There may be some challenges related to different parts not being 'real-life-compatible'; despite this, it is considered feasible for the development of a useful and relevant ship case.

It was agreed to use a starting point similar to the Norwegian Public Roads Administration LH_2 ferry project. Key public data[1] for this ferry includes: length, 80 m; width, 17 m; draught, 3 m; capacity in the order of 80 cars and 10 trucks, 300 pax.

Principal block diagrams were developed to visualize relevant onboard system configurations for both LH_2 and CH_2 storage. A main purpose of the diagrams is to develop a common basis and understanding of what components and systems are required and how they may be interconnected. This gives a common context to other parts of the project, for example the hazard identification studies. Under-deck storage was also chosen as a baseline to assess all hazards associated with the storage of hydrogen in a vessel. The LH_2 and CH_2 storage capacities and bunkering frequencies applied were part of the generic case assessment.

Section 4.2.1 shows a principal sketch of a fuel-cell power installation with its primary components. The block diagrams shown in Sections 4.2.1 and 4.2.3 contain principal system layouts for a compressed gas and a liquefied storage hydrogen system. Keywords and descriptions of the various components that are common for both system block diagrams in Sections 4.2.1 and 4.2.3 are listed here. CH_2 and/or LH_2 tank hold spaces and spaces containing the fuel-cell power installation are expected to include the following systems or components:

- Vent mast system (for control and emergency).
- Air ventilation system (normal and emergency).
- Separate ventilation spaces (pipe in duct, fuel-cell spaces, tank connection space, etc.).
- Structural fire protection.
- Fire detection and fire extinguishing systems.
- Hydrogen leakage detection.
- Void(s).

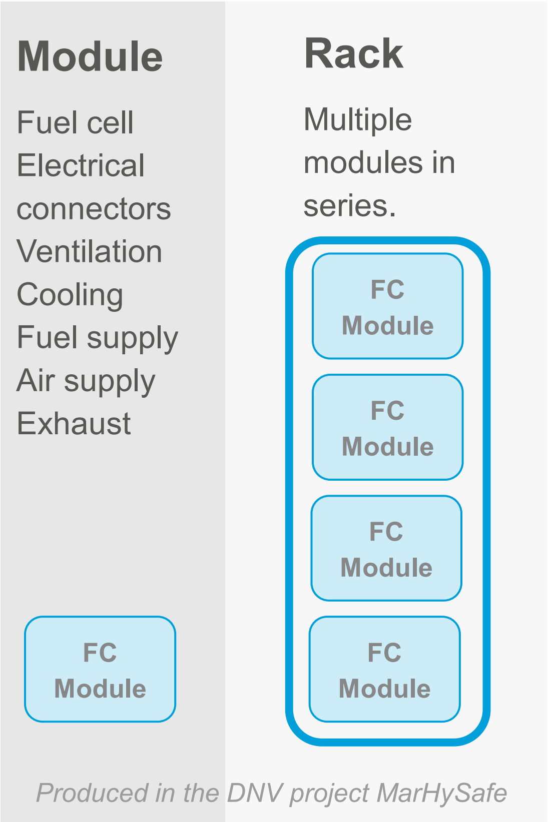
The compressed and liquid hydrogen block diagrams are illustrated in Sections 4.2.1.1 and 4.2.3. It should be noted that the tank connection space is only identified as its own space for the liquefied hydrogen storage case.

4.2.1 Fuel-cell power installation

The fuel-cell (FC) power installation will include:
- Proton-exchange membrane fuel cell (PEMFC; see 4.2.1.1 below) module(s);
- Fire protection (structural fire protection, fire detection and fire extinguishing);
- Hydrogen leakage detection;
- Auxiliary systems including
  - power conversion
  - FC control system
  - ventilation system
  - cooling system
  - vent system for FC exhaust air and hydrogen blow-off/purge system
- Neighbouring spaces.

FIGURE 4.4

Principal sketch for fuel-cell configurations, from module to rack level with modules connected in series.



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[1] https://www.tu.no/artikler/den-forste-hydrogenfergen-kommer-til-norge-i-november/497571?key=fkrrOUMv

Based on current PEMFC technology developments, and with experience from the development of maritime battery systems, the industry is adopting the term fuel-cell module. A module is typically identified as a unit that includes all the basic components necessary for the FC to properly function. A combination of several modules is typically called a 'rack'. The exact rack configuration onboard a vessel would depend on the power demand from the system in relation to the power output from a single FC module. The modules can be installed in series and/or in parallel to each other. A principal sketch for modules with included sub-components and racks is found in Figure 4.4.

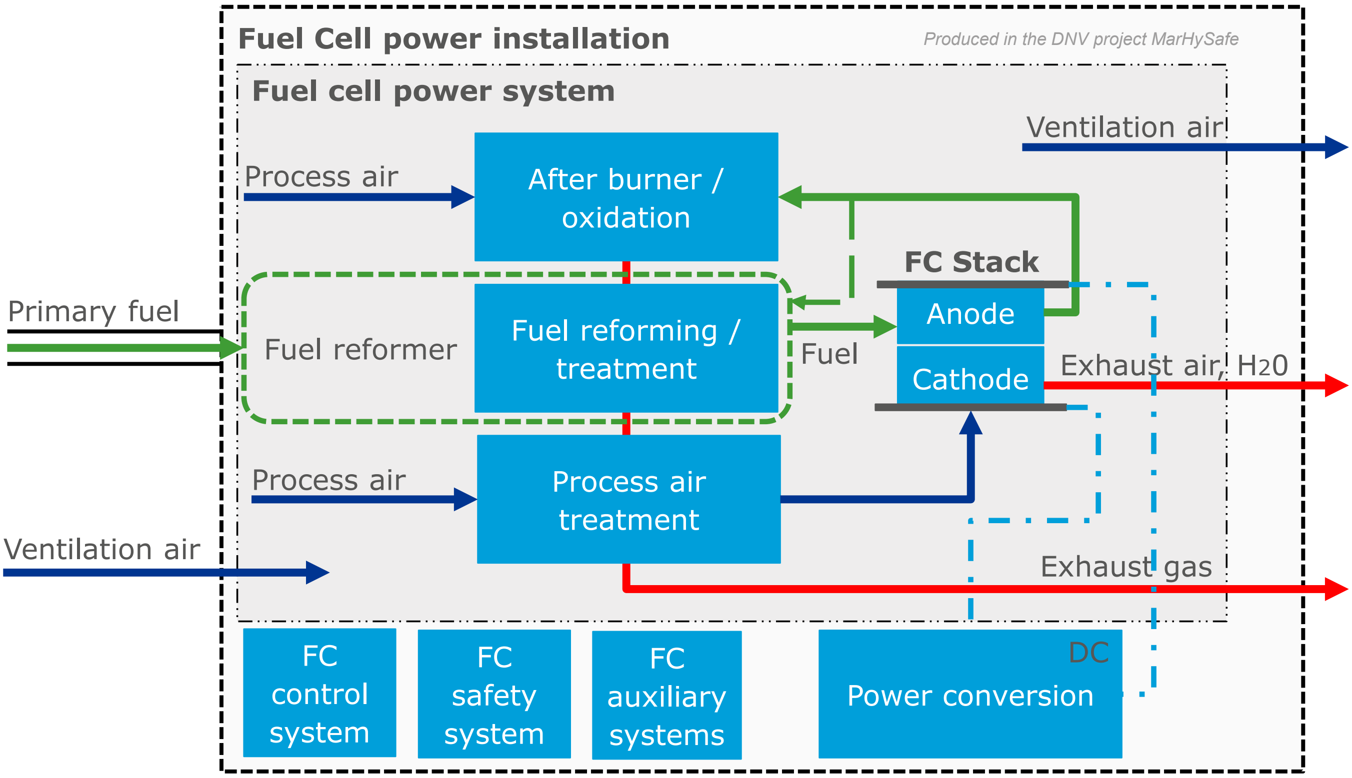
Regardless how the FC modules are combined onboard, the FC power installation will also include auxiliary machinery (such as cooling pumps) and equipment necessary for power conversion and power distribution to the vessel.

The FC power installation can be installed in one single FC space onboard the vessel, or it could be distributed to several FC spaces. While specific FC racks would be expected to be located within one space, the auxiliary equipment needed to operate them might be located in one central technical space providing support to multiple FC power systems on board. See Figure 4.5 for a detailed system description, with the FC stack in the middle surrounded by the components of a power system and power installation respectively.

Background information includes ongoing IMO work processes, which are available (IMO CCC 5/3, 2018), (IMO CCC7/3, 2020).

FIGURE 4.5

Fuel-cell power installation, in line with forthcoming IMO guidelines (IMO CCC7/3, 2020).



4.2.1.1 Fuel cells

Fuel cells produce electricity in an electrochemical process that converts the chemical energy of the fuel into electricity through reacting hydrogen with oxygen over a catalyst, with water as a by-product.

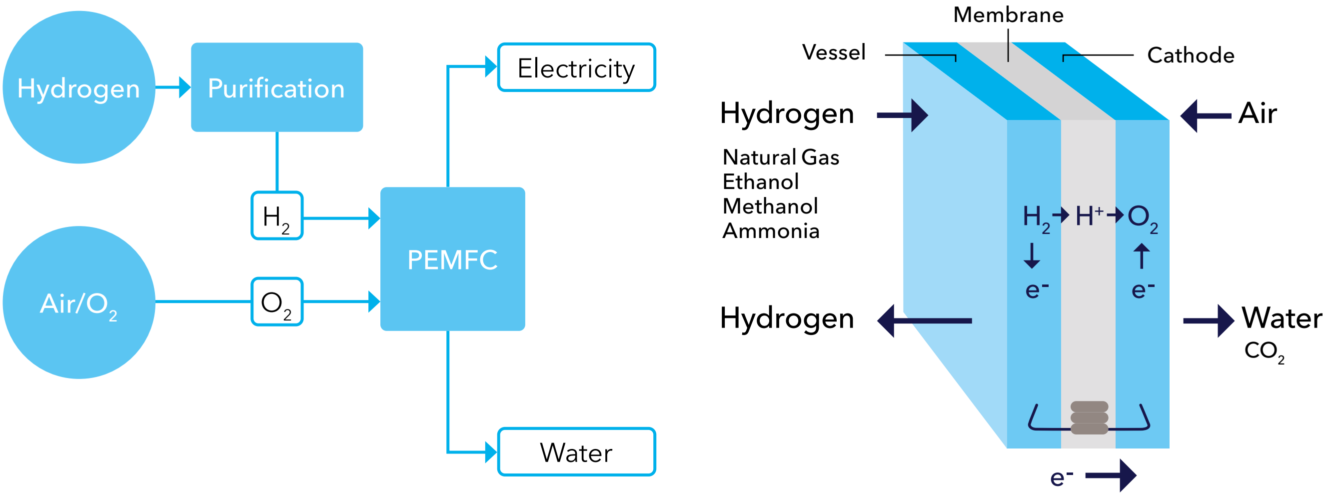
Proton-exchange membrane fuel cell

A proton-exchange membrane fuel cell (PEMFC) is also referred to as a polymer electrolyte membrane fuel cell. PEMFC uses polymer electrolyte membranes to conduct protons for ion-exchange purposes; it separates the hydrogen from the oxygen.

The basic operation of a PEMFC is shown in Figure 4.6. A fuelling system delivers hydrogen to the anode side of the FC, where it is converted into electrons and protons. The electrons flow through a circuit to the cathode, generating electricity, and being taken up by oxygen. The protons diffuse through the PEM to the cathode side of the FC and combine with the reduced oxide to form water. PEMFC has a high power-to-weight ratio and a low operation temperature that allows for flexible operation (DNV GL, 2017), an advantage for transportation applications.

FIGURE 4.6

Principal sketch for a proton-exchange membrane fuel-cell system (DNV GL, 2017).



4.2.2 Compressed hydrogen system

Figure 4.7 outlines the system layout for compressed gas hydrogen (CH_2) storage below deck.

For storage of compressed hydrogen, the tank hold space needs to include the following items:

- CH_2 tank bundle(s), typically 250 bar (based on current marine certification status; higher pressures are expected in the future).
- Fuel lines.
- Hydrogen vent system (pressure-relief system for the tank bundles).
- Ventilation system (artificial ventilation to provide continuous air changes to the tank hold space).
- Pressure regulating unit(s).
- Fire protection system.
- H_2 detection system.
- Safety systems (fire detection, firefighting system, emergency shutdown system).
- Structural fire protection (insulation towards neighbouring spaces).

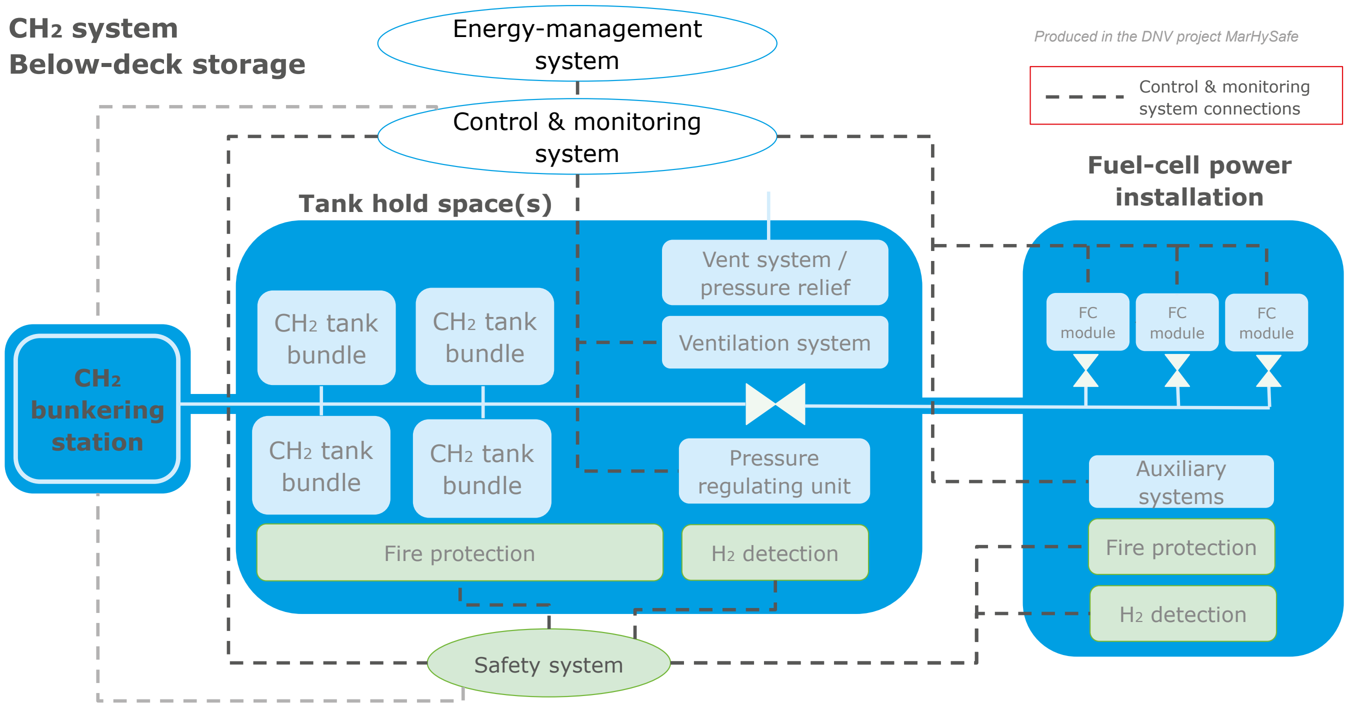
The primary fuel supply lines onboard the ship are assumed to be pipe-in-pipe, from the pipe from the CH_2 bunkering station to the ship fuel-storage system.

The bunkering station for CH_2 is assumed to be located onshore as a fixed installation, but filling from a truck may also be an option. In the future, bunkering of hydrogen from a dedicated bunkering vessel, with the main function of transferring hydrogen to the ship, may also be an attractive option (MossMaritime, 2018) .

Transfer of hydrogen from the bunkering station may be achieved by pressure balancing, or by direct compression of hydrogen gas before transfer to the ship. For pressure balancing, the hydrogen storage pressure(s) at the bunkering station needs to be higher than that required by the ship. This is typically achieved by cascade filling, where hydrogen is filled from land-based tanks storing hydrogen at different pressure levels and where the filling operation starts by filling from the lowest-pressure tanks. In the generic ship case, hydrogen at 250 bar is required. Therefore, a higher storage pressure is needed in the bunkering station. The alternative bunkering approach is to use a booster compressor to increase the pressure during bunkering of hydrogen into the ship.

FIGURE 4.7

Generic block diagram for compressed gas hydrogen (CH_2) with below-deck storage.



4.2.3 Liquid hydrogen system

Figure 4.8 outlines the system layout for storage of cryogenic hydrogen in liquid form (LH_2) below deck.

The following features need to be included.

Tank hold space:

- Liquid hydrogen (LH_2) tank (cryogenic).
- Hydrogen vent system (pressure-relief system for the hydrogen-storage system).

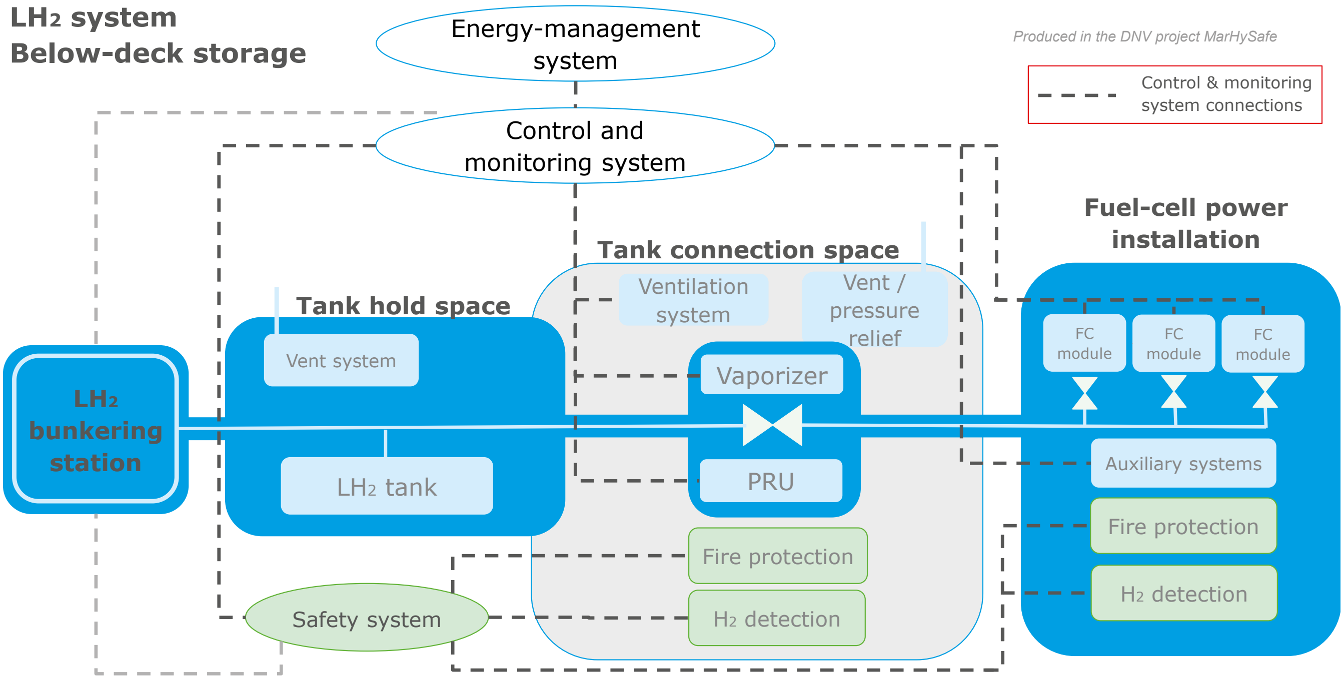
Tank connection space (TCS):

- Fuel lines.
- Vaporizer (for LH_2).
- Pressure regulating unit (PRU); e.g., conditioning tank, pressure build-up unit, or liquid pumps.
- A conditioning tank may be needed to mitigate the risk of sloshing due to insufficient driving force generated by the conditions of LH_2. Typically, an inlet pressure of about 3.5 bar is required to the FC system. A conditioning tank will typically have intermittent operation; it warms up the liquid at an equilibrium temperature for 5 bar.
- Hydrogen vent system (pressure-relief system for the hydrogen fuel-transfer system).
- Structural fire protection (insulation towards neighbouring spaces).
- Ventilation system (artificial ventilation to provide continuous air changes to the TCS).
- H_2 detection system (e.g., audible detection, gas detectors).
- Safety system (fire detection, firefighting system, and emergency shutdown system).

LH_2 bunkering of ships may be achieved by pressure fill (flow by differential pressure of two tanks), or by cryogenic pumps. In any case, three main components make up the LH_2 bunkering station; a LH_2 source tank, inert gas supply, and flexible bunkering hose assembly. Two hose connections are needed, one for inert gas/liquefied hydrogen, and one for cooled hydrogen gas return. Inert gas is used to remove moisture and air to ensure a pure fuel supply for bunkering. Due to its low boiling point, liquid helium may be used as an inert gas and for pre-cooling of the bunkering line. Due to limited helium supplies, other options may be sought, for example pre-cooling with nitrogen or hydrogen.

FIGURE 4.8

Generic block diagram for a system with liquid hydrogen (LH_2) storage below deck. PRU=Pressure regulating unit, including small conditioning tank.



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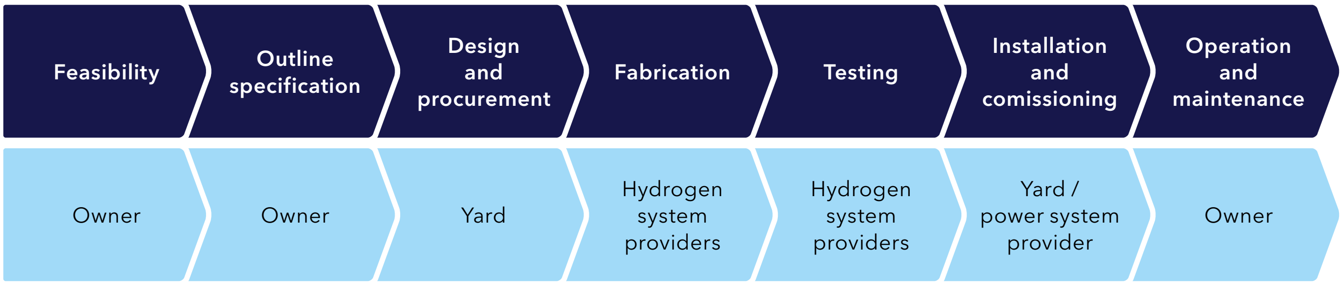
5 MARITIME HYDROGEN IMPLEMENTATION PHASES

The process to implement a hydrogen system onboard a vessel will generally follow normal practice for marine applications. Figure 5.1 illustrates the ship building process and the responsible party for the different project phases.

FIGURE 5.1

Visualization of the implementation phases and the responsible party for a maritime hydrogen project in the shipbuilding process.



Feasibility	Outline specification	Design and procurement	Fabrication	Testing	Installation and comissioning	Operation and maintenance
Owner	Owner	Yard	Hydrogen system providers	Hydrogen system providers	Yard / power system provider	Owner

5.1 Feasibility

It is recommended to undertake a feasibility study before making the final decision regarding the use of a hydrogen-fuelled vessel.

The purpose of the feasibility study is to evaluate alternative solutions as appropriate for the case considered. Whether the intention is a purely hydrogen-fuelled vessel, or a hybrid solution, a clear objective needs to be established. The motive(s) for the study – economic, environmental, other reasons, or a combination of these – needs to be established to define the objective(s) to be achieved.

Expected operational modes and operational profiles with relevant load variations, targeted life of the system, and other parameters, need to be considered in the feasibility stage. Evaluation of strengths and weaknesses (e.g., SWOT analyses) of alternative solutions with respect to technical issues, environmental aspects, and economics are relevant in this phase. The results of the feasibility study, which should include a rough sizing of the whole fuel and power system with related considerations on bunkering, will be used to determine whether the project should proceed to the next phase.

The dimensioning of the hydrogen systems, and thereby also the costs, will be strongly influenced by the ship's power demand, the degree of hybridization, and characteristics of available bunkering infrastructure. Possible onboard placement(s) for the main hydrogen system components should also be considered at this stage.

It is also adviceable to estimate CAPEX and OPEX for alternative relevant value chains, and to simultaneously evaluate energy losses and GHG footprints for the alternatives during the feasibility stage.

It is recommended to initiate the Alternative Design Approval process and the related contact with the Administration during the feasibility stage (see PART B and Chapter 6.2 of this Handbook).

5.2 Outline specification

If the feasibility study is successful, an outline specification should be written to scope the intended system for purchase and further engineering. The outline specification is used by the shipowner when yards are invited into the process, even before the bid process is started, and is part of the basis for this process and price and contract negotiations.

The outline specification includes the main criteria for the system as given by the shipowner. These will be project-dependent, but typically include regulatory requirements, relevant standards, lifetime requirements, overall functionality, ship load profiles, and power input/output requirements. Good and realistic functional requirements for the systems enable a designer/yard to design and price a system, and to pick the right system components and vendor for the vessel. In cases of planned retrofitting of hydrogen and fuel-cell systems in existing ship systems, emphasis should also be put on the integration between existing and new power-management systems.

Several key topics should be addressed in the outline specification, as shown by the following examples.

Redundancy

- For purely hydrogen-powered vessels, two completely independent fuel-containment systems and energy converters may need to be considered.
- For hybrid-powered vessels (e.g., one main source of power is based on fuel cells), two completely independent systems may need to be considered.

Safety

- The vessel shall be as safe as conventionally powered vessels (see Chapter 6 and the risk-based methodology outlined in Chapter 8).
- The reliability of the complete system must be at least as good as a conventional vessel.
- Loss of power shall not affect critical vessel functions.
- Single failure of critical modules shall not compromise the integrity of the vessel.

Segregation

- Fuel cell space(s) shall be accessible for replacement of parts of the system.
- Tank hold space(s) storing hydrogen shall provide protection against external hazards such as fires and mechanical impact, and protect the vessel against fire and explosion risks.

Onboard hydrogen systems

- These shall demonstrate robustness for long-term exposure in a marine environment (temperature, moisture, list, trim, roll, etc.).
- They shall be maintainable such that defective parts can be substituted safely and effectively. Competence, technical, and process requirements shall be identified.
- System and component lifetime should be such that the business case is economically reasonable.
- There shall be alarms and shutdown functions on several levels.
- It is recommended that important hydrogen system parameters are logged and stored in a non-volatile memory.

Applicable standards, rules, and regulations have to be considered at this stage, and these include the applicability of the Alternative Design. Reference is made to Chapters 6 and 7 detailing the status of these at the time of publication of this Handbook. The status of these needs to be examined. Best practice documents may become available as more experience is gained. The overriding principle remains that any alternative should maintain an overall safety and reliability level that is found to be equivalent to, or better than, a conventional solution.

Typically, the approval of preliminary design (see 6.2.1.3) will be completed by the end of the outline specification.

5.3 Design and procurement

When the shipbuilding contract is signed, the responsibility and further design work is normally transferred to the yard. The yard prepares procurement packs for the various system components. It is recommended that potential system-component providers are consulted at this phase.

The safety and reliability of the hydrogen systems need to be a main priority for a hydrogen-fuelled vessel. The components must be of good quality and compatible with hydrogen service to secure a safe and reliable system throughout the lifetime. The integration and testing of the complete system are of similar importance to the quality of the single components. When the system-component providers have been established, it is strongly recommended to start/update/refine the quantitative risk and explosion analyses (see Chapter 8), since several safety aspects may depend on the specific selected components and configuration(s).

Best practices regarding engineering details and relevant codes and standards need to be addressed in the design and procurement phase. Input regarding these is provided in Chapter 7.

5.4 Fabrication and testing

ASME-3.31.12 (ASME-B31.12, 2019) gives input on inspection, examination, and testing for hydrogen piping and may provide useful input for the development of requirements.

For further input, see Chapter 7.

5.5 Installation and commissioning

Experience has shown that it is critical to manage interfaces between systems. The interfaces between the hydrogen and fuel-cell systems and the other ship systems are therefore an area of particular focus.

The hydrogen systems will need to communicate with the ship's power-management system, and key hydrogen and fuel-cell system information will need to be displayed on the vessel's bridge.

Proper installation documentation must be provided by the hydrogen system suppliers.

All interfaces must be tested before the installation can be signed out, and a proper test and commissioning plan must be made for the testing to be done at the yard before final sign-out. This task should not be underestimated and needs close cooperation between the hydrogen system suppliers, the supplier of the other power plant components, and the yard. Functional testing of the safety features of the spaces containing hydrogen systems – and of aspects such as ventilation, gas detection, and fire detection – must also be performed.

5.6 Operation and maintenance

This section summarizes the recommendations identified for the operation and maintenance of maritime hydrogen systems:

- A maintenance and operational plan including emergency operation shall be established.

5.6.1 Documentation requirements

The general requirements in section 5, on operation and maintenance, in ASME-B31.12 (ASME-B31.12, 2019) provide useful input to the development of the written operation and maintenance documents.

5.6.2 Operation manual

Description of a programme for training all onboard personnel that may be in contact with any hydrogen system is needed as part of the operation manual.
Personnel responsible for any onboard bunkering emergency procedures need to receive training on hydrogen-specific emergency procedures.

5.7 Maintenance

A plan for systematic maintenance and function testing shall be kept onboard showing in detail how components and systems shall be tested and what shall be observed during the tests. The plan shall include the following:

- Verification of the remaining lifetime for the hydrogen systems.
- Test of all instrumentation, automation, and control systems affecting the hydrogen systems.
- Test intervals to reflect the consequences of failure involving a particular system. Functional testing of critical alarms should not exceed specified intervals (normally three months). For non-critical alarms, the longest intervals are normally not to exceed 12 months.
- Acceptance criteria.
- Fault identification and repair.
- List of the suppliers' service net.

The different hydrogen systems and components will have different maintenance needs and maintenance recommendations. This should be included in the maintenance plan. Information about periodic testing should also be included in the vessel's unmanned machinery space (E0) manual.

PART B

REGULATIONS, CODES, AND STANDARDS FOR HYDROGEN AS MARITIME FUEL

Chapter 6 introduces the international regulatory framework and outlines the Alternative Design approval process for hydrogen-fuelled vessels. Relevant rules and standards for hydrogen fuel cells, hydrogen storage, and hydrogen bunkering are also introduced.

Chapter 7 gives a first summary of engineering details for LH_2 and CH_2 systems on ships.

6 THE REGULATORY FRAMEWORK

The International Maritime Organization (IMO) is the United Nations specialized agency responsible for the safety and security of shipping. IMO is the global standard-setting authority for the safety, security, and environmental performance of international shipping.

Its main role is to create a regulatory framework for the shipping industry that is fair and effective, universally adopted, and universally implemented. IMO measures cover all aspects of international shipping – including ship design, construction, equipment, manning, operation and disposal – to ensure that this vital sector remains safe, environmentally sound, energy efficient, and secure.

The International Convention for the Safety of Life at Sea (SOLAS) defines internationally adopted minimum requirements for the construction, equipment, and operation of ships. Flag States must ensure that these minimum requirements are met. Commercial vessels engaging in international trade must therefore be designed, constructed, maintained and operated in accordance with SOLAS. Several Codes are also made mandatory under SOLAS, and typically include detailed technical requirements for specific vessel types.

SOLAS Ch.II-1 Part A-1 Regulation 3-1 states that in addition to the requirements contained within SOLAS, ships are to be designed, constructed, and maintained in compliance with the structural, mechanical, and electrical requirements of a Classification Society which is recognized by the Administration (Flag State).

Specific prescriptive rules and regulations are not yet in place for the use of hydrogen as a marine fuel, but SOLAS II-I opens the way for a structured design process based on risk assessments in cases where a ship is deviating from prescribed rules. The purpose is to prove that the chosen solution is providing an equivalent safety level to the one required in SOLAS. This process is commonly referred to as the 'Alternative Design' approach.

IMO's work activities are structured into several sub-committees. Its Marine Safety Committee (MSC) has a Sub-Committee on Carriage of Cargo and Containers (CCC) that is responsible for work on the IGF Code. This code (IGF Code, 2016) provides the regulatory framework for the adaptation of low-flashpoint marine fuels like hydrogen. It provides the basis for accepting that an Alternative Design approach is used to verify compliance for ships using gas fuels other than LNG – for example, hydrogen.

Work has begun to include fuels cells (FCs) in the IGF Code, and they are expected to be included in the future as a new part of the IGF Code. In the meantime, FCs are expected to be covered through interim guidelines. The purpose is to ensure that more experience with FCs is gained before regulations are included in a revision of the IGF Code. Such revisions take part within the four-year cycle of SOLAS revisions. The finalization of the FC Interim Guidelines is foreseen in 2021 (at CCC7) and will come into force after adoption at the MSC. The final fuel-cell requirements will be included in Chapter E of the IGF-Code as an Amendment of this code. This means Chapter E will most likely formally enter into force as a new part of the IGF Code in 2028. However, it is considered likely that the interim guidelines will be used when completed.

No work to cover storage of hydrogen as fuel has been initiated in IMO. One way of introducing hydrogen storage may be to develop a new interim guideline to the IGF Code; i.e., a similar approach to that for fuel cells.

Regulations, codes, and directives are legal requirements imposed by legislative bodies, and are mandatory. Directives are implemented at EU level and are not used as an instrument by IMO. In contrast, standards, guidelines, and codes of practice are voluntary documents unless mandated in the regulations.

Maritime regulations and rules exist on three levels. They are:

- International regulations developed by IMO;
- National regulations; and,
- Class rules.

Other international codes and standards can support these processes. The main objective of the codes and standards presented is to assist and support the approval process for hydrogen-fuelled vessels. The use of some of these standards may be requested by a Class Society and/or the Flag State, and some may be required as part of the approval process for specific components and/or sub-systems.

6.1 The IGF Code

The main international Code applicable to hydrogen-fuelled SOLAS vessels is the International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels (IGF Code, 2016). Please note that for gas carriers, the IGC Code Chapter 16 applies, not the IGF Code.

The IGF Code entered into force on 1 January 2017 (IGF Code, 2016) and is the mandatory international regulation for cargo ships with a gross tonnage of 500 or more. It also applies to passenger vessels on international voyage using gases or other low-flashpoint fuels, defined as fuels with flashpoint below 60oC. These ships are required to hold international safety certificates. The IGF Code contains detailed prescriptive requirements only for liquefied natural gas (LNG) as fuel. For fuels other than LNG, the IGF Code refers to the 'Alternative Design' approach. This means that the IGF code does not contain specific requirements for fuels other than LNG, but these fuels can still be used if it is proven that the safety level is maintained compared with a ship using conventional fuel. This is a risk-based approval process with a high degree of uncertainty.

In IMO, requirements for FC installations are work in progress, and acceptance of such installations will therefore need to follow an Alternative Design process. Several Classification Societies have developed their own rules for FC installations. These rules do not cover the storage and distribution of low-flashpoint fuels like hydrogen, but they specify requirements for the FC power installation (see Chapter 4.2.1). To ease the Alternative Design process, Flag Administrations have an option to accept Class rules that they view as covering the required safety aspects. Some of these Class rules are based on prescriptive requirements, which tend to be easier for everyone involved to relate to compared with the more complex Alternative Design process.

For Norwegian-flagged ships using gases or other low-flashpoint fuels like hydrogen, the Norwegian Regulation for ships using fuel with a flashpoint of less than 60 °C applies (FOR-2016-12-27-1883, 2017). This regulation makes the IGF Code mandatory for all Norwegian-flagged ships including those not required to hold international safety certificates. It also requires that the ship satisfies a recognized Classification Society's rules for ships using fuel with a flashpoint less than 60 °C. In Canada, Transport Canada has issued some guidance documents that cover Canadian-flagged vessels and requirements for the use of a Recognized Organization. However, the documents seem to be prepared with natural gas in mind (Transport Canada, 2019). National implementations of the IGF Code may vary, so both the relevant national regulatory status and the position of the relevant Flag State need to be identified for planned projects.

6.1.1 IGF Code Part A

According to the IGF Code Part A, a low-flashpoint fuel like hydrogen is allowed as long as the Alternative Design approach demonstrates that the hydrogen-specific systems are as safe, reliable, and dependable as new and comparable conventional oil-fuelled ships. SOLAS regulation II-1/55 specifies how this risk equivalence shall be demonstrated, and this needs to be approved by the Administration. SOLAS regulation II-1/55 points to the method specified in MSC.1/Circ 1455 (MSC.1/Circ 1455, 2013); see Chapter 6.2 in this Handbook for further details.

The IGF Code Part A contains a specific list of function-based requirements for appliances and arrangements related to the use of low-flashpoint fuels that must be fulfilled (see Table B.4). Paragraph 4 of IGF Code Part A details requirements for risk assessments and analysis of explosion consequences to ensure that the necessary assessments are carried out to eliminate or mitigate adverse effects on people on board, the environment, or the ship. Sections in this paragraph state:

'Consideration shall be given to the hazards associated with physical layout, operation and maintenance, following any reasonably foreseeable failure.' (Para. 4.2.1)

'[…] risks shall be analysed using acceptable and recognized risk analysis techniques, and loss of function, component damage, fire, explosion and electric shock shall as a minimum be considered. The analysis shall ensure that risks are eliminated wherever possible. Risks which cannot be eliminated shall be mitigated as necessary. Details of risks, and the means by which they are mitigated, shall be documented to the satisfaction of the Administration.' (Para. 4.2.3)

'[Limitation of explosion consequences covers] any space containing any potential sources of release and potential ignition sources'. (Para. 4.3)

6.2 The Alternative Design approval process

The approval of conventional oil fuelled ships is a well-known and predictable process with prescriptive rules and regulations based on decades of experience. For new technologies like hydrogen-fuelled ships, there are no prescriptive rules or regulations in place. The approval will therefore be based on a risk-based approval process where an equivalent level of safety compared to a conventional oil fuelled ship needs to be demonstrated. This risk-based approval process is referred to as the Alternative Design approach.

The Alternative Design approach as required by the IGF Code for hydrogen-fuelled ships is expected to create a comprehensive, and rather expensive, design and approval process with a high degree of uncertainty. However, the Alternative Design approach opens for solutions not covered by prescriptive rules, and it is developed for new technologies and novel solutions. For such cases it may be equally efficient, and it offers an assessment process that is more flexible than prescriptive rules.

