METAFUEL – MARINE ALTERNATIVE FUELS

Risk-Based Safety Framework for Methanol, Ammonia & Hydrogen

12/2025

EXECUTIVE SUMMARY

Purpose and Scope

Project METAFUEL aims to provide a practical, evidence-based methodology to enable maritime stakeholders to select and implement the safe use of methanol, ammonia, and hydrogen as alternative fuels on both retrofits and newbuild ships.

The project identified the fuel properties and unique hazards associated with the use of such fuels during ship operations, from bunkering through to use at the ships' engine room. Hazard identification and risk assessment was carried out using HAZID and bowtie analysis to identify the hazards associated with all fuel handling systems and operations, and the systems required to control them. This process was further informed by drawing on information from a literature study of existing hazard identification material from various relevant sources, as well as a visit to a methanol-fuelled ship and discussions with existing ship operators.

A regulatory overview of IMO guidelines and Classification Society rules was carried out to provide the basis for a detailed gap analysis of the safety aspects associated with each fuel which are not considered sufficiently prescriptive in current regulatory guidelines. This was initiated by mapping the safety considerations for each fuel handling zone, the requirements for the systems required to control and mitigate the risk of associated hazards, and the gaps in the regulatory guidelines. A stakeholder decision support tool and a gap analysis matrix of the current development stage of ship fuel handling zones was developed. The decision support tool can be used by maritime industry stakeholders to make safety decisions that meet their specific needs and that are up to date based on the current IMO regulations and guidelines. A gap analysis matrix is designed to evaluate the readiness and maturity of each segment of the fuel handling value chain at a high-level.

Two examples selected from a gap analysis carried out in developing the decision tool are used to highlight how research institutes, such as DBI, can help address areas where existing IMO legislation and Classification society guidance is not sufficiently prescriptive. These examples were chosen to demonstrate how testing and CFD simulation by maritime and safety research institutes can provide guidance to industry regulators to provide prescriptive rules and enable projects to obtain faster approval through use of data from testing and CFD tools to support design, approval, and operations.

What was analysed

1. Fuel Properties and Hazards. The properties of alternative fuels and the associated unique hazards that must be considered when such fuels are used on board were mapped. These properties include minimum ignition energy, flammability, auto-ignition temperature, toxicity, storage state, dispersion behaviour, and material properties (e.g. methanol–elastomer attack, ammonia stress corrosion, hydrogen embrittlement).
2. Fuel Handling Architecture. A common four-zone reference architecture was developed for the project, as follows:

    1. Bunkering station and transfer to storage
    2. Storage tank, tank connection space and transfer to fuel preparation room
    3. Fuel preparation room and transfer to engine room
    4. Engine room.

In addition, interfacing systems (e.g. ventilation and detection systems) common to all zones were identified.

3. Design risk management. A risk-based approach was proposed for informing and optimising the safe design of a ship by ensuring that the risks of major accidents such as fire, explosion and toxic release are systematically identified, assessed and managed based on the principles of process safety. This approach has been used in the project to identify the safety functions required to prevent, control or mitigate the risk associated with major accidents associated with the alternative fuels considered in the project and to map the impact of the properties of those fuels on the requirements for safety functions.
4. Regulatory and Standards Framework. The requirements of the IGF Code, IMO interim guidelines (methanol MSC.1/Circ.1621; ammonia MSC.1/Circ.1687), and Class Rules (DNV/LR/ABS/BV), noting EU policy drivers (FuelEU, EU ETS) and relevant ISO/IEC/ATEX references were reviewed to provide a benchmark for the gap analysis to identify areas where more prescriptive rules are required for the use of alternative fuels.
5. Human Factors Engineering. A visit was paid to a methanol ship comprising a walk-through of the ship's fuel handling zones and held informal discussions with crew on how the properties of methanol affect how fuel is handled, both in day-to-day operations or when things go wrong. It was noted how alarms, ventilation and procedures are used in practice, and how layout or access can affect human actions and responses. This information was used to provide recommendations on how human factors should be considered during ship design and operation.

Deliverables

- A library of requirements for each of the safety functions controlling or mitigating the risk associated with major accidents, mapped against each fuel's unique properties, for each of the fuel handling zones of a ship.
- Fuel-specific tables that translate properties into zone-specific risks and functional requirements (e.g. methanol's low flashpoint and low-luminous flame → LEL + flame cross-zoned detection; NH_3 toxicity → dedicated drains/neutralization & intake isolation; H_2 buoyancy/low MIE & LH_2 cryogenics → high-level detection, detonation/flashback protection, vent-mast siting).
- A gap analysis comparing the safety function requirements with what is prescribed by current guidance and legislation, highlighting where guidance is goal-based, ambiguous, inconsistent, or missing — particularly regarding detector alarm levels/placement, ventilation requirements, shutdown actions on ventilation failure, vent mast siting, sizing of pressure relief devices, double-wall annulus monitoring, drainage/effluent segregation, static-control programs, fire protection and hydrogen materials/cryogenic specifics.
- A decision support tool to help maritime industry players achieve faster project approval and for regulators to develop prescriptive rules for the industry.
- A gap analysis matrix designed to evaluate the readiness and maturity of each segment of the fuel handling value chain. The gap analysis matrix uses the technology readiness level (TRL) framework to provide a clear picture of which areas are technically mature, and which require further

standardization, testing, or regulatory development before widespread adoption can occur.

Evidence from Testing and Simulation

- Methanol fire suppression tests. Controlled pool fire trials showed that (i) nozzle K-factor and spray geometry materially affect cooling and extinguishment; (ii) centreline application with higher K-factor achieved full extinguishment in the test matrix; (iii) even without extinguishment, correctly tuned mist significantly improves tenability (ambient temperatures decreases). This output can be used to inform local application design, setpoints, and verification.

- Ammonia dispersion simulation (port case). Scenarios for ship-to-ship and pipeline-to-ship bunkering under summer/winter and storage modes show that semi-refrigerated releases yield larger initial vapour clouds and longer lethal ranges than fully refrigerated releases, that offshore footprints exceed those on land, and that winter tends to shorten footprints. These gas dispersion analysis results help to support siting, standoff distances, intake management, and emergency planning.

What this means for design and approval.

- A zone-based, fuel-specific architecture, combined with application-specific cause and effect logic and a risk-based approach to safety in design, is essential to demonstrate equivalent safety where legislation text is incomplete.

- Human Factors Engineering shall be integral to ensuring safe operations and emergency response, including alarm quality/consistency, SIMOPS/bunkering task design, access/egress in PPE, and training that reflects the specific properties of each fuel type (e.g. low-visibility flames (methanol), toxicity (NH_3), and rapid escalation (H_2)).

- The decision support tool allows industry stakeholders (e.g. owners/designers/ports/regulators) to select fit-for-purpose measures for safe design and operations.

Priority Gaps to Address for All Fuels and Required Future Work.

1. Detection and ventilation: Clearer definitions of detection alarm levels, detector geometry, auto-boost, and shutdown actions on loss of ventilation.
2. Ventilation and pressure relief: Processing-first hierarchy, two-phase PRD sizing, and no-re-ingestion siting validated by gas dispersion analysis.
3. Double wall/annulus management: Continuous monitoring, purge/extraction, and conditions for restart.
4. Suppression systems: This should reflect to the specific flammability and toxicity aspects of each fuel.
5. Ignition source control: Continuity bands, insulation-flange philosophy, survey methods.
6. Drainage/effluent segregation and proof of capacity for wash-down/mist runoff (incl. alcohol-containing water and cryogenic condensate/ice).
7. Materials verification (NH_3 corrosion, H_2 embrittlement, LH_2 MDMT/anti-icing) and proof-testing.

Roadmap (High-Level).

The METAFUEL Roadmap outlines near term, medium term, and long-term actions to guide safe implementation and regulatory alignment of alternative marine fuels.

- Near term: Focus on enabling safe approvals of methanol, ammonia, and hydrogen projects under existing frameworks through consistent, evidence-based risk assessments. Strengthen documentation, quantify safety functions, and apply experimental and simulation data to validate designs. Early coordination between shipyards, Flag State, Classification Societies, and port authorities ensures aligned criteria and reduces uncertainty.
- Medium term: Build on early experience to standardize evaluation methods and certification protocols across the industry. Develop shared risk assessment models, harmonized testing standards, and open data frameworks to improve consistency, transparency, and trust in alternative-fuel safety practices.
- Long term: Transition from risk-based approvals to globally targeted prescriptive rules. Integrate validated data and methodologies into IMO regulations and Classification Society guidelines, establishing quantitative performance benchmarks. Enable digital, continuously updated frameworks that embed real-world learning and support a stable, scalable shift to carbon-neutral marine fuels.

Conclusions

The METAFUEL project gives industry stakeholders a clear, defensible risk-based pathway between the properties of alternative fuels and hazards associated with them to safe, class-ready designs, based on systematic evidence and a decision tool that turns high-level goals into ship-specific, verifiable solutions for methanol, ammonia, and hydrogen.

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Prepared by: LST, JCS, GSK, RMM, PEV, MPJ, SEM
Reviewed by: BAV
Approved by: THU

Responsible for revision: PEV, RMM, LST

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1. INTRODUCTION

The global maritime industry is undergoing a fundamental transformation as it moves to align with international decarbonization targets set by the UN, IMO, and EU. Shipowners, engine manufacturers, equipment suppliers and ports are preparing for a rapid shift toward low- and zero-carbon fuels, supported by an expanding regulatory framework and accelerating commercial demand. Among the most promising candidates for near and medium-term adoption are methanol, ammonia, and hydrogen. These are fuels that offer substantial potential for reducing greenhouse gas emissions, but which also introduce new and significant safety challenges when compared to conventional marine fuels.

While experience exists from carrying these fuels as cargo, their use as fuel introduces different operational contexts, equipment, and hazard pathways. Alternative fuels possess hazardous properties that fundamentally alter the fire, explosion, toxicity, and materials-related risk landscape on board ships. Methanol's low flashpoint and near-invisible flame, ammonia's acute toxicity and corrosiveness, and hydrogen's wide flammability range, low ignition energy and cryogenic storage challenges each require robust design, verification, and operational strategies. At the same time, current guidelines and prescriptive requirements remain incomplete, fragmented across interim IMO circulars, evolving class rules, and non-harmonized industry practices. The pace of the green transition means that stakeholders must make well-informed safety decisions now, even as standards continue to mature.

The METAFUEL project was established to address these challenges by developing a systematic, evidence-based methodology for identifying, evaluating, and managing the safety implications associated with methanol, ammonia, and hydrogen when used as marine fuels. The project combines literature review, hazard identification, bowtie analysis, regulatory assessment, human factors evaluation, and scenario-based testing and simulation to build a coherent decision foundation for ship designers, owners, ports, regulators, equipment manufacturers and other maritime stakeholders. A key outcome is a decision support tool and a gap analysis matrix designed to assist maritime stakeholders in assessing fuel-specific risks, understanding system maturity levels, and selecting appropriate safety measures for both newbuilds and retrofits. The work aims to provide clarity where existing rules are goal-based rather than prescriptive, enabling stakeholders to demonstrate safety equivalence and accelerate regulatory approval.