IMO provides the methodology for the Alternative Design process in the document 'Guidelines for the approval of alternatives and equivalents as provided for in various IMO instruments' (MSC.1/Circ 1455, 2013). The process for approval of preliminary design is illustrated in Figure 6.1, and the process for final design in Figure 6.2. These figures show clearly that close interaction is required between the Submitter (the Project Owner) and the Administration throughout the approval process, and that the Submitter needs to approach the Administration very early in the process. The exact requirements may vary on a case-by-case basis, depending on the Administration and factors relating to the design and its maturity.

Alternative Design is a generic process not specific for hydrogen, and has already been applied for new technologies and solutions in the maritime business. One example is almost all classes of new Cruise ships since 1990. For these vessels, the process commonly includes quantitative fire and evacuation simulations and use of Computational Fluid Dynamics (CFD). The early applications were based on the provisions in SOLAS Chapter 1, Regulation 5, with the studies typically conducted based on credible fire scenarios based in turn on engineering judgement. The fire sizes were hence not risk-based but rather based on typical fire sizes expected in the relevant areas.

FIGURE 6.1

Overview of the approval procedure for preliminary design required according to the Alternative Design approach (MSC.1/Circ 1455, 2013), describing the roles of the Administration (Flag State) and the Submitter (Project Owner).

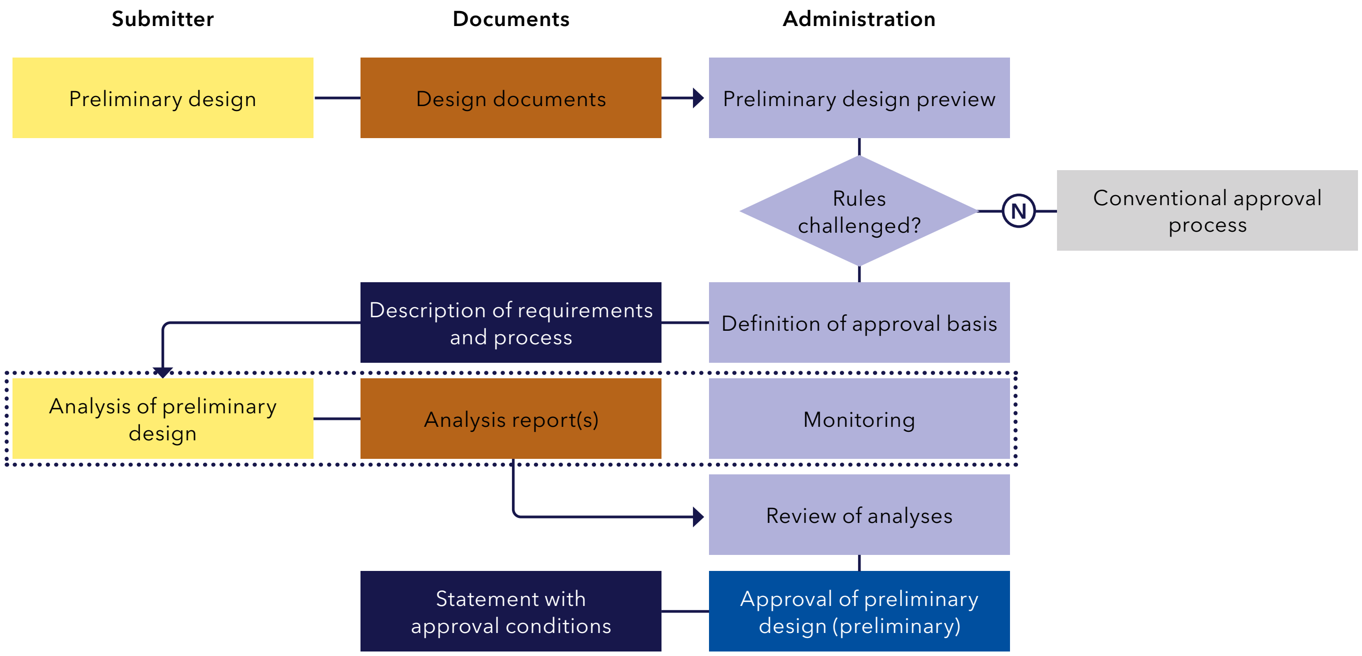
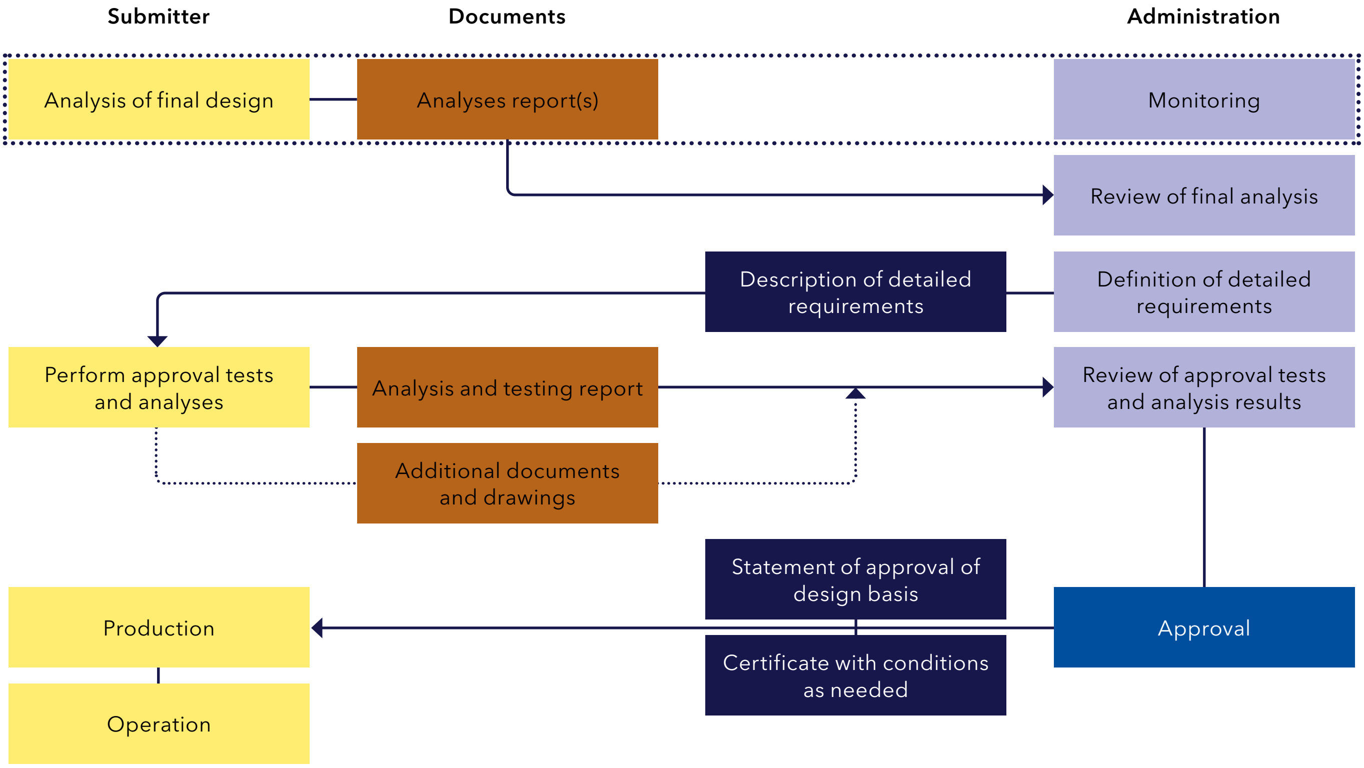


FIGURE 6.2

Overview of the approval procedure for final design required according to the Alternative Design approach (MSC.1/Circ 1455, 2013), describing the roles of the Administration (Flag State) and the Submitter (Project Owner).



Formally, the Alternative Design process is separated into phase 1, preliminary design (milestones 1 and 2); and phase 2, development of final design (milestones 3, 4 and 5). The milestones are:

1. Development of a preliminary design;
2. Approval of preliminary design;
3. Development of final design;
4. Final design testing and analyses; and,
5. Approval.

When applying the Alternative Design approval process, several iterations may be needed to build confidence towards the approval body (Flag Administration) and prove equivalent safety. A key challenge is how to apply and adopt the process for the hydrogen-specific risk cases. The experience and knowledge gained through the early maritime hydrogen projects may therefore be important building blocks to enable future rule-based approval. Chapters 6.2.1 and 6.2.2 detail the Alternative Design approval process for maritime hydrogen and FC systems based on current knowledge. Chapter 6.3 provides a basis for how an equivalent level of safety may be demonstrated.

6.2.1 Preliminary design phase

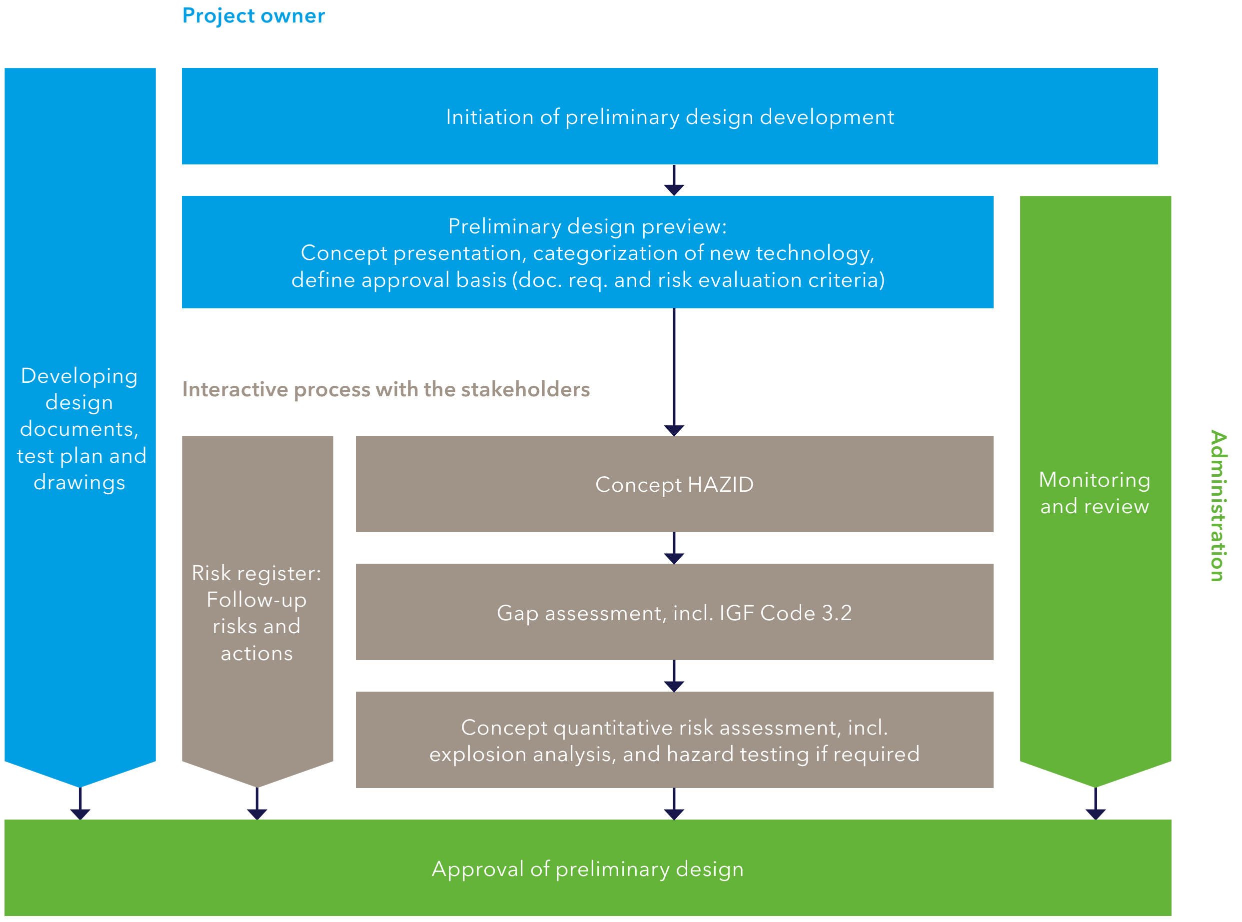
The preliminary design is analysed in the first phase and covers the two first milestones in the overall approval process. The goal in this phase is to achieve an 'Approval of preliminary design'. Figure 6.3 illustrates the recommended steps towards an 'Approval of preliminary design' for a hydrogen-fuelled ship (MSC.1/Circ 1455, 2013). The process is iterative in nature and some of the steps may therefore need to be repeated.

It is common that a statement of preliminary approval outlines requirements for further analysis or other conditions that need to be fulfilled in the final approval phase. The issuing of a 'Statement of preliminary assessment', which is also known as 'Approval of preliminary design' (MSC.1/Circ 1455, 2013), by the Administration does not imply that final approval will be granted.

NMA has previously provided an interpretation of the process and requirements to obtain approval of preliminary design based on the IMO framework (IGF Code, 2016), (MSC.1/Circ 1455, 2013), as shown in Figure B.1.

FIGURE 6.3

Proposed steps in the process towards 'Approval of preliminary design' for hydrogen-fuelled ships.



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6.2.1.1 Initiation of Preliminary Design Development/ Preview

Initially, the Submitter (Project Owner) needs to develop a draft description of the project. This draft includes the general arrangement, components, and the boundary conditions of the ship system, including physical boundaries and system interfaces.

The objective is to develop a common understanding of the planned design and systems to enable the subsequent tasks in the submission and approval process. The definitions of terminology need to be clarified to avoid misinterpretation and thus increase the efficiency of the process (reference is made to Chapters 2 and 4.2).

To facilitate the start of the approval process, the Project Owner needs to organize a preliminary design preview meeting with the Administration to:

- present the concept and identify those rules, standards and/or regulations that are being challenged;
- start planning for how items requiring special attention – e.g., detailed risk analysis – can be handled in the Alternative Design process. The decision whether the Alternative Design, or particular items of the design, requires risk-based analysis may be based on the methodology below (MSC.1/Circ. 1455 § 4.6.4) for categorization of new technology; and,
- define the approval basis – required design and analysis documents (see Table B.1 and Table B.2 in Appendix B, as well as the Administration's risk evaluation criteria (Chapter 6.3).

The preliminary design preview meeting should include relevant people from the Project Owner and professionals from the different disciplines, including risk assessment.

Categorization of new technology

As there is not yet a track record for the use of hydrogen storage and FC solutions in ships, these components and onboard solutions will typically be classified as new and unproven. Table 6.1 may be helpful to understand how new technology can be categorized. Although the intention may be to use FCs and hydrogen-storage tanks that have a track record from the use in transport applications like hydrogen cars or trucks, the use in hydrogen-fuelled ships will be a new application area. Hence, the technology is unproven for the marine environment/conditions/application, giving it the rating '4'.

TABLE 6.1

Categorization of new technology (MSC.1/Circ 1455, 2013).

Application Area	Technology status		
	Proven	Limited field history	New or unproven
Known	1	2	3
New	2	3	4

IMO has developed an approval matrix as a guidance document to the Submitter to estimate the extent of the work that needs to be performed and submitted for approval based on the categories in Table 6.1.

For a new application of novel or unproven technology (Category 4), the following will apply (MSC.1/Circ 1455, 2013):

- Basic risk assessment (HAZID as a minimum) is required. The same is the case for Category 3, and also for Category 2 unless the 'rule challenge is deemed insignificant or of negligible impact on safety and environment'.
- Due to the novelty of the design, quantified risk assessment of all risk contributions will then be required as it may not be possible to rank the hazards credibly. Hence, all may need to be examined in depth. It is recommended that those undertaking the analyses are independent and competent so that objective HAZID/risk assessment and analyses can be performed.
- Applicable rules and guidance documents in this process will be IMO circulars on alternative arrangements, and class guidance on risk-based approval.
- Additional tests, surveys, and compliance control may also be needed after commissioning. This would typically be continuous monitoring with review and reporting to the Administration, until a sufficient level of experience is gained.
- Review by a third party is recommended.

As more experience is gained with maritime use of FCs and hydrogen-fuelled ships, available solutions can be expected to be ranked as more mature, but extensive analysis may still be required in the period until rules are in place.

A Category 3 solution (see Table 6.1) is defined as either a new application of a technology with limited field history, or a known application of new or unproven technology. According to the existing procedures (MSC.1/Circ 1455, 2013), both the basic risk assessment (HAZID), and minimum semi-quantified analysis will be required. All medium and high hazards may be examined by means of quantified analysis, by analysts with operational experience and in-depth experience of risk assessment.

A Category 2 solution (see Table 6.1) is defined as either a known application of a technology with limited field history, or a new application of proven technology. According to the existing procedures (MSC.1/Circ 1455, 2013), further analysis beyond a basic risk assessment (HAZID) may still be required, but it depends on the outcome of the basic risk assessment. Medium and high hazards may need further examination, and those undertaking analyses should have operational experience and general knowledge of risk-assessment techniques.

This illustrates that extensive risk analyses can be expected for some time to come, but this experience can be used to develop the needed knowledge base for the future rules.

Definition of the approval basis

The Administration needs to define the approval basis with respect to scope of analysis and evaluation criteria. MSC.1/Circ. 1455 (MSC.1/Circ 1455, 2013) states: 'In order to accomplish this, the Administration and the Submitter may have to meet one or several times to discuss the alternative and/or equivalency, its purpose and objectives, deviations from conventional approaches, relevant rules and regulations, possible deviations from or lack of rules and regulations, requirements that may not be covered by the rules, proposed operations and potential impact on other systems, components, etc.'

The Administration and the Submitter should agree on:

- design and analysis documents required for approval of preliminary design; and,
- risk evaluation criteria for the qualitative and quantitative analysis process, including for total risk level (see Chapter 6.3 describing possible methods for evaluating 'proof of equivalence' and risk criteria).

6.2.1.2 Developing preliminary design and documentation

During the Preliminary design phase, the Project Owner will be required to submit design documents and analysis documents, as specified by the Administration, according to the Alternative Design process. See Table B.1 and Table B.2 in Appendix B for required design and analysis documents in MSC.1/Circ. 1455 for approval of preliminary design. Third-party involvement in the risk analysis is a general principle and may be required by the Administration. Reference is made to IMO 1455 § 6.2.5 on competence requirements for the team undertaking the analyses.

As illustrated in Figure 6.3, the concept phase HAZID (Chapter 8.2.1), quantitative risk assessment and explosion analysis should be considered as integrated parts of the Alternative Design approval process. It should therefore not be undertaken before the Alternative Design process is initiated with the Administration. It is recommended to include the Administration in the HAZID and other workshops that will be undertaken during this process.

Role of the Administration

It is recommended that the representatives of the Administration who take part in the initial Preliminary design preview meetings should also take part in the definition of the approval basis, and should monitor the subsequent analyses and follow the project until final approval. This way, the Administration's representatives will be able to take advantage of the learning process that occurs throughout the entire Alternative Design approval process.

The Administration may involve or delegate authority to a Recognized Organization (RO). An RO is an organization that has been assessed by a Flag State and found to comply with the IMO Code for Recognized Organizations (RO Code); e.g., a classification society.

Stakeholder interaction

The development of the preliminary design and documentation requires broad stakeholder involvement. It is therefore important that all stakeholders, including representative shipowners, operators, designers, and suppliers, etc., understand the Alternative Design process and the implications in terms of resources assigned, time limits, etc. Regular interaction between the Project Owner and the Administration is important.

Risk register to follow up risks and actions

During the execution of the analysis in the preliminary design phase several risks and follow-up actions (e.g. design modifications, tests, analysis, research, reviews, and simulations) will be identified. It is essential that the Project Owner arranges for a systematic risk register to be kept to ensure:

- all risks and actions are stored, accessible, and followed up with suitable intervals;
- traceability between risks and actions; and,
- transparency of the risk process for stakeholders and the Administration (e.g. enabling status updates).

Following the principles of systematic risk management will also support the efficiency and progress of the Alternative Design process.

6.2.1.3 Approval of preliminary design

The preliminary approval may not be granted until all hazards and failure modes related to the design are identified and until control options (or plans for how to achieve control) for these hazards and failure modes are described. The following conditions should be satisfied prior to granting preliminary approval:

1. No 'showstoppers' are identified – otherwise a re-evaluation of the preliminary design phase, and possibly improvements, should be carried out.
2. The alternative and/or equivalency was found to be feasible and suitable for its expected application.

6.2.2 Development of final design

The final design is analysed in the second phase. It covers milestones number 3, development of final design; 4, final design testing and analyses; and 5, approval.

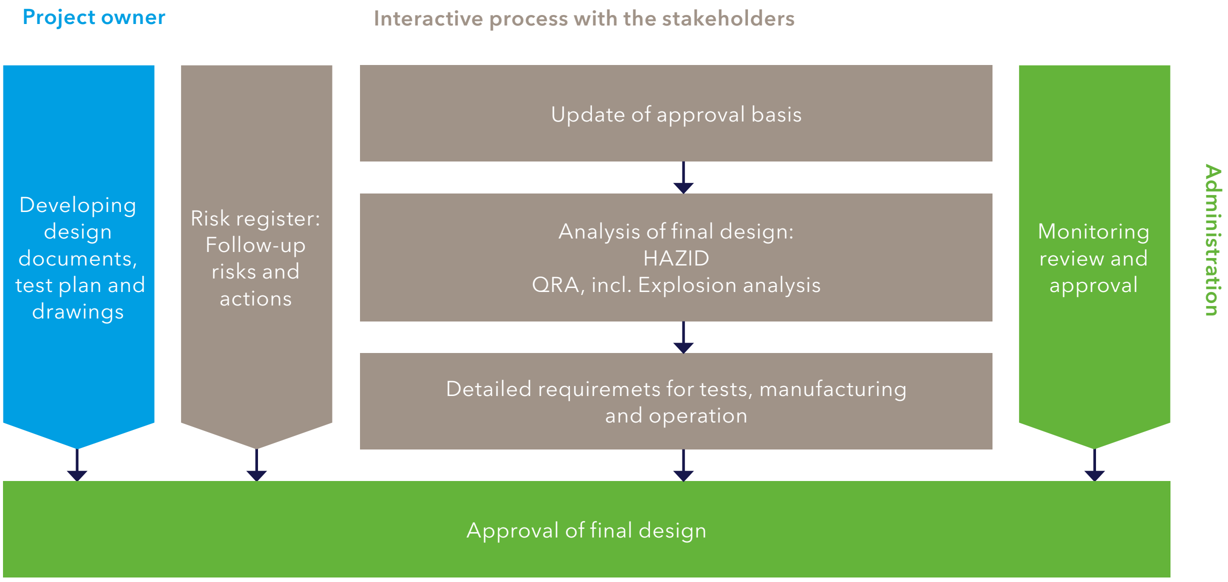
The approval of final design is required to gain the Approval from the Administration (Flag State), such as the Norwegian Maritime Authority (NMA). An Approval from a Class Society is not the same as the Approval from the Flag State unless the Class Society is authorized by the Flag State to act as a Recognized Organization (RO) as per SOLAS X-1/1. Exactly what is delegated by the Flag State to the RO, typically Class Societies, is regulated by individual Flag State agreements. Some Flags do not delegate. Within EU member states, all (and only) IACS[3] members can be used as ROs.

In the final design phase, the analyses from the preliminary phase need to be updated to reflect the final design. This includes updating the approval basis and including any requirements for further analyses and/or other conditions associated with the preliminary approval. Design and analysis documents (see Table B.1 and Table B.2 in Appendix B) may need to be updated to reflect the final design. HAZID, quantitative risk analysis (QRA) and explosion risk analysis (ERA) need to be conducted to reflect the final design, and may need to be revised until it can be demonstrated that the final design meets the equivalence criteria (Chapter 6.3). The risk register established in the preliminary phase should be updated as new information becomes available. Chapter 8 provides details regarding the use of QRA and ERA and describes the use of risk-based design in maritime. Chapter 9 presents relevant risk mitigation/control measures for the process of meeting the risk-equivalence criteria.

The approval process is extensive and, as shown in Figure 6.4, a high degree of interaction between the Submitter (Project Owner) and the Administration is also required in the final design phase. As illustrated in Table B.3, the list of the required design and analysis documents is more comprehensive compared with preliminary design approval.

FIGURE 6.4

Proposed steps in the process towards final approval for hydrogen-fuelled ships.



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[3] IACS: International Association of Classification Societies.

Figure 6.4 outlines the proposed steps in the process toward final approval based on the minimum requirements (Figure 6.2). The actual process will depend on the complexity and the features of the chosen concept and its design. Therefore, the process might identify need for further modifications of the requirements. Modifications and reassessment of different steps should be expected, and each step could include a series of iterations. The extent of iterations depends on the input and feedback between the Administration and the Submitter (Project Owner).

6.2.2.1 Detailed requirements for tests, manufacturing, and operation

The main objective of the final interactive step between the stakeholders is to verify function and reliability and use this to detail requirements for approval tests, manufacturing, and operation. Approval tests may include testing and analysis to confirm engineering and design assumptions in the quantitative (risk) analyses. This may include test acceptance criteria for the vessel and its hydrogen subsystems. The Submitter will perform the required tests for review by the Administration. An outcome of this step may be limitations and/or requirements related to manufacturing and operational measures.

6.3 Proof of equivalence and risk criteria

The present chapter gives recommended risk-level definitions and criteria to be met when demonstrating equivalence. The approach to calculate the risk is outlined in Chapter 8.

As introduced in the previous chapters, the overall goal of the IGF Code Part A and the Alternative Design approach is that the safety, reliability and dependability of the hydrogen systems shall be equivalent to that achieved with new and comparable conventional oil-fuelled main and auxiliary machinery. The equivalence of the Alternative Design shall be demonstrated as specified in SOLAS regulation II-1/55, and the methodology is outlined in Circ.1455 (MSC.1/Circ 1455, 2013). Neither of these documents specify which approach or what level of detail should be used in the process of demonstrating the safety equivalence.

Currently, equivalent solutions are evaluated in comparison with existing arrangements that are fully covered by prescriptive regulations and could be fitted in the vessel under consideration following the applicable regulations. Sometimes this approach relies on redesign of preventive and mitigating measures based on a selected 'worst case' that may not be risk-based. For hydrogen, it is assessed that a relatively small hydrogen leak can result in unacceptable scenarios (see examples of Simplified assessments of explosion consequences in Appendix C). This shows that a worst-case leak size can easily result in a 'showstopper' event for the hydrogen-fuelled ship. If a selected case involves too small a leak, it may result in under-design of the safety functions. Finding the right balance can be tricky. Therefore, a risk-based approach is recommended, assessing all possible leak sizes up to full-bore rupture of the hydrogen piping and equipment.

As explained in Chapter 6.2.1, current hydrogen fuel systems are 'new' and 'unproven' for maritime applications. Due to the lack of an adequate regulatory framework, and the nature of the risks, a QRA that considers the safety implications for the ship as a whole is found necessary. To facilitate the proof of equivalency, the results of the QRA could be evaluated towards a preliminary agreed risk criterion.

IMO provides the Guidelines for Formal Safety Assessment (FSA) for use in the IMO rule-making process (MSC98/23/Add.2, 2018), a tool that structures the application of risk analysis and cost-benefit assessment techniques. The FSA methodology is proposed to help in the evaluation of new regulations for maritime safety and protection of the marine environment. The FSA methodology can be used as a guideline for projects that need to be evaluated by the IMO member states – this may have far-reaching implications in terms of either costs to society or to the maritime industry. The FSA methodology can also be used for situations where there is a need for risk-based decision making on alternatives for how to reduce risk.

The latest revision of the FSA guidelines is MSC-MEPC.2/Circ.12/Rev.2 (MSC98/23/Add.2, 2018). Its item 9.2.2 highlights the status regarding the use of risk criteria: 'There are several standards for risk acceptance criteria, none as yet universally accepted'. The risk-evaluation criteria recommended in the FSA Guidelines are based on an individual risk and Societal Risk/FN Diagram, and this is the common basis for the use of such criteria in the maritime industry.

6.3.1.1 Individual risk

The basis for individual risk criteria is the consideration that the level of risk that will be accepted for an individual will depend upon whether the risk is taken involuntarily or voluntarily, and whether or not the individual has control over the risk. Passengers, for example, are involuntarily exposed to risks while crew members can be aware and may have control over the same risks.

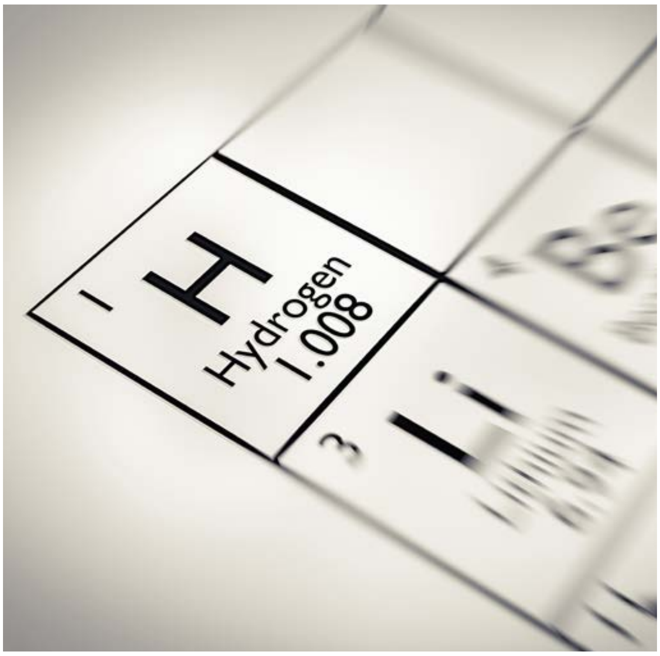
Individual risks are broadly used in different industries. Examples of the lower and upper bound risk-acceptance criteria are listed in Table 6.2.

TABLE 6.2

Quantitative risk evaluation upper and lower bounds (MSC98/23/Add.2, 2018). The extracted examples are provided for illustrative purposes. Specific case-by-case criteria should be explicitly defined.

Decision parameter		**Acceptance criteria**	
		Lower bound - ALARP[a] region	**Upper bound - ALARP region**
		Negligible (broadly acceptable) fatality risk/year	Maximum tolerable fatality risk/year
Individual risk	Crew member	10^{-6}	10^{-3}
	Passenger	10^{-6}	10^{-4}
	Third parties, member of public ashore	10^{-6}	10^{-4}
	Target values new ships[b]	10^{-6}	Above values to be reduced by one order of magnitude
Societal risk	To groups of above persons	To be derived by using economic parameters ref: (MSC 72/16, 2000)	

a: As low as reasonably practicable'(ALARP).
b: While it is recommended that the maximum tolerable criteria for Individual Risk as listed should apply to all ships, it is proposed ref: (MSC 72/16, 2000) that a more demanding target is appropriate for comprehensive FSA studies.



6.3.1.2 Societal risk

Society generally has a strong aversion to multiple-casualty accidents, and therefore the perception is that a single accident that kills 1000 people is worse than 1000 accidents that kill a single person (MSC98/23/Add.2, 2018). Societal risk expressed by an FN diagram shows the relationship between the frequency of an accident and the number of fatalities. The FN-diagram therefore allows the assessment not only of the average number of fatalities, but also of the risk of catastrophic accidents with many fatalities. The FSA guideline outlines how to define societal risk acceptance criteria on different ship types and/or marine activities. The original FSA guideline developed by IMO introduced different societal risk criteria for different ship types expressed by a FN diagram (MSC 72/16, 2000). Figure 6.5 and Figure 6.6 illustrate how this may look for selected ship types.

Ways of quantifying risk vary, and different definitions are available. Societal (or group) risk of fatalities is the probability of death experienced by all people affected by the activity. This includes all passengers and crew as well as any people on other ships who may be involved, e.g., in collisions (DNV GL, 2014).

In general, it is possible to define a number that represents the risk on a ship, e.g., the individual risk, societal risk and Potential Loss of Life (PLL). PLL is the expected value of the number of fatalities per ship year, considering all fatalities as equally important.

Suggestions for societal risk criteria are given by Skjong and Eknes (Skjong R. E., 2001) and (Skjong & Eknes, 2002). These are referenced in the FSA Guidelines and used in all FSAs since 2000. The FN curve is likely to be dimensioning on a passenger ship, while it is unlikely to provide a dimensioning criterion for a cargo ship, for example. Societal risk criteria can also give a fair comparison between different types of ships as suggested in the same paper. To calculate the ship societal risk (FN curve), a QRA needs to be performed for the ship (reference is made to Chapter 8). Since it is the risk contribution due to hydrogen as a fuel that is to be found, the contribution from hydrogen incidents to the risk curve needs to be quantified.

FIGURE 6.5

FN curves for different tankers shown together with established risk acceptance curves (MSC 72/16, 2000).

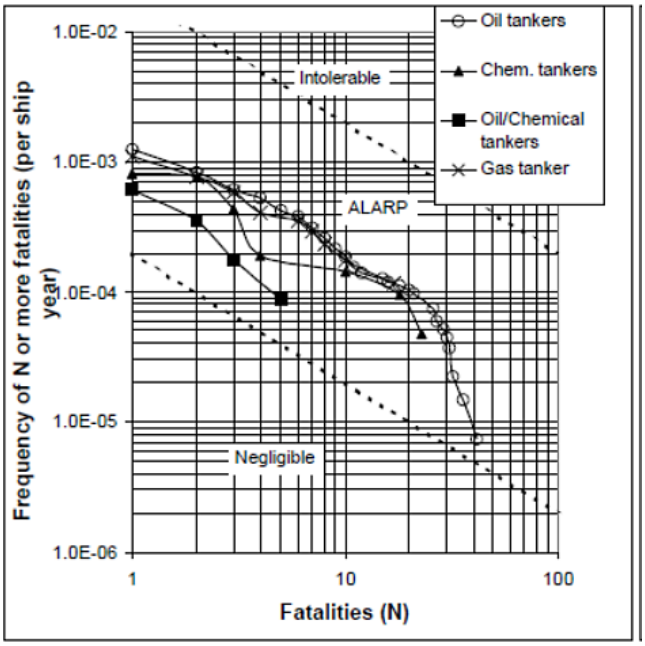
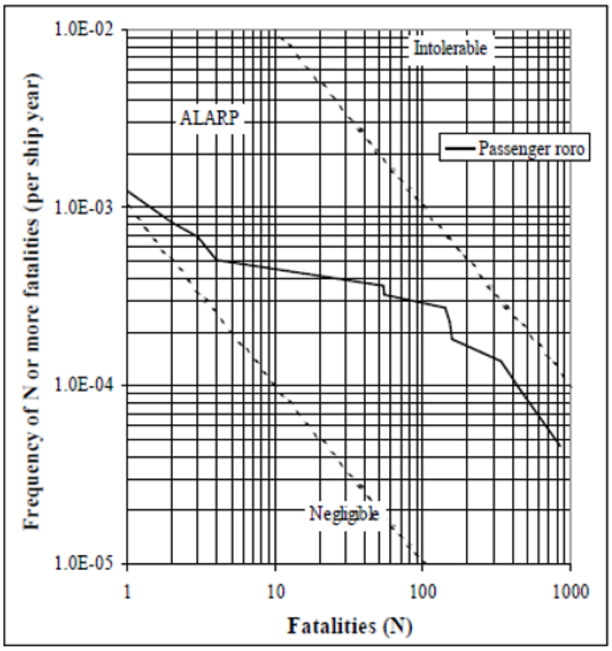


FIGURE 6.6

FN curve example for passenger/RoRo ships based on data for a fleet of seven vessels, crew of 140, and annual turnover USD 50 million. Vessel is carrying 1,900 passengers, has an annual operating revenue from tickets of USD 16 million, and occupational health statistics are from US and Norway (MSC 72/16, 2000).



6.3.1.3 Functional requirements criteria

The NORSOK standard Z013 (NORSOK-Z-013-AnnexG, 2010) includes a detailed procedure for explosion risk analysis (ERA) where the use of CFD simulations is prescribed (in Annex G). More details of this procedure are given in Chapter 8.2.3. Results from the ERA are used to give input to the QRA to calculate the total risk/FN curve. This combined QRA and ERA approach has become standard for oil and gas processing platforms in the North Sea, and several regions internationally are also using it. The ERA is a probabilistic approach for explosions since they can result in unacceptable consequences. The method is used to rank these events by their frequency and show that these unacceptable events will not occur with a frequency higher than the acceptance frequency. The results from the method are then a tolerance pressure that the critical walls and decks (defined barriers) must withstand. This pressure is used to set the Design Accidental Load (DAL). A margin on the DAL is usually included to make it more robust. The NORSOK QRA and ERA approach is hence used both as a practical method to define acceptable strengths of the barrier(s), and to be used when calculating the FN curve to show that the total risk is acceptable. The FN curve will include a contribution from explosions, which depends on the design strength of the critical walls and decks. The analysis needs to include an assessment of fatalities in case the critical barrier breaks down because of the explosion and/or the subsequent fire. Such barriers could be the walls and decks between the hydrogen spaces(s) and the rest of the ship.

Since the calculation of a societal risk curve of the entire ship is a long process, relevant acceptance criteria for the critical barriers should be established. This makes it possible to run sensitivities and test different mitigating measures without the need to calculate the FN curve each time. This is in line with the Cost-Benefit principles outlined in the FSA approach.

Based on common practice from the offshore industry, the approach could be that breakage of a critical barrier (wall or deck) to the rest of the ship in a way that disrupts main ship functions may be allowed if the frequency is less than 1.0E-4 per year. These commonly used acceptance criteria for safety functions in the offshore industry may need to be adjusted based on ship characteristics such as number of passengers/crew/people that may be exposed. For a large passenger ship, for example, this acceptance frequency should be reduced. With separate acceptance criteria for safety functions, the required structural strengths for walls and decks surrounding the hydrogen equipment can be determined before the total FN curve is calculated. This approach has so far not been used for hydrogen-fuelled ships, but the above discussion describes a possible approach.

If the acceptance criteria for safety functions are changed, the total societal risk will also change. Therefore, the level of the functional acceptance criteria can be adjusted so that the total societal risk criteria are met. For example, if the functional risk acceptance criterion is changed from 1.0E-4 to 1.0E-5 per year, then there will be 10 times fewer breakdowns of the wall around the hydrogen area. Then the number of fatalities due to this incident can also be reduced by an order of 10 times. It will also result in a much stricter requirement for the strength of the wall or other preventive and mitigating measures; hence, acceptance frequency can have a large economic impact.