This report documents the methodology and results of the METAFUEL project. It is structured to move from foundational knowledge, through hazard analysis and safety function mapping, to decision-making tools and evidence from simulation and testing. The structure is as follows:

- **Chapter 4** provides a detailed review of the hazardous properties of methanol, ammonia, and hydrogen, including their flammability, toxicity, dispersion behaviour, and materials compatibility.
- **Chapter 5** introduces a common four-zone fuel handling architecture (bunkering, storage, preparation, engine room) which forms the basis for the safety analysis across the three fuels.
- **Chapter 6** sets out the risk-based design methodology, including hazard identification (HAZID/HAZOP), qualitative and quantitative risk assessment, consequence modelling, and the application of inherently safer design principles.
- **Chapter 7** presents insights from Human Factors Engineering, based on operational observations and crew input, highlighting how crew behaviour, alarm quality, visibility, ventilation, and task design influence safe fuel handling.

- Chapter 8 summarizes the regulatory and standards framework for methanol, ammonia, and hydrogen, identifying where existing requirements are prescriptive, performance-based, or absent.
- Chapter 9 defines the safety functions required to prevent, control, or mitigate major accidents and maps these safety functions to the hazardous properties of each fuel type.
- Chapter 10 introduces the integrated decision support framework, which synthesizes safety functions, regulatory expectations, and hazardous properties into a structured assessment tool for stakeholders.
- Chapter 11 presents a gap analysis matrix evaluating the maturity of safety-critical systems across the alternative fuel value chain using a Technology Readiness Level (TRL)-based approach.
- Chapter 12 provides scenario-based testing and simulation results, including methanol fire suppression trials and ammonia dispersion modelling, to demonstrate where empirical evidence can support design and approval.
- Chapter 13 outlines a roadmap for near-, medium-, and long-term actions to support safe and scalable deployment of alternative fuels.
- Chapter 14 concludes the report by summarizing key findings, implications for the maritime industry, and the transition pathway toward prescriptive rules.

Collectively, these chapters form a comprehensive framework for understanding and addressing the safety implications of alternative fuels on board ships. They also provide practical, evidence-driven guidance that can support the maritime sector in achieving safe, timely, and economically viable decarbonization.

2. ABBREVIATIONS

Abbreviation	Definition
ABS	American Bureau of Shipping
ACH	Air Changes per Hour
AEGL	Acute Exposure Guideline Level
AFE	Advanced Fire Engineering
ALARP	As Low as Reasonably Practicable
AR-AFFF	Alcohol-Resistant Aqueous Film-Forming Foam
BLEVE	Boiling Liquid Expanding Vapour Explosion
BOG	Boil-off Gas
BRC	Breakaway Release Coupling
BV	Bureau Veritas
CCR	Central Control Room
CFD	Computational Fluid Dynamics
CH_2	Compressed Gaseous Hydrogen
DBI	Dansk Brand- og Sikringsteknisk Institut (Danish Institute of Fire and Security Technology)
DBB	Double Block and Bleed
DDT	Deflagration to Detonation Transition
DNV	Det Norske Veritas
EaT	Energy and Transport
EMSA	European Maritime
ER	Engine Room
ERC	Emergency Release Coupling
ESD	Emergency Shutdown
EU	European Union
FAT	Factory Acceptance Test
FKM	Fluoroelastomer (fluorocarbon rubber)
FMEA/FMECA	Failure Modes and Effects Analysis / Failure Modes, Effects and Criticality Analysis
FPR	Fuel Preparation Room
FVT	Fuel Valve Train
GHG	Greenhouse Gas
GVU	Gas Valve Unit
H_2	Hydrogen
HAZID	Hazard Identification
HAZOP	Hazard and Operability
HFE	Human Factors Engineering
HP	High Pressure
HVAC	Heating, Ventilation and Air Conditioning
ICE	Internal Combustion Engine
IACS	International Association of Classification Societies
IDLH	Immediately Dangerous To Life or Health
IGF Code	International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels
IMO	International Maritime Organization
ISD	Inherently Safer Design

Abbreviation	Definition
LEL	Lower Explosivity Limit
LFL	Lower Flammability Limit
LH_2	Liquid Hydrogen
LNG	Liquefied Natural Gas
LSA	Life-saving Appliances
LOPA	Layers of Protection Analysis
LP	Low Pressure
MOBAT	Mobile Battery Testing Unit
MoC	Management of Change
N_2	Nitrogen
NBP	Normal Boiling Point
NH_3	Ammonia
NIOSH	National Institute for Occupational Safety and Health
NTP	Normal Temperature and Pressure
PPE	Personnel Protective Equipment
PRD	Pressure Relief Device
PVs	Pressure Valves
RRM	Risk Reduction Measure
QRA	Quantitative Risk Assessment
SAT	Site Acceptance Test
SIMOPs	Simultaneous Operations
TCS	Tank Connection Space
UFL	Upper Flammability Limit
UN	United Nations

3. DEFINITIONS

Term	Definition
As Low As Reasonably Practicable (ALARP)	The cost, in terms of money, time and effort, of implementing further risk reduction measures is grossly disproportionate to the benefit gained, in terms of lifetime risk reduction.
Boiling Liquid Expanding Vapour Explosion (BLEVE)	A sudden explosive release of expanding vapour and boiling liquid due to the catastrophic failure of a vessel that resulted from an external fire, corrosion, a manufacturing defect, or internal overheating [1].
Catastrophic Rupture	A physical explosion in which a sudden failure of a pressure vessel results in a blast.
Deflagration	A phenomenon in which combustion products propagate at the velocity below the speed of sound through the unburned mixture. Mainly characterised by a weak ignition source and laminar flame which creates either gradually rising overpressure or an overpressure with multiple peaks decreasing overtime.
Deflagration to Detonation Transition (DDT)	A mechanism created due to a disturbance or turbulence caused by an obstruction in an enclosed environment. The obstruction forces the formation of a shockwave and propagation of accelerated flames with a pressure peak that exceeds steady state detonation.
Detonation	A phenomenon when the combustion propagates through the gas mixture above the speed of sound with a shock wave travelling ahead of the flame front. The detonation mechanism requires a strong ignition source.
Electrical fire	A fire occurring due to a static electricity discharge or due to an electrical fault or failure.
Flash Fire	A sudden, intense fire caused by ignition of a mixture of air and a dispersed flammable substance.
Hazard	A potential source of harm (e.g. activity, situation, substance) to people, environment, assets or reputation.
Hazard Identification Study (HAZID Study)	A team-based study to identify the hazards and hazardous scenarios associated with a system or process. HAZID studies assess the system or process from a "top-down" perspective using a set of guidewords to prompt the team to identify and assess hazards and identify suitable actions for risk reduction to manage the associated risk.
Hazard and Operability Study (HAZOP Study)	A team-based study to identify potential safety and environmental hazards and operability issues associated with an industrial, chemical process. A set of guidewords are used to prompt the team to examine deviations from normal process conditions in a systematic and structured way.
Hierarchy of Controls	A method for identifying and ranking measures to protect people from hazards, arranged from the most to least effective.
Inherently Safer Design (ISD)	A design philosophy whereby the design focuses on the top of the hierarchy of controls (i.e. eliminate, substitute or isolate/separate) to "design out" hazards and prevent and control incidents, rather than relying on the use of additional engineering and administrative controls or PPE.
Jet Fire	A flammable high-pressure liquid or gas leakage released in a particular direction that is ignited.

Term	Definition
Layers of Protection Analysis (LOPA)	A tool used to determine the need for additional risk-reduction measures based on the risk remaining after existing safeguards.
Performance Influencing Factor (PIF)	Any condition that influences performance. These can be individual, job or organisation related. These factors can make human error more likely, leading to hazardous incidents.
Pool Fire	A fire involving an ignited flammable liquid spill resulting from a loss of containment or leakage from a vessel or pipeline.
Pressure Peaking Phenomena	A phenomenon occurring when a light gas (e.g., hydrogen) is released from a large orifice into an enclosure and the available ventilation is insufficient to exhaust the inflow. The resulting pressure rise can reach levels capable of destroying the enclosure within seconds [3].
Risk Acceptance Criteria	The level of risk considered acceptable, defined prior to conducting a risk assessment.
Risk Reduction Measure (RRM)	A physical or non-physical measure implemented to prevent, control, or mitigate a hazardous event.
Safety Function	The function of a system designed to prevent, control, or mitigate the risk associated with a hazard (e.g., containment, gas detection, escape). It is delivered through a combination of technical (equipment, systems, structures), operational (procedures, information), and organisational elements (competence, training, communication).

4. FUEL PROPERTIES AND HAZARDS

4.1. Purpose of the Chapter

The transition to methanol, ammonia, and hydrogen introduces fundamentally different hazard profiles compared to conventional marine fuels. Their behaviours under normal and abnormal conditions including ignition sensitivity, dispersion, toxicity, storage-state transitions, and interactions with materials shapes the design of safety systems across the four fuel-handling zones defined later in Chapter 5.

This chapter describes the physical, chemical and toxicological properties of methanol, ammonia, and hydrogen that are relevant to safety. These properties form the scientific foundation for:

- Design risk management (Chapter 6)
- Human Factors (Chapter 7)
- The Safety Functions (Chapter 9)
- Scenario-based testing and simulation (Chapter 12)
- Regulatory gaps (Chapters 8)
- Zone-specific safety function requirements (Annex C)

Understanding hazard behaviour is essential for ensuring that each safety measure or operational control directly corresponds to a real, measurable property of the fuel.

4.2. Comparative Overview of Alternative Fuels

Table 1 highlights the main relevant properties of each fuel, compared to methane, while a detailed description of the properties and hazards associated with each fuel can be found in Sections 4.3, 4.4, and 4.5.