Further work to establish an approach for hydrogen-fuelled vessels is recommended as a part of Phase 2. Preferably, this would be undertaken by integrating a full QRA and ERA into the Alternative Design approval process. As part of the ERA, the strength of the barriers related to the FN curve, and the acceptance frequency for barriers, can also be addressed.

6.3.1.4 Summary: suggested use of acceptance criteria

In summary, two types of quantification of risk are suggested, one for the societal risk on the ship, and one for functional requirements. The functional requirements will depend on the societal risk. Both risk definitions have a set of different options and definitions including different use and criteria of acceptance. The typical definitions for the two are:

- the total societal risk curve (FN curve) per ship; and
- the frequency of exceeding a pressure on the critical barriers, typically around the hydrogen space(s) due to explosion. This is given as a frequency exceedance curve with pressure on the x-axis, and frequency on the y-axis. The method for developing such a curve is described in 8.2.3.2, with an example of an exceedance curve in Figure 8.5. It should be noted that IMO has not defined or quantified an overall risk criterion for ships or ships' arrangements in general. It should also be noted that each ship has a different risk profile, depending on its type, arrangements, and operational profile. Each ship type represents different risks and importance to society, and this therefore needs to be discussed and clarified with the relevant Administration.

It is suggested to further develop the criteria and procedures described here during the first real projects with hydrogen so that useful criteria can be established. Such development needs to involve the societal risk curves for existing ship types. These curves can be used to represent all other risks on the ship, regardless of the propulsion system. The additional risk expected due to hydrogen propulsion can be calculated with an ERA, and the pressure exceedance curve can be converted to an FN curve after the strength of the walls around the spaces containing hydrogen is decided. The breakdown of the walls towards manned areas can result in a jump in the number of fatalities due to direct impact from the explosion or from a subsequent jet fire that leads to a larger ship fire.

An example of frequency acceptance criteria when using the FN curve is given in the IMO FSA guideline indicating three regions – 'unacceptable', 'ALARP', and 'acceptable'. Hence the approach is well-suited, during the establishment of robust hydrogen technology, to test different solutions with continuous improvements until good robust solutions are established. When this position is reached, it is likely that we will see the emergence of safe and acceptable design solutions that can be used to write codes and standards.

If the defined risk criteria are not reached, the designer should identify risk control options / safety barriers for implementation, based on their effectiveness for risk reduction. Operational methods or procedures shall not be applied as an alternative to a particular fitting, material, appliance, apparatus, or item of equipment, prescribed by the IGF Code.

6.4 Class rules and the role of the Classification society

Classification Societies' rules are normally more detailed and specific to reflect the safety level of international regulations such as the SOLAS Convention.

DNV's additional Class notation 'FC' is mandatory for all Classed vessels with FC power installations on board (see Chapter 6.6.1 for details). Found under DNV's Rules for Ships, Pt.6 Ch.2 Sec.3 (DNV GL FC Rules) The DNV rules for FC installations provide requirements aiming to ensure safe and reliable operation of the FC power installation. Existing class rules can ease the Alternative Design process, provided that the rules are acknowledged by the relevant Administration.

FIGURE 6.7

The qualification process from Approval in Principle to Approval.

6.4.1 Class approval process

Figure 6.7 illustrates the qualification process from an Approval in Principle (AiP) through to Approval.

An AiP is a standalone process, but as shown in Figure 6.7 it may be followed by a General Approval for Ship Application (GASA). An AiP can be an important step towards obtaining a Preliminary Approval in the Alternative Design process.

6.4.1.1 Approval in Principle (AiP)

Approval in Principle is recognized as an early-phase verification level for new design concepts or for existing designs in new applications. This is a pre-contract service, meaning that the AiP is undertaken before the contract between the Ship Owner and the Yard is established. The review is based on at least a minimum scope of documentation agreed with DNV where relevant safety aspects shall be covered, including functional aspects affecting the evaluation of the design. The AiP will identify technical items or issues that will need to be addressed during detailed design to prepare the design for Classification Approval.

The review process for an AiP may be initiated by a meeting where the designer presents the novel design and the intended application. This give DNV input to decide on the required scope of documentation. It is an advantage if the designer and DNV clarify issues, uncertainties, and provide feedback during the AiP process. Based on new knowledge, the required documentation may be modified during the AiP process.

Significant economic and technical efforts are required from a designer to issue the requested documentation for an AiP review. The results from an AiP process are therefore an important milestone for a designer.

If an AiP is granted, three documents are issued:

- **Approval in Principle Statement;** this document confirms compliance with the AiP requirements, specifies the rules that have been used for the review, and states the assumptions made in the evaluation.
- **Approval in Principle Letter;** describes the design that the AiP review covers, its limitations, assumptions, and the basis for the review. The letter describes the assumptions in more detail than the AiP statement. If an AiP is not granted, the reasoning will be included in the Approval in Principle Letter.
- **The Appendix;** normally summarizes all the comments to the provided documentation. These comments need to be addressed for the final approval of an installation onboard a ship, the General Approval for Ship Application (GASA), or at the Newbuilding Approval.

6.4.1.2 General Approval for Ship Application (GASA)

This verification level is developed to support designs that normally have achieved an Approval in Principle Statement and where the technical development is taken to a high and detailed level. Accordingly, a GASA examination covers a significantly more extensive scope of work and includes verification to a detailed level. The documentation requirement of the selected design is equivalent to an approval scope. The GASA review will generate comments similar to those for a normal approval.

6.5 International hydrogen standards

Hydrogen has been used throughout the world for a long time, as an industrial gas and, among other purposes, in the space industry. Therefore, standards and codes covering industrial use of hydrogen are in place, and some of these may be relevant for the use of hydrogen as fuel in ships. Standardization work related to the use of hydrogen as fuel in the land-based transport sector is newer, but the regulatory regime for the required hydrogen filling stations, and for hydrogen FC vehicles, is becoming established.

Standards from the American Society of Mechanical Engineers (ASME) and the American Petroleum Institute (API) are the most used for maritime applications in general. Other standards are used depending on geography; for example, EU directives and standards may be used in the EU area. ISO and IEC standards are also relevant for introducing hydrogen as ship fuel.

Due to their nature, global standard development organizations such as ISO (International Organization for Standardization) and IEC (International Electrotechnical Commission) focus on developing component standards and generic protocols. International (ISO and IEC) component standards are being developed to eliminate global barriers to trade. In this way, a hydrogen component (such as a hose or breakaway device) or an assembly (such as a reformer or dispenser) can meet the same design and testing criteria and thus can be sold across the globe without additional requirements.

Installation requirements of those components or assemblies (for example, separation distances) can vary by jurisdiction, but their design and testing requirements should not.

Since ISO and IEC standards are developed by the broadest spectrum of international stakeholders, they become 'super' standards. They should thus replace any existing similar or analogous national component standards. This consideration has the following implications:

- National component standards including those that served as seed documents for the development of international standards must be prepared to harmonize their design and testing requirements with the international standards. Essentially, national standards should become harmonized with adopted international standards, where the only deviations are references to specific relevant national standards and regulations and, when justified, to climatic conditions.
- National legislation and installation codes should recognize international standards or their national harmonized adoptions as the only/preferred listing or certification components standards.
- National installation codes should remove any design and testing requirements related to components and assemblies and focus solely on their installation requirements. They should also explicitly reference available international component standards or their national harmonized adoptions for design and testing requirements.

6.5.1 ISO/TC Hydrogen technologies

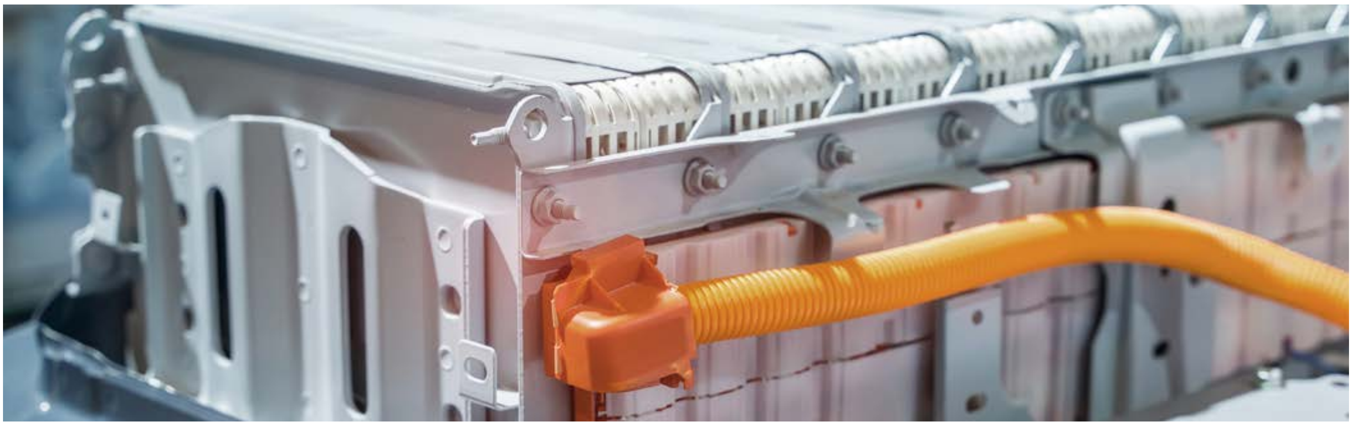
The ISO (International Organization for Standardization) with its Technical Committee (TC) 197 is a leading international body for standard documents for hydrogen technologies. The secretariat of this TC is held by the Standards Council of Canada (SCC). ISO/TC 197 is composed of 20 participating countries, including active participation from all the G7 countries, as well as China, Korea, India, Russia, etc. In combination with observing members, ISO/TC 197 global participation covers most of the biggest world economies.

The scope of ISO/TC 197 is standardization in the field of systems and devices for the production, storage, transportation, measurement and use of hydrogen. These standards are not widely used for the maritime industry. However, a recently planned and launched project for the development of a three-standards package for gaseous hydrogen fuelling protocols for hydrogen-fuelled vehicles (under the ISO 19885 series) is particularly relevant to MarHySafe. Once developed, their basic principles can be used for bunkering of maritime vessels, though a separate standard should be developed within this series specifically for maritime applications.

Also, a separate series number has been reserved for liquid hydrogen fuelling protocols – ISO 19886. This is currently a placeholder for future new work item proposals that can cover liquid hydrogen bunkering operations.

Some ISO standards considered of relevance for maritime hydrogen applications are mentioned in the following.
ISO TR 15916 Basic considerations for the safety of hydrogen systems

ISO TR 15916 gives an overview of safety-relevant properties and related considerations for hydrogen. Annex C gives an overview of low-temperature effects of hydrogen on materials, and the document also suggests suitable material-selection criteria, including how to consider hydrogen embrittlement.



ISO/TC 220

This is a standard for cryogenic land-based insulated storage vessels (vacuum or non-vacuum) for storage and transport of refrigerated liquefied gases. It also concerns design and safety of the vessels, gas/materials compatibility, insulation performance, and operational requirements of the equipment.

ISO 19880-3:2018 Gaseous hydrogen – Fuelling stations

Different parts of this standard may also provide useful input to other pressurized gaseous hydrogen systems. These potentially include Part 1: General requirements, Part 3: Valves, and Part 6: Fittings.

Detection of leaks

ISO 26142:2010 Hydrogen detection apparatus – Stationary applications

This standard defines the performance requirements and test methods for hydrogen-detection apparatus that measures and monitors hydrogen concentrations in stationary applications. The standard covers hydrogen detection apparatus used to achieve single and/or multilevel safety operations, such as nitrogen purging or ventilation and/or system shut-off corresponding to the hydrogen concentration. The requirements applicable to the overall safety system and the installation requirements are excluded. This standard sets out only the requirements applicable to a product standard for hydrogen-detection apparatus, such as precision, response time, stability, measuring range, and selectivity and poisoning. The standard is intended to be used for certification purposes.

Hydrogen piping network

The standard ISO 15649:2001 on piping for petroleum and natural gas industries is also used as a guideline for hydrogen technologies. This standard is applicable to piping within facilities and for packaged equipment, with exclusion of transportation pipelines and associated plant.

Pressure-relief devices

ISO 19882:2018 Gaseous hydrogen – Thermally activated pressure relief devices for compressed hydrogen vehicle fuel containers.

6.5.2 IEC Standards

Founded in 1906, the International Electrotechnical Commission (IEC) is the world's leading organization for the preparation and publication of International Standards for all electrical, electronic, and related technologies. These are known collectively as 'electrotechnology'. Millions of devices that contain electronics, and use or produce electricity, rely on IEC International Standards and Conformity Assessment Systems to perform, fit, and work safely together.

The IEC technical committee (TC) IEC/TC 105 Fuel Cells has a relevant role in hydrogen energy and FC technologies. Its stated scope is 'to prepare international standards regarding fuel cell (FC) technologies for all FCs and various associated applications such as stationary FC power systems, FCs for transportation such as propulsion systems, range extenders, auxiliary power units, portable FC power systems, micro-FC power systems, reverse operating FC power systems, and general electrochemical flow systems and processes'.

The standardization interests of individual projects can be grouped into the following areas: all types of FCs' safety and performance, use of reversible FCs for energy storage, and FCs' environmental performance-based lifecycle analysis.

Each of those is potentially relevant for maritime applications. Fuel-cell standards are listed in Chapter 6.6.

IEC 60079-10-1:2015 is a standard which covers the classification of areas where flammable gas concentrations may cause an ignition hazard. This standard defines an explosive gas atmosphere as a mixture with air under atmospheric conditions which after ignition permits self-sustaining flame propagation.

6.5.3 American Society of Mechanical Engineers (ASME)

ASME B31.12 Hydrogen piping, material compatibility

ASME standard ASME-B31.12_2014, and its updated 2019 edition, is the code for Hydrogen Piping and Pipelines (ASME-B31.12, 2019). It suggests standards for suitable materials, welding, inspection and testing, operations and maintenance, and quality programmes for piping. General considerations are expected to be applicable and transferrable to maritime use, but will need validation. The code is applicable to piping in gaseous and liquid hydrogen service, and to pipelines in gaseous hydrogen service up to and including the joint connecting the piping to the associated pressure vessels/equipment; but it is not applicable to the vessels and equipment. It is also applicable to the location and type of support elements, but not to the structure to which the support elements are attached.

ASME B31.3-2018 Process Piping. Test requirements for high-pressure piping.

This standard contains requirements for piping including piping that interconnects pieces or stages within a packaged equipment assembly. It covers materials and components, design, fabrication, assembly, erection, examination, inspection and testing of piping.

6.5.4 Compressed Gas Association (CGA)

The Compressed Gas Association (CGA, www.cganet.com) develops standards.

The following CGA standards may be particularly relevant for the design of hydrogen systems on ships:

CGA G-5-2017 Hydrogen

This standard provides information on the physical and chemical properties of hydrogen, and its proper handling and use. It intends to provide background information for those involved in manufacture, distribution, and use of hydrogen.

CGA G-5.4-2019 Standard for Hydrogen Piping Systems at User Locations

CGA G-5.4 describes the specifications and general principles recommended for CH_2 and LH_2 piping systems. This standard is intended for those involved with any aspects related to design, fabrication, installation, use, maintenance (etc.) of hydrogen piping systems. This standard is similar to ASME B31.12 Hydrogen Piping and Pipelines.

CGA G-5.5-2014 Hydrogen Vent Systems

This standard provides design guidelines for hydrogen vent systems for CH_2 and LH_2 systems, and provides recommendations for safe operation of such vents. The standard is intended for those who design, install, and maintain hydrogen vent systems.

Other relevant standards (but not all) from CGA include the following:

CGA H-5-2020 Standard for Bulk Hydrogen Supply Systems (an American National Standard)

This standard provides minimum requirements for siting, selection of equipment, installing, initiating, maintaining, and removing CH_2 and LH_2 bulk hydrogen supply systems.

CGA P-50-2014 Site Security Standard

This publication gives input for addressing security risks at fixed sites and is intended for managers at such facilities to make risk-based security decisions.

CGA P-74-2019 Standard for Tube Trailer Supply Systems at Customer Sites

This standard contains minimum requirements for high-pressure (CH_2) tube trailers and details requirements for tube-trailer supply systems.

6.5.5 Supplementary codes and standards

The aim of this subsection is to introduce supplementary standards that may provide useful input to the ongoing work in the MarHySafe project.

6.5.5.1 EN standards

Standard EN 13480:2002 is divided in seven parts specifying the requirements for industrial piping systems and supports made of metallic materials. It is a standard for cryogenic vessels developed for land-based application.

6.5.5.2 International Maritime Dangerous Goods Code (IMDG Code)

The IMDG Code covers hydrogen and other dangerous goods, but only as packed cargo. Transport of such goods in the ship's own cargo tanks is not included. The code gives requirements for CH_2 and LH_2, which are comparable to those for compressed natural gas and LNG. CH_2 and LH_2 as cargo cannot be transported by cargo or passenger ships which carry more than 25 passengers or 1 passenger per 3 m of overall length. LH_2 cannot be stowed below deck.

6.5.5.3 European Directives

The Agreement concerning the International Carriage of Dangerous Goods by Road (ADR) covers all road transport of dangerous goods as cargo. As for maritime, transport of own fuel is not included in ADR, but in other codes (ECE directives). ADR can be considered as the land-transport parallel to the maritime dangerous goods as cargo code (IMDG Code), and the structure of the IMDG Code and the ADR are consistent. Even though they cover hydrogen as cargo only (not as fuel), the codes can provide valuable input regarding requirements for hydrogen as a fuel in shipping. ADR includes provisions for both gas and liquid fuels. It also includes classification of dangerous goods according to the danger the different substances present, requirements for packing and tank provisions, and provisions concerning the conditions of carriage, loading, unloading and handling.

The ATmospheres EXplosible (ATEX) Directive, 2014/34/EU covers equipment for potentially explosive atmospheres, and is relevant for hydrogen storage and piping. It established key definitions and sets the boundary conditions for ATEX zoning.

The Pressure Equipment Directive 2014/68/EU (97/23/EC) (PED), is relevant for pressurized hydrogen storage and piping.

6.5.5.4 National Fire Protection Association (NFPA)

NFPA 2, Hydrogen Technologies Code

This code provides fundamental safeguards for the generation, installation, storage, piping, use and handling of CH_2 and LH_2. The code's aim is to apply broadly to the use of hydrogen.

6.5.5.5 Natural gas rules might provide some guidance

The current DNV rules for gas-fuelled ship installations 'Section 5 – Gas fuelled ship installations – Gas Fuelled' are not applicable for hydrogen as fuel. Part A-1 of the IGF Code (IGF Code, 2016) gives specific requirements for ships using natural gas as fuel, and Chapter 6 covers fuel-containment systems, but these are not applicable for hydrogen as fuel. Despite lacking hydrogen-specific rules, these natural gas rules have also been used in some cases to provide guidance for hydrogen.

It is important to note that these rules are intended for natural gas, which has different properties than hydrogen.

6.6 Energy conversion – Fuel Cells

Maritime hydrogen FC applications must satisfy requirements for onboard energy generation systems, and fuel-specific requirements regarding arrangement and design of the fuel-handling components, the piping, the material, and the fuel storage. In current regulations, these aspects are handled separately. The focus in this handbook revision was PEM FC technologies, but most codes and standards covering FC are general, technology agnostic, about the type of FC, and do not cover only PEM FC.

The process of approving a FC for maritime use starts with the Classification Society responsible for component approval, which will then assess the FC against their Class rules and relevant guidelines. The additional Class rules provide requirements to the FC installation itself and, together with other relevant codes and standards, may support the approval process for a FC vessel using hydrogen as fuel.

DNV's FC rules are introduced in the next sub-section together with key supplementary codes and standards.

6.6.1 DNV FC Class rules

Only the FC installation is covered by the DNV rules (DNV GL FC Rules). These rules include requirements for the design and arrangement of FC power installations and the spaces containing such installations. The rules cover all aspects of the installation, from primary fuel supply up to and including the exhaust gas system. They do not cover the remaining installation arrangements for the use of hydrogen as fuel; i.e., the hydrogen fuel storage, and preparation and distribution of hydrogen.

The following gives a brief introduction to DNV Class Rules for FC installations. Part 6, Chapter 2 of DNV's Rules for Classification of ships is 'Additional class notations' for 'Propulsion, power generation and auxiliary systems'.

Section 3 – Fuel cell installations – FC

This section sets requirements for the FC power systems, design principles for FC spaces, fire safety, electrical systems, control, monitoring and safety systems, manufacture, workmanship and testing. No fuel-specific requirements are included.

Two different class notations are possible. Which one is applicable depends on the planned use of the FC installation as follows:

FC(Power)

- Given to ships that fulfil design requirements in the Rules, where FCs are used for electrical propulsion.

FC(Safety)

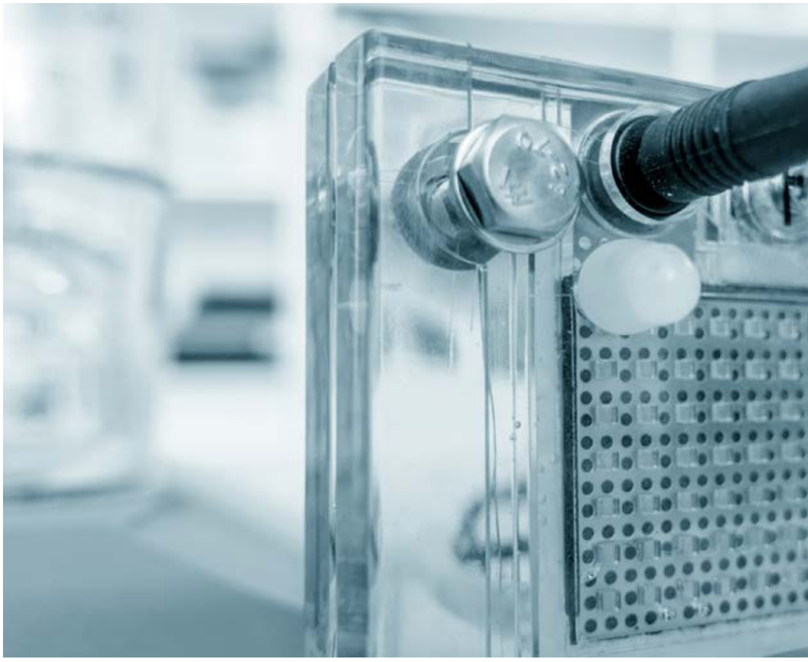
- Given to ships that fulfil the environmental and safety requirements in the Rules, where the main source of power is based on energy converters other than fuel cells.

Certification requirements for the components are given in the rule set for FC installations; see Part 6, Chapter 2, Section 3, [1.7] table 4.

DNV Class Rules, Pt.4 Ch. 1 on machinery systems are relevant for required environmental conditions. The Class guideline DNVCG-339 - Environmental test specification for electrical, electronic and programmable equipment and systems is applicable for all sub-components. It considers factors such as vibration inclination, humidity, and temperature.

This means that environmental testing must be at least on the same level as for other electrical equipment brought onboard ships, and the special considerations included in the additional class notation for FC installations needs to be met. Additional standards that are considered relevant by the Class Society are included below.

The DNV Fuel Cell rules (item 7.2.2) give input to facilitate the selection of appropriate electrical apparatus. This covers design of suitable electrical installations in hazardous areas and the division into zones 0, 1 and 2. DNV Class Rules Pt.4 Ch. 8 on electrical installations are relevant.



Key international standards considered applicable for FC installations in ships are:

- IEC 62282-3 Fuel Cell Technologies – Part 3-100: Stationary Fuel Cell Power Systems – Safety
  - The test programme may be based on this standard, but also needs to take the ship-specific environmental and operational conditions into account.
- IEC 60079-10 Electrical installations in hazardous areas
  - This standard outlines the principles for how hazardous areas are divided into zones 0, 1, and 2 and is needed for selection of electrical apparatus and design of electrical installations.
- IEC 60092-502 provides guidance and informative examples for tankers.

Additional FC standards used for design of land-based FC installations that may be relevant are:

- ANSI/CSA America FC1-2014 Stationary Fuel Cell Power Systems
- IEC 62282-2 Fuel Cell Technologies – Part 2: Fuel Cell Modules
- IEC 60079-10-1 Electrical Apparatus for Explosive Gas Atmospheres
- IEC 60068-2-6 Environmental Testing – Part 2-6: Tests – Test FC: Vibration (Sinusoidal)

Hydrogen storage onboard is not included in the scope of any of the standards mentioned above.

6.7 Hydrogen storage onboard

As long as formal prescriptive rules for storage of hydrogen used as fuel are not in place, it is suggested that a pre-contract assessment with an Approval in Principle, and possibly followed by a General Approval of Ship Application (GASA) review, is applied to reduce uncertainties prior to signing a formal newbuilding contract for a hydrogen-fuelled ship. The pre-contract service normally follows the following steps:

- Approval in Principal (AiP). The first step towards an approval for a hydrogen-containment system would be to carry out an AiP review (see Chapter 6.4.1.1). Prior to the AiP review there will be a review of the design to identify the need of documentation, and the relevant set of requirements that will be the basis for the AiP review will be defined.
- General Approval for Ship Applications – GASA (see Chapter 6.4.1.2).

As a basis for evaluation of onboard hydrogen storage, the following considerations are normally to be applied:

- DNV Rules for Ships Pt.6 Ch.2 Sec.5 cover LNG (DNV GL Rules, 2020). For hydrogen, special considerations will need to be taken, and additional requirements may be relevant.
- Safety basis for liquid hydrogen as fuel will be to apply the IGF Code safety requirements that only cover methane, with additional safety assessments related to the use of hydrogen as fuel.
- Adopting safety issues addressed in IMO resolution MSC.420(97) 'Interim recommendations for carriage of liquefied hydrogen in bulk' (IMO MSC.420(97)).
- Other standards/regulations relevant for the particular design; normally identified in the AiP process.
- Risk assessment to identify safety-related items for the design that are not covered by the above references.

6.7.1 Compressed hydrogen storage

There are no specific standards for the use of onboard compressed hydrogen (CH_2) as fuel for ships. However, existing DNV rules for compressed natural gas (CNG) may be used as a starting point for a more specific hydrogen evaluation. DNV Rules for ships Pt.6 Ch.2 Sec.5 address the use of CNG as fuel on ships. Here, the relevant requirements are either to apply the pressure-vessel rules defined in DNV Rules for Ships Pt.4 Ch.7, or to apply the rules for Compressed Natural Gas Ships (CNG) defined in DNV Rules for Ships Pt.5 Ch.8. There are no specific rule references addressing the storage of hydrogen.

For ship applications, the normal approach is to approve pressurized gas tanks on an individual basis. Individual tank designs will therefore need to be assessed by class, based on a list of requirements. The general guideline for application of storage of CH_2 may follow a safety assessment:

Steel cylinders:

- Design as Class 1 cylinders as defined in DNV Rules for Ships Pt.4 Ch.7 or as CNG cylinders as defined in DNV Rules for Ships Pt.5 Ch.8.
  - Cylinder material:
- No reaction with hydrogen (hydrogen embrittlement),
- Permeability of hydrogen,
- Content of other gases/contamination in gas - affecting corrosion of material.

Composite cylinders:

- Design according to DNV Rules for Ships Pt.5 Ch.8:
  - No reaction with hydrogen (aging),
  - Permeability of hydrogen,
  - Liner material suitable for hydrogen and properties as manufactured including fatigue safety.
- Alternative standards may be acceptable if considered conservative compared to addressed standard. Alternatively, additional testing may be required to fill gaps in the requirements.

Some land-based rules cover CH_2 storage and may provide relevant input for the future development of such standards for ship applications. Therefore, some of these are mentioned in the following.

Existing pressure vessel rules may be applicable for pressurized hydrogen-storage vessels to be used on ships. Road transport of CH_2 is regulated by the UN Model Regulation, the European Agreement Concerning the International Carriage of Dangerous Goods by Road (ADR), and the European Transportable Pressure Equipment Directive (2010/35/EU – 'TPED'). The Seveso III Directive (Directive 2012/18/EU) is applicable in case of storage of more than 5 tonnes of hydrogen.

European standards covering pressure vessels used for pressures exceeding 0.5 bar are harmonized with the Pressure Equipment Directive (PED). Some of the standards related to hydrogen storage are EN 1252-1:1998 on storage tank materials, EN 1797:2001 on gas/material compatibility, and EN 13648 part 1, 2, and 3 on safety devices for protection against excessive pressure.

Some American standards/guidelines, e.g., through ASME and NFPA may be relevant. US standards are not harmonized with EU directives, but can be used for practical purposes provided there is no conflict with other regulations, such as applicable European regulations.

6.7.2 Liquid hydrogen storage

The IGC and IGF (see Chapter 6.1) codes cover storage of liquefied gas onboard ships. C-tank rules for storage of liquefied gas will in principle cover hydrogen cooled to liquefied form. However, additional considerations will be required due to the properties of hydrogen, including the low storage temperatures.

The International Code for Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code)

This is an interim guideline of the IGC Code that currently allows carrying hydrogen as cargo for one pilot project (Australia to Japan), but the guideline is not yet part of the IGC code. It should also be noted that the IGC code does not include any scope related to hydrogen as fuel, and it does not allow for the use of any hydrogen as fuel on a ship, even if the ship may carry hydrogen as cargo. This means it is impossible to use as fuel any LH_2 vented from the cargo space, unless an equivalent safety level is demonstrated (MSC.1/Circ 1455, 2013).

For the carriage of LH_2 in bulk, carriers should comply with the International Convention for the Safety of Life at Sea (SOLAS), which defines minimum requirements for the construction, equipment, and operation of ships. Further, LH_2 carriers shall comply with the (IGC Code), as adopted by the IMO Resolution MSC.5(48) 2016, which defines the requirements for the construction and operation of gas carriers. The carriage of LH_2 is covered by the IGC Code scope as provided in its paragraph 1.1.1:

'The Code applies to ships regardless of their size, including those of less than 500 gross tonnage, engaged in the carriage of liquefied gases having a vapour pressure exceeding 0.28 MPa absolute at a temperature of 37.8 °C and other products, as shown in chapter 19, when carried in bulk.'

As hydrogen is not specifically described as a cargo in the IGC Code Chapter 19, Interim Recommendations for the carriage of LH_2 in bulk (Resolution MSC.420(97) adopted on 25 November 2016) have been developed based on paragraph 5 of the Preamble to the IGC Code. The preamble states that new products and their conditions of carriage will be circulated as recommendations, on an interim basis, prior to the entry into force of the relevant amendments.

The recommendations provide minimum safety requirements and consider the specific properties and hazards of hydrogen, based on the results of a comparative study of similar cargos listed in Chapter 19 of the IGC Code.
The interim recommendations were developed to facilitate the establishment of the Australia to Japan LH_2-carrier pilot project and may need to be reviewed if applied to vessels other than the pilot vessel.

6.8 Safety distances and hazardous zones

Criteria for safety distances are normally developed by standardization committees and are prescribed by standards or codes. A hazardous zone/distance is the research result for a specific project, and this exercise has not yet been conducted for hydrogen-fuelled ship applications.

Within ISO, a key purpose of safety distances is to prevent escalation of minor events to major events and prevent direct harm to people. Safety distances are therefore not intended to safeguard against catastrophic events.

Consequently, safety distances are not used or considered applicable as a risk-mitigation measure for low-probability, high-consequence events. It may then be reasonable to ask to what degree it is relevant to apply safety distances for hydrogen applications where explosion events cannot be disregarded.

An additional consideration is that there is limited physical separation distance available onboard ships.

There is also some confusion regarding terminology, and it needs to be noted that a safety distance is different from a hazard distance. Hazard has to do with the pure damage that one may sustain.

Hazardous area (classified area), (ref ISO 19880-1)

An area in which an explosive gas atmosphere is or may be expected to be present in quantities such as to require special precautions for the construction, installation, and use of equipment. The interior of many items of process equipment are commonly considered as a hazardous area, even though a flammable atmosphere may not normally be present, to account for the possibility of air entering the equipment. Where specific controls such as inerting are used, this can reduce the risk and may influence how the interior of such process equipment would be classified.

Hazard distance (ref ISO 19880-1)

Distance from the hazard to a determined physical effect value (damage) that can lead to a range of harm (3.34) to people, equipment, or environment. Consequence driven.

Safety distance (separation distance, safe distance, set-back distance) (ref ISO 19880-1)

Distance to acceptable risk level or minimum risk-informed distance between a hazard source and a target (human, equipment, or environment), which will mitigate the effect of a likely foreseeable incident and prevent a minor incident escalating into a larger incident. Safety distances could be split into Restriction distances, Clearance distances, Installation layout distances, Protection distances and External risk zone.

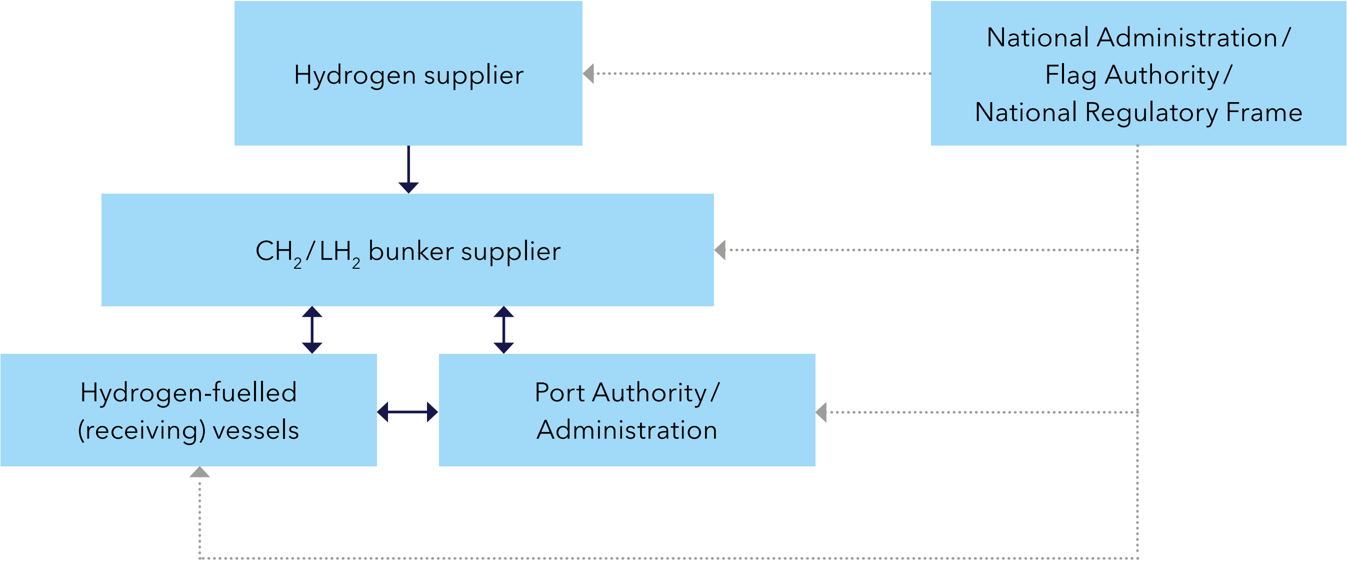
Both NFPA-2 and the European Industrial Gases Association (EIGA) include prescribed safety distances based on non-marine applications. NFPA-2 may provide relevant input despite being based on onshore hydrogen applications. The basis for NFPA-2 is jet fires, and explosions are not assessed to contribute to the risk. The larger leaks that can lead to explosions are disregarded since they are very unlikely, according to NFPA-2. Therefore, the most critical consequence in NFPA 2 is a jet fire and how this can cause escalation to other equipment. In a maritime context, explosions need to be included as they contribute to the risk (and safety distances). The use of a risk-based approach considering all risks with increasing hole sizes up to full-bore rupture, which is suggested in this Handbook, is considered a relevant approach. Further in-depth assessments would be needed to reach conclusions on the possible relevance of NFPA-2 for maritime use. The Society for Gas as a Marine Fuel (SGMF) has developed an introductory guide for natural gas as a marine fuel . This was based on gas dispersion, which appears relevant to cryogenic fuels. A flash fire can harm people inside the cloud, there is no need for an explosion.

According to a recent document from IMO (IMO CCC7/3, 2020), discussions are ongoing on whether FC spaces will be considered as hazardous zone 1. It is therefore not known how the FC part of the IGF Code (under development) will evaluate this. The DNV position is reflected in the DNV FC Rules.

It is uncertain to what degree existing gas standards will be applicable for hydrogen-fuelled ships. CFD modelling and gas dispersion analysis could be used to determine case by case hazardous zones. Previous work – may also provide relevant insight, for example the recent studies by SGMF on Simultaneous Operations (SIMOPs) during LNG Bunkering and Recommendations of Controlled Zones during LNG Bunkering .

FIGURE 6.8

Main stakeholders and information flows involved in a hydrogen bunkering operation. Inspired by (EMSA, 2018).



6.9 Bunkering

Bunkering operations for low-flashpoint fuels including hydrogen are characterized by the interaction of many stakeholders and different regulatory contexts. This imposes some challenges for safe bunkering. The different stakeholders involved in a hydrogen bunkering operation are shown in Figure 6.8.

This report considers bunkering to a permanent onboard fuel storage. For some ship applications, other storage solutions – e.g., swap solutions where the actual fuel storage is replaced instead of filled – may be relevant, but this is not included in the current study.

The IGF Code establishes technical and functional requirements on equipment for bunkering and the bunkering operation. However, the focus is to a large extent on the receiving vessel, and its preparation for safe bunkering. Therefore, the entire bunkering process, the bunkering connection, and the shore side bunkering installation needed, are not covered.

Areas not covered by the IGF Code will typically be the responsibility of national authorities. As an example, the Norwegian Directorate for Civil Protection (DSB) is the Norwegian national authority for the handling of flammable, reactive, explosive and pressurized substances, and hydrogen is part of these schemes. Bunkering of hydrogen and other flammable gases in Norway is covered by the Regulations of 8 June 2009 relating to the handling of flammable, reactive, and pressurized substances including requisite equipment and installations (FOR-2009-06-602). However, more specific provisions are needed on how to deal with bunkering of hydrogen, and the first version is currently under development by DSB. Today, entities must obtain consent from DSB for bunkering of flammable gases before any bunkering operation is allowed.

Existing regulations, codes and standards do not cover the challenges and safety concerns related to introduction of the new technical solutions needed for (fast) bunkering of large volumes of hydrogen to ships. Therefore, more knowledge is needed, the technology needs further development and real-life testing of the expected new solutions will be required. Work to initiate standardization activities to develop a fuelling protocol for maritime hydrogen is planned within ISO TC 197 (ISO19885-5 reserved, source A. Tchouvelev, MarHySafe HB review meeting 20/10-2020).

Risk-based approaches are likely to be required in defining safety distances for hydrogen bunkering. However, what is considered 'acceptable risk' for bunkering operations may vary and will typically be covered by general rules or practices, or by established criteria for the use of flammable gases in the individual countries or regions where the ship is to operate. Where such criteria are lacking, available experiences from other sectors, and in particular learnings from the development of land-based

[4] https://www.sgmf.info/assets/docs/sgmf-guide.pdf
[5] New Publications & BASiL (sgmf.info)

hydrogen infrastructure, may prove useful[6] (Hydro, DNV , 2003), (HyApproval, 2008).

To avoid a situation with a huge number of possibly conflicting approaches, work on aligning best practices is needed. It is therefore recommended that work on this topic is included in Phase 2 of MarHySafe.

6.9.1 Compressed gas

The ISO standard for hydrogen fuelling stations (ISO 19880-3:2018 Gaseous hydrogen – Fuelling stations) is considered relevant for gaseous hydrogen bunkering facilities and bunkering operations. Relevant parts are: 1 General requirements; 2 Dispensers; 3 Valves; 5 Hoses; 6 Fittings.

Part 3 covers various types of valves, and since break-away devices are considered as valves these are also covered in ISO 19880-3: Part 3. Other relevant standards are:

- **ISO 17268**
  Gaseous hydrogen land vehicle refuelling connection devices.
- **Directive 2014/94/EU**
  EU Directive on the deployment of alternative fuels infrastructure.
- **EN ISO 4126-1:2004**
  Safety devices for protection against excessive pressure – Part 1 – Safety valves.
- **EN 10216-5:2004**
  Seamless steel tubes for pressure purposes – Part 5 – Technical delivery conditions. Stainless steel tubes.
- **ISO TC 197**
  is about to initiate work on developing standards for high-flow bunkering of CH_2 to heavy duty applications.

A key safety concern during bunkering of CH_2 is that heat is released as hydrogen adiabatically compresses into the storage cylinders (ITM Power, 2019). This heat may soften the pressure vessels, and in the worst case leads to catastrophic failure. Therefore, it is very important to keep the flow rate of hydrogen controlled. Proper safety/communication protocols are especially important in this regard to allow the refueller to cease flow if the ship's pressure vessels get too hot. If the ship should move further than the length of the hydrogen refuelling hose at maximum extension, the system should include a 'break-away coupling'. This device will separate two halves of the hose in a controlled manner, while sealing each end and preventing the release of hydrogen.

Some standards produced for other applications that may be useful are introduced in the following:

- **IMO Resolution MSC 420(97)**
  Interim recommendations for the carriage of liquefied hydrogen in bulk.
- **ISO / TR 15916**
  Basic considerations for the safety of hydrogen systems (ISO/TR 15916 , 2015).
- **ISO/TS 18683**
  Guidelines for systems and installations for supply of LNG as fuel to ships.
- **ISO 20519**
  Ships and marine technology – Specification for bunkering of liquefied natural gas fuelled vessels.
- **ISO 13984:1999(en)**
  Liquid hydrogen – Land vehicle fuelling system interface.
- **ISO 13985:2006(en)**
  Liquid hydrogen – Land vehicle fuel tanks.
- **ISO 21012:2006(en)**
  Cryogenic vessels – Hoses.
- **SIGTTO**
  ESD Arrangements & Linked Ship/Shore Systems for Liquefied Gas Carriers.
- **SGMF**
  Gas as a marine fuel, safety guideline. Bunkering.
- **IEC 60079-10-1:2020**
  Explosive atmospheres - Part 10-1: Classification of areas - Explosive gas atmospheres.
- **DNV Rules and Guidelines – DNV-RP-G105**
  Development and operation of liquefied gas bunkering facilities.

An ISO TC 197 standard covers LH_2 bunkering procedure for airports, but this standard is old and is therefore not very relevant.

While lessons may be drawn from bunkering of LNG, with respect to bunkering of liquefied hydrogen, it is important to recognize that the two have different properties necessitating a different approach to safety-mitigation measures. This is discussed further in Chapter 10.

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[6] Dutch Hydrogen guideline: Installations for delivery of hydrogen to road vehicles, Hazardous Substances Series 35: version 1.0 (April 2015). https://content.publicatiereeksgevaarlijkestoffen.nl/documents/PGS35/PGS%2035%20voor%20website%20ondertekend.pdf

7 ENGINEERING DETAILS FOR HYDROGEN SYSTEMS

This chapter provides a first summary of considerations based on current experience regarding engineering for LH_2 and CH_2 systems on ships. The content will be developed, updated, and supplemented as more experience is gained. The aim is to include more engineering requirements in future revisions.

The ISO document 'ISO TR 15916 Basic considerations for the safety of hydrogen systems' (ISO/TR 15916, 2015) is considered a key reference document.

7.1 Planning and design of LH_2 and CH_2 installations

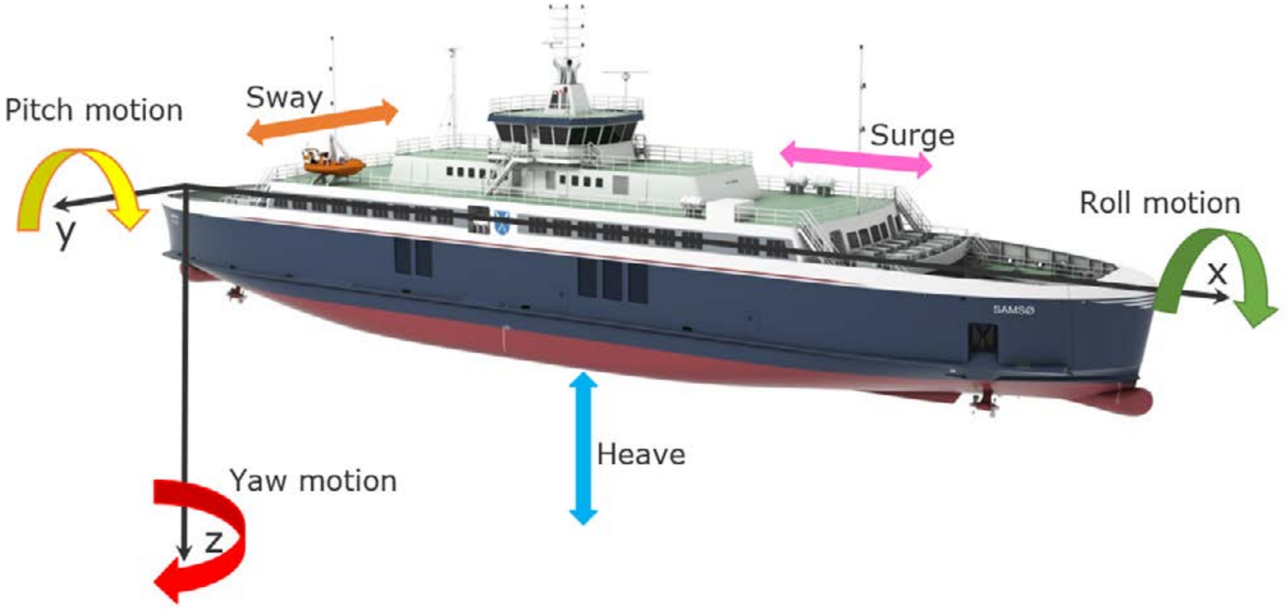
The following lists loads that need to be considered in the planning and design of LH_2 and CH_2 installations.

7.1.1 Pipe load definitions

- **Dead weight** – Sum of weights caused from all pipe items, pipe medium, insulation.
- **Internal and external pressure** – Pressures exposed to the internal and outer sections of pipe items.
- **Sustained loads** – Sum of dead weight, pressure, loads caused by flowing media, other applied loads not caused by temperature or thermal expansion.
- **Thermal expansion / impeded thermal contraction loads** – All loads where thermal operation conditions will have a significant influence on stress levels.
- **Occasional loads** – Loads caused by green sea (may occur due to water on deck) or pressure relief.
- **Live loads** – Loads caused by sag and hog effects of a ship combined with deck deflections and ship's bending moments (see Figure 7.1).
- **Dynamic loads** – Loads caused by vibrations and/or unexpected shock (see also 'Accidental loads').
- **Accidental loads** – Loads caused, for example, by ship collision, ship grounding.

FIGURE 7.1

Illustration of a ship's motions.



7.2 Materials and welding

Materials for liquid and gaseous pipe systems shall be suitable, selected according to specific design conditions and under observation of chemical / physical hydrogen properties, especially Hydrogen Induced Stress Cracking (HISC).

Reference is made to:

- **ISO 15156 Part 1 Part 2 and Part 3**. Materials for use in H_2S containing environments in gas production; and, applicable parts of
- **DNV rules for classification:** Ships (RU-SHIP) DNV-RU-SHIP Pt.2 Ch.1 to Ch.4 Materials & welding.

7.3 Pipe systems for LH_2 and CH_2 service

The applicable regulatory framework is outlined in Chapter 6. The below summarizes relevant maritime codes, technical rules and standards that may be used for reference when developing pipe systems for LH_2 and CH_2 service.

International maritime codes, technical rules and standards for reference

- **IMO Resolution MSC 420(97)**
  Interim recommendations for the carriage of liquefied hydrogen in bulk.
- **IGF Code**
  International Code of Safety for Ships using Gases or other Low-flashpoint Fuels.
- **ISO/TR 15916**
  Basic considerations for the safety of hydrogen systems.
- **EN 13480**
  Metallic industrial piping.
- **ASME B31.3**
  Process Piping.
- **ASME B31.12**
  Hydrogen Piping and Pipelines.
- **EN ISO 5817**
  Welding – Fusion-welded joints in steel, nickel, titanium and their alloys (beam welding excluded) – Quality levels for imperfections.
- **ISO 10675**
  Non-destructive testing of welds – Acceptance levels for radiographic testing.
- **ISO 11666**
  Non-destructive testing of welds – Ultrasonic testing – Acceptance levels.
- **EN 1779**
  Non-destructive testing – Leak testing – Criteria for method and technique selection
- **EN 13184**
  Non-destructive testing – Leak testing – Pressure change method
- **EN ISO 20485**
  Non-destructive testing – Leak testing – Tracer gas method

Applicable parts of DNV rules for classification: Ships (RU-SHIP):

- **DNV-RU-SHIP Pt.2 Ch.1 to Ch.4**
  Materials and welding.
- **DNV-RU-SHIP Pt.5 Ch.7**
  Liquefied gas tankers.
- **DNV-RU-SHIP Pt.4 Ch.6**
  Piping systems.
- **DNV-RU-SHIP Pt.4 Ch.7**
  Pressure equipment.
- **DNV-RP-D101**
  Structural analysis of piping systems (DNV, 2017a).

7.3.1.1 General design principles for LH_2 and CH_2 pipe systems

Observation of design loads is an essential requirement for both LH_2 and CH_2 pipe design and subsequent fabrication. For planning and layout of pipe systems for LH_2 and CH_2 service, the requirements provided by the IGF Code provide a starting point for a more specific hydrogen evaluation. The chemical and physical properties of hydrogen need to be observed regarding design and construction.

Planning and design of all pipe systems need to be carried out so that any damages caused by ship operation and green sea loads are avoided.

Piping and Instrumentation Diagram (P & ID)

The basic design document for liquid and gaseous hydrogen fuel and process systems is the piping and instrumentation diagram (P&ID). The P&ID shall include all components – e.g., pressure vessels, pumps, valves – connected with piping systems, as well as instrumentation for automation and control.

The P&ID shall specify all pipe sections with the design pressure, temperature, and type of operating medium. Installed components such as valves shall be specified with an individual TAG Number.

Pipe stress analysis

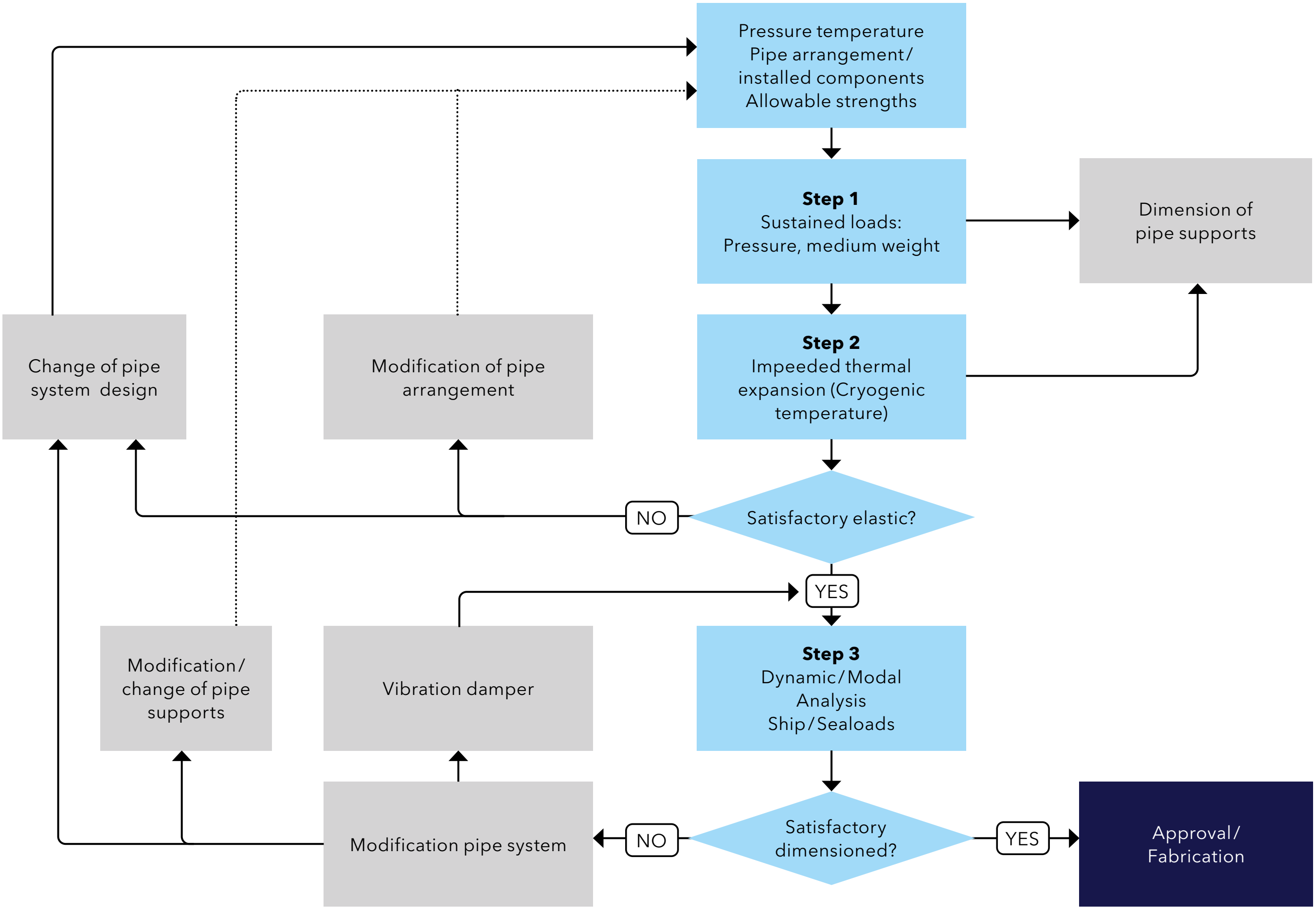
DNV Recommended Practice on structural analysis of piping-systems (DNV, 2017a) may be observed for additional guidance regarding stress evaluation and flexibility analysis.

Pipe systems subjected to LH_2 or CH_2 service conditions need to be evaluated on relevant stresses and flexibilities under observation of all loads including thermal expansion and (impeded) cryogenic contraction as defined in Chapter 7.1.1.

Double-walled pipe systems need to be evaluated with a pipe stress analysis under observation of inner and outer pipe expansions and fixed pipe supports arranged between inner and outer pipe. The principle of a pipe stress analysis is introduced in Figure 7.2.

FIGURE 7.2

Principle of the pipe stress analysis approach.



The pipe stress analysis needs to be carried out under observation of all components installed in the specific pipe system. Pipe supports designed either as fixed or sliding supports including defined degrees of freedom shall be included according to the respective pipe isometric (see Figure 7.3).

As Chapter 6.2 describes in detail, the hydrogen fuel systems intended for installation onboard ships need to be evaluated with a risk-based process that includes hazard identification (Section 8.2.1.1) and is followed by a risk-assessment process (Chapter 8).

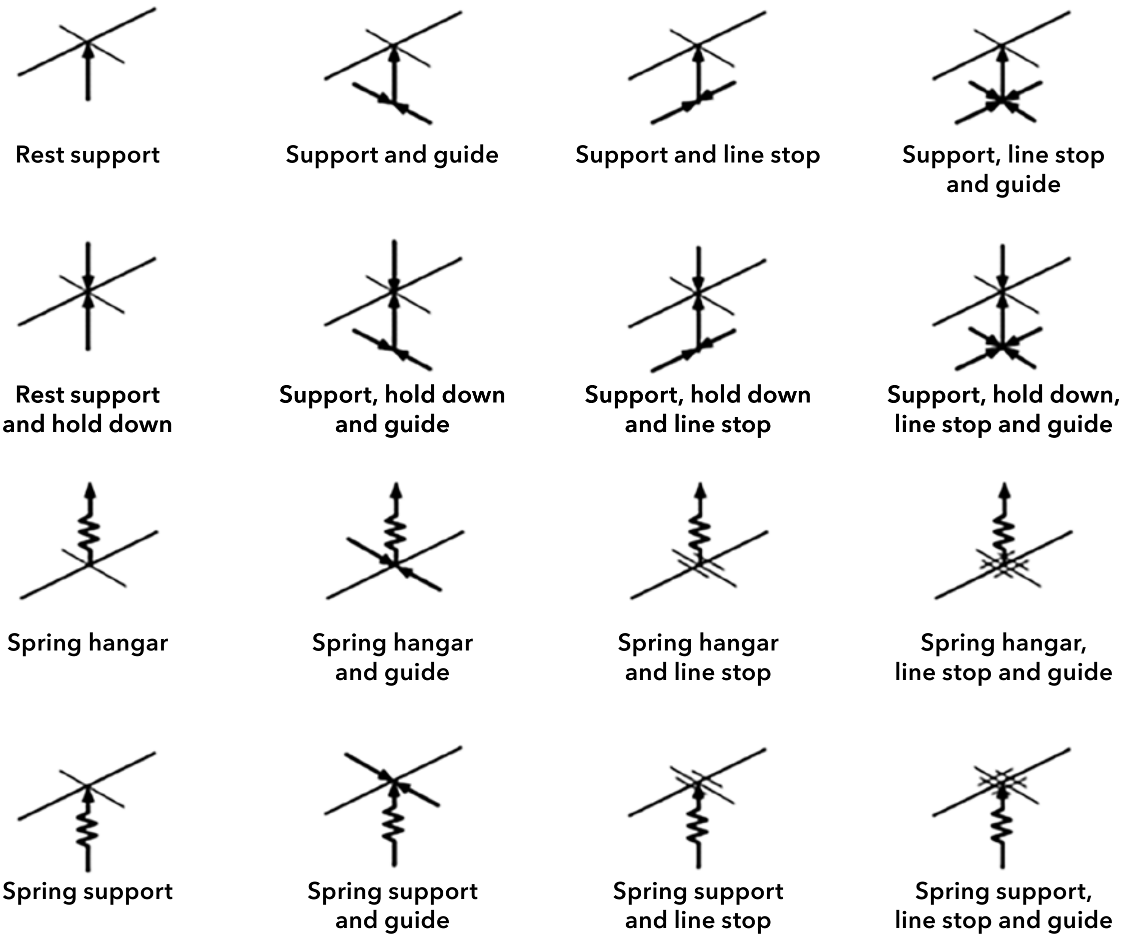
7.3.2 Pipe fabrication and welding

DNV Rules Part 2 Chapter 1 to Chapter 4 – Materials and welding and international recognized standards covered by DNV Rules may be observed for welding and fabrication of pipe systems for hydrogen service. Specific requirements for welding, post welded heat treatment, and non-destructive testing (NDT) provided by the IGF Code, may be used as a starting point for more specific hydrogen evaluation.

It is recommended that all inspections and tests are covered by an approved Inspection and Test Plan (ITP) covering applicable test standards. Additional quality control of components for complete hydrogen pipe fabrication may be covered by a separate Quality Control Plan (QCP).

FIGURE 7.3

Pipe support types (DNV, 2017a).



7.3.2.1 Pre-fabrication preparations

Fabrication of complete welded pipe systems requires a subdivision of the pipe isometric into pipe spools prior to fabrication. The subdivision into pipe spools depends on the installation conditions on the ship and the layout of the specific pipe system to be installed. The subdivision of the pipe isometric needs to be carried out with regard to pipe spool welding conditions on the ship and pipe welds necessary for preparation in onshore welding facilities.

7.3.3 Pipe components

Control and shut-off valves as well as Pressure Relief Valves (PRV) may be regarded as two of the most safety-related components to be installed in pipe systems for hydrogen service and process control. Such components may also be installed in other parts of the onboard LH_2, CH_2 and H_2 system, for example in relation to hydrogen-storage systems. The following sections provide input and recommendations for these components.

7.3.3.1 International standards and DNV Rules for reference

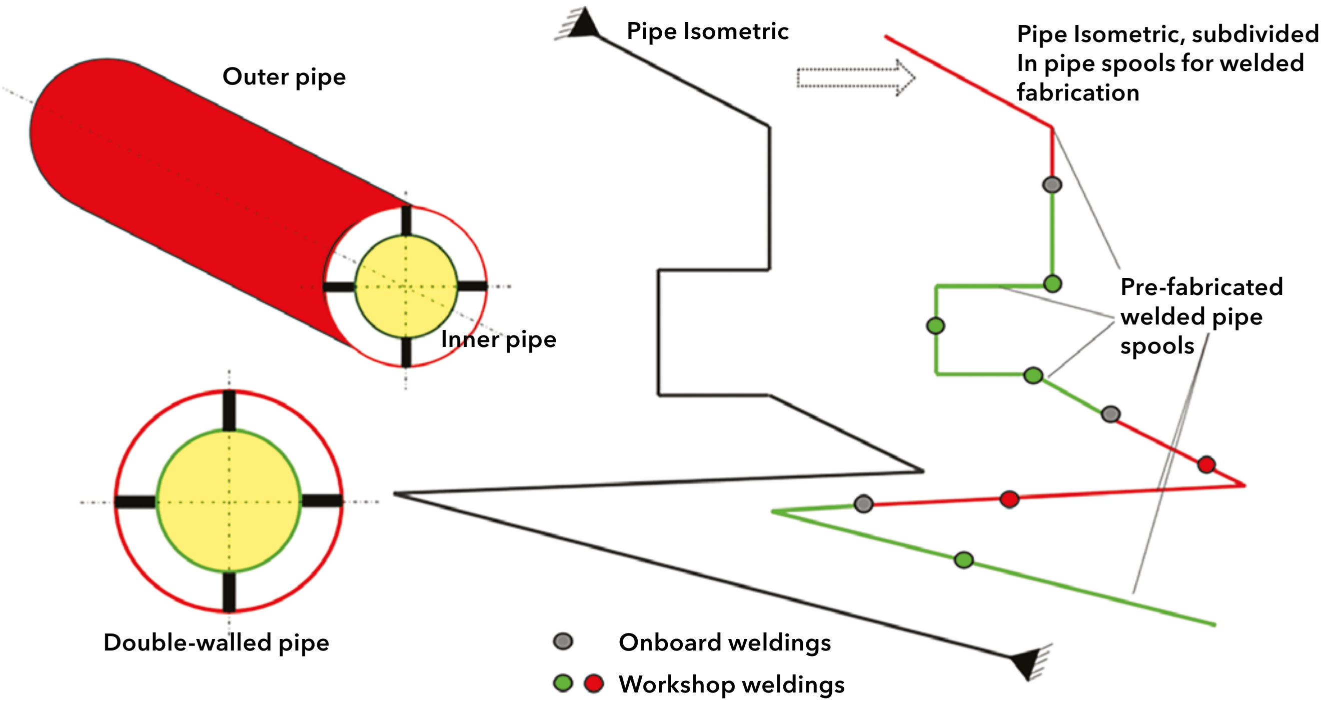
The following lists relevant international standards and DNV rules that may be used for reference. These are additional to standards for pipe systems mentioned above.

Standards and DNV Rules for all valve types

- **EN 12516-1/-2/-3/-4**
  Industrial valves:
  Part 1- Shell design strength
  Part 2- Calculation method for steel valve shells
  Part 3- Experimental method
  Part 4- Calculation method for valve shells manufactured in metallic materials other than steel
- **EN 13445**
  Unfired pressure vessels.
- **ASME B 16.34**
  Valves Flanged, Threaded, and Welding End.
- **DNV-CP-0186**
  Class programme DNV-CP-0186, Valves.

FIGURE 7.4

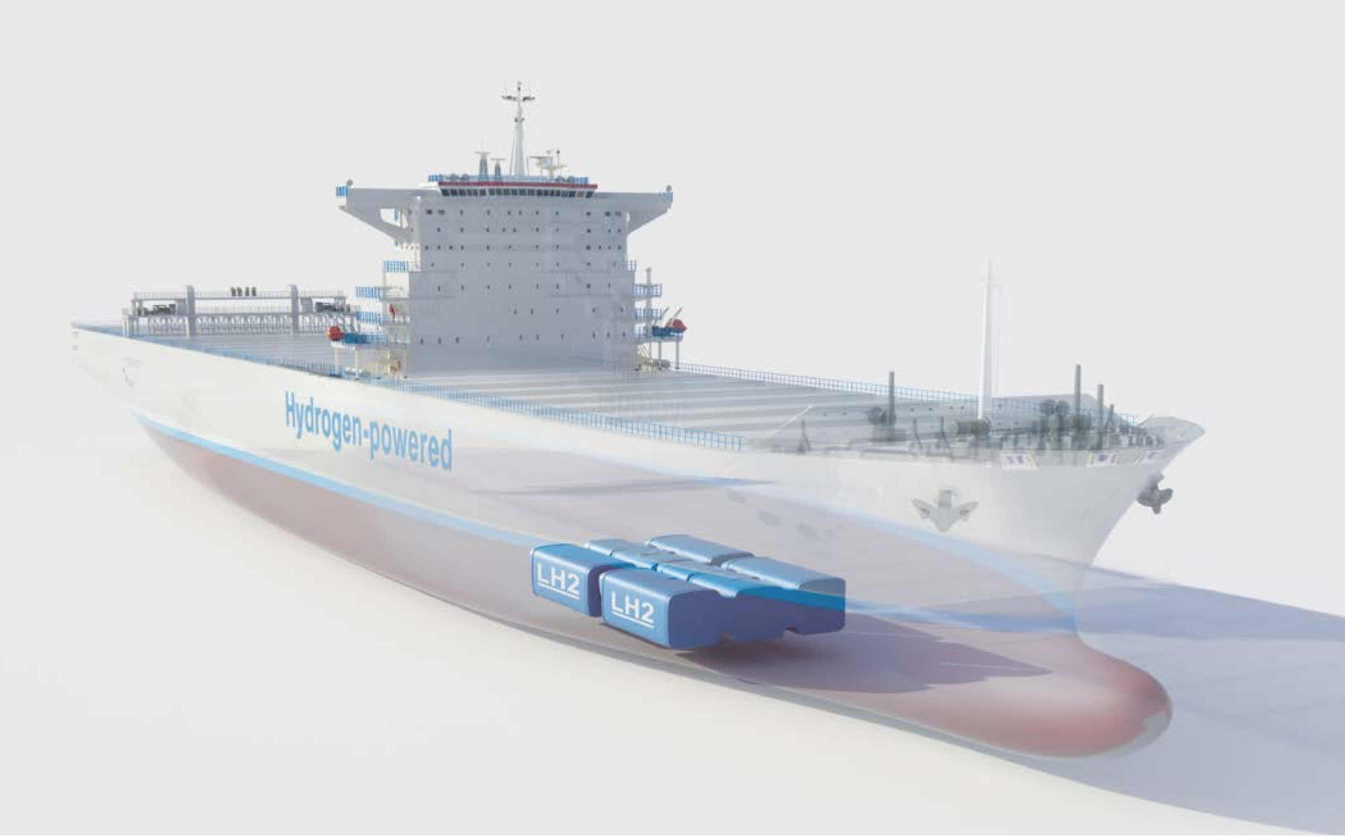
Welded pipe fabrication – subdivision into pipe spools.



International standards and DNV Rules for Pressure Relief Valves (PRV)

The following standards and rules are generally applicable for pressure relief valve applications:

- **EN ISO 21028-1**
  Cryogenic vessels – Toughness requirements for materials at cryogenic temperatures – Part 1: Temperatures below -80 °C
- **ISO 4126**
  Safety devices for protection against excessive pressure –
  Part 1: Safety valves
  Part 4: Pilot operated safety valves
- **EN 13648-1**
  Cryogenic vessels – Safety devices for protection against excessive pressure – Part 1: Safety valves for cryogenic service.
- **ISO 11114-1. Gas cylinders**
  Compatibility of cylinder and valve materials with gas contents – Part1: Metallic materials.
- **ISO 11114-2. Gas cylinders**
  Compatibility of cylinder and valve materials with gas contents – Part2: Non-metallic materials.
- **ISO 21013-1. Cryogenic vessels**
  Pressure relief accessories for cryogenic service – Part 1: Re-closable pressure relief valves.
- **ISO 21013-3. Cryogenic vessels**
  Pressure relief accessories for cryogenic service – Part 3: Sizing and capacity determination.
- **ASME VIII-1, Div.1**
  ASME Boiler and Pressure Vessel Code.
- **ASME B 16.34**
  Valves Flanged, Threaded and Welding End.
- **API 520**
  Sizing, Selection and Installation of Pressure-relieving Devices.



PART C
HYDROGEN SAFETY IN MARITIME CONTEXT

Part C of the Handbook describes recommended qualitative and quantitative risk-assessment methodologies applicable to maritime use of hydrogen, and the competence requirements for performing such assessments. More detailed descriptions of the approach and models used when performing quantitative risk analyses are also provided in Appendix C.

8 RISK ASSESSMENT

The main purpose of the risk assessment is to generate safe and robust designs and systems. When the risk assessment is undertaken as a part of the design process together with architects and process/system designers then safe, robust, and efficient systems can be obtained.

Ultimately, when the design has reached an optimal, constructible stage, then the documentation from the risk assessment can be used to get approval. Many different existing methodologies can be employed to assess risk in a structured manner. They can be divided into two main groups, qualitative and quantitative risk assessments. These two methodologies are often combined, with the assessment starting with the qualitative approach, and the quantitative approach being used on the most critical, risk-driving effects.

Risk assessments contain all types of assessments and methods that are risk-based and consider the safety risk of an installation. The risk assessment methods described in this Handbook includes HAZID, Technology Qualification (TQ), Quantitative Risk Analysis (QRA), and Explosion Risk Analysis (ERA). The QRA obtains the total risk including contributions from fires, explosions, collisions, grounding and falling loads that are caused directly or indirectly by the hydrogen system. This includes external events that become worse due to the hydrogen system. The ERA is integrated with the QRA by using the same basis for leak frequency and events. Due to the potential high explosion risk for hydrogen, the ERA is performed as a separate analysis considering ventilation, dispersion, and explosion consequences, often with the use of computational fluid dynamics (CFD) models. The results from the ERA are applied as input to the QRA when the total risk is calculated. As a part of these analyses, various other methods are used to assess consequences and frequencies.

Risk assessments consist of two main parts that need to be evaluated: namely frequencies (how often) and consequences (how serious). The combination of these gives the final risk. Both these parts are considered in the present chapter.

Applied methodologies and models are described, with emphasis on application areas and level of resolution and accuracy of the models. The most favourable way of controlling and reducing the risk is to prevent the unwanted events from happening. Possible risk-control measures are therefore presented and discussed separately in Chapter 9.

It is a central success criterion to have adequate competence available in the project team undertaking the risk analyses required. It is recommended that the project includes resources with competence regarding hydrogen safety and applicable hydrogen rules.

The project needs to have competence available to evaluate the relevant hydrogen technologies and their maturity, expected performance, and durability – i.e., the strengths and weaknesses. It is important to understand how the properties of hydrogen (gas, liquid, compressed gas as applicable) can affect safety and performance. If the team does not include specific safety modelling competence (leak, ignition, fire and explosion), it is recommended to establish a dialogue with such competence at an early stage.

It will be an advantage for the team to possess previous experience from marinization of equipment and systems that have not previously been used in the maritime industry.

8.1 Compliance-based versus risk-based approach

One of the main benefits from performing a quantitative risk assessment is to quantify the effect of different design solutions and safety systems and, in this way, to compare risks and use the comparison actively to decide how the safety can be improved to an acceptable level. The final solutions can then further be documented and used to obtain final approval when following the Alternative Design process.

A set of risk assessments for different ships and hydrogen systems, and experience from early vessel designs and prototypes, can be used, leading to robust hydrogen-fuelled ships. When robust systems and designs are established in the industry, it is time to establish Class rules and regulations. When the rules and regulations are in place to ensure safe constructions and operations, then a compliance-based regime can be developed.

However, in the meantime, and before good designs and rules are available, the innovative process involving risk assessments, yards, designers' architectural drawings, and safety systems design, can be used to find safety and cost optimal solutions that provide equivalent or better safety at affordable cost.

Figure 8.1 shows a roadmap to a normalized compliance-based maritime hydrogen regime. A combination of experience from maritime and other industries together with testing and a large set of modelling can be used to find optimal solutions before prototypes are built and operated. More general standards can finally be developed by using experience from prototype operations together with a mapping of key design parameters that can be put in a standard so that when these are followed, it is safe. Key design parameters can be arrangement designs, ventilation rates, segment sizes, and requirements for pipe-in-pipe solutions, inerting, etc. Digital risk models are available that can be used to investigate effects of such parameters. The approaches used to run such models are described in this chapter.

FIGURE 8.1

Safety roadmap where the fastest road goes through a digital and risk-based approach in the first three steps.

HAZID/TQ

HAZID with owners, contractors and safety consultants.
Develop a best solution and specify options that need to be investigated

→

Modeling and testing

Develop and run risk model with large number of options modeled in detail. Run experiments to test in full scale where models are uncertain

→

Select optimal solution

Quantified risks of all options is compared on same level using the same risk parameter. Costs of options is obtained from contractors. Overall cost and safety optimal solution is selected

→

Use model to develop standards

Generalize model to be valid for a range of application types that can be used by different operators. Run model for a set of normal parameters. Make a map of key parameters to be standardized

✓

These three steps can be used for each new/converted hydrogen-fuelled ship where the risk is quantified through a QRA and compared with conventional ship risks to achieve approval in an iterative process. The last step can be undertaken when the technology is mature enough and enough experience is gained from earlier projects and QRAs so that safe and robust standards can be developed.

8.2 Risk assessment approaches

Figure 8.2 shows the typical flow in a risk-based development process, typically starting with qualitative hazard identification and assessments (HAZID or TQ process), moving forward with quantitative analysis (QRA) and, based on this, selecting where more detailed explosion and/or fire risk analysis is needed.

A risk register as defined in Chapter 6.2.1.2 with a list of scenarios is first developed in the HAZID. The HAZID is qualitative and based on the experience among the participants. The hazards are identified and the needed safety barriers are evaluated during and after the HAZID and then applied as input to the QRA. In the QRA, event frequencies and consequences are quantified and, based on this, the total risk due to the hydrogen system is calculated. The HAZID and the QRA should also include external events that can cause escalation to hydrogen systems. These can be collisions, external fires, grounding or falling objects. A QRA examines leaks from the hydrogen system that may lead to accidental events like explosions and fires. Usually a QRA assesses possible impacts on both the ship integrity and people on board. Due to the explosion risk associated with hydrogen, an explosion risk analysis (ERA) will also be necessary. The ERA is integrated with the QRA, using the same leak frequencies, layout details, equipment/process piping data, and equipment segmentation as input. Results from the ERA are used to calculate the contribution from explosions to the total risk in the QRA. Ventilation, gas dispersion and explosion models in the ERA are detailed enough (usually with CFD) to take into account geometry effects and mitigating measures such as ventilation rates. The ERA can also be used to decide necessary explosion loads on the decks and walls to the hydrogen installation so that an explosion event does not escalate to the rest of the ship.

The QRA should also apply qualitative fire models to account for fire risks from the hydrogen systems. The fire consequences from hydrogen systems are normally similar to fire consequences for natural gas; therefore, the use of typical fire models is assessed to be sufficient. The leak and fire modelling still need to apply fluid and flow parameters that are specific for hydrogen (e.g., see Section 8.5).

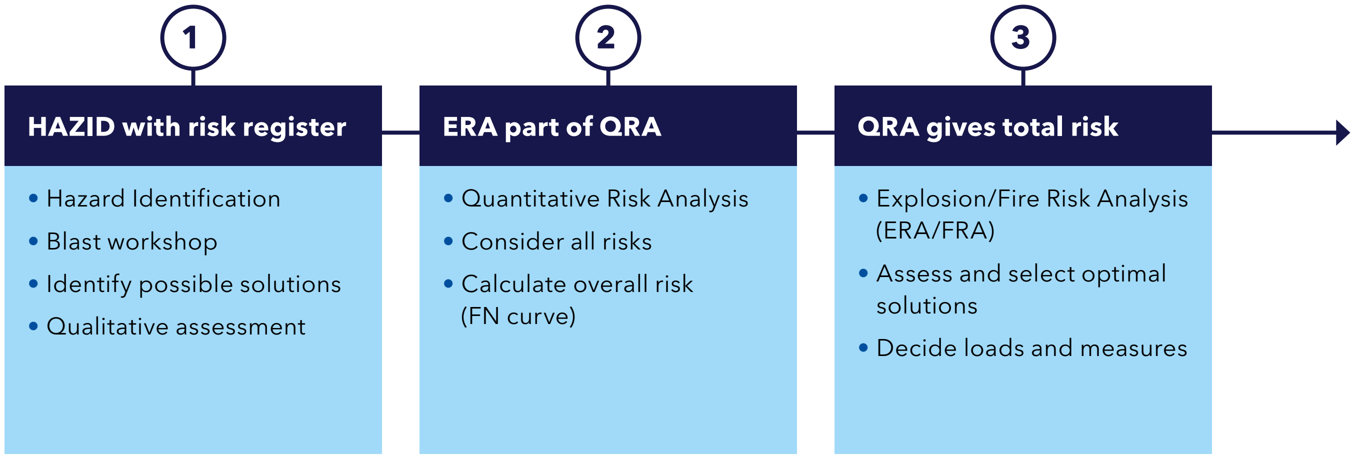
When the QRA and ERA are completed, they are used to calculate the total risk due to the hydrogen system. The total risk is then compared with the risk of a conventional vessel (see Chapter 6.3). If the total risk is found to be higher than on the conventional vessel, measures to reduce the risk can be suggested and implemented. Then the QRA and ERA need to be updated until an acceptable solution is obtained.