Table 1. Comparative Overview of Fuel Properties (Methanol, Ammonia, Hydrogen, Methane)

Fuel Properties			Methanol	Ammonia	Hydrogen	Methane
Flammability*	Minimum Ignition Energy (mJ)		0.174	40-170	0.017	0.274
	Flammability range (Lower and upper) vol. Fraction in %		6.0-36.5	15.0-28.0	4.0 - 77.0	5.3 - 17
	Auto-ignition temperature (°C)		385	650	585	537
	Laminar burning velocity (m/s)		0.48	0.07	2.7	0.37
	Limiting Oxygen Concentration (LOC) with nitrogen inerting (% volume)		11.5	15.5	5.0–5.5	12.0
	Flashpoint (°C)		11–12	-	-	-
Storage, release and dispersion	Normal Boiling Point (°C) - NBP		64.7	-33.4	-253	-162
	Physical state (NTP)		Liquid	Gas	Gas	Gas
	Storage state		Liquid	Compressed gas/Refrigerated liquid	Compressed gas/Cryogenic liquid	Compressed gas/ Cryogenic liquid
	Density (Kg/m^3)	L, NBP	791	682	70.85	450**
		G, NBP	-	0.89	1.312	1.819
		G, NTP	1.332	0.708	0.0838	0.6594

Fuel Properties			Methanol	Ammonia	Hydrogen	Methane
	Viscosity (zo) at NTP		544.0	253.6	8.76	11.2
	Heat of vaporisation (Enthalpy of Vaporisation) at NBP (kJ/kg)		1,100	1,370	445	510
	Cryogenic expansion ratio - Liquid at NBP/gas (NTP)		-	850	847	600**
	Specific gravity	L (Water:1)	0.791	0.682	0.071	0.45
		G (Air: 1)	1.11	0.59	0.07	0.55
	Toxicity - IDLH (ppm) as defined by NIOSH		6,000	300	Asphyxiation	Asphyxiation
	Corrosiveness		Mild	High	Low	Low to None
	Greenhouse potential		CO_2 emitted upon combustion	Indirect GHG (NO_x emissions)	None	CO_2 emitted upon combustion
	Odour		Slight alcohol smell	Pungent, strong odour	Odourless	Odourless
* Flammability ignition and combustion properties for air mixtures at 25 °C and 101.3kPa ** Average value used hence may vary depending on LNG composition Gaseous fuels do not have flashpoint values since they are already gaseous at ambient conditions.						
L = Liquid G = Gas NBP for methanol is blank since methanol is a liquid at NBP. Cryogenic expansion ratio for methanol is blank since methanol is a liquid at NTP.						

4.3. Methanol

Methanol is an alcohol-based fuel that has been commercially available for decades, primarily as a feedstock in the chemical industry. In recent years, it has gained renewed interest in the maritime sector as part of the industry's decarbonization strategy. The global maritime industry is actively seeking alternative fuels to meet ambitious greenhouse gas reduction targets and regulatory requirements from IMO. From an operational perspective, methanol's handling differs significantly from conventional fuels such as marine diesel oil, both in terms of safety requirements and crew training. The IMO's Interim Guidelines for the Safety of Ships Using Methyl/Ethyl Alcohol as Fuel (MSC.1/Circ.1621) underscore the importance of a structured understanding of its hazardous properties before widespread adoption.

Methanol holds substantial promise as a marine fuel due to its relative availability, logistical advantages, and potential to contribute to emissions reduction goals. Nevertheless, its hazardous properties - low flashpoint, wide flammability range, toxicity, and unique fire behaviour - underscore the necessity of robust design, monitoring, and operational safeguards. With proper mitigation measures, methanol can be adopted safely within the maritime sector, but its risks must be carefully addressed through regulation, ship design, and human factors such as training and awareness.

4.3.1. Flammable Characteristics

One of the most defining properties of methanol is its low flashpoint of approximately 11 to 12 °C, which is well below the ambient temperature in most marine operating environments. This means that methanol can readily form flammable vapour-air mixtures under normal conditions. Its flammability limits in air extend from 6 to 36 percent by volume, a much wider range than that of diesel or LNG, which significantly broadens the conditions under which ignition may occur. Although its auto-ignition temperature, at roughly 464 °C, is relatively high and reduces the likelihood of spontaneous ignition, methanol vapours remain highly susceptible to ignition by common shipboard heat sources. Perhaps the most concerning from an operational standpoint is methanol's nearly invisible pale-blue flame, which is extremely difficult to detect without specialised flame sensors, posing additional challenges for fire response crews.

4.3.2. Fire Hazards

The characteristics of methanol fires differ in important ways from those involving hydrocarbon fuels. The near invisibility of a methanol flame creates an immediate risk for personnel working in open deck areas and enclosed engine spaces, as visual detection is unreliable. Furthermore, while the heat release rate of methanol is lower than that of marine gas oil, methanol's complete miscibility with water allows spilled fuel to spread rapidly, thereby expanding the fire's footprint. Standard foam suppression systems used for hydrocarbon fires are less effective against methanol flames, and water spraying only dilutes the fuel rather than extinguishing the fire. Compounding this, methanol fires can release toxic combustion products, including carbon monoxide and formaldehyde, which significantly increase health risks to crew in confined spaces.

4.3.3. Explosion Hazards

The explosion risks associated with methanol primarily arise from the formation of vapour clouds. In poorly ventilated compartments or confined spaces, methanol vapours can accumulate quickly within their broad flammable range. The minimum ignition energy of methanol vapour is only 0.14 millijoules, meaning that even a small electrostatic discharge or contact with a hot surface can trigger ignition. While the explosion energy of methanol vapours is generally lower than that of natural gas, the consequences of a confined-space explosion are nonetheless severe, leading to structural damage and possible casualties. Bunkering operations are of particular concern, as the transfer of methanol between ship and shore tanks presents multiple opportunities for vapour release.

4.3.4. Non-flammable Hazards

In addition to its flammability, methanol poses serious non-flammable hazards, most notably its toxicity. Methanol is highly poisonous to humans when ingested, inhaled, or absorbed through the skin. Ingestion of 10 to 30 millilitres may be fatal, and even smaller quantities can cause irreversible blindness. Chronic exposure is equally concerning, as methanol is metabolized in the human body into formaldehyde and formic acid, which damage the optic nerve and central nervous system [4]. From a materials standpoint, methanol is corrosive to certain metals, including zinc and aluminium, as well as to elastomeric materials commonly used in seals and gaskets. Consequently, methanol-compatible materials must be used in tanks, piping, and pumps to ensure operational safety.

4.3.5. Properties Related to Storage, Release, and Dispersion

Methanol's storage requirements differ substantially from LNG and other alternative fuels, as it can be stored at ambient temperature and pressure. Nevertheless, tanks should be designed with inert gas blanketing or nitrogen systems to prevent the formation of flammable atmospheres. Bunkering operations should consider the risk of leaks and vapour release, necessitating the use of double-walled transfer lines, drip trays, and continuous leak detection systems. Methanol is readily biodegradable and miscible with water. In the event of a release at sea, methanol will dissolve fully in water, dispersing quickly but also creating an acutely toxic to aquatic organisms. This means that spills may create significant localised impacts despite the fuel's relatively rapid dispersion in water. In the atmosphere, methanol vapours are initially heavier than air, which can lead to hazardous low-level accumulation on decks before eventual dispersion by wind.

4.4. Ammonia

Ammonia is an essential chemical, with applications across multiple industries, including agriculture, refrigeration and cooling, chemical manufacturing, and water treatment. Its versatility and availability make it one of the most significant industrial chemicals worldwide.

Ammonia is emerging as a promising solution in the context of maritime decarbonization. The International Maritime Organization (IMO) has identified ammonia as a potential alternative fuel for the shipping industry due to its carbon-free combustion. However, its adoption poses significant technical and safety challenges that must be addressed before large-scale implementation. To overcome these hurdles, international organisations, research bodies, and private companies are actively engaged in developing technical standards, safety protocols, and updated codes of practice [5].

At standard temperature and pressure conditions, ammonia is colourless toxic gas. Ammonia has a boiling point of -33.34°C at 1 atmospheric pressure (atm.), meaning below these conditions, it becomes liquid. Ammonia gas is lighter than air, with a specific gravity of 0.588 (air = 1). Hence, it will eventually rise in the air after being released into the environment. Ammonia has a distinct pungent odour, making it easy to detect and an important safety feature. As a liquid, ammonia is colourless and transparent as well [6].

4.4.1. Flammable Characteristics

Ammonia gas is generally not considered a highly flammable product because of its high autoignition temperature of 651°C. This is the minimum temperature at which a flammable substance will spontaneously ignite without an external ignition source, such as a flame, spark or hot surface. Consequently, ignition sources and hot surfaces near a potential release must reach unusually high temperatures before posing a hazard. Even in controlled environments, such as engine cylinders, ammonia cannot burn on its own and requires a pilot fuel to initiate combustion. For this reason, ammonia is assigned an NFPA flammability rating of 1 (slight), indicating that it must be preheated before ignition can occur [7].

The lower flammability limit (LFL) of ammonia is about 15.2% in air, while the Upper Flammability Limit (UFL) is 27.4%. Achieving these concentrations in open air is difficult; however, in enclosed or poorly ventilated spaces, such levels can be reached [7]. This explains why the NFPA 704 hazard diamond for ammonia differs depending on whether it is stored in open or closed environments. In addition, ammonia can deflagrate if released into a confined space where an ignition source is present [8].

Figure 1. NFPA 704 hazard diamond for anhydrous ammonia showing fire (red), health (blue), instability (yellow), and specific (white) hazards for (a) open and (b) confined locations [8]

4.4.2. Fire Hazards

Ammonia poses distinct fire hazards on board ships despite its relatively high ignition temperature. When released, it can form flammable mixtures with air especially in enclosed machinery spaces or areas with poor ventilation creating conditions where a small ignition source such as a hot surface, electrical arc, or static discharge may ignite it. Liquid ammonia under pressure can also rapidly vaporize into large amounts of flammable gas, increasing the fire load in a short time. Because ammonia fires burn with an almost invisible flame, detecting and responding to them can be challenging, underscoring the need for effective leak prevention, proper ventilation, and continuous monitoring onboard.

4.4.3. Explosion Hazards

A Boiling Liquid Expanding Vapour Explosion (BLEVE) can occur when liquid ammonia is stored in a pressurised vessel at ambient temperature and the vessel is suddenly depressurised. This risk is not unique to ammonia; it is a physical explosion phenomenon common to many pressurised liquids, such as methanol or liquid hydrogen [9].

Liquid ammonia expands dramatically on vaporisation—about 273 times at –10 °C and 2.91 bar, 185 times at 0 °C and 4.29 bar, and 77 times at 25 °C and 10 bar. If this phase change occurs inside a vessel or tank, the pressure can rise rapidly, potentially leading to a leak and, in the worst case, a BLEVE. Such events are typically triggered when a pressurised vessel fails or when an external fire causes the vessel to weaken. Upon vessel failure, saturated liquid ammonia is suddenly exposed to atmospheric pressure, boils violently, and rapidly expands into vapour [10].

By contrast, the risk of a BLEVE is negligible when ammonia is stored as a saturated liquid at -33°C and ambient pressure. Under these conditions, the liquid is not pressurised, so a sudden vessel rupture does not lead to the same violent boiling and pressure-driven explosion mechanism. In case of external fire, the liquid ammonia becomes vapour with a much lower process speed.

4.4.4. Non-flammable Hazards

Toxicity is the most immediate and significant hazard associated with ammonia. Unlike conventional or most alternative fuels, ammonia is highly toxic to humans.

To guide emergency response and protect public safety, the U.S. Environmental Protection Agency (EPA), through its National Advisory Committee for Acute Exposure to Hazardous Substances, established Acute Exposure Guideline Levels (AEGLs), which define threshold concentrations for airborne chemicals based on exposure duration and health-effect severity and, unlike workplace limits, apply to the general population to assess risks during accidental chemical releases.

AEGLs are divided into three tiers. AEGL-1 identifies concentrations above which individuals may begin to experience mild and reversible symptoms such as irritation or discomfort. AEGL-2 represents concentrations that could cause more serious but still reversible effects, potentially impairing an individual’s ability to escape. AEGL-3 marks concentrations at which life-threatening effects or death may occur. Each AEGL level is defined for five exposure durations, from 10 minutes up to 8 hours, highlighting that both concentration and time are critical in assessing toxic risks [11].

Table 2. Acute Exposure Guideline Levels (AEGLs) for Emergency Response [12]

Guidelines	10 min	30 min	1 h	4 h	8 h
AEGL-1	30 ppm	30 ppm	30 ppm	30 ppm	30 ppm
AEGL-2	220 ppm	220 ppm	160 ppm	110 ppm	110 ppm
AEGL-3	2700 ppm	1600 ppm	1100 ppm	550 ppm	390 ppm

Regulatory short-term exposure limits (STEL) of up to 15 mins and time-weighted average (TWA) over 8 hours are established by the respective national workplace health and safety authorities of the USA to manage the exposure of ammonia to the workers during normal daily operations at their workplace. These values can be observed in the table below.

Table 3. Regulatory Limits for Ammonia Exposure [6]

Authorities or Organisations	STEL 15 mins	TWA 8 hours
California Cal/OSHA Permissible Exposure Limits (PELS) from 29 CFR 1910.1000	35 ppm	25 ppm
EU Indicative Exposure Limit Values in Directives 91/322/EEC, 2000/39/EC, 2006/15/EC, 2009/161/EU (12 2009)	50 ppm	20 ppm
UK Health and Safety Executive (HSE) EH40/2005 Workplace exposure limits	35 ppm	25 ppm
National Institute for Occupational Safety and Health (NIOSH)	35 ppm	25 ppm

Ammonia has an immediate impact on the respiratory system, reducing the intake of oxygen into the body. High concentrations of ammonia can cause bronchial spasm and even pulmonary oedema, leading to asphyxiation, which can be fatal. Additionally, ammonia’s moisture-seeking properties cause severe irritation to mucus membranes such as the eyes, nose, and throat. The effects of ammonia exposure at different concentrations on humans are summarised below:

Table 4. Effects of Ammonia Exposure [13]

Ammonia concentration in air (by volume)	Effects
20-50 ppm	Readily detectable odour
50-100 ppm	No impairment of health from prolonged exposure
400-700 ppm	Severe irritation of the eyes, ears, nose, and throat.

Ammonia concentration in air (by volume)	Effects
	No lasting effect on short exposure, aggravation of existing respiratory problems could occur
2000-3000 ppm	Dangerous, more than 30 minutes of exposure may be fatal
5000-10000 ppm	Serious oedema, strangulation, asphyxia, rapidly fatal

4.4.5. Properties Related to Storage

Liquid ammonia may be stored under the following conditions:

- Fully refrigerated ammonia
- Semi-refrigerated ammonia
- Non-refrigerated ammonia (Pressurised)

Each storage method maintains ammonia as a saturated liquid and operates within a defined temperature and pressure range:

Table 5. Storage Operating Conditions for Ammonia [6]

Storage condition	Operating temperature	Operating pressure
Fully refrigerated	-33.34 °C	1 bar
Semi-refrigerated	-10 °C to 4 °C	3 bar to 5 bar
Non-refrigerated (Pressurised)	19 °C to 37 °C	8 bar to 14 bar

In semi-refrigerated tanks, heat from the surroundings enters the system, producing boil-off that must be managed through appropriate insulation and refrigeration. The main advantage of non-refrigerated (pressurised) ammonia storage is that it does not require additional energy to keep ammonia in its liquid phase [7].

A fully refrigerated ammonia tank is designed for storing large quantities of ammonia. Depending on the design, these tanks may be built as either single-wall or double-wall structures. In a single-wall configuration, the tank is fabricated from low-temperature carbon steel and relies on an external insulation system. To ensure performance, the insulation must be completely sealed against moisture, since any ingress of air can lead to ice formation and a gradual loss of insulating capacity. Double-wall tanks, on the other hand, employ a composite design. The inner vessel is manufactured from low-temperature grade carbon steel, while the outer shell is made from conventional carbon steel. The annular space between the two walls is packed with insulating material, which enhances thermal protection and reduces the risk of heat transfer from the surroundings. Current regulations for the design of fully refrigerated tanks in Europe are:

- EN 14620 - Design and manufacture of site built, vertical, cylindrical, flat-bottomed tank systems for the storage of refrigerated, liquefied gases with operating temperatures between 0 °C and -196 °C
- PGS12 - Innovation in Ammonia Terminal Design
- DIN 4119 - Overground cylindrical steel-tank constructions - fundamental computation methods
- BS 7777 - Flat-bottomed, vertical, cylindrical storage tanks for low temperature service
- EEMUA 147 (1986) - Recommendations for refrigerated liquefied gas storage tanks

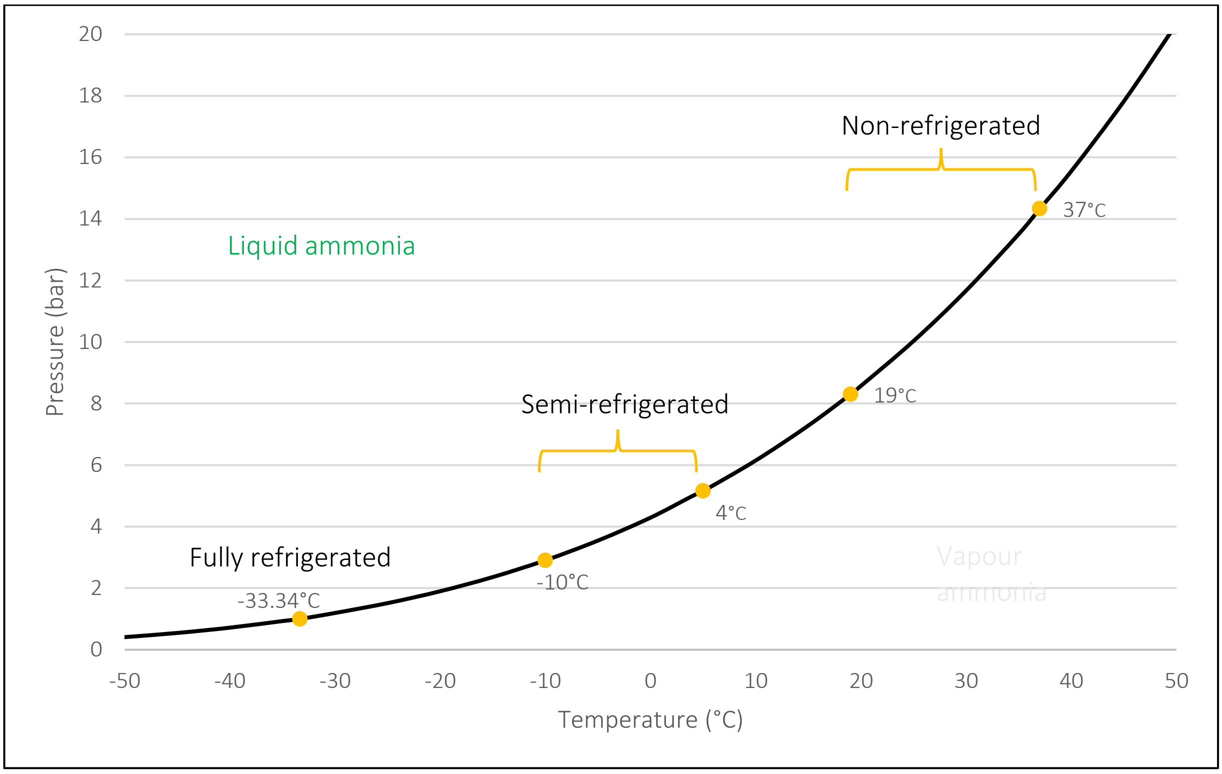


Figure 2. Ammonia vapour pressure at gas-liquid equilibrium (saturated liquid). [10]

4.5. Hydrogen

Hydrogen is an odourless, colourless, and tasteless gas at standard temperature and pressure that burns with an invisible flame and therefore requires specific gas and fire detection solutions. It is also non-toxic and non-corrosive. It is the most abundant element in the universe representing 90% of all matter by volume. Hydrogen is highly buoyant and diffusive and readily mixes with air upon release. The buoyancy is considered favourable for releases in unconfined spaces but may result in an unfavourable situation in confined spaces or in spaces with high accumulation [12].

Since the combustion product of hydrogen is water vapour, hydrogen is considered a clean and environmentally friendly fuel carrier. The gravimetric energy density of hydrogen is approximately 2.5 times that of natural gas of the same quantity. Due to its very low volumetric density, however, storing large volumes and quantities of hydrogen is a challenge, as 1kg of hydrogen occupies a volume of approximately 11m^3 [13]. As a result, hydrogen is commonly stored in a compressed or liquified (sometimes even solid) form to reduce the space requirements for storing, transportation, and use of hydrogen as a fuel.

The ability of hydrogen to deteriorate and weaken the mechanical properties of metals is called hydrogen embrittlement. Although hydrogen is non-corrosive, it can be absorbed by metals such as steel, potentially leading to structural failure, so choosing the right containment material is essential for safety.

In addition to the inherent challenges associated with hydrogen, the hydrogen storage methods mentioned above carry their own challenges related to high pressure and cryogenic temperatures. In this document, only challenges related to compressed and liquid hydrogen are considered.

4.5.1. Flammable Characteristics

The main risk associated with hydrogen is its high flammability.

4.5.1.1. Flammability range (LFL and UFL) - volume Fraction in percentage (%)

Hydrogen has the widest flammability limits of 4% - 75% in air and 4% – 95% in oxygen, which makes it highly reactive and hazardous. In the context of safety Lower Flammability Limit (LFL) is an important parameter because it means the extent of the hazardous zone within the area. The dependence of flammability limits on the room temperature had been empirically shown to indicate that the flammability range widens in a hydrogen-air mixture as the room temperature increases. As can be seen in Table 1 above, the flammability range of hydrogen is wider than that of methane (5.3% – 17%) but the lower flammability limit is comparable. This means that a small leak of any of the two fuels from the fuel system pose a similar risk of creating an explosive atmosphere.

4.5.1.2. Minimum Ignition Energy

Hydrogen has a MIE of 0,017mJ, the lowest of any comparable fuel (like the small static-electricity shock when touching a metal door handle). The ignition energy required to ignite a mixture depends on the hydrogen-air mixture composition, so that less ignition energy is required to ignite hydrogen in its stoichiometric condition. In addition, ignition energy could further be decreased due to increasing temperature, pressure and oxygen content. Since most ignition sources produce greater than 10mJ of energy, nearly all flammable fuels will ignite when mixed with air, provided their concentration is above their lower flammability limit [13]. High energy ignition sources, such as spark discharges and explosives which generate shock waves, can directly initiate detonation.

When compared to methane, hydrogen requires significantly less energy to ignite. The minimum ignition energy of hydrogen is 16 times less than that of methane (0.274mJ) and this applies for a wide range of hydrogen concentration as shown in Figure 3.