The risk register, the QRA, and the ERA can be considered a part of the risk-based design process where the risks are first identified and ranked qualitatively in the HAZID, then more detailed QRA and ERAs are performed to more accurately calculate the high-risk scenarios. When the risks are quantified, they can also be added so that the total risk is found. The total risk can then be aligned with a similar vessel to show equivalence (see Chapter 6.3).

It is recommended that the HAZID, QRA and ERA are performed by an independent, competent, company so that objective assessments can be performed.

FIGURE 8.2

A risk-based approach starts with coarse HAZID (in the preliminary approval phase) and uses more detailed QRA and ERA and FRA when specific high-risk elements are identified.



With a proper ERA, it is possible to model the effects of mitigating measures introduced in Chapter 8.3.3 and to rank them against a common risk parameter. This way, the safest and most cost-effective measure can be found. Such a modelling approach which employs CFD tools is advisable and can be used to investigate a large range of designs and measures at a relatively low cost compared with building prototypes and physically testing the systems. Methods, effects, and approaches that need to be followed in a detailed ERA are described in the following sections including Chapter 9 and Appendix C.

8.2.1 Qualitative risk assessment and HAZID

HAZID is a structured brainstorming with the purpose of identifying all relevant hazards, their consequences, and mitigating measures already included in the planned design. An outcome of the HAZID is a first evaluation of overall risk level and a basis for evaluating the need for further mitigating measures. It is recommended that the HAZID provides a risk register to inform the quantitative risk assessment (QRA) scope.

Another common form of qualitative assessment is the failure mode effect and criticality study (FMECA) where root causes are assessed in detail with cascading failure modes. For FMECA studies, it is important to clearly document the consequences and evolution of the failure modes (e.g., 'valve fail open') studied, while a HAZID study will collect several possible root causes and consequences under for a given hazardous event.

Further information and other qualitative methodologies such as FMECAs, HAZOPs, fault tree analysis, or structured 'what-if?' checklists, can be explored in DNV's recommended practice for Technology Qualification (DNV Oil & Gas, 2019).

Different methodologies could be used for maritime hydrogen fuel applications, and the usefulness of the methodology chosen will partly depend upon availability of details regarding design and the knowledge and experience of the assessment team. In this Handbook, HAZID has been employed to assess two generic ship cases corresponding to the recommended preliminary approval phase as illustrated in Figure 6.3. Specific projects might necessitate the use of other methods, to the satisfaction of the Administration (typically the Flag State, or Recognized Organization acting on behalf of the Flag State).

8.2.1.1 HAZID planning

The HAZID provides a unique meeting place for designers, engineers, operational and safety personnel, and the Administration. It is recommended (MSC.1/Circ 1455, 2013) to include the Administration in the HAZID, as this is considered to have positive effect on the whole approval process. The benefits of including Administration representatives include:

- The Administration will be able to point to issues relevant for approval that may be discussed.
- The Administration may have expertise within certain areas of the design under consideration and may therefore contribute by drawing attention to issues that may unintentionally have been left out of discussions.
- The amount of questions and misunderstandings will be reduced during the review of the HAZID and in the overall approval process.
- When running the HAZID, it is advised to structure the brainstorming in sub-sessions, and to ensure that all different main system components are properly addressed and included. The hydrogen system components should include associated hydrogen piping and valves, venting pipes, and vent mast.

HAZID is an important part of the process to obtain preliminary approval, and to minimize the risk of unknown hazards being identified only at a later stage in the approval process. It is essential to ensure that the HAZID team and competence is adequate (ref. Section 8.2.1.3). Key requirements for the HAZID are also outlined in Chapter 4.8 in MSC.1/Circ. 1455.

Further input on safety assessment and hazard identification principles are outlined in Appendix B of DNV-OS-A101 (DNV Oil & Gas, 2019).

The HAZID results should be documented in a HAZID report and the actions recorded in the risk register. The HAZID report should be submitted to the Administration (Flag State). As shown in Chapter 6.2.1, it is recommended that the preliminary design phase include a concept QRA; the HAZID results will provide input to this analysis.

8.2.1.2 HAZID scope

The main concern relating to the introduction of hydrogen as a ship fuel is loss of containment of hydrogen causing a leak affecting some area on the ship. There are many possible causes for such events, and in most cases, there will be several 'stages'. This means, for example, that a failure may develop over some time before an actual hydrogen leak occurs. Hence, a different 'chain of events' may eventually be the cause of a leak of hydrogen.

A root cause analysis can be used to identify the 'starting point' in the various chains of events that may eventually lead to a leakage of hydrogen. Possible root causes include, among others, material-related failures such as hydrogen embrittlement; fabrication and manufacturing failures; various possible human errors during operation and/or maintenance; design not fully considering the marine environment; sloshing and 2-phase issues related to cryogenic hydrogen storage and its components; and, insufficient design parameters. Security-related risks should also be identified and addressed.

Which parameters are applicable and to what degree may vary greatly between projects based on their maturity, their objective, planned operation, and on the specific components and systems selected.

The following input indicates what typically needs to be considered. Reference is also made to safety related properties presented in Chapter 4.1 and the generic hydrogen system configurations presented in Chapter 4.2:

- Hydrogen storage system
  - CH_2 and/or LH_2 storage tank(s) and additional storage system equipment as pipes and valves directly mounted on the hydrogen storage tank(s).
  - LH_2 processing system comprising vaporizers with additional heating systems.
- Hydrogen FC installation.
- Hydrogen bunkering volumes, bunkering frequency and how the hydrogen will be supplied to the ship.
- All hydrogen system components including probable leak points for single and double wall piping , valves, venting pipes, and vent mast.
- Consider aspects such as component mechanical or material failure – e.g., hydrogen embrittlement, corrosion, material compatibility issues, human error, faulty operation (e.g., causing out of specification temperature(s) or pressure(s)).
- Overall ship aspects related to layout, system interfaces including interfaces between the hydrogen system(s) and the ship's hull structure.
- External impacts, typically collision, grounding or falling objects.
- Related electrical systems.

8.2.1.3 HAZID team and competence requirements

The role of the HAZID facilitator is particularly important. As part of the facilitation, the HAZID facilitator needs to ensure that the HAZID is organized and run in such a way that all the available competence is brought to the table during the HAZID. The project (Submitter) may be asked to supply details to the Administration regarding the knowledge and experience of their project team members and other participants.

The IMO Alternative Design guideline (MSC.1/Circ 1455, 2013) points out that the Administration may consider whether the composition of the HAZID team ensures that all relevant areas of expertise are represented and heard in the process when reviewing the HAZID report. The Administration reserves the right to request further participants if certain areas have not been adequately covered.

The following outlines the minimum competence requirements to be included in the HAZID team and in the HAZID workshops to ensure that the results are credible and that possible showstoppers are identified:

- HAZID facilitator
- Hydrogen safety expertise covering hydrogen safety properties, leaks, fires and explosions; simulation tools for hydrogen leaks, fires and explosion
- Specialists in 3D CFD simulation tools for hydrogen systems and safety
- Equipment suppliers, in particular suppliers of FC system, hydrogen storage system, and bunkering system
- Ship and system designers
- Shipowner
- Hydrogen supplier (bunkering provider)
- The Administration (Flag State)
- Class Society, and
- If selected at the time of the HAZID, the shipyard and the system integrator should also participate.

8.2.2 Quantitative risk assessments

When the relevant failure modes and hazards are identified and agreed upon, it will at the current stage of development be necessary to quantify the risk in greater detail. This is performed with quantitative risk assessment methods.

A typical quantitative assessment method is the Quantitative Risk Analysis (QRA) which will provide a numerical value to the overall risk considering all hazards. The QRA will rely on many sources and models for the underlying failure modes, such as leakage frequencies, ignition probabilities, inventory and leak rate, ventilation and dispersion effects, explosion and fire consequence, and structure response.

Since gas explosions can be a critical driver for the overall risk, a separate explosion risk analysis (ERA) is described with more detail than the other risk elements (see Figure 8.3).

The chain of events can be manipulated, and risk can actively be reduced with appropriate safety systems and robust, good overall design. Elements that can be considered to find a safe solution can be modelled as sensitivities during the risk analysis. These are considered in the present chapter.

8.2.3 Explosion risk analysis (ERA)

The ERA is used to quantify and consider the risk of explosions on a detailed level. It is common to perform ERA for offshore oil and gas production platforms due to the high explosion risk and the cost-driving effects of explosions. The DNV class notation for battery powered ships also requires an ERA due to the possibilities of thermal runaway and gas explosions in Lithium-ion battery rooms.

8.2.3.1 Background to ERA

ERA became common for offshore production platforms in the aftermath of the Piper Alpha accident in 1988. During subsequent experimental programmes (Selby, 1998) it was discovered that explosions could generate pressures that were almost one order of magnitude higher than models predicted. Due to the possibilities of high explosion pressures, it was found that platforms could not be designed using a worst-case or deterministic approach. Schemes such as ALARP (as low as reasonably practicable) and probabilistic approaches to find the explosion risk were introduced into the oil and gas industry. This way, one could use a systematic approach to assess protection measures to ensure all reasonably practicable risk-reduction measures are implemented. The procedure that was developed in Norway (NORSOK-Z-013-AnnexG, 2010) is used as basis when describing the ERA and consequence analyses in the present and previous sections.

Due to its high burning velocity and low ignition energy, the explosion risk can be high for hydrogen applications, and this can be critical for maritime hydrogen applications. It is therefore recommended to apply an ERA approach with elements adopted from the oil and gas industry and applied for a maritime setting.

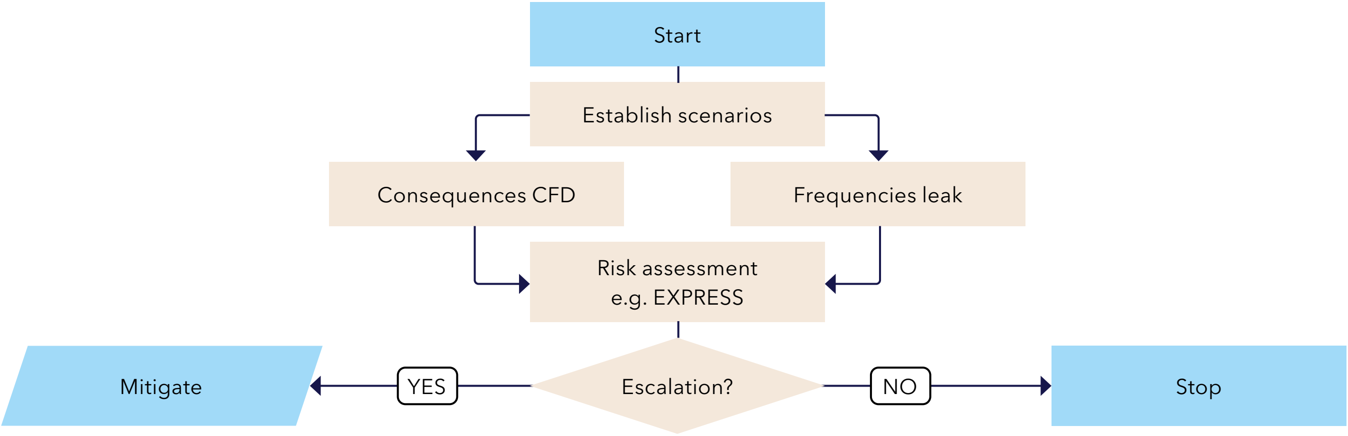
A possible way of reaching a tolerable risk level for hydrogen as ship fuel is to implement efficient measures to prevent explosions above a certain threshold size and to protect against explosions below that size. To demonstrate that the explosion risk is acceptable, an ERA can be undertaken. In the analysis it is necessary to include the effects of the measures to protect against explosions.

8.2.3.2 Brief methodology description

An advanced quantitative explosion risk assessment methodology includes a systematic and complete assessment of both the frequencies and the consequences of the events that can lead to an explosion. A flow diagram for such an analysis is shown in Figure 8.3. The frequencies are obtained for leaks from piping and equipment, and the ignition probability is obtained from transient

FIGURE 8.3

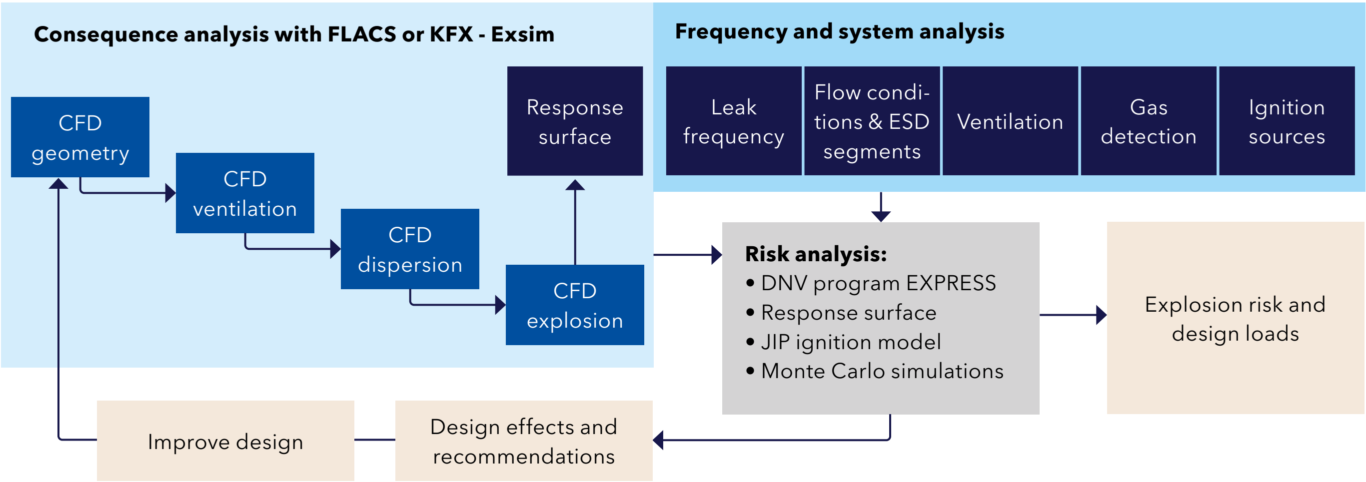
Flow diagram of the main elements for quantitative risk analysis or explosion risk analysis.



CFD - Computational Fluid Dynamics, **EXPRESS** - DNV tool

FIGURE 8.4

Flow diagram for applying the EXPRESS explosion risk analysis approach.



models considering the build-up of the hydrogen cloud. The consequence assessment follows the chain of events from inventory assessment, emergency shutdown (ESD) segregation, leak size and duration, ventilation, gas dispersion, detection, ignition and explosion, and further on to structure loading and response.

ERA is a formal risk analysis which is performed to document risk and the results may be measured against frequency risk acceptance criteria for similar vessels to show equivalence. Results may also be used to demonstrate compliance with the functional requirements in the IGF Code (see Appendix B); and if available, the frequency may also be measured against acceptance frequencies for the maritime application/usage considered. This method is regularly used in the oil and gas industry when assessing explosion risk on gas processing facilities. See the acceptance criteria described in Section 6.3.1.4.

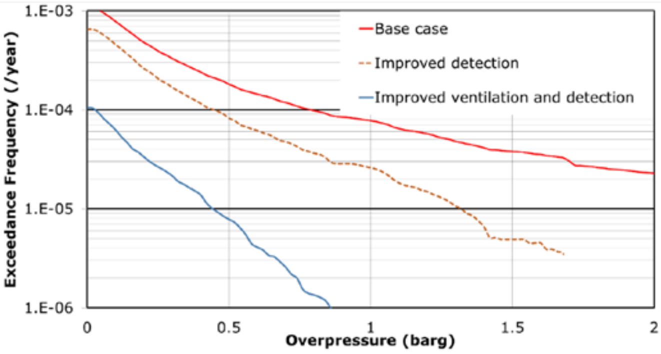
The primary use of the method is to assess the risk-reduction effect of relevant measures such as ventilation or gas detection, and to use it to optimize cost-efficient solutions which also have acceptable safety.

DNV’s program EXPRESS (Huser, Foyn, & Skottene, 2009) (Huser, Eknes, Foyn, Selmer-Olsen, & Thevik, 2000) (Huser & Kvernvold, 2000) (Huser, Foyn , Rasmussen, & Tveit, 2001) can be used to calculate the risk with a MonteCarlo approach for any gases including hydrogen. The MonteCarlo approach is applied because each scenario is modelled as transient, and a large number of scenarios with different parameter combinations are simulated. With this approach, it is run until convergence and the total number of scenarios is this way reduced making it an efficient approach.

The analysis can be performed with detailed CFD models or simplified predefined models for gas dispersion, ventilation, explosion and load response combined with a detailed modelling of leak frequency and ignition probability. The principles for the modelling applied is described in Appendix C. It is primarily gas leaks that are considered top events, and the process segmentation and conditions are used to specify gas leak versus time as a starting point for the scenarios. The preventive and mitigating measures as described in Chapter 9 are, or can be, included in the tool. This way the risks can be compared between the different measures, and decision support can be made to select the needed and most efficient protective and mitigating measures. An example of the final results from the tool is shown in Figure 8.5 quantifying, for example, how improving the ventilation can reduce the frequency by an order of magnitude.

FIGURE 8.5

Result from explosion risk analysis in terms of Exceedance Frequency as a function of overpressure.



Curves show accumulated frequency for exceeding the pressures. For the Base-case curve, it can be seen that the overpressure with a frequency of 10-4 per year is approximately 0.8 barg. With an improved gas detection scheme, the same frequency gives a pressure of 0.45 barg, and when both gas detection and ventilation is improved, the pressure is reduced to 0.05 barg.

8.3 Risk-based design in a maritime setting

When applying hydrogen to a maritime setting it can be necessary to employ additional safety measures compared with maritime systems with hydrocarbon gas or non-maritime hydrogen systems. This is primarily due to the more extreme explosion potential and high ignition probability of hydrogen combined with the tight quarters and restricted evacuation possibilities onboard a ship.

8.3.1 Risk comparison hydrogen versus natural gas

When assessing the general explosion risk considering the properties of hydrogen compared with natural gas, it is often argued that the risk is higher for hydrogen than for methane or natural gas. (see Chapter 4.1). Natural gas is here used in the comparison, and a similar comparison is valid for gases evaporating from conventional marine fuels.

For such a comparison, one can consider a general gas fuel system with tank(s), gas processing, piping and an engine/FC where the gas is consumed. At this point, the effects of compressed or liquefied gases, or gas on deck or below deck, are not introduced. Hence, the comparison applies generally.

Due to lack of hydrogen-specific leak frequency data, it is common to use a similar leak frequency for hydrogen and natural gas (Hyapproval), see Appendix C.

When gas leaks from a high-pressure system, the release will be sonic and the speed of sound and the density are gas properties that causes different behaviour considering otherwise equal pipe pressures and hole sizes. Since hydrogen has four times higher speed-of-sound and eight times lower density hydrogen causes a volumetric release rate approximately three times larger, but a lower mass release rate (see Figure C.2). Due to the larger volume of hydrogen, the cloud volume will be larger when considering total gas volume at concentrations above flammable concentration.

Consider a leak inside a confined area where a plume is formed by a high-speed, partly-impinged jet zone, and a passive cloud is dispersing within the area before it is thinned out. Since the flammability range of hydrogen is much larger, hydrogen will also have the possibility to form a larger flammable cloud as long as the gas concentrations are above lean concentrations (above 5–10%) and it is not igniting early. For such relatively large leaks, natural gas will form a rich gas which is impossible to ignite. For smaller leaks, hydrogen will not reach a flammable concentration, hence hydrogen systems do not have higher risk if the amount of gas leaking is small enough, under a certain limit (which depends on the ventilation rate in the area). Moreover, the larger cloud sizes can expose more ignition sources with hydrogen, and hydrogen can ignite with a weaker ignition source (as little as static electricity in the hair can cause an ignition). Therefore, the risk of an ignited cloud can be significantly larger for hydrogen considering otherwise equal conditions.

In addition to a potentially larger ignitable gas cloud, when a gas cloud with a high concentration of hydrogen ignites, it can create maximum explosion pressures that are 5–10 times higher than for natural gas (Royle, 2007) in an outdoor explosion in a congested region. The higher flame velocity of hydrogen causes it to reach higher pressures with a smaller gas cloud than for natural gas. For hydrogen, it is further possible to obtain Deflagration to Detonation Transition (DDT) with a relatively small cloud or within a small room, whereas methane/natural gas does not detonate in real conditions. The hydrogen explosions occur more rapidly, and yielding walls with some inertia have no or very little time to open and relieve the pressure before it is too late, causing the peak pressure to happen even with conventional explosion release panels. Purpose-built light and fast-acting explosion panels would be a required to provide explosion relief for hydrogen explosions.

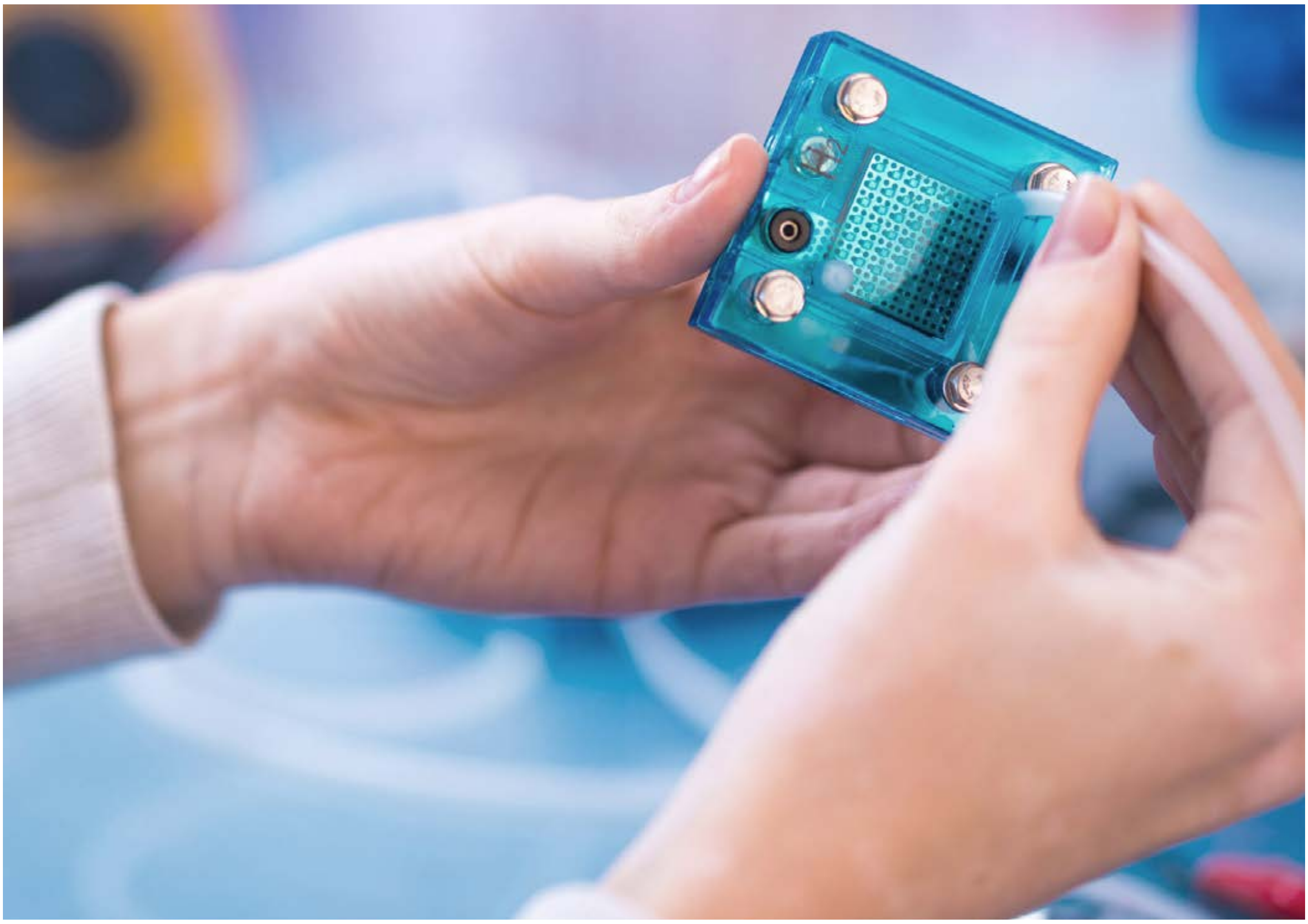
The increased potential for DDT causes higher risk of an extreme catastrophic event due to hydrogen. This can be considered more critical for maritime applications, and its occurrence should therefore be avoided. The characteristics of a detonation can cause the risk to increase even more in an open area if the flammable cloud extends outside a congested region. This is because when a detonation has started in a congested region, it can also sustain itself outside that region. If a large gas cloud fills first a congested region, and then continues outside this region, a DDT can happen in the gas within the congested region, reaching up to 10–20 barg. Such a detonation can continue in the unburnt gas outside the congested space with an ongoing detonation until the end of the cloud is reached. Examples of this phenomenon can be seen in the Buncefield incident (Johnson, 2020) which ruined cars and buildings in a large region due to a gasoline vapour gas cloud that developed over a large area during calm wind conditions at night. Experimental evidence indicates that if a detonation did not occur, the explosion pressure would drop when it entered an open area, resulting in less damage. Methane would develop lower pressures in a congested region and no detonation would occur, thus there is every expectation that more violent effects would occur for hydrogen.

With a similar level of leak frequency as conventional gas systems, and a rapid increase in hydrogen applications in society (all transport, including maritime, as well as housing, and industry), it can be expected that hydrogen incidents will be common.

The ignition properties are worse for hydrogen compared with conventional natural gas. It can therefore be expected that more of the hydrogen leaks will ignite than the natural gas leaks.

In summary, extreme explosions are more likely to happen with hydrogen compared with natural gas, and extreme explosions can happen in a smaller area for hydrogen than for a natural gas explosion. It is noted that in other approaches, used mainly for land-based systems, a credible leak size is typically established and used as design cases. In such cases, it is often only relatively small leaks that are assessed (e.g., (Tchouvlev, 2007)), and for such small leaks, extreme explosions are not feasible. For these cases, it is the fire risks that becomes dominant. Fire risks are not found to be more severe for hydrogen. For maritime systems, the more extreme leaks should also be considered due to the new and more critical application area. Hydrogen represents high consequence and low frequency events. Efforts can then be made to reduce the consequences and frequencies so that the risk becomes acceptable.

Due to the smaller cloud volumes needed to generate an explosion, the potential for extreme explosions with hydrogen, the expected increase in hydrogen equipment, and the higher ignition probabilities, the risk from hydrogen systems can be higher than for conventional natural gas systems. Therefore, more safety measures and dedicated safe designs need to be in place for hydrogen systems. Safe designs to prevent leaks, ignitions and explosions need to be considered at an early stage during a development project so that inherently safer designs can be installed. More preventive and mitigating measures than is normal for gas-fuelled ships can also be needed if the design itself is not inherently safe. This way, inherently safer maritime systems can be implemented. In-depth knowledge of hydrogen behaviour, and safety modelling, can be used actively during the design process to find the most effective design and mitigating solutions, and to show that the system is safe when the final design is obtained. It can then, finally be shown that the hydrogen systems have equivalent or better safety than conventional systems. The different models and measures are described in the following sections.



8.3.2 Design scenario/case definition and the approach of inherently safer solutions

This subsection introduces possible approach(es) of defining 'design cases'. This is an alternative to a 'worst-case' scenario approach, which may be requested by the Administration (Flag) based on their interpretation of how to demonstrate risk equivalence according to Alternative Design (Chapter 6.3).

Establishing inherently safer solutions should follow a risk-based approach instead of using only a 'worst case scenario'. In a risk-based approach, all possible leak sizes are considered, and associated with a frequency. Through the risk-analysis process, the frequencies of all small to large events are established. If the large events can be shown to have a low frequency, below the acceptance criteria, then it can be shown that the solution is safe and acceptable. If the frequency is too high, measures can be applied until acceptable risk is obtained. The final solution can then be shown to have similar risk levels as existing comparable vessels.

Solutions that are inherently safer for hydrogen should try to stop the event as early as possible in the chain of events, preferably concentrating on preventing any release in the first place. Safety measures like welded connections, good production routines, good inspection and maintenance routines, standardization of requirements etc. will contribute to prevent leaks. However with the foreseen increase in hydrogen applications, a greater number of market players, cost pressure, and a potential lack of resources with in-depth hydrogen specific competence, it is still likely that both small and large leaks with potentially accidental consequences will also happen in the future. Therefore, it is necessary to consider that a large leak can happen, and to design the system inherently safer to mitigate such a leak where this is possible. It should primarily focus on preventing leaks that can lead to a critically large gas cloud. The threshold when a critically large gas cloud can occur then also needs to be established. A simplified assessment to find critical cloud sizes is given at the start of Appendix C, followed by a more detailed modelling approach and status. In the future, this approach can be simplified by pre-calculating scenarios and tabulating the conditions where critical clouds occur, as described in Chapter 11.2.1.

A gas leak is characterized by three parameters – the hole size, the gas pressure, and the inventory or volume of the pressurized system. This hole size and pressure can be used to calculate an initial leak rate, and the inventory used to calculate a duration of the gas leak and a leak-rate profile. A gas-release model calculation is needed to obtain this relationship. A similar and more complex assessment is needed for LH_2 releases where the boiling inside the reservoir and the flashing during the release also need to be considered.

Cloud size is dependent on both the release rate and the inventory together with configuration and ventilation conditions at the leak location. These four key elements can be used to develop a map where zones of allowable and no-go conditions appear. An approach for developing such a map for a typical room with hydrogen is provided in Section 11.2.1. For example, in a room with six Air Changes per Hour (ACH), there will exist a specific upper gas-leak size limit which has the potential to create a critically high explosion pressure.

8.3.3 How to make inherently safer designs and systems

Risk can be considered based on the chain of events that can lead to an unwanted situation. The typical chain of events is illustrated in Figure 8.6, where it is emphasized that any event should be prevented as early as possible in the chain. An inherently safer design can be obtained by assuring that clouds are kept below a certain limit so that it cannot lead to a catastrophic explosion.

Since the probability of leaks in pressurized gas systems cannot be eliminated, an alternative is design to prevent a critical cloud size. When considering possible leak scenarios, the hole size, gas pressure and gas inventory should be quantified. With a risk-based design, all scenarios up to a full-bore rupture of the connected piping should be considered. The largest events are not likely but, due to the severity of a potential hydrogen explosion, they should be considered. The risk assessment is used to demonstrate that the risk is acceptable. If it is not shown that the risk is acceptable during the first round of the risk assessment, inherently safer designs should be sought and could, for example, be based on managing leak scenarios that could lead to a critical cloud size. The first parameter to be considered is the inventory of gas in the piping and systems. Generally, piping systems (with single walls) and valves have the highest leak potential, and these can be isolated with Emergency Shutdown Valves (ESDV), except for the storage tanks. In this way, piping systems can be made safer with a reliable gas detection and shutdown system. Additional measures may also be needed for large-inventory systems such as storage tanks. The layout and arrangement of leak points can also be considered to make the design inherently safer. A full list of protective and mitigating measures is provided in Chapter 9. The overall risk needs to be assessed, including a proper leak, dispersion, and ventilation analysis to show that the amount of gas that can leak is below a certain threshold limit for the given ventilation conditions.

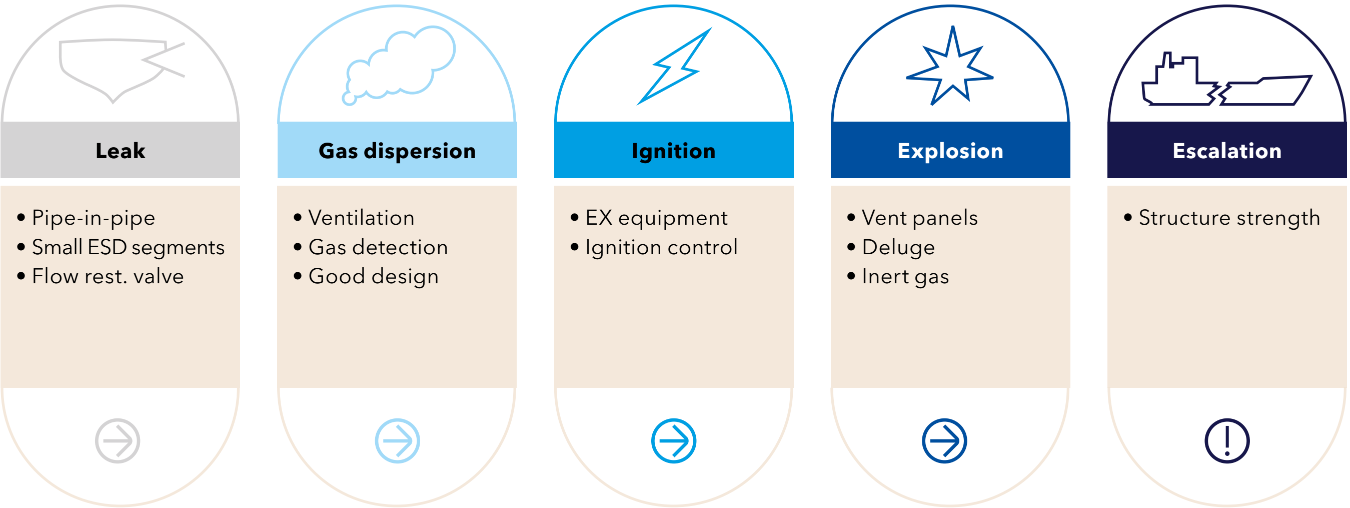
Recommendations can be developed for typical maritime applications that will give a map of gas and ventilation conditions that are allowable. A set of CFD gas-dispersion cases can be performed with varying leaks and ventilation rates so that acceptable dispersion conditions can be mapped out as further described in Section 9.6 for individual analyses, and in Section 11.2.1 for a general analysis.

8.3.4 Why CFD tools are recommended

Most of the effects that occur related to gas release, ventilation, and dispersion with hydrogen are relatively well captured with commercially available Computational Fluid Dynamic (CFD) tools which account for important dynamic and geometric effects. Explosion effects are also well-captured up to detonations, and this is in the pressure range that efforts related to mitigations should be put. Scenarios that lead to detonations are important to be aware of, and the CFD simulations can give an indication of that. Simplified tools for dispersion such as Phast integral models can give a coarse indication of the phenomenon in a setting with no geometry elements. When such tools are used, it is necessary to employ conservative assumptions where the models are uncertain, which can lead to designs that are either overly conservative or in some cases unsafe. It is therefore recommended to use 3D dynamic CFD tools to model hydrogen risk cases since this method can give higher accuracy leading to tailored systems that are documented as safe and can be used to provide inherently safe and cost-effective solutions at the same time. Further description of the different consequence models and their use is provided in Section 8.4.

FIGURE 8.6

Chain of events and associated measures to prevent or mitigate consequence. Prevention has the best effect when applied early in the chain.



ESD - Emergency shutdown

8.4 External risks

The impact of external risks and high frequency or high consequence scenarios shall be quantified during the QRA process. The QRA should consider threats to the ship's main functions and the maintainability of the ship's safety arrangements.

A key issue here is the location of the hydrogen storage system, meaning the hydrogen storage tank(s) and connected equipment that in case of a rupture/leakage may cause a release from the onboard hydrogen storage.

It is advised that the collision/grounding and hydrogen storage system damage risks are evaluated early in the design process considering that the impact of, for example, collision or other external risks (e.g., dropped objects) to a hydrogen storage/tank system may have a high (near 100%) probability of generating a fire and/or explosion. Collision and grounding should be evaluated by using collision and grounding statistics for the relevant ship type so that the probability of the accident scenario is quantified. IGF Code LNG tank location distances should not be used directly for hydrogen storage. The probable risks implied by the tank location should be assessed on a case-by-case basis.

An IMO document on collision and grounding damage statistics provides relevant background for evaluations of collision and grounding damage for ships (IMO SLF 55/INF.7, 2012). These statistics are input to calculations of probabilistic damage stability as required by SOLAS. Usually, the calculations are undertaken by dedicated software (NAPA) that can also be used to estimate the probability for storage-tank damage in case of a collision causing water ingress to the ship.

It is also recommended that possible security risks are identified and addressed.