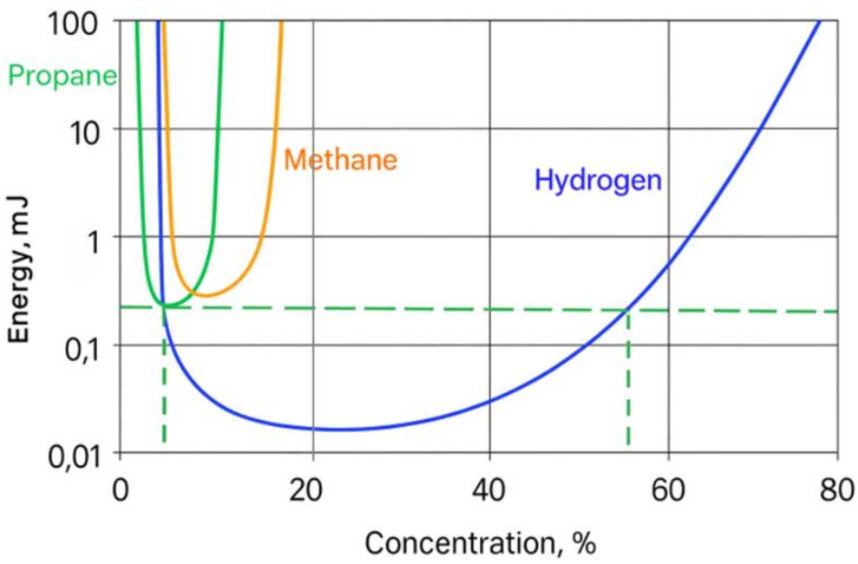


Figure 3. Ignition energy vs. gas concentration for hydrogen, methane and propane [14]

While hydrogen is used in a ship, the potential ignition sources could be a short-circuit, sparks or arches from electrical motors or switches used, and in case there is leakage or formation of explosive atmospheres. An explosive atmosphere can be ignited by static discharges if it carries enough energy. According to a 2015 research under project HyResponse [14], mechanical sparks induced from fast closing valves, sparks from catalyst particles and electrostatic discharge from particulate filters that are not grounded are other relevant ignition sources in a ship [15].

4.5.1.3. Auto-Ignition temperature

The auto-ignition temperature of a fuel is the lowest temperature at which that fuel may spontaneously ignite and combust without an external spark or flame (ignition source). Auto-ignition temperature depends on pressure and oxygen availability. It is given at standard temperature and pressure and with ideal concentration of oxygen.

According to research coordinated by IMO, between 30%-50% of all fires in merchant ships originate in the engine room and approximately 70% of these fires are caused by oil leaks from pressurised systems. These oil fires are caused by contact between the leaking oil (from large leak or small but persistent leak) meets hot surfaces that have higher temperatures compared to oil auto-ignition temperature. The hot surfaces and other heat sources that can serve as heat sources in the engine room could be engine surfaces, bearing of rotating machinery heating up or faulty electrical equipment [16].

Fuel oils have lower auto-ignition temperatures compared to gaseous and lower flashpoint fuels covered by the IGF code. Hydrogen poses different fire and explosion hazards since it is in gaseous form, or it vaporises rapidly upon leakage. Hydrogen has auto-ignition temperature of 585°C which is significantly higher than that of conventional fuel oils that are a bit higher than 200°C. The risk of fire for auto-ignited fuels is higher hence classification societies and SOLAS have a limit of 220°C as acceptable surface temperature for equipment that encounter oil.

Since most ships will be powered by dual-fuel engine that use oil as pilot fuel, the risk of IGF code fuel (in this case hydrogen), are in addition to engine room fires of pressurised oil [16].

4.5.1.4. Burning velocity

Hydrogen has a laminar burning velocity of 2.7m/s, which is seven times that of methane (0.37m/s). This higher burning velocity means that there is greater flame acceleration in congested areas. This also means higher pressures caused by resistance in confined spaces such as openings and venting ducts that hydrogen is released from. The severity of an explosion depends on several factors, the main one being the "reactivity" of the fuel. This "reactivity" is basically how fast the flame moves through a flammable mixture (cloud). Deflagration explosion results from subsonic flame propagation through the hydrogen-air mixture but when a flame travels even faster, deflagration transitions to detonation. Detonation is a self-sustaining combustion explosion in which there is supersonic flame propagation through hydrogen-air mixture. Detonation has a leading shock of up to 20bar and this causes gas compression to the point of auto-ignition. The shockwave is maintained by energy from the subsequent combustion [17].

The detonation limits of a fuel refer to a range of fuel concentrations in an air-fuel mixture where a detonation can be initiated and propagated. The factors that influence the detonation limits are the mixture composition, initial temperature and pressure, ignition source, geometry and confinement, and mixture heterogeneity [17].

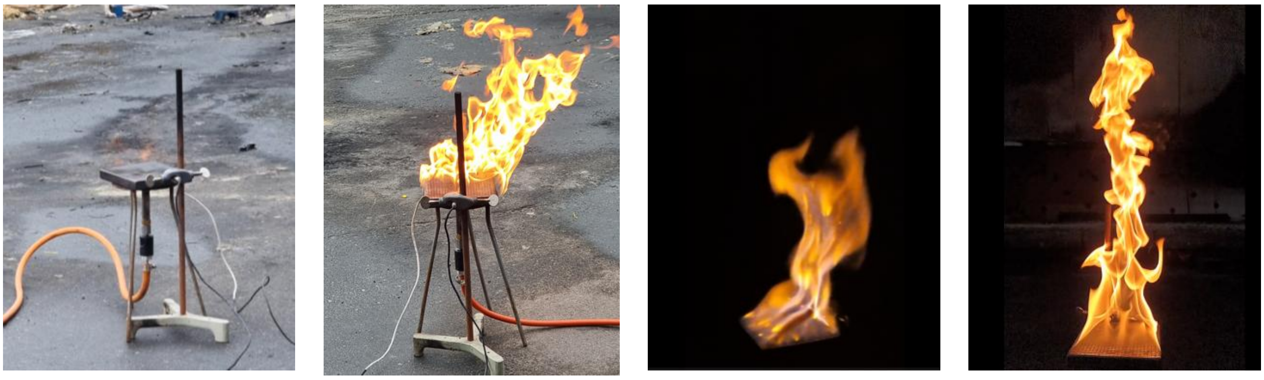
4.5.1.5. Limiting Oxygen Concentration

LOC is the minimum oxygen concentration that is required to sustain a fire or explosion within a combustible mixture, such as fuel, air, and inert gas. It can be regarded as the maximum allowed oxygen concentration of a fuel-air-inert gas mixture in which an explosion will not occur. Its units are percentage volume of oxygen (%

vol.) The LOC depends on the inert gas type, temperature and pressure. When hydrogen is used onboard ships, it is important to avoid flammable atmosphere and to achieve this, purging with inert gas is used to reduce oxygen concentrations. Hydrogen systems with LOC 5% require more thorough purging than hydrocarbon fuels which have LOC range of 11-15%. Inert gas is also used as a safety barrier to prevent ignition in secondary spaces and enclosures hence awareness is needed while developing purging procedures [17].

4.5.2. Fire Hazards

The flame produced is hot and almost invisible in daylight, with a low flame radiation. A hydrogen flame emits less radiation than a hydrocarbon flame, which means that for the same amount of radiated heat, the hydrogen flame is hotter than that for comparable fuels. As a result, objects directly within a hydrogen flame heat up more quickly. The reduced heat radiation means, however, that surrounding objects or people receive less thermal energy unless they are within the flame. Additionally, because hydrogen flames are nearly invisible, people do not physically sense the heat until they are closer to the flame than compared to a hydrocarbon fire. For comparison, hydrogen has a flame temperature of 2045˚C in air versus 1980˚C for propane. For comparison, methane has a flame temperature of 1,930 -1,980°C depending on whether it is CNG or LNG. Unlike hydrogen, propane is not a clean burning fuel, meaning combustion products and soot contribute to the burning of propane which makes the flame visible even in the broad daylight conditions, whereas hydrogen flames are barely visible in cloudy and rainy days (Figure 4) and essentially invisible during jet fire conditions on a cloudy day (Figure 5).



a) b)

Figure 4. Comparison of hydrogen and propane burning behaviour. Left to right: (a) Daylight, rainy-day conditions; (b) Indoor, no-light conditions. Images from the Burn Stuff Project archives (DBI, E&T).

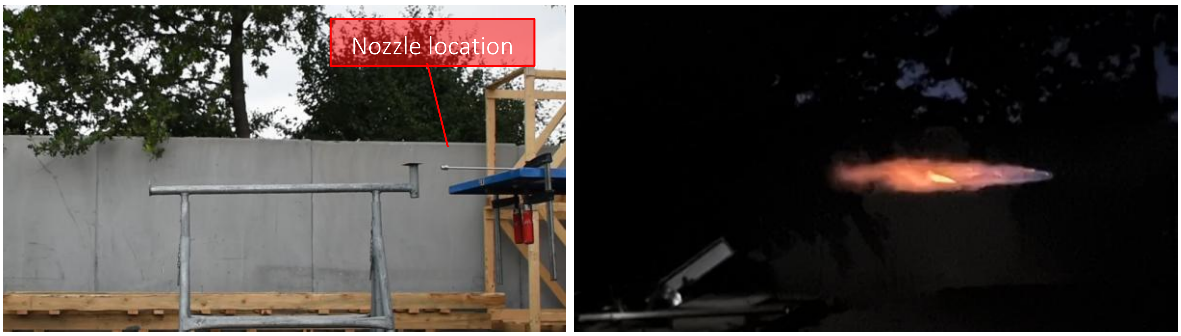


Figure 5. Low-pressure hydrogen jet fire testing under varying ambient conditions. Left: Cloudy daylight. Right: Outdoor nighttime. Images from the Burn Stuff Project archives (DBI, E&T).

4.5.3. Explosion Hazards

Hydrogen's small molecule size and low vapour density make it unique compared to other fuels. It has high buoyancy and diffusivity, causing leaking hydrogen to rise and disperse quickly in air. While this property may provide a safety advantage in an outside environment (such as in the open deck when used onboard a ship), hydrogen can accumulate in confined spaces and reach a flammable concentration at high points within those spaces. Combustion in enclosed spaces differs from that in open environments due to a significant rise in pressure. In open areas, gases can expand freely, using part of their energy to push against the ambient pressure. In contrast, in confined spaces, the energy produced during the chemical reaction stays within the system, raising the internal energy of the gas. As a result, combustion in confined environments typically takes place at higher temperatures and pressures compared to combustion in open air.

Figure 6 (retrieved from [13]) shows a comparison of the pressure waves generated for various mechanisms of hydrogen explosions. The velocities of the combustion process vary significantly which affects the pressure generation which could be in the range of few hundreds of millibar to several bar. Depending on the dispersion and congestion levels within the interest area, the explosion mechanism and magnitude can vary significantly.