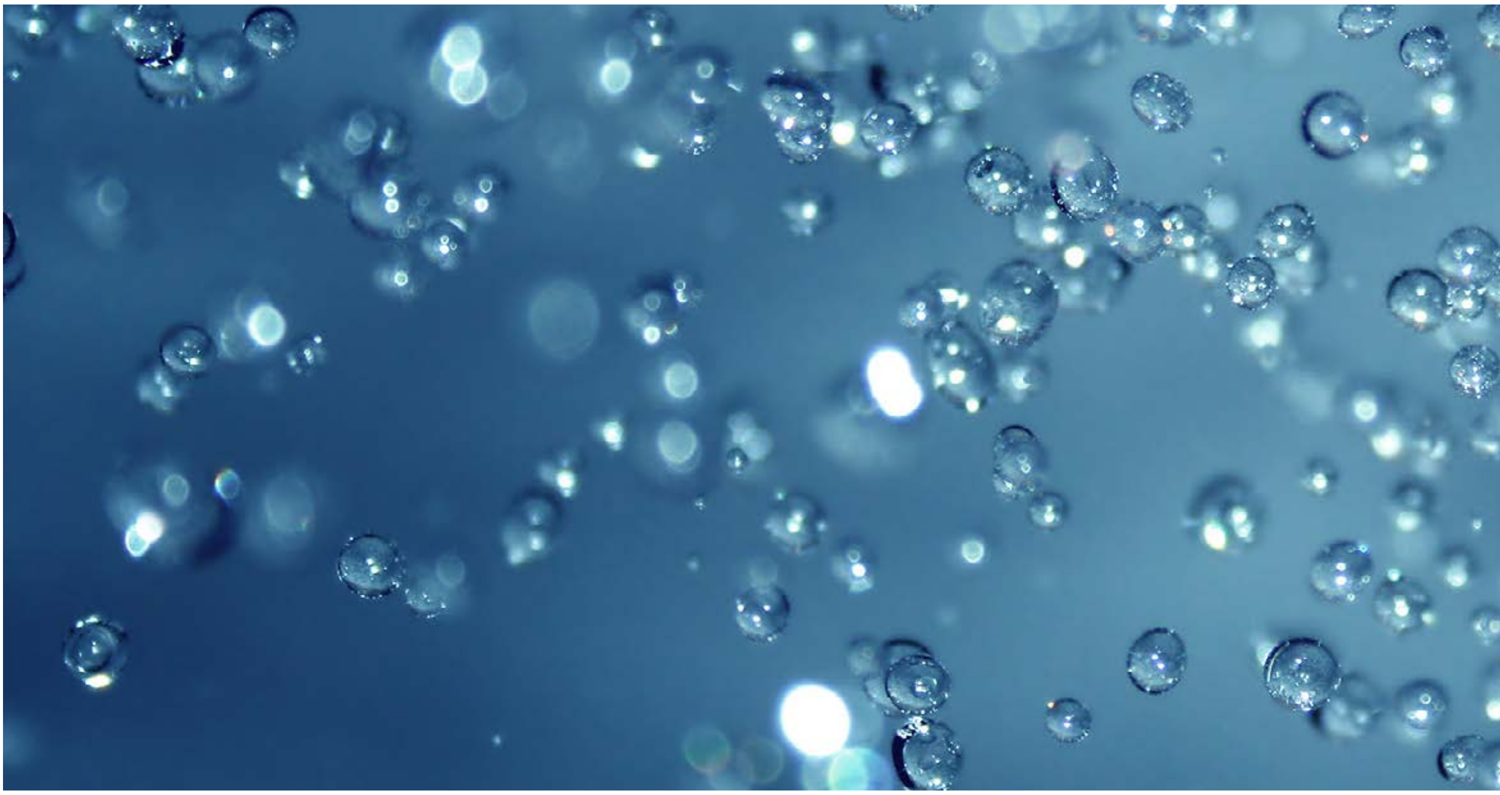
8.5 Methodologies for quantitative risk assessment

The different types of analyses that are performed in a QRA include leak frequency, ignition probability, and consequence analyses. Each of these have different methodologies with different level of resolution and detail, and different application areas. These main methodologies are described in Appendix C.

A summary of a simplified assessment of explosion consequences, and a summary of status of the different consequence models is provided here.

8.5.1 Summary - critical mass of hydrogen

The example in Appendix C, page C-3 indicates that a typical maritime room with normal ventilation (typically around 12 ACH) can only survive a gas leak with less than 220 g hydrogen in total. The example applies a relatively moderate leak of 10 g/s, rapid gas detection after 10s, and a small segment inventory size of 100g.



The general rule-of-thumb formula giving the mass of H_2 that can leak without causing the walls to break can be written as:

$$m_{H2max} = \frac{(P_{wall} V)}{176} (kg)$$

Where Pwall is the pressure on the bulkhead or deck that will cause it to break open (0.5 barg is a typical wall strength when no reinforcements are applied), V is the volume of the room in m^3. The maximum mass of H_2, m_{H2max} (kg) is the sum of H_2 that is released before ESDVs are closed and the remaining H_2 in the segment after ESDVs are closed – i.e., the total mass of H_2 that can leak.

The formula can be used to obtain a quick estimate of the segment size that can be mitigated with typical maritime ventilation and detection conditions. A larger room can accommodate a larger segment size. The given rule-of-thumb can hence be used to assess if the segment sizes are small enough to prevent a critical explosion given normal ventilation conditions. If the segment size is larger then other, additional measures need to be considered.

The ventilation is the primary measure to be investigated. With an increased ventilation rate (above normal), the segment size and the amount of gas that can be mitigated can also be increased. A study with gas dispersion in the room can be performed to quantify the relation between amount of gas and needed ventilation rate. A proper CFD model of ventilation and dispersion is recommended to develop such relation. It is then possible to establish rules for needed ventilation rates in typical engine rooms and with typical segment sizes. Measures are further described in Chapter 9.

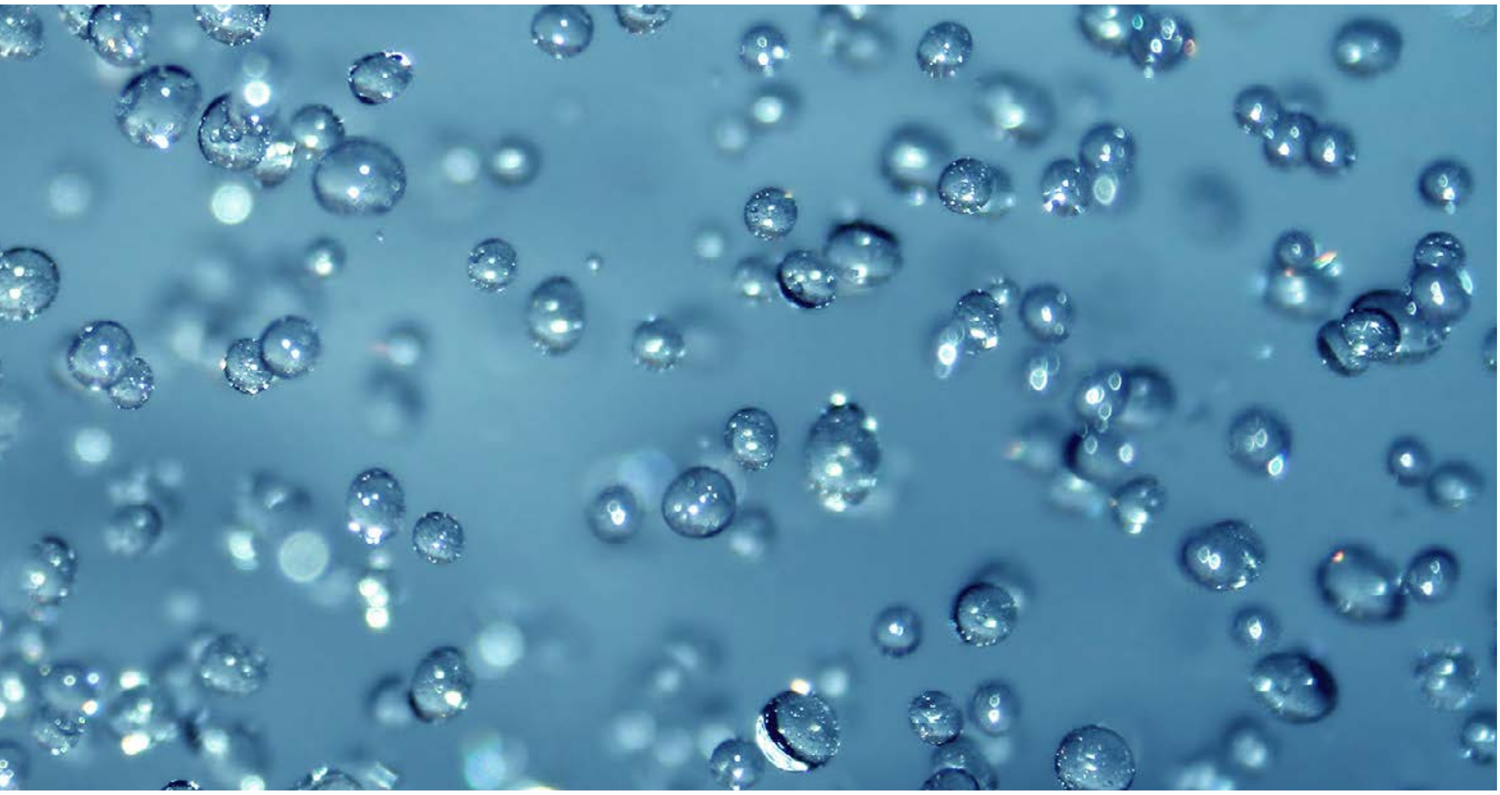
8.5.2 Summary consequence modelling status

When considering the scenario involving gas leak, ventilation, dispersion and explosion these phenomena are captured with commercial CFD models for hydrogen up to a deflagration. DDT and detonation modelling effects are not well-captured; however, DDT is a critical situation that should be prevented before it happens. Hence, its accurate modelling may not be required in a typical design process.

Hydrogen fires can be modelled and are validated for some cases.

Models for the effects of complex, active mitigating and preventive measures are typically not well validated for hydrogen services. This is the case for pressure-relief panels, deluge on gas detection to prevent explosion pressure build-up, and for other complex measures that involve multiphysics effects.

Phenomenological models are available for jet dispersion and fires for hydrogen.



9 POSSIBLE RISK MITIGATION/CONTROL MEASURES

In this section, possible measures to limit and control the potential risk related to the use of hydrogen as a ship fuel are reviewed and discussed. These are examples of possible measures, and the potential effects need to be documented and validated individually based on the specific case.

General applied design principles and measures that can reduce risks are presented. Some are relevant for both gaseous and liquid hydrogen, others are specific measures for either gaseous or liquid hydrogen.

9.1 Safe design

Ensuring safe layout and process designs at an early stage can be an advantage for reducing explosion and fire risks. At an early stage, the large building blocks are developed and arranged, and it is possible to have a large impact on safety by considering fire and explosion risks at this stage. Some general principles can be considered as a means to improve safety at an early stage:

- Storage of high-pressure hydrogen tanks in the open, above deck can be advantageous since leaks can be dispersed in the open air, reducing cloud size, and the lack of confining walls will reduce the explosion severity. It is important, however, that the gas is not allowed to build up within the equipment on deck, as this congestion within the cloud can lead to a severe explosion. There are also challenges with storage above deck that need to be considered. These can include greater difficulty in detecting gas leaks; reduced ship stability due to increased weights at a higher location in the vessel; lack of protection from green sea and weather/ice, leading to a need for weather protection; increased leak frequency due to more corrosion and possible impact from outdoor activities, etc.
- With hydrogen storage and FC rooms under deck, segregation from manned and critical areas by distance and/or strong walls and decks should be considered.
- Hydrogen spaces for storage and FCs should be placed with at least one wall or deck bordering an area without people and critical equipment. This needs to be carefully designed based on the general design principle to include a weaker wall or deck that will collapse in the direction causing minimum damage to people and assets. Such direction could be towards aft, to the sides, or upwards through the deck to an open, unmanned location, high enough above the sea to prevent water ingress, and away from personnel or passengers. Naval and hydrogen specialist support would be needed to place the hydrogen equipment.
- Comparing safety of compressed hydrogen (CH_2) versus liquid hydrogen (LH_2) for systems that otherwise have the same capacity, it is assessed that LH_2 can have some advantages. This is primarily because leaks are less frequent for liquid systems due to larger tanks, fewer valves, and lower pressure. Leaks from high-pressure tanks can be more severe (larger amounts of gas) and happen more often than for lower-pressure tanks. Liquid hydrogen systems also have unfavourable effects that need to be considered. These include the possibility of cryogenic consequences due to a leak, evaporator leaks into water pipes, complex bunkering procedures, etc.

- Pressurized hydrogen tanks and other equipment need to be segregated to limit the amount of gas that can leak. It is a trade-off between many segregation valves, and the increased leak frequency caused by more valves. The strategy to follow should be developed for each system since there are many factors that need to be considered. If, for example, a long-lasting fire is possible due to a large hydrogen reservoir, the firefighting system needs to be designed so that it can be applied during the entire duration of the fire. If the leak is not ignited in the initial part of the leak, the explosion risk will increase with a longer-lasting release compared with a short release. Therefore, it can be advantageous to have more segregation valves to reduce the explosion risk.

9.2 Detection and alarms

Gas detection can be provided with point gas detectors that detect gas concentrations and give an alarm or a signal for automatic shutdown at a pre-set gas concentration. Line gas detectors are also available. They work on the principle of detecting a change in the gas density along a line between two sensors.

Acoustic leak detection is a relatively new technology that can be applied to detect small leaks from high-pressure tanks. If a small leak occurs in a location with good ventilation and good dilution, it may not be detected by a point gas detector due to the low concentration. In such cases, it can be recommended to consider acoustic gas detectors. A small leak can develop into a larger leak (as happened for the Sandvika incident in 2019, see Appendix A); hence, it can be advisable to detect leaks as early as possible.

Gas detectors should primarily be located in the ceiling and close to possible leak sources if indoor. Outdoor, the gas detectors should be located both at high level and close to possible leak sources. Buoyancy of hydrogen can cause gas from small leaks to generate a stratified layer of hydrogen at high points in the ceiling. For larger leaks, and if the ventilation is strong, hydrogen can be distributed in the room. To ensure early detection, it is therefore also relevant to have gas detectors near the leaking equipment at lower elevations. See also the ventilation section, Section 9.6.

When it comes to fire detectors for hydrogen, detection by increased temperature may be more appropriate due to the low thermal radiation levels from a small hydrogen fire.

Actions following detection of a gas or fire should be automatically initiated at certain set levels. It can also be based on a 'voting system', with action on two or more detectors being activated, for example.

A fire detection system should be capable of detecting the flame from the combustion with satisfactory accuracy. The fire detection should not be susceptible to false alarms from the sun, lightning, welding, lighting sources, and background flare stacks. The fire detection system response time should meet the requirements for the specific application for prevention of loss of facility, equipment, and protection of personnel.

Special imaging systems are required for determining the size and location of a flame for assessment of the hazard, because hydrogen flames are invisible in daylight conditions.

Hydrogen fire detection technologies

Thermal fire detectors classified as rate-of-temperature-rise detectors and overheat detectors are considered reliable. Thermal detectors need to be located at or very near the site of a fire.

Optical sensors for detecting hydrogen fires may be based on ultraviolet (UV) or infrared (IR). UV systems are sensitive, but may be susceptible to false alarms and can be blinded in foggy conditions. Typical IR systems are designed for hydrocarbon fires, and may need some development/validation to be considered sensitive to hydrogen fires. Newer technology such as dual-band systems incorporating logic may deserve further consideration as they claim to feature the capability to trigger quickly on UV, but not activate an alarm unless the appropriate IR bands register.

Imaging systems are mainly available in the thermal IR region and do not provide continuous monitoring with alarm capability. The user is required to determine if the image being viewed is a flame. UV imaging systems require special optics and are expensive.

Further investigation of maritime hydrogen fire detection technologies needs to be carried out.

9.3 Ignition control

Ignition control is to shut down possible ignition sources on gas detection. This is typically done on electrical and other systems that are not critical to have running during an incident.

Another key factor is to control and minimize the presence of potential ignition sources, and to ensure physical separation between ignition sources and locations with potential for leaks.

9.4 Isolation and shutdown

Hydrogen flowing from or to a tank is isolated with isolation valves upon gas detection. The isolation of a smaller hydrogen volume is essential to minimize the amount of gas that can leak. When the valves are closed, the hydrogen system also needs to be shut down.

The hydrogen volume within the isolated segment will leak (if the hole is in that segment) and therefore represents the amount of gas that can lead to an explosion or a fire. A maximum mass of gas in an isolated segment can be used as a design criterion to prevent critical explosions. Chapter 8.5.1 summarizes how to calculate this.

Isolation should be initiated automatically for hydrogen systems. A manual shutdown can be unreliable and can lead to a large gas cloud before a shutdown is performed.

For larger segments such as storage tanks and longer pipelines, it is also relevant to start blowdown of the gas to a safe location. Such blowdown typically starts automatically or manually on gas detection alarm. This will also reduce the duration of the leak.

The above description is general for both compressed and liquid hydrogen. For LH_2 piping and storage systems, further issues need to be accounted for. The design of isolation and shutdown systems for LH_2 should be considered in Phase 2 of the MarHySafe JDP.

9.5 Vents and pressure-relief systems / masts

Vents and pressure-relief systems are additional to the ventilation systems which only consider the air ventilation and HVAC systems in the different ship areas containing hydrogen systems (see 9.6).

The vent system handles controlled releases of gas, such as blowdown releases and planned releases during maintenance etc. Blowdown may be initiated either automatically or manually as a result of gas detection or other abnormal process conditions, and the target is that this is done before a leak has caused a fire or an explosion.

Pressure relief is typically initiated automatically when the pressure in a tank exceeds a pre-set level during a fire. Pressures are released through the Pressure Release Valves (PRV). The purpose is to empty the stored gas tanks to a safe location to prevent tanks from bursting, and to reduce the duration of the fire. For LH_2 tanks, the design case for pressure relief is typically loss of vacuum insulation. This will result in a rapid heating and boiloff.

These two systems (vents and PRVs) can be separate systems with separate piping and masts.

Some examples for PRVs, but only for pressurized natural gas, can be found in the IGF Code Chapter 6. (7.3) (IGF Code, 2016). The purpose is to prevent escalation from external fires to tanks. The tank needs to be depressurized fast enough to survive during an external fire. Existing requirements give an external heat load that tanks need to survive, but do not consider the properties of hydrogen. Therefore, separate assessments are needed for hydrogen in order to be able to develop recommendations for sizing of vents and PRVs for hydrogen tanks.

It can be advantageous to have separate piping systems and vent masts for the vent and the PRV systems to create independence of the systems.

Piping from vents and PRVs to the vent mast can be subject to air ingress from the top of the vent mast. If the piping is filled with hydrogen, it can lead to a detonation inside the piping. Recommendations for the relationship between lengths and diameters need to be made to prevent high pressures in the ducting. Alternatively, a strong enough piping system that can withstand a detonation from inside can be considered.

Release points on vent/PRV masts and from heating, ventilation, and air conditioning (HVAC) outlets need to be classified with safety distances. Until standardized sizes of such safety zones are developed, separate gas dispersion simulations can be performed to set the distances.

9.6 Ventilation

In case of a hydrogen leakage into an enclosed volume, ventilation may be needed both for hydrogen dilution and extraction purposes. Ventilation is usually required for maritime technical spaces. Such space ventilation is usually needed in addition to any separate ventilation on units such as fuel cell modules located in the relevant space. Key objectives of the ventilation of such spaces are to prevent build-up of flammable gas due to leakage from any piping or other components leading to the units located in the space, or from any unit located in the space. The interaction between ventilated units in the room and the rooms own ventilation system is described in Section 9.6.6.

Tests at DNV's Spadeadam Testing & Research facility (DNV, 2020a) with large LH_2 releases inside a closed room connected with a HVAC ventilation mast show that if the gas is ignited outside, it can burn back. However, the mix in these tests was rich; hence, burn back through the vent mast went slowly and did not result in any explosion in the mast. Also, the concentration of H_2 in the room was high so that it did not result in a critically high explosion pressure. It is expected that if the leak of hydrogen was smaller, a more combustible cloud could have been created, resulting in a critically high explosion pressure. Hence, a general requirement of ventilation systems and gas systems should be to prevent gas concentrations above 5–10% in the room and in the ventilation ducting.

9.6.1 Ventilation rate and arrangement

The strength of the ventilation (quantified as number of air changes per hour, ACH), is important to specify since it can have a major impact on the explosion risk. With a higher ventilation rate, the gas is better diluted, and this can lead to a reduced risk. The ventilation rate in the room should be specified in accordance with the possible leak scenario that can happen in the room. The principle should be to ensure that a dimensioning leak scenario should be diluted by the ventilation so that an explosive atmosphere could not be possible. Section 11.2.1 proposes an assessment for determination of the ventilation rate needed, together with other safety system settings and room characteristics.

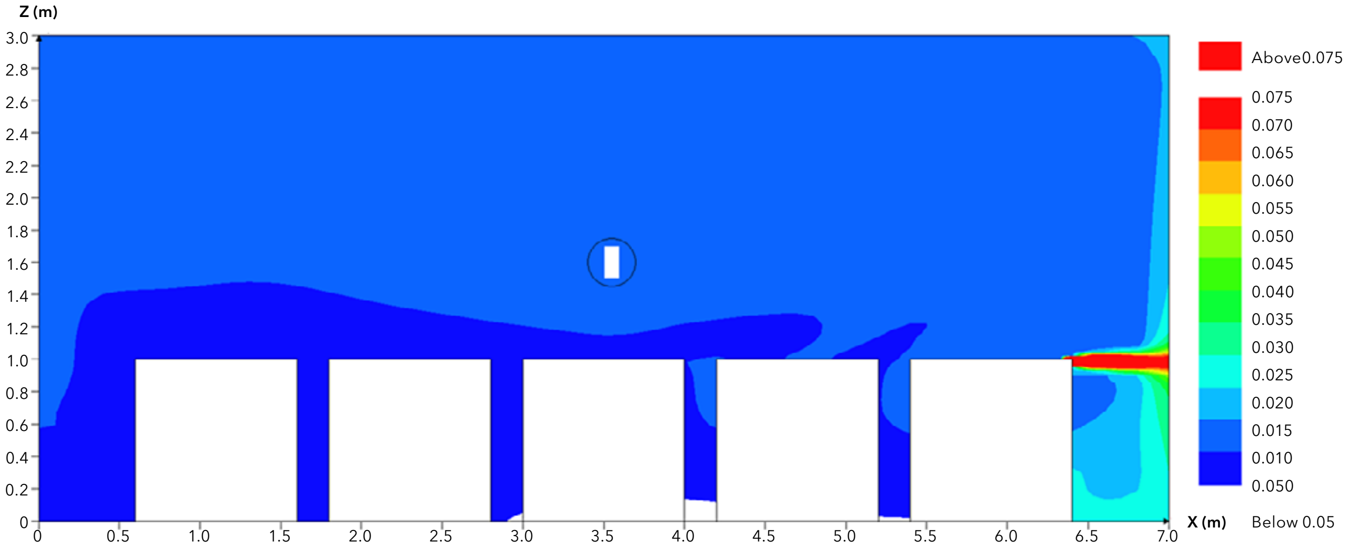
Assessments of required ventilation rates need to be based on possible leaks from hydrogen-containing equipment, and on failure or under-dimensioning of other barriers (such as the cabinet ventilation) that can lead to hydrogen in the room. The main parameters that govern the explosion risk in the room are the mass of hydrogen that can leak (kg), the ventilation rate (ACH, 1/h), and the room volume (m^3). A dependency of these parameters can be used to understand and investigate the ventilation rate needed for a given room volume and a given mass of gas that can leak. This dependency typically shows how the required ventilation rate increases when the mass of gas that can leak is increasing for a given room. A small room can develop a critical cloud with less gas than a large room, meaning that small rooms will need to change air at a greater rate than a large room (provided the same mass of gas is leaked). The room and ventilation configurations are also influencing the required ventilation rates to a lesser degree. The mass (kg) of gas that can leak is here used as the main parameter to describe the leak scenario. The leak profile (leak rate versus time) will also influence the cloud size, and it is assumed that the hole is large enough that the gas leaks out over a short time, less than a minute. If the leak rate is very small, then it will be diluted, and it can leak over a long time without causing any harm. If the leak rate is continuous over a long time, then a steady-state cloud size will build up that reach a constant volume or concentration until the leak is finished. Therefore, for long lasting leaks, the leak rate (kg/s) can also be used as a parameter to assess the required ventilation rates.

The ventilation arrangement is also important. The air flow should be arranged so that air goes through the room with as few dead zones as possible and avoiding recirculation of air. Hydrogen is lighter than air, and to prevent a small leak creating a stratified layer of hydrogen at the ceiling, it is beneficial to have the extraction in the ceiling and inlet near the floor. When the leak is large or the air flow in the room is strong, then hydrogen can be well mixed and have a momentum which causes the hydrogen gas to be more distributed in the room. It is therefore also possible to have higher hydrogen concentration in places other than near the ceiling (see Figure 9.1). This can have some impact on the location of gas detectors (see also Section 9.2).

Typical ceiling configurations include structural beams, cable gates and pipe racks that may contribute to risk of formation of unwanted gas pockets that may be difficult to ventilate efficiently unless specific measures are implemented. Extraction ducts can be placed in such pockets with suction as near the ceiling as possible to prevent layering hydrogen from small leaks. If the ceiling is flat, having several extraction nozzles to cover the area can be necessary. With a slanted ceiling, the number of extraction points can be reduced to cover only the highest points.

FIGURE 9.1

Example showing gas concentration contours in a fuel-cell room with a jet leak.



The colour legend shows mass concentration of hydrogen, where 0.04 is LFL. When the jet hits a wall, it does in this case spread in all directions and this results in gas also near the floor. Buoyancy effects are acting only for lower velocity flows.

9.6.2 Optimization of ventilation arrangement

Good design of the ventilation system in a hydrogen room can be obtained by a dedicated distribution of inlet and outlet ducts. Efficient and cost-optimal ventilation design can be found by using CFD modelling actively to specify inlet and outlet layout when simulating possible gas leaks. This way, pockets with poor ventilation conditions can be avoided. With a well-designed ventilation system, the dilution efficiency can be increased, resulting in a reduced explosion risk, and possibly reducing the need for fans.

9.6.3 Reliability of ventilation system

The reliability of the ventilation system should be high enough that it runs as intended when a leak occurs. Good inspection and maintenance routines are recommended to ensure this.

The failure probability of the ventilation system can have an impact on the risk of a catastrophic explosion event. Therefore, this probability should be quantified and accounted for as a part of the explosion risk analysis. It is typical to presume better than 95% availability on demand of the ventilation system.

9.6.4 Fan types and locations

Ventilation with extraction fans and under-pressure in the room is usually required for maritime rooms where there is a possibility that combustible gas will be generated. This is required to prevent gas leaking to unwanted and uncontrollable locations through small openings in the walls and decks that are usually not gas tight. HVAC fans on the outlet can then be an ignition source for gas that enters the extraction ducts. Fans on the outlet therefore need to be explosion rated.

A combined ventilation with fans on both the inlet and the outlet can be used as long as a small negative pressure is maintained in the room. Inlet fans then do not need to be explosion-proof if they are located at a safe distance from possible gas leaks. Since non-explosion-rated fans are more efficient and quieter than explosion-rated fans, it can be beneficial and also cost efficient to install fans on both the inlet and the outlet, with a slightly larger fan on the outlet.

9.6.5 Ventilation outlet and inlet ducts

The outlet duct needs to lead the gas to a non-hazardous area. A safety zone, based on the design leak scenario in the room, can be established around the outlet. A flammable concentration in the duct may cause an explosion that can lead to DDT in the duct, provided the duct is long enough. The outlet duct can therefore be designed to prevent this, based on a relationship between diameter and length.

Inlet air needs to be supplied from a location with uncontaminated air.

9.6.6 Interaction between hydrogen system and space ventilation

An own-ventilation system is required for the FC modules in the FC power installation. This ventilation system is typically predefined and designed by the FC manufacturer. The FC module ventilation system should be considered and included in the overall assessment of the ventilation and explosion risk for the FC space. Several factors that can influence the explosion risk associated with the FC space should be considered. Examples of such factors in include: inlet and outlet duct location; failure of module ventilation; process air consumption by the reaction in the FC; large leaks in a module/rack; explosion and fire in the FC space; and, leak segment gas inventory (mass and volume of H_2 with associated leak rate and leak duration).

9.6.7 Natural ventilation and layout

Hydrogen systems located above deck, and where there is natural ventilation, are often better ventilated than mechanically ventilated rooms, and the explosion risk can therefore be reduced.

When the leak is small, the buoyancy of the leaked hydrogen causes the gas to go upwards, helping to reduce the cloud accumulation. For medium and larger jet leaks, the high momentum of the leak will cause clouds to accumulate along the ground before they are eventually driven upwards by buoyancy. The explosion incident at the Sandvika hydrogen refuelling station in 2019 is an example of such a scenario where a gas cloud was generated from a leak near the ground before it could escape due to buoyancy (see Appendix A).

Therefore, the ventilation conditions also need to be considered for outdoor hydrogen equipment so that accumulation and explosion can be prevented. When a gas cloud can be generated within a congested region outdoors, it can also cause a critically high explosion if the volume and congestion level is above certain limits. Configuration of large elements such as the hull and buildings on land, and wheelhouses and building/equipment on deck, will have an influence on the dispersion and explosion scenario, and on the risk. The arrangement and configuration of the larger items should therefore be assessed during the early stages of the development with the aim of reducing explosion risk. Sound design principles can be indicated as follows:

- Ensure air flow in one primary direction around the hydrogen equipment so that gas is taken away without accumulating in wakes or stagnant zones.
- Avoid placing hydrogen equipment inside corners and downwind of large items.
- Consider the prevailing wind direction in an area when designing the arrangement. The ventilation flow direction around the hydrogen equipment should be aligned with the prevailing wind as much as possible. If hydrogen equipment is located above deck, the prevailing wind is from front to aft on the ship. For a bunkering station, the local wind rose should be considered to find the prevailing wind direction.
- If wind walls are located upwind of the hydrogen equipment, wind walls with perforations or openings in parts of the wind wall are recommended to ensure sufficient ventilation in the area downwind of the wind walls.
- Covers or ceilings above hydrogen equipment should be slanted with the lowest points in the middle so that gas accumulation under plates is avoided.
- The area where hydrogen equipment is located should be as open and tidy as possible with as few structures or unnecessary equipment as possible. Railing, piping, cabling, equipment and temporary storage should be prevented or kept covered as much as possible. Piping and cabling can be kept under deck or underground, and railings can be made as open as possible, etc.
- The airgap between hull and quay can be a critical area if gas is accumulated. There can also be hidden confined spaces or pockets under the quay where gas can accumulate. Gas should be prevented from entering these areas. Special care should be taken for LH_2 spills, which can lead to cold, heavy gas. Jet leaks that can be directed downwards can also result in clouds under the quay before gas is lifted by buoyancy.

9.7 Storage system leak control

Gas storage systems can be safety critical since they contain enough gas to cause a critical explosion if a leak releases the stored hydrogen. The critical scenario(s) is expected to be identified during the preliminary phase of the Alternative Design process. As an example, this could be a leak in the first connecting valve, potentially leading to a long-lasting leak. With insufficient ventilation, this can lead to a critical cloud with explosion and long-lasting jet fires as possible consequences. Some measures are available to help make the tank storage system inherently safe, however.

First, a flow restriction valve (also called 'excess flow valve') can be placed at the outlet of the tank. A flow restriction valve works by closing completely if a pre-determined flowrate through the outlet is exceeded. The valve includes a spring-operated plate that closes due to the forces of the excessive flow. Gas dispersion simulations for the tank space, together with modelling of the ventilation rates and internal space arrangements, can be performed to decide which flowrate would be acceptable, though it will always have to be greater than the maximum flow required in normal operation. As a result, flow restriction valves cannot be used to protect against release scenarios that are within normal operational flows, though here other control measures can be used, such as ventilation.

Another option is to locate the top of the tank(s) in a completely open space, which leads to any gas leaking from the storage system being dispersed in the open air. A leak can still ignite and cause a fire that can threaten the other tanks. Systems with passive fire protection and for cooling the tanks in a fire need to be assessed.

A third measure could be to locate the tanks inside an inert room with an off-gas duct leading the gas to a safe location outside. Alternatively, a closed box tight around each tank and around the valve, together with a pipe-in-pipe configuration for the piping system, can also be a solution.

The solutions and safety systems that are installed to prevent or reduce the explosion risks also need to consider the fire risks. For example, if CH_2 tanks are not equipped with Pressure Reduction Devices (PRDs) – which could be due to minimizing the number of valves – then a safe emptying of the tank during a fire cannot be performed. In this case, the tank needs to be constructed with a 'self-venting' capability during a fire, as is the case with composite tanks, for example. The system may need to be tested in full-scale situations to show that it works as intended.

9.8 Fire control and fire protection

An overall fire and explosion safety philosophy and strategy needs to be developed. Fire control and protection is a central part of the strategy.

The main goal of the fire strategy should be to prevent escalation of the incident to other parts of the ship or fuel systems that can lead to yet more escalation.

Larger hydrogen jet fires have similar properties as natural gas jet fires, though the hydrogen jet fires do have higher flame temperatures. For smaller fires, the flames are near invisible and a lower fraction of heat is radiated from the fire than would be the case with natural gas. A fire detection system needs to consider the properties of hydrogen flames and use appropriate flame detectors, such as IR detectors.

A strategy can be to stop ventilation upon fire detection so that the air supply to the room is halted and the fire eventually extinguishes. This can be combined with adding fire-suppression agents. If the leak continues after the air supply is stopped, a way to lead the excess gas out of the room to a safe location is also needed. A vent leading to a safe location without causing air ingress could be used, and such a system would need careful design.

The fire strategy needs to consider the explosion hazards of hydrogen gas that can occur if the fire is extinguished and hydrogen is still leaking. If fire is suffocated in the room, it can still build up with hydrogen gas from the leak. The strategy then needs to be developed to flush out the hydrogen without mixing it with air. Flushing with an inert gas is an alternative to consider.

Fire control systems (water sprays) and manual firefighting can also be applied to cool the equipment without extinguishing the fire if there is a chance of an explosion. This can be the strategy in rooms where air is available, such as when ventilation is not shut down, and in large semi-open or fully open areas. If the area is congested, it can still be an explosion hazard, and a controlled fire is better than a gas leak that can lead to an explosion.

Strategy for fire control and protection should be developed by the designer and validated and possibly optimized with QRA if a risk-based approach is being used. It is also advised that the need for passive fire protection (PFP) is assessed and optimized based on QRA. When using PFP, one needs to make sure that the PFP is appropriate for H_2 flames and, if needed, cryogenic exposure.

Preventive measures against fires can include automatic or manual process shutdown systems that limit the quantity of hydrogen leaking (preferred), as well as sprinklers, deluge systems, water spray systems, and dry-chemical extinguisher systems.

Appropriate automatic fire detection and suppression systems for hydrogen systems containing significant hazards should be provided.

Because of the danger of reignition or explosion, hydrogen fires are normally not extinguished on purpose until the supply of hydrogen is shut off. Reignition may occur if the fire continues in other materials, or a metal surface in the flame is not cooled with water or by other means. Hydrogen can also ignite due to other mechanisms since it has a lower ignition energy than hydrocarbons.

Care should be taken to prevent water ingress into LH_2 storage systems when using water for hydrogen-fire suppression.

Small hydrogen fires can be extinguished by dry-chemical extinguishers or with carbon dioxide, nitrogen, and steam.

9.8.1 Fire-suppression agents

Although the hydrogen fire should not be extinguished until the hydrogen flow can be stopped, water sprays (for example) shall be used to extinguish any secondary fire and prevent the spread of the fire.

Carbon dioxide may be used in the presence of hydrogen fires (not for extinguishing). Although some toxic carbon monoxide may be produced in the flame, it will not be a large amount. Anyone breathing in the hot flame gases will be affected regardless of the presence of carbon monoxide. The carbon monoxide will be reduced to tolerable levels by the time the flame gases are diluted with fresh air and reach breathable temperatures. Dry chemicals are better than carbon dioxide because they make the flames visible.

9.8.2 Deluge installation

Strong consideration should be given to the installation of deluge systems along the top of storage areas for secondary fire protection. The deluge systems should be capable of being manually or automatically actuated depending on how secondary fire protection is best achieved. Also, any surface capable of becoming an ignition source should be cooled so that it does not constitute a hazard. Fire extinguishing systems shall be used to cool manifold piping, relief vents, and transfer pump facilities, but not for vent stack openings.

10 BUNKERING

Bunkering operations will be subject to other (additional) requirements compared with the ship. As described in Chapter 6.9, there are many stakeholders involved, and the ability to define safe bunkering operations will be influenced by many factors, ranging from ship design through to the management of the bunkering operations within ports.

Importantly, LH_2 bunkering management will be able to build on the experience and knowledge gained from the introduction of LNG as a marine fuel. The stakeholders face many issues common to the planning and implementation required for handling LNG. In many ways, the step from existing bunker fuels to LNG, with its cryogenic and gaseous hazards, was more difficult than the transition to LH_2 will be.

However, this existing experience with LNG is only a starting point, and we need to be keenly aware of the differences between LNG and LH_2. As described in Chapter 4.1, if released from containment, hydrogen has physical properties that can result in more severe outcomes and also additional hazards (such as liquefaction of air). There are also operational issues that will influence the engineering of the bunkering operation and potentially have safety implications. For example, if bunkering times remain the same, volumetric flowrates for LH_2 will need to be greater than would be the case for LNG. In a loss of containment event, this could well influence the amount of fuel released. The lower LH_2 temperatures compared with LNG will also influence the engineering and have an effect on how the bunkering operation can be carried out safely.

CH_2 bunkering guidance will most likely build on existing experience of handling compressed flammable gases onshore. Experiences gained from previous development of CH_2 refuelling systems for buses, trucks, and trains will be relevant, though faster filling and larger volumes will be required for ship applications.

The safety of bunkering operations will be enhanced if these issues are addressed early, ideally at the concept stage. This includes ship design, port spatial planning, and the approach to be used for bunkering. Bunkering with CH_2 is likely to be shore-to-ship, as for LH_2 operations in the early stages of use of hydrogen as a marine fuel. However, ship-to-ship bunkering of LH_2 will be required as the scale of operations increases, as has been the case with LNG.

New procedures will need to be developed as new knowledge is developed, and specific guidance documents and specific provisions produced to ensure safe bunkering of hydrogen on ships. Important elements of the guidance will be related to:

- definition of roles and responsibilities;
- methods for defining safety zones and the control measures required within these safety zones;
- interactions with other ship simultaneous operations (SIMOPS), such as cargo loading and passenger embarkation;
- equipment standards and safety systems, both active and passive;
- ensuring personnel are competent, aware of the hazards, and suitably trained;
- monitoring and checking of bunkering operations; and,
- development of emergency procedures.

In order to introduce hydrogen as a widely used fuel in shipping, international harmonization of bunkering technology, requirements, and procedures will be needed. Bunkering in different ports, in different countries that may offer different technological solutions, procedures, and requirements will be a barrier. Different ships will have different design and requirements regarding bunkering rates and other parameters. There is a need for regional and preferably international cooperation to develop standardized and harmonized bunkering solutions, guidelines, and practices for hydrogen to become relevant for international shipping.

Assessment of hydrogen bunkering operations will most likely be risk-based, and will use the methods described in Chapter 8 to identify and manage the safety hazards and security risks. It is recommended that a bunkering risk assessment of all sub-components of the fuelling station, the transfer system including the special H_2 couplings, and the bunkering procedures is undertaken.