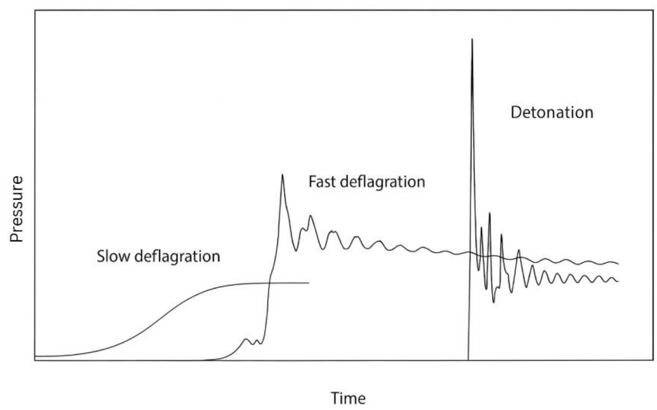


Figure 6. Profile comparison of pressure waves for hydrogen deflagration and detonation

One significant characteristic of hydrogen compared to any hydrocarbon gas is the ability to detonate and transition from deflagration to detonation. Such mechanisms require strong ignition and/or high congestion or confinement to create a high level of turbulence. Under such conditions the combustion propagates with a leading shock wave that is self-sustained and creates a peak overpressure order of magnitude higher than during deflagration. It is reported [13] that although DDT is a less likely in congested regions within open areas due to the ability of gaseous hydrogen to disperse quickly in the atmosphere, since liquid hydrogen's low temperature and a tendency of being less buoyant, hazardous concentrations tend to accumulate to higher concentrations in the open area. Hence, additional measures such as limitation of strong ignition sources, good natural or forced ventilation and less congestion should be considered.

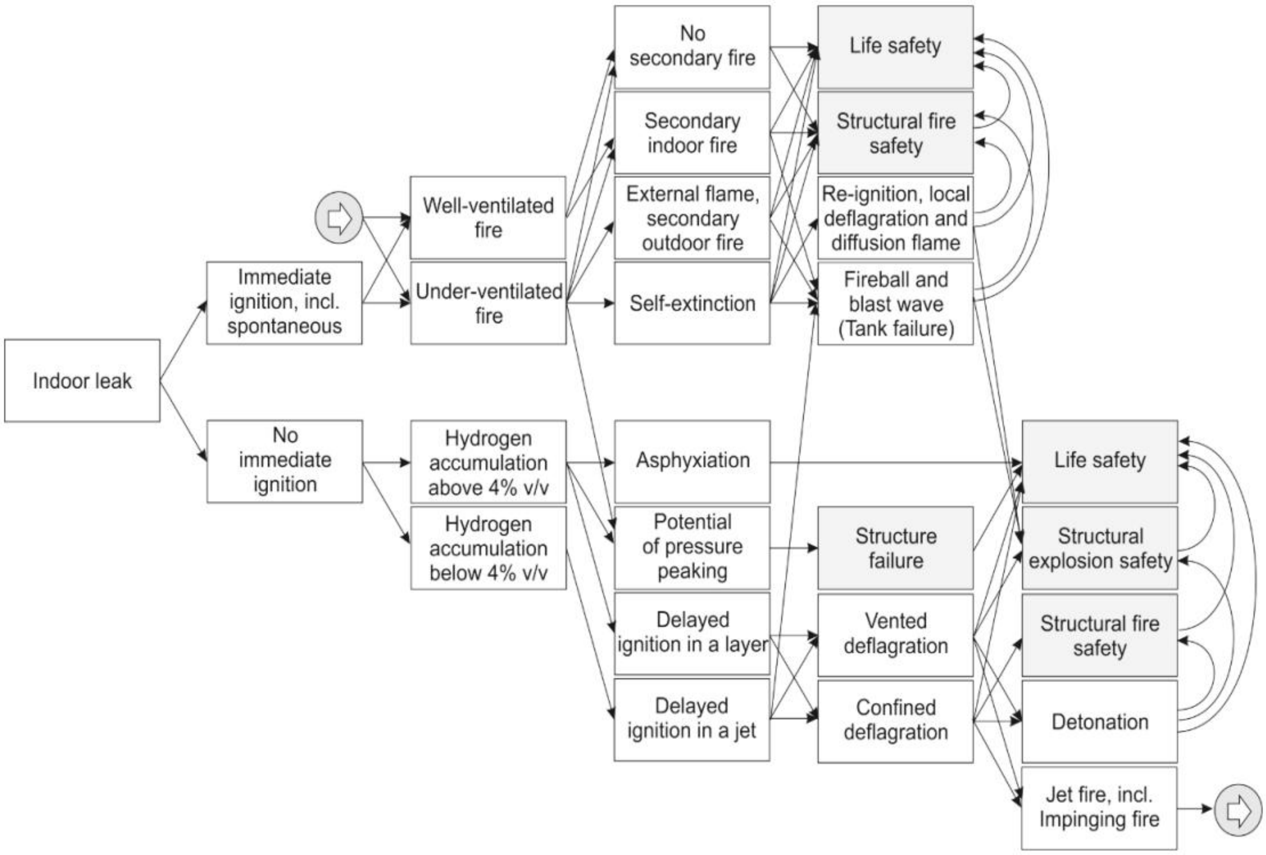
4.5.4. Non-flammable Hazards

Hydrogen is a non-poisonous, non-toxic and non-carcinogenic gas, considered as a simple asphyxiant. In confined spaces, hydrogen disperses and displaces air, which consists of 21% oxygen by volume. Oxygen levels below 19% are harmful to humans, with effects such as headache, dizziness, drowsiness, and unconsciousness. When oxygen concentrations drop below 12%, the risk of death drastically increases.

Skin contact with liquid or cryo-hydrogen may cause severe cold burns, frostbite, tissue damage and tissue death. Upon thawing frozen tissue can cause extreme pain, while even a short exposure of eyes to cold vapour could lead to instant freezing of eye tissue and permanent optic damage [13]. Exposure to a very cold gas could provoke asthma and difficulty in breathing, while extended exposure to cold hydrogen vapours could result in severe lung damage and hypothermia.

Pressure Peaking Phenomenon is a special characteristic of hydrogen that is not observed in other flammable gases. It occurs in unignited hydrogen release conditions in enclosed spaces where the hydrogen release rate is higher than can be exhausted with natural ventilation. It has been shown that overpressure build-up from rapid unignited hydrogen releases can be sufficient to have a destructive effect on buildings [15]. Special consideration should therefore be given to accidental unignited hydrogen releases and pressure peaking phenomenon while using hydrogen onboard ships.

Leakage of hydrogen onboard a ship can play out in different scenarios, and this has been studied and described in [18] as shown in Figure 7.



Note: White boxes correspond to hydrogen phenomena and grey boxes to the consequences [18]

Figure 7. Safety related phenomena and consequences.

4.5.5. Properties Related to Storage, Release and Dispersion

To implement robust safety barriers for storage and usage (distribution) of hydrogen onboard, other physical properties of hydrogen must be well understood. This is also important to predict the behaviour of hydrogen under different leakage scenarios.

4.5.5.1. Normal boiling point

The normal boiling point of a liquid is the temperature at which its vapour pressure is equal to surrounding pressure, and the liquid changes into a vapour. When the external pressure is less than the one atmospheric pressure, the boiling point of a liquid is less than its normal boiling point. When the external pressure is equal to one atmospheric pressure, the boiling point of a liquid is called the normal boiling point and when the external pressure is greater than one atmospheric pressure, the boiling point of the liquid is greater than its normal boiling point.

Liquids can change to vapour at a temperature lower than their normal boiling point through evaporation. This is a liquid surface phenomenon where the molecules near the edge escape to the surroundings as vapour. This is different from boiling where the molecules anywhere in the liquid escape and form vapour bubbles within the liquid.

The temperature at the boiling point is referred to as saturation temperature. The liquid at this stage can be saturated with thermal energy and any more addition of energy results in phase transition.

To ease storage and transportation of gases, they are liquified and stored in liquid state, and this helps reduce storage volumes. When hydrogen is cooled close to its normal boiling point, this results in Liquefied hydrogen (LH_2) with a normal boiling point of -253°C, which is 90°C colder than liquid natural gas (LNG). This creates an additional safety challenge that needs to be taken into consideration in hydrogen storage and distribution onboard a ship [17].

LH_2 is stored in vacuum-insulated vessels that minimise the heat input from the surroundings. Heat input from the surroundings causes accumulation of boil-off gas above liquid LH_2, increasing the tank pressure. When this is combined with tank's design pressure, it increases the liquid boiling point hence allowing storage for extended periods. In case of loss of insulation (partial or complete), there will be significant heat ingress inro the LH_2 tank, increased rate of pressure rise and increased boil-off rate. When the vapour pressure in the tank reaches the set point of the tank’s pressure relief valves, hydrogen vapour is released automatically, and this results in continuous discharge of hydrogen through the vent mast outlet at the open deck. The stored LH_2 and the ambient large temperature difference makes boil-off gas management a safety critical aspect that is more challenging than that of LNG. During normal ship operation, the boil-off gas management can compensate for heat input but a loss in tanks insulation can cause the LH_2 to evaporate within hours.

LNG and LH_2 can both cause embrittlement of normal ship steel (carbon steel) if exposed to leakage. There are limited studies that compare the effects of LNG and LH_2, but it is expected that LH_2 will evaporate more easily hence requiring less energy from its surroundings. The cooling down of structural material to brittle transition will almost be instantaneous when exposed to cryogenic leakages.

Additionally, another safety concern with cryogenic LH_2 is that due to its low temperature, all gases (except helium) that come in contact with LH_2 are condensed and solidified. That means that if air or any gas enters a LH_2 system, solidification causes restrictions in the piping system and interference of normal valve operation.

Surfaces that are not properly insulated, can be cooled to temperatures below oxygen normal boiling point (-183°C) hence condensing the air around it. Since this condensed air is enriched with oxygen, the flammability of any organic material with which it is in contact with increases significantly. The materials can also become embrittled. In case of an event where LH_2 is spilt in an enclosed space or loss of insulation of a hydrogen containment or piping system, the ambient temperature in these spaces drops significantly. If these spaces contain equipment that is needed for safety of the ship, it is important to ensure that they are still operational after the event.

Cryo-pumping, a process where a very cold surface (e.g., LH_2 or its cold piping) condenses or adsorbs warmer gases onto itself, it effectively “pumps” those gases out of the surrounding volume. The local pressure drops, and more gas is drawn in, which then also condenses—creating a self-reinforcing “pumping” effect. That means that large quantities of condensed or solidified material can accumulate and if at some point the system is warmed for maintenance, the material will vaporise causing a large increase in pressure or formation of explosive clouds [17].

4.5.5.2. Expansion ratio from liquid-to-gas

The expansion ratio of a liquified gaseous fuel is the volume a given amount of substance in liquified form compared to the volume of the same amount of substance in gaseous form at room temperature and pressure. Hydrogen volume increase from phase change from liquified to gaseous form is 847. LH_2 rapidly boils to gas if released to a room with ambient temperature and pressure creating an explosive atmosphere. LH_2 released into a confined space causes a pressure increase which can cause structural damage depending on leaked volume of hydrogen, volume of the space and the availability of a sufficiently sized pressure relief arrangement. LH_2 released into a confined space at ambient temperature evaporates quickly, this causes a reduction in temperature and air displacement, both which are hazardous to personnel present in that space. To avoid detrimental risk of pressure build-up of gases in hold spaces, enclosures and venting systems due to rapid evaporation of LH_2, such systems need to be designed to cope with LH_2 rapid evaporation in case of leakage [17].

4.5.5.3. Asphyxiation

Significant leakage of hydrogen causes a risk of asphyxiation due to oxygen depletion. Asphyxiant gases displace and dilute oxygen from the air, causing people to suffocate. Hydrogen, methane, nitrogen and helium are examples of simple asphyxiants. Simple asphyxiants have no other health effects apart from suffocation [12].

4.5.5.4. Hydrogen embrittlement

Hydrogen embrittlement is the degradation of a metal’s mechanical properties—especially ductility and fracture toughness—caused by absorbed hydrogen, which can lead to delayed cracking or brittle fracture under load. Hydrogen embrittlement effect is multi-factor and some of the variables that influence the extent are metal metallurgical properties, environment & chemistry, temperature and exposure time, stress & loading state of the metal, geometry & design details of the metal, hydrogen concentration, exposure mode & operations, among others. Most metals absorb hydrogen at high pressures. When steel absorbs hydrogen, it results in embrittlement, and this can lead to failures in tanks, equipment and piping systems. Hydrogen material problems are mostly related to improper material choice and welds.

Failures of hydrogen-containing components due to embrittlement can lead to release of significant amount of hydrogen with corresponding accompanying hazards such as low temperature from cryogenic release to high temperature and pressure from a potential ignition. The choice of material for hydrogen systems is a key part of hydrogen safety onboard ships [19].

4.5.5.5. Gaseous storage

Gaseous hydrogen (CH_2) is hydrogen stored in compressed form to high pressures (250-700 bar). CH_2 hence has high stored (potential) energy and release of this energy can generate strong pressure effects that depends on release rate, even without subsequent combustion. Sudden release from high pressure systems can result in spontaneous ignition without presence of apparent presence of ignition such as fire, hot surfaces, sparks etc. There is little fundamental explanation of how spontaneous ignition of high-pressure hydrogen could occur and this is still one of the main unresolved problems of hydrogen safety.

Bunkering of hydrogen from the shore introduces several safety challenges, one of them being the time taken to bunker. This can be solved by use of swappable compressed hydrogen storage units that can be recharged at the shore. This differs from the current shipping practise where fuel storage tanks are permanently on board a ship and which must be certified under the IGF code. That means there will be connection and disconnection of these tanks which increases the risk since there is no control of such tanks when not onboard and the risk of lifting off and on to the ship [17].

4.5.5.6. Density and specific gravity

Gaseous hydrogen has a density and specific gravity of 0.0838 kg/m^3 and 0.07 respectively at NTP. This means that hydrogen is 14 times less dense than air at the same conditions hence any release or leakage of hydrogen to the air means that it will rise and disperse in an open environment.

Hydrogen gas significant buoyancy becomes an asset in ship design since when released to the atmosphere, it rises and disperses rapidly. Special consideration is needed however when hydrogen vapours at cryogenic temperature is released since saturated hydrogen is heavier than air and hence remains close to the ground until the temperature rises [20].

Hydrogen has the smallest, lightest molecule of any gas and this means that it permeates through materials, passes through smaller leak paths, diffuses more rapidly in surrounding media, and has greater buoyancy than other gases. This means that released hydrogen tends to rise and diffuse but if confined, it accumulates in high spots and reach potential ignition sources such as ceiling lights. Since leaks are always a concern, hydrogen vessels and piping systems require good seals.

At NBP, LH_2 has a density of 70.85 kg/m^3 and a specific gravity of 0.07085 meaning it is 14 times lighter than water. When LH_2 absorbs heat from the surroundings, its volume increases a property indicated by coefficient of thermal expansion, which at NBP is 23 times that of water for ambient conditions. The density decrease of LH_2 may result filling up of tanks and hence causing over-pressurisation, discharge of LH_2 or both [17].

4.5.5.7. *Viscosity*

Viscosity is a fluid's internal resistance to flow – Shear motion. Hydrogen viscosity is extremely low - both as compressed gas (CH_2) and especially as liquid (LH_2). Low viscosity means small defects or clearances pass disproportionately high flows (for a given pressure), so seals, valve seats, and instrument fittings that are "tight" for other media can leak hydrogen. In storage, LH_2's low viscosity and temperature promote fast, thin jets and rapidly spreading films/pools that wick into insulation and create hidden cold spots. For CH_2 service, small leaks form energetic, turbulent jets that entrain air and disperse quickly upward after the initial momentum phase. These properties increase leak likelihood, jet throw, and dispersion distances [17].

4.5.5.8. *Corrosion*

Hydrogen itself is a non-corrosive gas but since stainless steel is used in storage of hydrogen, attention needs to be paid to pitting, the common form of corrosion displayed by stainless steel. Hydrogen promotes pitting in stainless steel by destabilising and damaging the protective passive film, increasing the surface's active sites, and accelerating anodic dissolution. Austenitic grades (e.g., 304L) are susceptible to pitting/crevice corrosion and external stress-corrosion cracking (especially under tensile stress and drying–wetting cycles). The risk comes from the chloride-rich environment and condensation associated with storage, release, and dispersion [17].

5. SHIP FUEL HANDLING ARCHITECTURE

5.1. Purpose of the Chapter

The safe use of methanol, ammonia, and hydrogen on board ships depends heavily on how the fuel is received, stored, prepared, and supplied to the propulsion system. Although the three fuels differ significantly in their hazardous properties (Chapter 4), all can be integrated into marine systems using a common four-zone fuel-handling architecture.

This chapter defines that architecture and establishes a consistent framework used throughout Chapters 6–12. It enables system-level hazard identification, supports the bowtie analysis (Chapter 9), anchors the definition of safety functions, and ensures alignment with regulatory expectations, including the structure of IGF Code requirements.

Cross-cutting systems (e.g. ventilation and detection systems) common to all zones are also introduced in this chapter. The intention is to give the reader a clear picture of what physically exists in each part of the system so that later chapters can build on this baseline when discussing hazards, safety functions, operability, and regulatory/class/flag compliance.

5.2. Fuel Handling Zone Reference Layout

The generic layout considered in this study comprises the following fuel handling zones:

1. Bunkering station and transfer to storage – Zone 1
2. Storage tank, tank connection space and transfer to fuel preparation room – Zone 2
3. Fuel preparation room and transfer to engine room – Zone 3
4. Engine room – Zone 4

These zones are functionally distinct but operationally connected. Each zone may present a different hazard profile due to changes in fuel physical state, pressure, temperature, and proximity to crew. The fuel handling zone layout is shown in Figure 8.

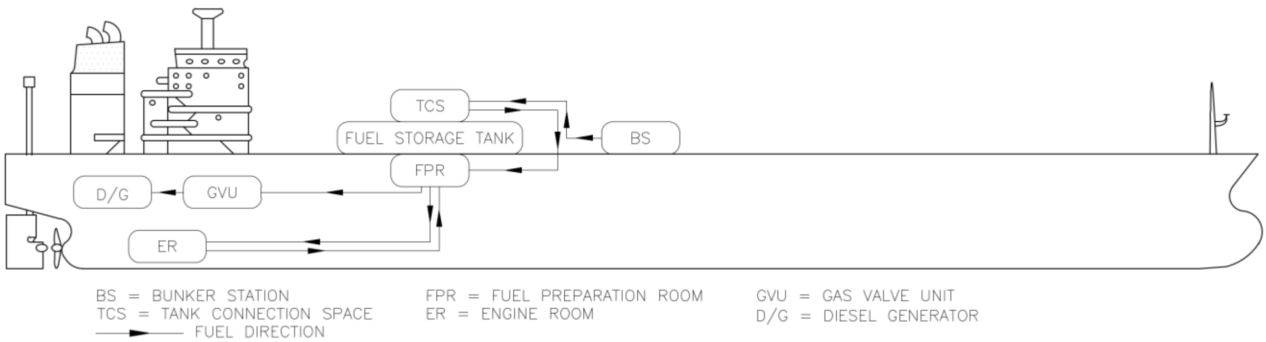


Figure 8. Overview of four-zone reference layout

5.2.1. Bunkering Station and Transfer to Storage

5.2.1.1. Purpose

The bunkering zone covers all ship–shore or ship–ship transfer operations, including manifold connections, transfer hoses, emergency shutdown (ESD) interfaces, and bunkering line routing.

5.2.1.2. *Key Hazards*

The key hazards in this fuel handling zone for methanol, ammonia and hydrogen are:

- Methanol: Spills, flammable vapour, invisible flame fires, contamination during transfer
- Ammonia: Toxic releases, flashing liquid on hose rupture, deck-level toxic plumes
- Hydrogen: High-pressure leaks, cold hazards, spontaneous ignition risk, vent mast flow reversal

5.2.2. Storage Tank, Tank Connection Space and Transfer to Fuel Preparation Room

5.2.2.1. *Purpose*

To store fuel safely at design conditions and provide the first barrier set (isolation, pressure relief, measurement) before distribution to preparation/conditioning systems. The storage zone maintains the fuel in a safe, stable state and ensures pressure/temperature compatibility with downstream systems.

5.2.2.2. *Storage Concepts by Fuel*

- Methanol is stored onboard as a liquid at ambient conditions using integral or independent tanks.
- Ammonia is stored in pressurised tanks (8–14 bar), semi-refrigerated tanks (3–5 bar) or fully refrigerated tanks (1 bar, −33°C). Pressurised tanks are usually of Type-C (ambient) and refrigerated (−33°C @~1 bar) variants.
- Hydrogen is stored as CH_2 (compressed) at 350–700 bar cylinders/racks or as LH_2 (cryogenic liquid at −253°C in vacuum-insulated tanks). CH_2 is stored using composite/type-C bundles on open deck whereas LH_2 is stored in vacuum-insulated, double-walled tanks.

5.2.2.3. *Key Hazards*

The key hazards in this fuel handling zone for methanol, ammonia and hydrogen are:

- Methanol: Vapour formation in ullage space, Oxygen ingress due to inadequate inerting, Spill through tank top penetrations
- Ammonia: Toxicity scenarios due to valve or flange leakage, BLEVE risk for pressurised tanks during fire exposure, Stress corrosion cracking leading to leak propagation
- Hydrogen: Fast leak leading to high-velocity jet fires, spontaneous ignition from high-pressure rupture and cryogenic embrittlement of tank supports (LH_2).

5.2.3. Fuel Preparation Room and Transfer to Engine Room

5.2.3.1. *Purpose*

To bring the fuel to engine-ready state (in pressure and temperature), provide final isolation and safety barrier before the engine spaces, and integrate detection, ventilation and ESD logic. The Fuel Preparation Room accommodates fuel conditioning systems such as vaporizers, fuel pumps, metering skids, filters, inert gas supply, and (for hydrogen) pressure-regulation equipment.