Detailed bunkering procedures for hydrogen need to be established, considering the engineering of the specific systems. Bunkering workshops to discuss requirements for the first bunkering facilities were conducted as part of MarHySafe Phase 1. The points below summarize procedural steps for hydrogen bunkering based on the early-phase development information available. It should be considered as input to the next phase of MarHySafe:

- Connection of liquid hydrogen supplier, at present typically a LH_2 truck, to the LH_2 fuelling station.
- Connection of the onshore H_2 fuelling station to the ship.
- Testing of tightness and purging of complete LH_2 fuelling line (based on experience from land-based hydrogen refuelling, this is initially assumed to be with helium). Procedures need to consider that N_2 and O_2 may liquefy or even solidify in direct contact with liquid hydrogen.
- Tightness tests may be conducted with helium prior to each bunkering operation. Reference is made to Standard (NS-EN ISO 20485:2018) as a current guidance document. Due to the physical properties of LH_2, nitrogen is not recommended. Due to limited availability of helium, it is expected that other options will be sought.
- Cool-down procedure of the LH_2 supply system prior to bunkering (for CH_2 bunkering the procedure is foreseen to depend on the bunkering facility set-up).
- Bunkering of hydrogen.
- Stop hydrogen bunkering procedure (e.g., ESD shutdown).
- Emergency shut-down procedure.

Due to the differences between H_2 and natural gas, the determination of hazardous distances/zones for bunkering of hydrogen will not be the same as defined (standardized) hazardous areas used for LNG bunkering. Dispersion of gaseous hydrogen due to unexpected leakage is different compared with natural gas (methane). The hazardous area determination will depend on the results provided by the risk assessments and the regulatory framework applied. The scope of hydrogen bunkering risk assessments needs to include evaluation of probable ignition consequences including deflagration/detonation events as applicable.

11 KNOWLEDGE GAPS AND INPUT TO PHASE 2 PRIORITIES

This chapter presents current knowledge gaps related to maritime hydrogen safety based on the overall objective of safe and efficient introduction of hydrogen-fuelled vessels and the findings from MarHySafe Phase 1. The key knowledge gaps and how the MarHySafe JDP suggests working on closing these in Phase 2 is discussed.

A main finding was that the full scope of the Alternative Design approval process is not well understood. Flag States may also have different interpretations of the Alternative Design process and its requirements. MarHySafe considers the Alternative Design approval process to be both needed and useful to ensure safe and reliable introduction of hydrogen-fuelled vessels. Therefore, improving the understanding of the full scope of the Alternative Design process will be a key objective for MarHySafe Phase 2. This will be used to make the process more effective and to contribute to reduced approval time for future projects.

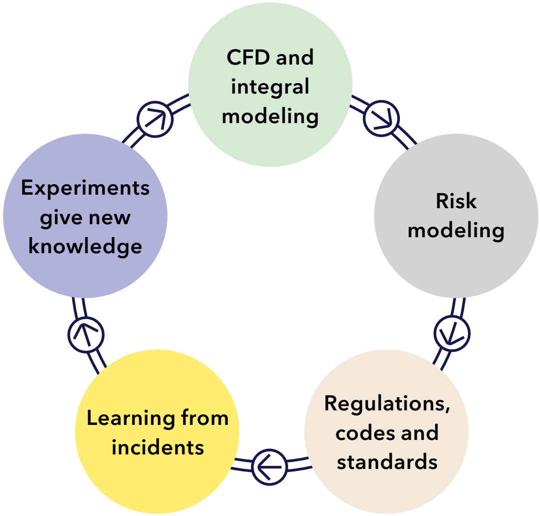
Based on the findings from Phase 1, it is suggested to maintain in Phase 2 the focus on hydrogen stored in the CH_2 and LH_2 forms. Therefore, it is not presently foreseen that other potential maritime hydrogen carriers such as NH3 and LOHC will be included in the work scope. MarHySafe Phase 1 focused on use of hydrogen in PEM FC, but the principles of other common FC types were included; for example, in the FC power installation descriptions (Figure 4.5). It may be relevant to include other FC technologies/converters during Phase 2. Based on findings from Phase 1 and input from the project partners, it is important to avoid scope creep and maintain the focus needed to be able to deal with the knowledge gaps related to pure hydrogen.

Hydrogen-fuelled vessels will need safe and reliable supply of hydrogen to operate, and the technology and standardized systems needed to ensure this still need development. To enable this, more focus needs to be put on bunkering/fuelling in Phase 2.

Closure of the gaps related to maritime hydrogen safety and the regulations, codes, and standards applicable to the introduction and use of hydrogen as ship fuel needs to be knowledge-driven. The knowledge development can be illustrated by a learning circle where new knowledge in one part may lead to closure of knowledge gaps in other parts of the circle. This process of continuous learning and improvement is illustrated in Figure 11.1.

FIGURE 11·1

Chain of activities for continuous learning and improvement to improve hydrogen safety.



A range of disciplines and activities need to be involved, while ensuring close collaboration and learning between these is a key to success. This includes learning from other relevant hydrogen safety activities, including those focused on non-maritime applications. Some knowledge is generic in the sense that it is more related to hydrogen and hydrogen's properties and safety-related behaviour than to the application. Some knowledge will be specific to maritime use.

The safety-related knowledge development includes the following:

- Experiments give large and full-scale evidence of selected critical events and effects. The scale is important as many physical processes are scale dependent.
- Models are developed, validated based on experiments, and run for real conditions for a large range of events.
- Running many CFD models gives input to risk assessments that identify the total risk and risk drivers. The hydrogen application (vessel or bunkering facility) can be approved and operations can run.
- Industry standards and guidelines can be developed (and improved) when experience from operations is gained and risks are even better understood and accepted. Development of technical solutions for hydrogen-fuelled ships will take time, and new solutions will be developed as technology matures. During this period, guidelines will need to be updated and developed in line with the solutions.
- Incidents may still happen, and investigation and learnings from incidents can be important (EHSP, 2019).
- New insight may lead to identification of possible new root causes. New experiments may be needed together with the other activities in the circle.

11.1 Current knowledge gaps and suggested Phase 2 activities

For Phase 2, it is foreseen that the scope will be widened compared with Phase 1. The main Phase 1 tasks will continue in Phase 2, and some tasks like bunkering will need more focus. In addition, it is suggested that further topics are included. Realization of new tasks, and in particular the suggested experimental test programme, will depend on budget (external funding and/or collaboration) and partner approval. Activities to establish effective collaboration with other projects working on maritime hydrogen safety challenges and pre-normative research activities will be important to speed up the process toward future standardization. Such dialogue has therefore been initiated for the EU-supported project, Ecosystemic knowledge in Standards for Hydrogen Implementation on Passenger Ships (e-SHyIPS).

Contribution to early standardization of hydrogen-fuelled ships is suggested as a new task (see Chapter 11.1.6). The start time of this depends on the knowledge development generated in other tasks and collected in revised versions of the Handbook. Harmonization of approaches and methods for estimation of safety distances / hazardous zones (see Section 11.1.4) may be part of the early standardization activities, and may also be part of the needed activities related to bunkering. More knowledge is needed before any specific approaches can be recommended.

11.1.1 The Alternative Design process in practice

As described in detail in this Handbook, the current approval regime for hydrogen-fuelled vessels is founded in SOLAS and Part A of the IGF Code pointing to the use of the risk-based Alternative Design process approach to demonstrate risk equivalence. The overriding purpose is to demonstrate that the safety is equivalent to that achieved with conventional systems (fuels). The Alternative Design process requires significant effort to demonstrate compliance with MSC.1/Circ 1455 (MSC.1/Circ 1455, 2013). The process tends to be considered as complicated, expensive, and time consuming, but it is needed to build experience and knowledge before prescriptive regulations can be developed. It is therefore proposed that Phase 2 of MarHySafe shall work with and identify real case(s) where the Alternative Design process can be carried out to learn and provide input to future rule development. Due to the urgency of this task, work on this has already been initiated in collaboration with the Green Shipping Programme.

A key part of the Alternative Design process activities is to carry out risk analyses with risk-control measures incorporated to reach an equivalent safety level. This may be undertaken by comparing hydrogen risk(s) with risks for conventional fuel(s), possibly by comparing the risk for a hydrogen ship with the risk for 'conventional', 'standard' ship(s).

The assessment described in 11.2 is suggested to form a solid basis for developing sound design principles as a basis for rules and standards. This approach is utilizing the available models and risk-based approach that is described in this Handbook. Taking such an approach for the first few hydrogen ships can then provide sufficient experience for use to develop robust and cost-efficient codes and standards.

11.1.2 Validate and update the Handbook

A central part of Phase 2 will be to validate the Handbook based on practical user experience, feedback from the Handbook users, and new knowledge. A structured review process is suggested to facilitate this. MarHySafe partners and other Handbook users will be invited to contribute; for example, users representing ongoing maritime hydrogen demonstration projects.

An important aim of this validation process will be to collect, develop, and present the required understanding of the risks. This will enable moving towards the knowledge and experience level where specific recommendations for hydrogen-fuelled vessels and the needed bunkering systems can be developed.

In addition, the results from the activities in all the other work tasks will be fed into the updates of the tentative Handbook.

11.1.2.1 Training material for first users

In the next few years, the first hydrogen-operated ships will be put into operation, but the operational experience is missing. It is therefore suggested to use the Handbook as input to develop training material for the first users.

It is also suggested that the Phase 1 results from MarHySafe are used as input to develop introductory materials and a training programme/course for designers, builders, integrators, crew, staff, maintenance personnel and others who are new to hydrogen or to its maritime application. The materials and programme/course should aim to cover engineering, operation, and maintenance.

In addition to this Handbook, some sources exist that may provide input; but as far as is known, none are specific for maritime use of hydrogen. The US Department of Energy (DOE) Hydrogen Tools site on hydrogen safety training materials is one example. Recent work has been done to update the Hydrogen Incident and Accident Database (HIAD). It is recommended to monitor the development of HIAD. It is further recommended to monitor the associated work in the European Hydrogen Safety Panel (EHSP) for new learnings and information about hydrogen incidents and accidents through the EHSP task force on data collection and assessment. Information from these sources may be valuable for providing practical real-life examples for training purposes, and for future revisions of the Handbook.

Reference will also be made to learnings that can be gained from existing LNG marine operations.

11.1.3 Bunkering of hydrogen

Review planned hydrogen bunkering solutions, including possible inert gas solutions (helium/nitrogen), and existing ones as they become available. Assess operational and technical risks. Use input from land-based hydrogen filling stations and LNG bunkering as applicable.

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[7] https://h2tools.org/training-materials
[8] https://www.fch.europa.eu/page/european-hydrogen-safety-panel

The work should include a gap review of available regulatory framework (regulations, codes and standards) and best industry practices, as well as relevant Recommended Practices. Information are mainly available for land-based hydrogen fuelling and marine LNG bunkering. It will be important to identify and assess gaps regarding needed scaling up to large hydrogen bunkering volumes and the increased bunkering rates needed for efficient introduction of hydrogen fuelled ships. Due to lack of marine hydrogen bunkering experience, consideration of marine conditions, compatibility with hydrogen properties, and learning from LNG experience will be important elements in the work ahead.

Goal will be to develop the first 'Best Practice' or a 'DNV Recommended Practice' (RP) for safe hydrogen bunkering. A similar document exists for LNG bunkering, and may be a feasible starting point. The feasibility for a DNV RP for bunkering of LH_2 could be evaluated through a SWOT Analysis, and a new DNV RP for LH_2 bunkering could be developed on the basis of the existing DNV-RP-G105 Development and operation of liquefied natural gas bunkering facilities.

11.1.4 Safety distances and hazardous zones

Different approaches exist, but these need validation against maritime terminologies and needs. Work is needed to come up with a harmonized approach for the safety and/or hazard distances for the use of hydrogen as ship fuel. One approach may be to consider the quantity of hydrogen as a variable.

Smaller safety distances are available in a ship arrangement than for most land-based applications, but additional safety measures could be added to compensate in relation to the quantity of hydrogen. Another issue is that safety distances are normally not used and considered applicable as a risk-mitigation measure for low-probability high-consequence events (e.g., explosions). It may therefore be important to evaluate when it is relevant to apply safety distances (and if methodologies from other hydrogen application areas can be applied).

11.1.5 Experimental test programme

An experimental test programme for Phase 2 may be developed, and tasks prioritized based on findings from MarHySafe Phase 1, interaction with collaboration projects, and based on results from the planned Phase 2 task to pre-calculate risk assessments (Chapter 11.2). Further work may be needed to capitalize on the NPRA LH_2 test project results (DNV GL, 2020a) (DNV GL, 2020). The goal of the experimental design will be to contribute to filling in knowledge gaps (preliminary outline below) and will include a needed improvement of risk modelling tools applied as part of the Alternative Design process.

There are significant differences and uncertainties associated with the modelling of ignited hydrogen releases and other factors required to predict hydrogen risk. Improved understanding of the factors contributing to the hydrogen risk and the possible mitigating measures are therefore needed. This will lead to improved understanding of how fires and, in particular, inhomogeneous releases contribute to the explosion risk and the total risk picture, both for compressed gas and liquid releases.

This understanding will be important for dimensioning, modelling, and validation of leak detection, ventilation systems, and other risk mitigation measures. Early leak detection, ventilation, explosion-relief surfaces, inerting of spaces, and deluge are examples of such measures.

11.1.6 Regulatory knowledge gaps

The current status of identified relevant regulations, codes, and standards is reviewed in Chapter 6. In addition, DNV's previous review for the European Maritime Safety Agency (EMSA) of the use of FCs in shipping provides an overview of regulatory gaps for the use of hydrogen and FCs in shipping (DNV GL, 2017).

In brief, DNV and other Class society FC rules need to be further developed as knowledge and experience increase. The compilation of findings and learnings from MarHySafe in this Handbook, and future handbook revisions, will be a key enabler for this process.

It will take time before FCs are covered in the IMO framework, but in the meantime draft documents may provide some guidance. MarHySafe's next phase aims to develop the knowledge needed to start the process of drafting some requirements as the first basis for the coming standardization and harmonization process regarding procedures and requirements covering storage and utilization of hydrogen. The approach described in Section 11.2 is recommended to obtain regulations based on first principles that provide the acceptable maritime safety level in the most timely and cost-effective manner.

DNV has initiated work with a class guideline on hydrogen as ship fuel. When the draft is completed, the MarHySafe partners will be invited to join the hearing process that is part of the standard process when developing new class documents.

As part of a suggested task on early input to standardization including input to new maritime standards, it will be feasible to establish collaboration and liaison with standardization representatives; for example, relevant ISO TC 197 committees, ISO TC 8 on Ships and marine technology, and IMO.

A similar process will be needed for bunkering.

11.2 Phase 2 – Pre calculate risk assessments to develop standards

A good and complete hazard identification and assessment exercise is an important basis for the QRA. There is a need to carry out a set of full QRAs of relevant hydrogen ship concept(s) including LH_2 and CH_2 storage arrangements and the most relevant storage locations (above and below deck).

Based on experience from LNG, it is believed that certain external risks may have a significant contribution to the risk level. For example, for some ship configurations/segments, collision risk may be a dominant risk contributor. The collision risk will be influenced by ship type/operation, storage-tank volumes/configurations, and ship operations, but there is a need to understand how this will affect the risk picture for the vessel as a whole.

11.2.1 Produce set of explosion risk assessments

A set of systematic, dedicated explosion risk assessments is recommended to develop thresholds of needed ventilation rates and other mitigating and preventive measures in rooms where hydrogen can leak. This approach can also be applied to assess the other sensitivities investigating different leak frequency and ignition probability models, and other modelling approaches as needed to establish the robustness of the assessment. Ultimately, the results can be used to form the basis for development of a class rules set for maritime hydrogen.

11.2.1.1 Purpose

The purposes of such assessments can be to obtain the optimal protection and design, and to develop recommendations towards standardisation for the following:

- Establish the type and volume of gas leak scenarios at which the explosion risk becomes critical in an enclosed space with hydrogen.
- Establish the required ventilation rate and pattern given a set of possible transient leak-rate scenarios.
- Establish combined Emergency Shut Down (ESD) settings and ventilation rates that provide acceptable risk levels to obtain acceptable risk.
- Establish the required wall strengths for an enclosed space (room) provided, given ESD and ventilation rates.
- Establish when further measures are needed, such as explosion vent panels and pipe-in-pipe fuel gas systems.
- Investigate effect of different ventilation arrangements in hydrogen spaces.
- Investigate effects of different enclosure (room) volumes and arrangements of spaces.

11.2.1.2 Scope of assessment

The assessment consists of the following main steps:

- Identify representative and typical enclosures (spaces) where hydrogen leaks can occur. Two or more different room configurations should be selected and the drawings should include the planned installations with planned placement and volumes of hydrogen pipes and equipment.
- Establish possible leak scenarios considering transient leak rates, different hole sizes, and initial leak rates.
- Develop a CFD model for the space (room) including the ventilation system.
- Develop a matrix of cases with varying ventilation rates or other measures to be investigated. For each setting of the ventilation rate, perform the following CFD simulations:
  - Run ventilation simulations to establish the airflow in the room before any leak occurs.
  - Run gas dispersion CFD simulations. A set of different scenarios is necessary to include the effect of different leak locations, leak directions, and initial leak rates.
  - Run gas explosion CFD simulations with a set of different cloud sizes in the room.
  - Run the explosion risk analysis for this ventilation rate.
- Compare all explosion risk analysis results and establish what ventilation rate is required to reduce the risk to acceptable levels.
- A simple computer application or a matrix/formula can be developed where the user inserts the main room characteristics (volume, congestion, gas inventory, etc.). The program then calculates, by means of interpolation in the risk-analysis results matrix, the acceptable ventilation rate or other measures needed in the room.

11.2.1.3 Why use a probabilistic approach?

It is suggested to use a quantitative probabilistic approach because it includes a range of possible leak cases with associated leak frequency and ignition probability. This has proven necessary since hydrogen explosions can in theory create unacceptably high explosion pressures that can cause catastrophic outcomes on a ship. With a probabilistic approach, the high-consequence, low-frequency events are included in the assessment, and risk acceptance criteria are used to show that only acceptable events can happen with a frequency above the acceptable frequency.

With the more common deterministic approach, the project needs to establish a worst credible design scenario, and this can be a subjective assessment which gives an outcome that can be arbitrary and sometimes overly conservative or non-conservative.

11.2.1.4 Accuracy of approach

Models are available that can resolve with an acceptable accuracy most scenarios and effects. As a tool to investigate effectiveness of a range of designs and measures, the CFD consequence models have, in general, sufficient accuracy. The combination of transient CFD models with high-resolution risk assessments, as described in Chapter 8 and Appendix C, provides an approach with an acceptable accuracy in both the consequence and frequency part. The CFD models for gas dispersion and explosion of hydrogen are well established with validated models up to the level of DDT explosion cases. Detonation pressures that occur after a DDT are not captured in explosion CFD models; however, the approach will give a high unacceptable pressure (typically above 5 barg), which can be representative enough. The assessment of threshold values for pressures where the explosion starts to be unacceptable is the most important, and this happens before any DDT occurs at pressure typically below 1 barg. With this approach, the system will be designed to not cause explosions above critical pressures that can destroy walls or decks in the hydrogen room.

The modelling of complex dynamic effects when mitigating measures are also included can be less accurate. These can be the effects of explosion release panels; effects of deluge and explosion-pressure supressing agents; release of LH_2 in ventilated rooms, etc. For such realistic effects, it can be essential to perform experiments together with validating and updating models.

The highest uncertainty in the risk models is often in the leak frequency and ignition probability models. These models still capture large variations in hole size and the dynamic effects of a leak. Although some uncertainty is associated with the final risk level calculated, the overall risk results are well suited for comparison between different risk analyses, as long as the same approach is applied for all risk analyses. A final safety margin can also be added to the results so that the robustness of the assessment is maintained.

11.2.2 Comparison of leak frequency models

Hydrogen-specific data is needed to estimate more reliable frequencies for hydrogen leaks. This is important input data in all quantitative risk analyses. Leak frequencies depend on the equipment, its use, its manufacture, the materials used, the environmental conditions, ageing, etc. Currently, leak frequencies for hydrogen have to be estimated based on historical data for 'general' offshore equipment, typically with very different pressures and equipment dimensions. With better data, the uncertainty in risk analyses can be reduced. Previous work – such as the Hydrogen Incident and Accident (HIAD) database, and H2LL database[9] supported by the U.S Department of Energy– will provide useful input. HIAD was originally developed jointly by DNV and EU-JRC during the EC Co-funded Network of Excellence HySafe, and it is now being maintained and further developed by JRC.

The different leak frequency models will be established and reviewed, UK HSE (HSE, 2010) and HyRAM[10] at least, see information about leak frequencies in Appendix C. Typical leak frequency numbers for hydrogen systems will be calculated for each model and compared. Comparison will be performed on a typical hydrogen application for maritime use. The results will be discussed with possible differences assessed.

[9] Lessons Learned | Hydrogen Tools (h2tools.org)

[10] Hydrogen Risk Assessment Model (HyRAM) | Hydrogen Tools (h2tools.org)

11.2.3 Ignition probabilities for hydrogen

It is a common belief that the ignition probability for hydrogen would be higher than for natural gas. However, the industry has neither established nor quantified the typical level of ignition probability for hydrogen leaks, nor whether or how it will be different for CH_2 and LH_2 leaks. It is therefore suggested to calculate the ignition probability for hydrogen with available models for ignition probability, and to use results from ongoing R&D projects and activities considering hydrogen. These sources include, among others, The project for Prenormative Research for Safe Use of Liquid Hydrogen (PRESLHY[11]) , H21[12], and the European Hydrogen Safety Panel (EHSP[13]) , which may release new updates on hydrogen incidents and accidents (EHSP, 2019[14]).

The available ignition probability models (JIP ignition and MISOF[14]) for natural gas include the fundamental properties of the gas so that they can be applied for any gas as long as these properties are known. Experience has shown that it is very challenging to develop a reliable basis for refinement of ignition modelling. More work is needed to close knowledge gaps regarding how environmental conditions, gas concentrations, and temperature(s) may affect ignition probabilities. For example, should LH_2 and CH_2 releases be associated with different ignition probabilities due to cryogenic/cold temperature effects?

11.2.3.1 Purpose

The purpose is to investigate 'typical' ignition probabilities for hydrogen, considering relevant maritime configurations and different sizes of leaks. These will also be qualitatively compared with established ignition probabilities for natural gas and data for hydrogen as it becomes available.

The aim is to improve the understanding of hydrogen ignition risk by developing ignition probabilities for hydrogen and using natural gas as a benchmark. This is needed to assess expected risk associated with hydrogen systems when comparable natural gas system risks are available.

11.2.3.2 Scope of assessment

The following steps are proposed:

- Establish a risk-assessment model (for the hydrogen configuration) that can be used to calculate ignition probabilities. The same risk model that is described in Chapter 11.2.1 can be applied. This includes a transient gas leak and cloud development where the volume of the combustible cloud is established from CFD simulations. The ignition probability is proportional to the combustible cloud volume, and this is used in the assessment.
- Run CFD models with a set of leak and ventilation scenarios. If this task is performed together with the task in Section 11.2.1, the same CFD simulations can be applied. If not, new cases need to be established. Cases includes gas leaks, ventilation, and gas dispersion. It is assumed that the gas ignites at variable times during the leak scenario, not only at the time of maximum cloud size.
- Establish ignition densities for relevant ignition sources in the configurations where hydrogen is present. These sources can be electric light and equipment, sparks, static electricity, etc. Such densities for hydrogen are developed in the DNV PhastRisk tool, and these can be adopted.
- Run the risk assessment tool for the relevant scenarios where the combination of cloud development and ignition density is used to calculate the final ignition probabilities.

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[11] EU FCH JU 2.0 co-funded research project on knowledge gaps for liquid hydrogen. PRESLHY ended spring 2021 and includes an experimental programme.

[12] Gas industry projects designed to support conversion of UK gas networks to carry 100% hydrogen.

[13] https://www.fch.europa.eu/page/european-hydrogen-safety-panel

[14] Modelling of Ignition Sources on Offshore oil and gas Facilities.

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H2
HYDROGEN

APPENDIX A

Learning from previous accidents

There are many examples of accidents leading to important new knowledge, and of this knowledge and understanding providing the background for developing new rules and practices. The Hydrogen Incident and Accident Database, HIAD 2.0, maintained by the European Commission's Joint Research Centre (JRC) is a database of hydrogen incidents and accidents that was first developed jointly by DNV and JRC as part of the NoE HySafe. The work on developing HIAD has recently been revitalized by the Task Force on Data collection and assessment through the European Hydrogen Safety Panel. They have released their first report (EHSP, 2019), and efforts are underway to populate HIAD with more data. It is therefore recommended that MarHySafe JDP Phase 2 follow this development for learning purposes.

The Hydrogen Incident Reporting and Lessons Learned website (H2incidents.org) database was a similar initiative maintained in the United States until 2010. There have also been initiatives towards reporting of incidents as part of EU-funded projects, but it is not known if these have been made available for analysis or learning purposes.

This section introduces selected recent accidents with potential relevance for MarHySafe. The aim is to undertake more work to ensure learning from selected past events in further phases of MarHySafe.

The events selected for inclusion here are also often mentioned in discussions related to hydrogen safety, and it is therefore of relevance to understand what actually happened in these events.

Hydrogen filling station event – Sandvika, Norway, 14 June 2019

This event happened at a three-year-old public hydrogen filling station for cars in Sandvika near Oslo. The station was located less than 10 m from a public road. The event started as a small leak, and available logs of the hydrogen tank pressure apparently showed that the initial leak lasted around 2.5 hours before an explosion occurred. It has been estimated that between 1 and 3 kg of hydrogen leaked from one of the hydrogen tanks before the leak ignited. During this period, there were no leak detections or alarms from the plant.

Although investigation of this event is not finally concluded, some learning is available. One is the importance of early leak detection and action for any small leak of hydrogen in order to prevent a more serious event. Another is that congestion could be a challenge for storage of compressed hydrogen, including in semi-confined spaces as this (the station had external walls, but no roof). Stochiometric composition of a smaller cloud in a room is a simplification usually made in modelling. This assumption, called conversion to an equivalent stoichiometric gas cloud (a parameter called Q9 for outdoors and Q8 for indoors in FLACS[18]), is not necessarily a conservative assumption. It aims to make an equivalent cloud size that would generate a similar explosion pressure, and this is a simplification for both experimental and modelling work. This is one of the sources of uncertainty which should be investigated further.

FIGURE A.1

Picture showing the source of the failure that eventually led to an explosion.

The root cause of the initiating leak was identified at two bolts that were supposed to seal the high-pressure tanks. The bolts were not mounted with the correct torque. Key learnings from this include the importance of quality control throughout the entire manufacturing process, and the importance of minimizing, and if possible reducing, confinement. This hydrogen refuelling station (HRS) will not be re-opened and the facilities are being removed from the site. UNO-X, the company that operated the station, has decided to discontinue its hydrogen operations.

Explosion and fire – California, US, 1 June 2019

This was an explosion and fire at a gas reforming plant during filling of a tanker. There were no injuries, but several trucks caught fire.

Explosion in natural gas reforming plant and forklift HRS – North Carolina, US, 7 April 2020

An explosion in a natural gas reforming plant and forklift HRS damaged 60 nearby homes. There were no serious injuries.

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[15] www.hysafe.org
[16] European Hydrogen Safety Panel | www.fch.europa.eu
[17] Sources: Budstikka local newspaper, and Teknisk Ukeblad tu.no.
[18] FLame ACceleration Simulator. Software from Gexcon, Norway.

APPENDIX B

Approval process – Design and analysis documentation for preliminary approval

Table B.1 gives a summary of design documents that may be required to be developed and submitted as part of the process towards preliminary approval. Note that the first three documents in Table B.1 may be combined into an overall document describing the vessel and hydrogen fuel system. Table B.2 summarizes analysis documents that may be required as part of the preliminary approval.

Figure B.1 illustrates the Norwegian Maritime Authority (NMA) interpretation of the input, documentation, and analysis steps required in the process to reach approval of the preliminary design for a hydrogen-fuelled vessel in Norway. Documents required by the NMA for approval of Alternative Design are listed in Table B.3.

The functional requirements that must be fulfilled according to the IGF Code (IGF Code, 2016) are listed in Table B.4.

TABLE B.1

Design documents that may be required to be submitted for approval of preliminary design (in left column) and examples in relation to maritime hydrogen systems (in right column).

Design Documents (MSC.1/Circ 1455, 2013): § 4.6.7 and § 6.1.1.1	Examples for hydrogen applications
Description of the alternative and/or equivalency design, including design basis	High-level hydrogen system description, specifications as H_2 volumes, pressures, LH_2 or CH_2, FC/ICE and inherent safety features. High-level vessel and operational description
Functional description	Functional description of relevant hydrogen system by means of text and visual illustrations by Process Flow Diagram (PFD), block diagrams, principal sketches etc.
Identification of interfaces between the design and other systems/operations	Description of interfaces with auxiliary systems (e.g., heating, cooling, ventilation, gas venting, dual -fuel systems (diesel oil or other fuels), battery systems etc.
Preliminary general arrangement drawings	General Arrangement (GA) drawing showing location of hydrogen fuel systems and auxiliary systems.
Preliminary detail drawings of subsystem	Process & Instrumentation Diagram (P&ID) covering all hydrogen systems and interfaces to other ship systems. Note: For HAZID documentation, the failsafe condition of valves should be indicated on the P&ID, and whether it is local and/or remotely operated.
List of codes and standards	List of codes and standards that are considered to be applied, with particular reference to the IGF Code. Reference is made to Part B of this Handbook for relevant regulations, codes, and standards.
Risk assessment plans	Plan for how to conduct the HAZID and quantitative risk assessment. Third-party involvement in the risk analysis is recommended.
Further design basis documents, if necessary.	Additional documentation and/or analysis may be required by the Administration or RO throughout the process. This may include, for example, a Safety Philosophy document.

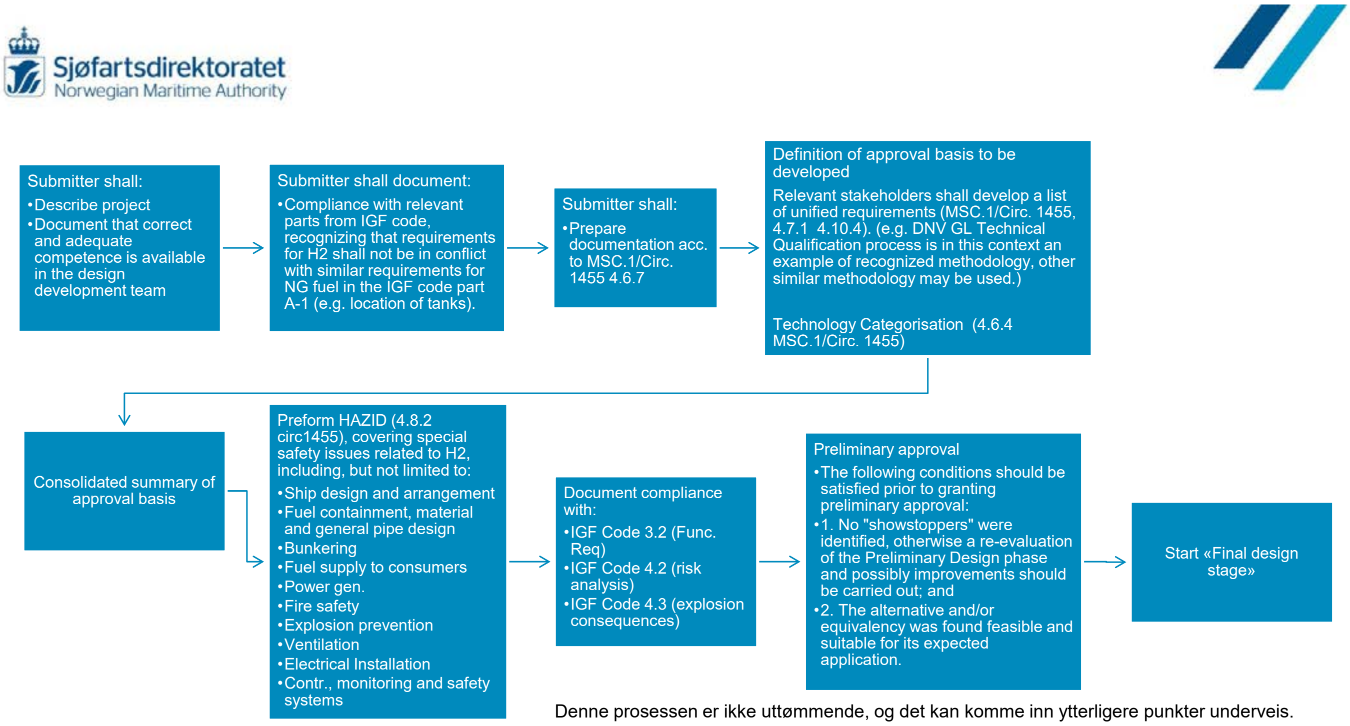
TABLE B.2

Analysis documents that may be required to be submitted for approval of preliminary design (in left column) and examples in relation to maritime hydrogen systems (in right column).

Analysis documents (ref. MSC.1/ Circ. 1455)	Examples for hydrogen applications
Gap assessment (§ 4.6.3)	The gap assessment should as a minimum cover potential gaps towards IGF functional requirements (Table B.4).
Categorization of new technology (§ 4.6.4)	The assessment should be structured by means of a 'system break-down structure' – a hierarchy of subsystems and components/equipment. For further description on categorization of new technology, see Chapter 6.2.1.
Hazard Identification - HAZID (§ 4.8.2)	Should be arranged as HAZID workshop with relevant stakeholders. Reference is made to Chapter 8.2.1 (Qualitative risk assessment/HAZID).
Quantitative risk assessment (§ 4.8.6)	A suitable risk model should be developed based on the HAZID to perform quantitative analyses. Chapters 8.2.2 and 8.2.3 describe the approaches for quantitative risk assessment and explosion risk analysis. More detailed consequence analyses and models can be applied as part of design of maritime hydrogen and fuel cell systems. Such methods (see Chapter 8.5) are used both to find cost-optimal designs and to provide the required safety documentation.

FIGURE B.1

Illustration of NMA interpretation of process for approval of preliminary design.



Submitter shall:
- Describe project
- Document that correct and adequate competence is available in the design development team

Submitter shall document:
- Compliance with relevant parts from IGF code, recognizing that requirements for H2 shall not be in conflict with similar requirements for NG fuel in the IGF code part A-1 (e.g. location of tanks).

Submitter shall:
- Prepare documentation acc. to MSC.1/Circ. 1455 4.6.7

Definition of approval basis to be developed

Relevant stakeholders shall develop a list of unified requirements (MSC.1/Circ. 1455, 4.7.1 4.10.4). (e.g. DNV GL Technical Qualification process is in this context an example of recognized methodology, other similar methodology may be used.)

Technology Categorisation (4.6.4 MSC.1/Circ. 1455)

Consolidated summary of approval basis

Preform HAZID (4.8.2 circ1455), covering special safety issues related to H2, including, but not limited to:
- Ship design and arrangement
- Fuel containment, material and general pipe design
- Bunkering
- Fuel supply to consumers
- Power gen.
- Fire safety
- Explosion prevention
- Ventilation
- Electrical Installation
- Contr., monitoring and safety systems

Document compliance with:
- IGF Code 3.2 (Func. Req)
- IGF Code 4.2 (risk analysis)
- IGF Code 4.3 (explosion consequences)

Preliminary approval
- The following conditions should be satisfied prior to granting preliminary approval:
- 1. No "showstoppers" were identified, otherwise a re-evaluation of the Preliminary Design phase and possibly improvements should be carried out; and
- 2. The alternative and/or equivalency was found feasible and suitable for its expected application.

Start «Final design stage»

Denne prosessen er ikke uttømmende, og det kan komme inn ytterligere punkter underveis.

TABLE B.3

Documents required by the NMA for approval of Alternative Design.

1.1	**M12 Machinery**
1.1.1	Fuel cell exhaust arrangement
1.1.2	Hydrogen containment system documentation
1.1.3	Fuel cell air inlet arrangement including filters
1.1.4	Bilge piping system diagram, and drainage arrangement drawing in FC module, if applicable
1.1.5	Arrangement and specifications of piping systems for gas freeing and purging of fuel cell and hydrogen piping
1.1.6	Safety relief valve sizing calculations
1.1.7	Cooling/ heating water system in connection with FC fuel system if fitted
1.1.8	Hydrogen piping and instrumentation diagram
1.1.9	Tank and capacity plan
1.1.10	Design philosophy for the machinery and propulsion arrangement
1.2	**B11 Fire**
1.2.1	Fixed gas detection and alarm systems
1.2.2	Fixed fire detection and alarm systems
1.2.3	Fixed fire extinguishing system
1.2.4	Fixed water deluge system to protect the storage tank (if applicable)
1.3	**B19 Structural fire integrity**
1.3.1	Ventilation capacity analysis
1.3.2	Mechanical ventilation system diagrams
1.3.3	Structural fire protection drawing
1.3.4	Hazardous area
1.3.5	Explosion analysis
1.4	**E16 Electrical systems**
1.4.1	Control and monitoring systems
1.4.2	FMEA
1.4.3	For ships dependent on FC systems – electrical power systems
1.4.4	Single line diagram for main power, auxiliary power and control power distribution
1.4.5	Fuel cell certification
1.4.6	Plans, particulars for the fuel cell
1.4.7	Fuel cell safety description
1.4.8	Fuel cell test procedure at manufacturer, and quay and sea trial
1.4.9	Fuel cell design criteria
1.4.10	Electrical power conductors to the fuel cell stacks documentation
1.4.11	Semi-conductor converters
1.4.12	Short circuit contribution capability
1.5	**S14 Structural**
1.5.1	Material documentation
1.5.2	Explosion analysis
1.6	**F General**
1.6.1	Reliability and availability analysis
1.6.2	General arrangement plan
1.6.3	Risk assessment
1.6.4	Functional requirements, reference is made to Table B.4
1.6.5	HAZID workshops
1.6.6	Operation and maintenance manual
1.6.7	On board test procedure of hydrogen installation

TABLE B.4

Functional requirements as provided in the IGF Code (IGF Code, 2016) Part A:3.

Functional requirements - IGF Code Part A:3
The probability and consequences of fuel-related hazards shall be limited to a minimum through arrangement and system design, such as ventilation, detection and safety actions. In the event of gas leakage or failure of the risk reducing measures, necessary safety actions shall be initiated.
The design philosophy shall ensure that risk reducing measures and safety actions for the gas fuel installation do not lead to an unacceptable loss of power.
Hazardous areas shall be restricted, as far as practicable, to minimize the potential risks that might affect the safety of the ship, persons on board, and equipment.
Equipment installed in hazardous areas shall be minimized to that required for operational purposes and shall be suitably and appropriately certified.
Unintended accumulation of explosive, flammable or toxic gas concentrations shall be prevented.
System components shall be protected against external damages.
Sources of ignition in hazardous areas shall be minimized to reduce the probability of explosions.
It shall be arranged for safe and suitable fuel supply, storage and bunkering arrangements capable of receiving and containing the fuel in the required state without leakage. Other than when necessary for safety reasons, the system shall be designed to prevent venting under all normal operating conditions including idle periods.
Piping systems, containment and over-pressure relief arrangements that are of suitable design, construction and installation for their intended application shall be provided.
Machinery, systems and components shall be designed, constructed, installed, operated, maintained and protected to ensure safe and reliable operation.
Fuel containment system and machinery spaces containing source that might release gas into the space shall be arranged and located such that a fire or explosion in either will not lead to an unacceptable loss of power or render equipment in other compartments inoperable.
Suitable control, alarm, monitoring and shutdown systems shall be provided to ensure safe and reliable operation.
Fixed gas detection suitable for all spaces and areas concerned shall be arranged.
Fire detection, protection and extinction measures appropriate to the hazards concerned shall be provided.
Commissioning, trials and maintenance of fuel systems and gas utilization machinery shall satisfy the goal in terms of safety, availability and reliability.
The technical documentation shall permit an assessment of the compliance of the system and its components with the applicable rules, guidelines, design standards used and the principles related to safety, availability, maintainability and reliability.
A single failure in a technical system or component shall not lead to an unsafe or unreliable situation.

APPENDIX C

Methodology for Quantitative Risk Assessments

Leak frequencies

This chapter introduces available sources for hydrogen leak frequency data. Leak frequencies can be obtained from collections of historical events, and such data are developed by the following organizations:

- For process equipment; UK HSE (HSE, 2010).
- For pressure tanks; OGP data (OGP, 2010).
- For dispensers and filling hoses; RIVM (RIVM, 2009) (VROM, 2005).

These frequency databases are used when assessing generic safety distances for hydrogen refuelling stations, HRS (DNV GL, 2019). The RIVM and HSE databases formed the basis for leak frequencies in HYAPPROVAL (HyApproval, 2006).

The leak frequencies are calculated for individual systems by counting the amount of equipment that can leak (pipe lengths, valves, flanges, compressors, tanks, etc.). Each equipment type has a leak frequency distribution over possible hole sizes.

Other assessments and databases are also available and used for hydrogen such as used in HyRAM (SANDIA, 2009). The SANDIA approach is deterministic and reports leak frequencies related to hole size as a percentage of the pipe flow area.

A simple comparison is performed between the SANDIA and DNV approaches to find total leak frequencies for HRS. SANDIA (SANDIA, 2009) reports a leak frequency for a 0.1% leak area for a 1000 barg HRS to be 0.06 per year. DNV (DNV GL, 2019) calculates a total leak frequency of 0.18 per year for a small leak with 2 mm hole size and a 950 barg HRS. Calculations are performed for two different refuelling stations, so the numbers cannot be compared directly. The comparison indicates that the DNV leak frequencies can be higher than the SANDIA frequencies, however a more rigorous assessment should be performed to assess the validity of the leak frequency models and relevance to a maritime environment.

Ignition probabilities and modelling

The ignition probability is used in the probabilistic risk analysis to quantify the probability of ignition given a leak. Hydrogen has different and mainly lower ignition energy and higher energy density than natural gas. Hence, it is a concern that the ignition probability will most likely be higher for hydrogen compared with natural gas, though the degree of difference is uncertain. Therefore, dedicated assessments and models for ignition probability for hydrogen need to be used.

The leak scenario with a gas or liquid leak from a hydrogen source is used as a basis when assessing the ignition probability. It is the gas that mixes with air that is ignited. Ignition can happen immediately when the leak starts, or at some time after, causing a delayed ignition. If the ignition occurs immediately once the gas leak starts, then it causes only a fire. If the ignition occurs sometime later, when it has developed a flammable gas cloud, then it is a delayed ignition and this can cause an explosion, and thereafter a continuing fire. The delayed ignition with explosion can happen quite quickly if the hydrogen leak is large. For example, an initial leak rate of 1 kg/s can generate an explosive cloud after only 2–3 seconds. If this is ignited, it can lead to a delayed ignition with explosion as early as 2–3 s. For smaller leaks, it can take longer to build up an explosive atmosphere, and a delayed ignition can happen any time as long as there is gas in the area.

In the event tree in the risk analysis, separate ignition probabilities are used for delayed and immediate ignition, because they have different consequences.

Ignition probability models for hydrogen are typically based on models that work for natural gas. Such natural gas models are available with different level of resolution. The most detailed models consider the transient development of the gas cloud and ignition sources (DNV Report no. 99-3193, 1999), (MISOF and JIP Ignition), and other models plot or tabulate the ignition probability (UKOOA and Cox, Lee & Ang). Work is ongoing in DNV to assess ignition probability for hydrogen leaks that may expose household appliances in buildings. The results will indicate whether different applications cause more ignitions with hydrogen compared with natural gas.

For use in a maritime setting, the ignition probability needs to be calculated for each case since no tabulated values are developed.

Ignition probability models are mainly developed for gas and for hydrocarbon liquids at normal temperatures. Ignition probabilities are not established for liquid hydrogen at low temperatures. Research is ongoing to investigate ignition properties for liquid hydrogen spills in the PRESLHY project. Due to the cold temperature, it may be more difficult in some instances to ignite clouds with lower than normal temperatures.

Transient ignition probability models

When the fire and explosion risk is a major risk driver, it is recommended to apply the most detailed approach involving a transient gas cloud development. This model consists of two main elements; first, the transient flammable cloud volume; and second, the ignition density of the ignition sources. The ignitable cloud volume of hydrogen is larger than for natural gas. This is because hydrogen has a wider concentration range of flammability and, in a like-for-like release, the volumetric flow rate will be higher than for natural gas. Hydrogen has a lower ignition energy for all concentrations; and for concentrations above 15%, the difference in ignition energy is significant. This needs to be accounted for when defining the densities of ignition sources. An ignition source that has a small density for natural gas will have a higher density for hydrogen. Hence, hydrogen may require the additional consideration of ignition sources that are not considered for natural gas. Examples include, among others, ignition caused by static electricity or compressibility effects in releases from high-pressure tanks.

As part of its EXPRESS tool, DNV currently uses the JIP ignition model (DNV Report no. 99-3193, 1999) that was developed for natural gas, with a modification for hydrogen. This model uses CFD simulations of hydrogen releases to find the transient ignitable cloud volume. The cloud-filling fraction in the area is multiplied with an ignition source strength for each defined ignition source in the area. The model accounts for both constant and intermediate ignition sources. The model can also account for actions that control the ignition probability by shutting down ignition sources or isolating the leak source. Hence the model can be used to assess effects of ignition and leak control.

The ignition probability model used in DNV Safeti (QRA model) is also a combination of a gas dispersion model and ignition densities.

Tabulated ignition probability

Simplified tabulated ignition probabilities can be found in the literature for hydrogen as well (Tchouvlev, 2007). However, care should be taken when using these ignition probabilities as this example only considers very small releases, and this needs to be justified by careful identification of leak frequency distribution for different release sizes. They were developed as a part of a specific DNV project for a hydrogen refuelling station that is outdoors, and the values may not be well-suited for maritime indoor releases inside a room with hydrogen.

Applied consequence analyses and models

Consequence analyses models are available in two main categories: the 3D Computational Fluid Dynamics (CFD) model; and the 1D phenomenological models, including simplified ‘rule-of-thumb’ calculations. CFD models include the highest resolution in time and space. Phenomenological models are typically limited to idealized situations where only the consequences in an open environment are considered. Simplified rule-of-thumb calculations are used to get a quick overview of the situation, and some of them are given in this Handbook.

The CFD models are used when local geometrical and gas dynamic effects need to be accounted for, whereas the 1D models are used to get a quick understanding of the potential hazards or consequences. The two models are often used in combination where first the 1D models are used to establish an overview of the risk and to point at risk drivers and high-risk areas. The 3D models are then used to assess in greater detail the effect of local geometries, dynamic effects, and safety systems.

The specific models that can be used for an accident scenario that can unfold due to a gas leak are described below. The first chapter describes a simplified rule-of-thumb and engineering assessment that can be applied to get an overview of the consequences. The following chapters describe each modelling step in more detail, with emphasis on the maturity of the available models and their recommended use. The recommended use of the more detailed models is typically as an aid to test and optimize the design and protection measures. Therefore, the different protective means and strategies are also mentioned in this chapter. A full description of the risk mitigating and controlling measures is provided in Chapter 9.

Simplified assessments of explosion consequences

To provide a quick way to get an overview of explosion risks for hydrogen applications, the following rules-of-thumb and typical assumptions are provided.

Cloud size estimate in a mechanically ventilated room

Hydrogen in a fully enclosed room or space with mechanical ventilation is considered.

The scenario with a hydrogen leak is considered. The leak can be characterized with the total amount of hydrogen that is leaking (kg). The leak size is above seeping size (larger than typically 1 g/s) so that gas with 100% hydrogen concentration will be present in some distance downstream of the leak. The amount of hydrogen is first estimated based on the initial leak rate and the duration of the leak. For a small hole size that is much smaller than the pipe size (typically a hole area less than 30% of the pipe area), a constant leak rate can be assumed until it is detected. After it is detected, the valves are closed, and the inventory volume of the segment can be used to estimate the total amount of gas that is leaking. The total amount of hydrogen is then the leak rate times the duration until detection, plus the amount of gas in the segment.

For example, if the segment contains 100 g hydrogen, and the initial leak rate is 10 g/s, and the time to detection (and isolation of the segment) is 10 s, then the total amount of hydrogen that is leaking is 200 g.

Cloud build-up inside a room with mechanical ventilation can be estimated by assuming that the hydrogen is mixing with air to form an explosive cloud. Since the combustible concentration range for hydrogen is large (4–75%) most of the hydrogen that is released will contribute to forming a combustible cloud. An example of mechanical ventilation rate typically used in a maritime setting is below 100 ACH. This rate corresponds ideally to 1 air exchange in the room every 36 s. If the leak finishes before 30 s, the ventilation will not have time to extract gas from the room. The gas will mainly be moving within the room partly towards the ventilation outlet. Ventilation in a room will set up high velocities only close to the inlet and outlet nozzles. The air movement velocity in most parts of the room is small, typically less than 0.5 m/s with 100 ACH. Figure C.1 shows a typical distribution of velocity vectors in a room with mechanical ventilation. The velocity in the room is therefore relatively low to help dilute and extract gas from a short-duration leak above a certain size. The ventilation is, however, effective enough to extract smaller seeping leaks. There is a direct relation between the ventilation rate and the leak rate where it can work effectively to extract the gas; with an increasing ventilation rate, a larger leak rate can be mitigated.

In this example, if the leak lasts longer than 30 s, gas will start getting extracted and mixed with the air. At some time, a steady-state cloud size will be established. That takes typically 1–3 minutes depending on the ventilation and leak rates.

During the initial gas build-up phase, it can conservatively be assumed that most of the hydrogen is contributing to an explosive cloud. CFD simulations performed with a 30s release and variable leak rate, leak direction, and wind conditions show that, at most, 70% of the released hydrogen is contributing to form an explosive cloud. Considering a group of large cloud size cases, approximately 60% on average of the leaked gas was forming an explosive cloud. Hence, a rule-of-thumb can be that 60% of the leaked hydrogen gas can be assumed to contribute to an explosive atmosphere (provided the leak rate and leak duration is above critical values).

The volume of the cloud can now be estimated by using the amount of hydrogen available to calculate the maximum explosive cloud volume.

The total volume of the cloud can be calculated as follows.

The mass of hydrogen from the leak (m_{H2}) is first converted to a volume of hydrogen (V_{H2}) in the combustible cloud,

$$V_{H2} = \frac{0.6 m_{H2}}{\rho_{H2}} (\mathrm{m}^3).$$

Here, it is multiplied with 0.6 since only 60% of the hydrogen is assumed to be contributing to the combustible cloud. Due to the low density of hydrogen, the volume of hydrogen in the cloud becomes large.

The total volume of an equivalent stoichiometric cloud (Vtot) can be obtained by applying 30% hydrogen in the mixture with air, and applying the volume of hydrogen in the cloud from the above equation:

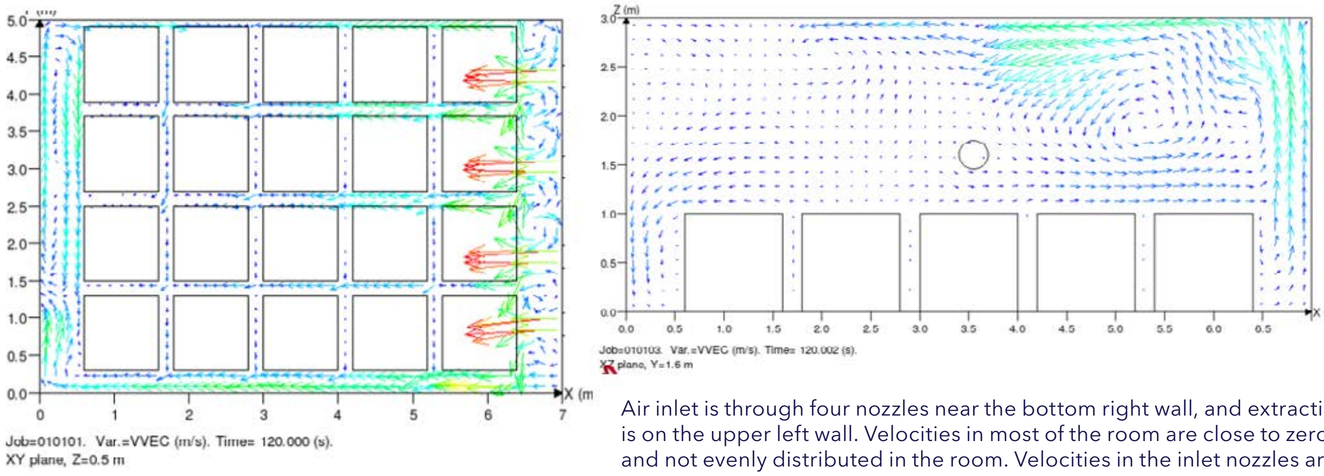
$$V_{tot} = \frac{V_{H2}}{0.3} = \frac{2 m_{H2}}{\rho_{H2}} = 22 m_{H2} \, (\mathrm{m}^3)$$

Applying hydrogen density = 0.09 kg/m^3. Here, m_{H2} is given in kg, and the constant has dimensions m^3/kg.

If the example above is used, the 0.2 kg H_2 gas will result in a cloud of 4.4 m^3.

FIGURE C.1

Distribution of velocity vectors in a room from a generic CFD simulation.



Horizontal cut

Vertical cut

Air inlet is through four nozzles near the bottom right wall, and extraction is on the upper left wall. Velocities in most of the room are close to zero, and not evenly distributed in the room. Velocities in the inlet nozzles are high, shown by red colour.

Explosion pressure in a room

In a fully enclosed room or enclosure, an explosion will generate pressure due to the production of hot combustion products that are unable to expand due to the confinement, and the pressure therefore rises. In an open environment, the combustion products would expand to eight times the volume of the original cloud. As a result, a simple linear equation with the volume of the stoichiometric equivalent flammable gas cloud (Vtot) and room volume (V) can be used to calculate the maximum pressure if confinement remains (Bjerketvedt, Bakke, & Wingerden, 1992):

$$P = \frac{8V_{tot}}{V}\ \text{(barg)}$$

Hence, in a small room, less gas is needed to generate high pressures than in a larger room. Note that a mixed cloud that is not fully stoichiometric would result in a lower expansion ratio and hence a lower pressure.

This expansion effect is about the same for different gases such as methane and hydrogen. However, for hydrogen, the combustion goes much faster and this can lead to higher pressures since the pressure rise can be too fast to allow effective venting. When the maximum pressure is reached, it will stay high until it is vented out through openings.

Pressure is also generated due to the combustion that is accelerating during an explosion. This effect is dominating in an outdoor explosion where expansion can occur, resulting in turbulent flow that enhances combustion rates.

In an intermediate sized room, both the expansion and accelerating effects can be present, causing local higher pressures than in the expansion equation. The room size where the accelerating effects start dominating is smaller for hydrogen than for methane due to the faster burning velocity of hydrogen. For hydrogen, it is indicated that the accelerating effect can contribute for rooms less than 80 m^3 in volume. Simulations performed indicate that local pressures can increase 20% above the estimates with the expansion formula. In larger rooms, the pressures can be much larger and even reach DDT and detonations.

Note that the accelerating peak pressures are local and likely short duration, whereas the pressures produced by confining the combustion products are longer duration and are applied on all walls and decks in the room at the same time.

Estimation of wall pressure

The two equations above can be combined and the wall pressure can be expressed by the available amount of hydrogen in a leak:

$$P_{wall} = \frac{176\ m_{H2}}{V}\ \text{(barg)},$$

where m_{H2} is given in kg, and V is the room volume in m^3. Note that the constant also has dimensions.

If the wall strength is 0.5 barg (which is a typical number), the maximum mass of hydrogen that can leak is:

$$m_{H2max} = 0.0028\ V\ \text{(kg)}$$

A 80 m^3 room, can maintain its integrity with a gas leak involving a mass release up to 0.22 kg H_2. It should be noted that this mass needs to be released in a relatively short time period. This does not apply to long-duration releases where the ventilation has the ability to continuously remove the hydrogen from the room.

Summary – critical mass of hydrogen and other measures

In summary, the above example indicates that a typical maritime room with normal ventilation can only survive a leak with below 220 g hydrogen in total for a moderate and short duration gas leak. In the example quoted earlier of a moderate leak of 10 g/s with quick gas detection and isolation of the leaking pipe segment after 10s, this quantity of hydrogen would be released by a small pipe segment containing just 100g of hydrogen. That is, 100 g is released before valves are closed and 100 g after.

A formula for the mass of hydrogen that can leak without causing the walls to break can be written as:

$$m_{H2max} = \frac{P_{wall} V}{176}\ \text{(kg)}$$

Where Pwall is the pressure on the bulkhead or deck that will cause it to break open (default 0.5 barg as a typical wall strength when no reinforcements are applied), V is the volume of the room in m^3. The maximum mass of hydrogen, m_{H2max} (kg), is the sum of hydrogen that is released before ESDVs are closed and the rest of the hydrogen in the segment after ESDVs are closed.

The formulas can be used to obtain a quick estimate of the segment size that can be mitigated with typical (low) maritime ventilation conditions. A larger room can accommodate a larger segment size since the gas can expand more without generating high pressures. The above rules-of-thumb can hence be used to assess if the segment sizes are small enough to prevent a critical explosion with normal ventilation conditions. Due to the rapid leak and cloud development for hydrogen, normal ventilation rates are not sufficient to dilute the gas, hence the formula above does not account for the ventilation rate. With increased ventilation rates, the maximum amount of hydrogen that can be tolerated would also increase. If the segment size and total amount of gas that can leak is larger, then other measures also can be investigated.

Ventilation is a much-used measure. With an increased ventilation rate, the segment size and the amount of hydrogen gas that can be mitigated increase. A study with gas dispersion in the room can be performed to quantify the relations between total amount of hydrogen gas, initial release rate (or release duration), and needed ventilation rate. A proper CFD model of ventilation, leak, and dispersion is recommended to develop such a relation. It is then possible to establish rules for needed ventilation rates in typical hydrogen rooms and with typical segment sizes (GL, 2019a).

Further description of measures is covered in Chapter 9 and in Chapter 11.2.

Leak inventory and leak rate assessment

Models for calculation of leak rates from a pressurized system given a hole size are available and tested for hydrogen. Comparisons performed typically show that models with pure gas or liquid are reliable when using standard, textbook gas dynamic or liquid equations. As for other fluids, the shape of the hole and the CD factor can vary, and that can have an influence on the leak rate assessment. It is however normal to consider a round hole shape as representative since this is normally what is used for validation of the models. Approximate release rates are plotted in Figure C.2 using standard thermodynamic equations with constant properties. The release rate for methane is also plotted, indicating an increase in the release rate due to the increased density.

The thermodynamic properties of the gas can be important for leak rate calculations and these are typically available for pure hydrogen and gas mixtures using tabulated values or thermodynamic equilibrium packages such as HYSIM or CHEMCAD.

It is important to calculate the rapid changes in leak rate of hydrogen with a dynamic approach so that the correct time dependent amount of gas leak is found. Hydrogen can be stored at extreme high pressures, and the leak rate vs. time profile can therefore be important for the gas dispersion calculations.

The effects of the safety systems such as gas detection and shutdown valves, or the effect of manual closures, also need to be accounted for.

A normal approach to calculate the leak rate in a QRA is to use the initial leak rate as a constant leak rate until the shutdown valves are closed, and calculate the further reduction in the leak rate until the segment is emptied. This can be conservative for large hole sizes (larger than typically 10% of the pipe area) which in reality can give a reduction in the leak rate before the shutdown valves are closed. This approach works well for smaller hole sizes.

If only one or two hole sizes are used as representative in the risk assessment, the selected hole size is often decisive for the outcome of the risk assessment. Hence, to avoid the dependency, it is recommended to apply a higher resolution in the leak sizes in the risk assessment. It can improve accuracy to select five or more initial leak rates (or hole sizes).

Traditionally in QRAs it is common to use three representative initial leak rates – small, medium, and large – to assess the risks. Typical examples from natural gas are 0.5, 5 and 50 kg/s. In order to avoid results being dependent on the selected initial leak rate, it is best to select a range covering the possible span of leak rates.

Leak rates can then be selected that approximately double the leak rate for each step up, and cover two orders of magnitude. For hydrogen it can be recommended to start with a lower leak rate than for natural gas, and a good starting point would be to use the following leak rates: 0.05, 0.1, 0.2, 0.5, 1, 2, >5 kg/s.

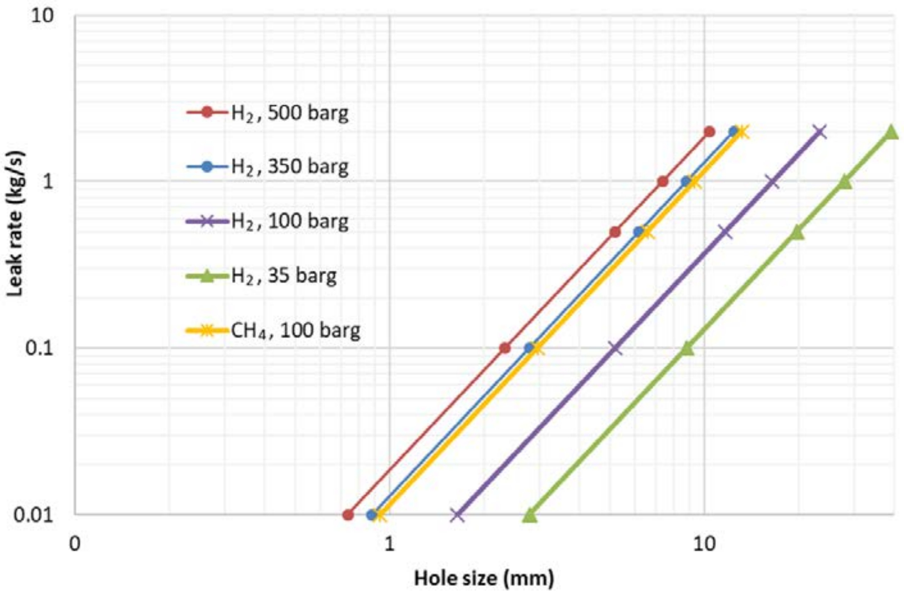


FIGURE C.2

Approximate leak rate as a function of hole size for different constant pressure reservoirs for hydrogen. The leak rate for methane is plotted for 100 barg. A CD factor of 0.8 is used in these calculations.

Mechanical and natural ventilation modelling

Mechanical ventilation inside a room with hydrogen can be an important measure to reduce the fire and explosion risk. Modelling of airflow in the room is performed with CFD as an aid to ensure a good flow that can remove any leaking gas quickly. Modelling is used to optimize ventilation systems to prevent dead zones and regions with recirculating air that can build up flammable gas clouds, also for small leaks. In regions with dead zones or slow recirculating air, it is possible for a smaller leak to generate larger clouds as long as it is not detected and is allowed to generate a larger flammable cloud over time. If it is found that a dead zone exists, it can be suggested to add gas detectors, or improve the ventilation ducting and -rate so that local ventilation conditions are improved. The CFD modelling can be used to suggest and test where improvements would be most effective.

Natural ventilation is also modelled with CFD when a gas leak can happen outside (bunkering or storage above deck). Modelling of geometry elements that can influence the gas dispersion and therefore models is used to obtain a layout configuration that gives best ventilation conditions.

Available CFD models are well suited for such ventilation modelling both inside a room with forced ventilation and outside with natural ventilation.

The wind/air-flow modelling is usually performed before a gas leak scenario is started and is used among initial conditions for the gas dispersion simulations.
Gas dispersion modelling

To have control of gas dispersion is the main and most complex issue when it comes to explosion risk control and mitigation. Since hydrogen explosions can cause large damage if the gas cloud is of sufficient size, most efforts need to be made to prevent build-up of critically large gas clouds.
Hydrogen has a different speed of sound, flammability range, and ignition energy than common gases, hence it is important to capture these properties in the model. This can be achieved with CFD and advanced ignition probability models.
The purpose of gas dispersion modelling is to generate an overview of the size of the flammable gas cloud from possible hydrogen leaks. The volume of the flammable cloud is primarily dependent on the amount of gas that is leaking and the duration/speed of the leak. The time history of the gas leak (leak profile) is hence important to include in the modelling. This leak profile should be representative for the actual piping system that leaks. Pipe diameters, pressures, temperatures, and inventories are the main properties that decide the leak profile. The leak can then be characterized by parameters such as initial leak rate (kg/s) and the total mass of gas leaked (kg) given a shape of the leak profile. When the gas is released, the ventilation rate and airflow pattern in the room or in a semi-open area is decisive for the gas cloud development. A poorly ventilated area can build up a critical cloud from a very small leak, whereas a well-ventilated area can dilute the gas from a relatively large leak.

Other parameters such as leak location, leak direction and ventilation rate (wind speed) are also important for the gas cloud size, hence several gas dispersion simulations should be performed so that these effects are also captured.

The modelling of gas dispersion of hydrogen with commercial CFD tools is as good as for other gases. 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 (lower flammability limit) concentration can be used to represent flammable gas clouds.

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 perform experiments to validate the CFD and leak models for realistic scenarios with gas dispersion. Such experiments can provide validation based on a few cases, and this can make the use of CFD models more reliable when such models are used for a large number of cases. Such experiments can reduce the need for safety margins in the dispersion modelling, possibly resulting in reduced need for costly safety measures.

There are principles that can be used to develop generic gas dispersion properties for hydrogen clouds in a room or in a naturally ventilated area. Such principles can be utilized to develop, for example, generic rules for the need for ventilation and gas shutdown systems, etc. An approach to develop such rules is proposed in Section 11.2.1.

Gas dispersion modelling with phenomenological models is used for outdoor releases such as from vent stacks. These models are also available for hydrogen gas (in Phast, for example) and are typically validated for idealized conditions. If vent stacks are located away from geometry elements, the models can be used to decide safety-zone sizes around vent stacks, etc. A margin is typically included by using 50% LFL as the concentration at which the size of the flammable cloud is found. Since these models do not include geometry effects, they can only be used for open conditions. The models are not dynamic and therefore not well suited to capture transient development from, for example, a full-bore rupture that reduces the leak rate rapidly.

Explosion modelling

Vapour cloud explosion modelling is performed to find the pressures that can occur on walls and areas near the location of gas clouds. The pressures are then used to assess the structural response on walls and decks and, based on this, the need for reinforcement or explosion venting can be assessed.

CFD models should be used for the area close to the gas cloud to find the explosion pressures. As no other tools than CFD exist, performing experiments is the only other way to find the maximum explosion pressures near the source. Phenomenological models such as the Multi-Energy (ME) method (used in Phast, for example) are used to calculate the pressure reduction as a function of the distance from the source. These models need the source pressure as input.

Commercial CFD codes (e.g., FLACS and KFX Exsim[19]) for hydrogen explosion are validated for different experiments indicating that the models are capturing the general trends although discrepancies exist. 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. The trend with increasing pressures at increasing cloud size is captured in the range of interest up to a critical explosion pressure for hydrogen. Deflagration to Detonation Transition (DDT) is not captured by the models, however; this effect usually starts happening at higher pressures than are acceptable for maritime constructions (at and above 1 barg overpressure). If pressures of 1 barg and above are predicted from flame acceleration (not confinement as in enclosed rooms), it should be assumed that DDT will occur. Therefore, CFD models can be used to capture explosion pressure as a function of the cloud size in the relevant pressure ranges. Explosions that reach DDT and detonation above 1 barg are critical, and it is relevant, though not essential, to be able to accurately predict how high pressures are reached. Measures need to be implemented to prevent DDT and detonation. Research on DDT and detonation for hydrogen in realistic environments is needed to better understand how this can be modelled.

When a detonation occurs, it becomes self-sustainable within a gas cloud. This means that a deflagration can start within a congested region and develop to a DDT before the edge of the congested region is reached. In the case when a detonation is reached within the congested region, it can also continue with a very high-pressure detonation outside the congested region as long as there is also a flammable gas cloud outside that region. If it is only a deflagration in the congested region, then the explosion will die when it reaches beyond the congested region. A large gas cloud which extends outside a congested region can therefore cause a more severe explosion than a small deflagration that is restricted to the congested region. Therefore, it is essential to prevent the onset of detonation within a congested region. As hydrogen is more reactive and has a much higher burning velocity than hydrocarbons other than acetylene, the onset of detonation can happen earlier than for other gases. DDT cannot happen in realistic conditions with methane. CFD explosion modelling can be used to indicate when DDT might be possible, and to design the safety systems (ventilation, gas detection, ESD, etc.) that can prevent such limits being reached.

There are several parameters in addition to the cloud size that affect the explosion pressure, and which also need to be included in the modelling. These are the cloud location, ignition location, cloud shape and cloud gas concentration. Variations in explosion pressure caused by these parameters are often larger than the variations that occur due to uncertainty in the models. To be able to capture the explosion pressures that can occur it is therefore necessary to run a larger number of cases where the contributing parameters are varied. Results can then consist of hundreds of scenarios, and statistics are used to assess the impact in a risk analysis framework.

Phenomenological models such as the ME method are well suited to calculate the decay of pressure away from the combustible region. A common approach combines CFD models for near and intermediate field, and ME method for the far field.

Other types of explosion, such as pressure tank rupture explosions and boiling liquid expanding vapor explosions (BLEVEs) can also cause critical consequences. Such phenomena are typically modelled with simplified phenomenological models (e.g., in Phast). These models have few or limited validations for hydrogen when it comes to realistic, larger scales. In cases when such explosions are driving the risk, it is therefore recommended to perform experiments to investigate consequences. In typical risk assessments, these phenomena are not found to be driving the risk; therefore, extensive use of the models is not normally needed, and development of models is not prioritized.

Projectiles from explosions

Loose or weakly fixed objects can become projectiles and cause damages and fatalities during explosions. Established models for this phenomenon are lacking. Research to better understand these consequences is needed so that they can be protected against. Typical strategy is to design areas with sufficient strength that projectiles from explosions are avoided.

In areas where explosions can take place, everything needs to be properly fixed. This can be piping and equipment; structural elements and plates; and, firefighting and other safety equipment, etc. The use of hydrogen areas for temporary storage should be prevented. Wall and deck plates, windows, and window frames also need

[19] KFX Exsim - Kameleon FireEx Exsim. Software from DNV.

to be properly fixed and have the strength needed to ensure that plates or window frames do not become projectiles and flying objects.

The explosion simulations give the pressure and drag forces that can be used to design walls, windows, piping and structural elements, etc.

Fire modelling

Hydrogen has some different fire characteristics than other gases and liquids, though the fire differences are less pronounced than the explosion differences. Considering pure hydrogen, a small fire has an invisible hot flame with no smoke. The temperature inside the flame is higher than for natural gas. For larger fires, the flame becomes radiative, with a red or white flame. The radiation level is then comparable to natural gas. These characteristics need to be accounted for when detection, protection, and firefighting means are established. In many cases, a hydrogen fire exposes other substances or materials causing it to be visible and produce smoke.

Fire modelling is typically performed in areas where fires can occur in order to find the extent and amount of fire protection needed, and to develop strategies for fire ventilation, escape and evacuation, rescue and firefighting, etc.

A fire in a room with hydrogen can have damaging and catastrophic consequences, hence it should be prevented or reduced to a minimum. Since a gas leak and explosion can have even worse consequences than a fire, the strategy is typically to cool down the objects within the fire and not extinguish it. Modelling can be performed to assess the effects of fire protection methods such as Passive Fire Protection and deluge in order to establish the best distribution and volumes of the water flow.

CFD models for gas fires in complex rooms and areas are used to address the consequences and protection means. One of the most advanced models is DNV's Kameleon FireEx – KFX, often referred to as KFX. This model is well established for hydrocarbon fire application and is also validated for some hydrogen fires. Research is ongoing and needed for further development of CFD codes for prediction of complex hydrogen fires.

Phenomenological models for hydrogen jet fires are also available (e.g., Phast). These models are used for open jets where no effects of obstacles are present. The size of jet fires can be predicted.

The primary protection against a fire's impact on structure is to reduce the duration and size of the fire. Typically, fires that last less than five minutes will cause limited damage to steel structures. Longer-duration fires are therefore primarily prevented by the use of ESD and blowdown to a safe location.

Active Fire Protection (AFP) and Passive Fire Protection (PFP) are also used to protect against fires in areas and in cases when a fire risk is present. Some AFP means (deluge and water mist) can also be modelled with CFD. The optimization of PFP can be performed by simulating both fire impact and structure response with 3D CFD and Finite Element (FE) tools. This way PFP can be added only where it is needed. This can reduce the cost and weight of the installation, and also reduce the effect of corrosion under insulation (CUI), which can be difficult to detect. It should be noted that there are currently no confirmed testing procedures for PFP in hydrogen applications.

In areas where a fire can lead to escalated events (e.g., rupture of pressurized fuel storage tanks), the fire can be of long duration, and there may also be potential for secondary large explosions. Here, there is a need to prevent this from happening. If this is within an enclosed room, strategies involving inerting or shutdown of ventilation can be used. The fire can then be suffocated, or it follows the air and burns at the outlet of the room where it meets air. When this strategy is used, it is important to have a method to flush out the hydrogen gas after the leak is finished. An inert gas is needed for this since mixing in air can cause a secondary explosion that can be critically large. The design of such systems can be performed with CFD tools. Other strategies for storage-room fire protection are to reduce the flow from a leak to a level that does not create a flammable cloud. This can be done in combination with a ventilation system.

Cryogenic flow modelling

Storage of hydrogen in liquid form (LH_2) involves a temperature as low as -253 °C. This is colder than any other fuel gases and therefore poses other protection and modelling challenges. The phenomenon is investigated with testing and experiments, though modelling capabilities of special effects due to hydrogen is limited. The effect caused by condensation of nitrogen and oxygen together with water vapour is special for hydrogen, and can be present for larger liquid spills. One concern is that liquid oxygen can mix with hydrogen and cause an even more explosive atmosphere when it is evaporating. Also, Rapid Phase Transition (RPT) when LH_2 is spilled on water may be possible causing physical (non-combustion) pressure waves in the atmosphere and underwater (to be confirmed by the SH2IFT project[20]). A large cryogenic spill in itself may be critical if it falls or is sprayed on unprotected steel. The cool temperatures can cause many materials to become brittle and, if they are under stress, they may undergo brittle failure. Selecting of correct grades of steel and protection may be needed in areas where this can occur.

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[20] Safe Hydrogen Fuel Handling and Use for Efficient Implementation (SH2IFT). See https://www.sintef.no/projectweb/sh2ift

[21] KameleonFireeX-LNG, KFX-LNG specialist CFD tool for LNG pool spread and fire from DNV.

It is possible to undertake modelling of LNG with adapted software (for example a special version of KFX called KFX-LNG[21]). It is then possible to model the spread of cryogenic liquid on a surface, as well as the evaporation and downwind dispersion of natural gas. Spray leaks of LNG can also be modelled with KFX, including cooling effects when the cool spray hits structural beams. Such models are not yet developed for LH_2 services. Research and development are needed to investigate effects of LH_2 with realistic scales and geometries, and to develop and validate models.

Some Cryogenic Spill Protection (CSP) materials exist for LNG services. However, CSP materials are not commercially developed and tested for LH_2 services (at least to DNV's current knowledge). The effects will depend on the LH_2 leak size and duration; but due to the fast evaporation rates of LH_2, this effect will be smaller than for LNG. Liquid hydrogen has additional potential consequences due to condensing out and freezing N_2 and O_2 from the air. The effects of this are uncertain and need further testing to improve the knowledge.

Structural response modelling

Structural response modelling may be needed to consider possible rapid pressure pulses and possible consequences of heating of structures due to fires originating in hydrogen and non-hydrogen areas. Depending on the design case, this may therefore include exposure of non-hydrogen areas caused by hydrogen-related events, and how non-hydrogen events may affect the hydrogen-related areas/systems.

Other potential external risks to the onboard hydrogen systems including the storage will need to be addressed. Potential cryogenic/low temperature effects in case of LH_2 leakage may also need to be addressed.

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Summary – consequence modelling status

When considering scenarios from the perspective of the gas leak, ventilation, dispersion and explosion, these phenomena are captured with commercial CFD models for hydrogen up to a deflagration. DDT and detonation modelling effects are not well captured. However, DDT is a critical situation that should be prevented before it happens. Hence, its accurate modelling may not be required in a typical design process.

Hydrogen fires can be modelled and the modelling is validated for some cases.

Models for effects of complex, active mitigating and preventive measures are typically not well validated for hydrogen services. This is the case for pressure release panels, deluge on gas detection to prevent explosion pressure build-up, and other complex measures that involves multiphysics effects.

Phenomenological models are available for jet dispersion and fires for hydrogen.

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