5.2.3.2. *Key Hazards*

The common hazards in this fuel handling zone are high-pressure leaks, accumulation of flammable/toxic vapors, ignition from motors, drives, instrumentation and human exposure during maintenance. The following are fuel-specific hazards in this zone:

- Methanol: Liquid leakage leading to vaporization leading to gas accumulation resulting in LEL conditions and invisible flame ignition.

- Ammonia: Toxic gas accumulation in enclosed spaces, corrosion at low-flow points and moisture ingress leading to stress corrosion cracking.

- Hydrogen: Creation of explosive atmospheres at ceiling level, jet fire risk and DDT (deflagration-to-detonation transition) in confined spaces.

5.2.4. Engine Room

5.2.4.1. Purpose

To deliver conditioned fuel to utilisation units (main engine, diesel generator(s)) with secondary barriers to prevent/mitigate any leak in a machinery space that is normally kept "gas-safe". In this zone, ignition sources are unavoidable.

5.2.4.2. Key Hazards

The common hazards in this fuel handling zone are high-energy ignition sources, leaks near heat sources, backflow and flashback (hydrogen) at engine interface and ignition, fire propagation via hot surfaces, ventilation failure, fuel line rupture, and accumulation of vapours pockets, bilges or overheads.

5.3. Cross-cutting Systems

5.3.1. Detection and Alarms

Fuel handling spaces must be equipped with continuous detection and clear alarm signalling to ensure early identification of leaks or abnormal conditions. For example:

- Multi-point fixed detection appropriate to the fuel:

    - Methanol: LEL (flammable) detection; optional ppm methanol monitoring in critical spots.

    - Ammonia: NH_3-specific toxic detectors (ppm-level) plus area alarms.

    - Hydrogen: H_2 sensors at high points; pre-alarm and trip thresholds (e.g. 10% LFL warn, 25% LFL shutdown—actual setpoints).

5.3.2. Ventilation

Ventilation systems must provide reliable air exchange to prevent accumulation of flammable or toxic vapours in enclosed or semi-enclosed areas. For example:

- Methanol: Ventilation must prevent vapour accumulation in methanol fuel spaces and maintain safe dilution levels.

- Ammonia: Ventilation must control ammonia vapours effectively to avoid toxic concentrations in enclosed areas.

- Hydrogen: Ventilation must ensure rapid dispersion of hydrogen to prevent the formation of ignitable mixtures.

5.3.3. Hazardous Area Classification

Fuel handling zones are classified according to the likelihood of vapour release, ensuring equipment selection and installation meet appropriate safety standards. For instance, electrical equipment selection and cable routing per zone classification and fuel properties.

5.3.4. ESD and Automation (Cause and Effect Philosophy)

Emergency shutdown and automation follow a defined cause-and-effect logic that ensures rapid, coordinated actions in response to critical events. For example:

- Methanol: ESD logic must isolate methanol systems quickly to limit the spread of flammable liquid or vapour.
- Ammonia: ESD functions must ensure rapid shutdown of ammonia transfer and ventilation to contain toxic releases.
- Hydrogen: ESD must react instantly to hydrogen gas detection, isolating sources and stopping ignition risks.

5.3.5. Pressure Relief and Controlled Venting

Pressure relief and venting arrangements must safely discharge excess pressure to designated locations, avoiding hazardous conditions in occupied spaces. For example:

- Methanol: Pressure relief for methanol systems must route vapours to safe venting points away from personnel.
- Ammonia: Ammonia pressure relief must manage toxic releases through controlled, high-integrity vent paths.
- Hydrogen: Hydrogen relief systems must vent rapidly and vertically to prevent accumulation and ignition.

5.3.6. Purging, Inerting and Blowdown

Systems must allow for controlled purging, inerting, and blowdown to maintain safe atmospheres during start-up, shutdown, and maintenance operations. For example:

- Inerting: methanol tanks are typically N_2-inerted whereas hydrogen and ammonia lines and tanks use N_2 purge where allowed.
- Purging sequences: before maintenance or changeover, fuel lines and GVU/FVT are purged to a safe vent header; verify oxygen/fuel concentration limits before opening.
- Blowdown: hydrogen (CH_2/LH_2) systems include controlled blowdown to H_2 vent mast; LH_2 requires warm-up and boil-off handling steps.

5.3.7. Materials and Compatibility

All components must be constructed from materials compatible with the fuel's physical and chemical properties to avoid degradation or failure. For example:

- Methanol: Materials must withstand methanol's solvent properties and prevent degradation of seals and components.
- Ammonia: Materials must be compatible with ammonia to avoid corrosion, stress cracking, or brittleness.
- Hydrogen: Materials must resist hydrogen embrittlement and maintain integrity under cyclic loading.

5.3.8. Firefighting: Suppression and Protection

Firefighting systems must provide effective suppression and passive protection tailored to the characteristics of the fuel and the equipment layout. For example:

- Methanol: foam/water spray suited to alcohol (AR-AFFF), consideration of low-luminous flame visibility.
- Ammonia: toxic control (water fog for knockdown and absorption), evacuation/SAR protocols.
- Hydrogen: rapid flame detection (UV/IR), eliminate ignition sources, protect exposures; no “pool fire” for CH_2 but jet fire/detonation risk covered by separation and venting.

5.3.9. Fire Detection

Fire detection systems must provide rapid identification of heat or flame development throughout all fuel handling spaces. For example:

- Methanol: Fire detection must account for methanol’s nearly invisible flame, ensuring rapid heat or flame sensing in all methanol-handling spaces
- Ammonia:
- Hydrogen: Fire detection must rapidly sense heat or flame due to hydrogen’s low ignition energy and the near invisibility of hydrogen flames

Other cross-cutting systems will be further analysed in under safety function requirements in chapter 9 and annex C of this report.

6. DESIGN RISK MANAGEMENT

6.1. Purpose of the Chapter

This chapter summarises the application of risk management to inform and optimise the design of a ship, based on the principles of process safety, which have already been established as good practice in other industries involving the storage and handling of substances with the potential for major accidents such as fire, explosion and toxic release (e.g. the oil and gas and chemical industries). It describes why a risk-based approach to design safety is required, and how a systematic process of hazard identification, risk assessment and risk management interact to demonstrate equivalent or higher safety of alternative fuels relative to conventional fuels, as required under IMO goal-based frameworks and class society alternative design processes.

This risk-based approach has been used in the METAFUEL project to provide the foundation for the use of bowtie analysis to identify the safety functions required to manage the hazards associated with the use of alternative fuels, and the mapping of the specific hazardous properties of each type of fuel (see Chapter 4) on the requirements for those Safety Functions, described in Chapter 9, and thus to inform the decision support logic described in Chapter 10.

6.2. Why a Risk-based Approach is Necessary

There are two basic approaches to demonstrating that a design is safe, namely:

- Prescriptive approach
- Risk-based approach.

The first of these involves ensuring that the design is compliant with applicable legislation codes and standards and the incorporation of best engineering practice. The regulatory and standards landscape for methanol, ammonia, and hydrogen as marine fuels is described in Chapter 8.

While implementation of legislation, codes and standards gives good coverage for well-understood hazards and applications, however, they may not be sufficiently prescriptive for new or developing technologies or for specific applications, including the use of alternative fuels discussed in this report. Furthermore, even a purely prescriptive approach contains requirements for hazard identification and risk management, to ensure that the requirements are implemented specifically for their application. A risk-based approach should therefore be taken to ensuring the ship design is safe, based on the principles of process safety management.

This chapter describes this risk-based approach, which should be implemented during the design of a ship, and maintained throughout its operational lifecycle. This approach has been used to identify the specific requirements for safety functions associated with the alternative fuels considered in this project and thus to inform the decision support framework described in Chapter 10.

Due to the potential for major accidents inherent in the use of methanol, ammonia or hydrogen as fuel sources, and the resultant need for more complex measures for risk reduction, risks need to be managed differently to those associated with conventional workplace hazards. The risk management process described in this chapter is based on the principles of process safety as follows:

- All hazards shall be identified, assessed, understood and controlled.
- The risk associated with the identified hazards shall be reduced to a level which is As Low As

Reasonably Practicable (ALARP).

- As far as reasonably practicable, the principles of Inherently Safer Design (ISD) shall be applied.
- A suitable combination of risk reduction measures (prevention, detection, control and mitigation) shall be provided to manage risks and maintained throughout the lifecycle of the ship.
- All systems provided to protect people, and the environment shall be suitable for the expected hazardous scenarios against which they are designed to protect.
- Adequate means of escape shall be available for personnel in all circumstances.
- Any changes to the design or operation which may impact the risk, or introduce new hazards, shall be assessed as part of a robust Management of Change (MoC) process.

Furthermore, it is essential that risk management (including MoC) is an integral part of the overall design process and not used simply to confirm decisions already made.

The steps involved in the risk management process are summarised below and described in the following sections.

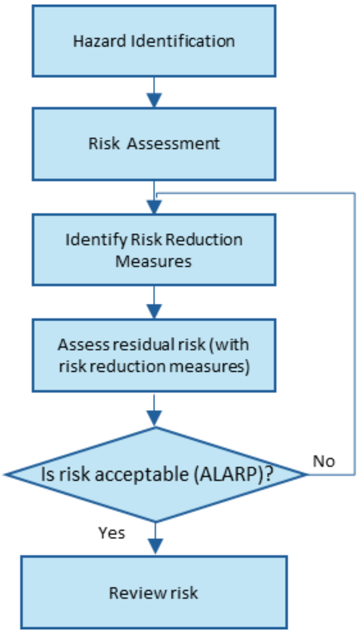


Figure 9. Risk Assessment Flowchart

6.3. Hazard Identification

The aim of hazard identification is to ensure that all hazards associated with a system are identified and the associated risks assessed, and to raise potential actions for risk reduction.

The process begins by defining the system to be studied (i.e. the ship) and its boundaries. Once this is established, the hazards associated with the system may be identified. Early identification of hazards enables the application of the most effective and efficient design to achieve acceptable risks, including the application of Inherently Safer Design (ISD) principles.

Various methods for hazard identification may be used (e.g. HAZID, HAZOP, FMEA), depending on the level of detail available and whether a 'top-down' or 'bottom-up' (system or component level) approach is required. Hazard identification must not be undertaken as a desktop exercise carried out by an individual, but should involve a dialogue between suitably experienced subject matter experts, typically in the form of a workshop led by an experienced facilitator to ensure a systematic and focused approach and ensure collaboration between relevant disciplines from design, operations, safety, etc. The need for a structured dialogue involving subject matter experts is even more critical when dealing with novel technologies or applications, where new hazards may be introduced and existing controls and mitigation may not be sufficient, and therefore the insights provided by subject matter experts are essential.

A preliminary hazard identification study should be conducted during the early phases of a project to identify any significant safety-related or environmental issues. While there may not be enough information at this stage to allow detailed identification of the causes and consequences of hazardous events or to identify specific risk reduction measures, a hazard identification study can be used to identify significant hazards, including those outside the ship which could impact on the ship design and operation, and thus provide early input to the ship layout (including the location of escape routes and emergency access) and requirements for fire and explosion protection and emergency response. It can also be used to inform the planning of risk assessment activities in subsequent design stages, including more detailed hazard identification and risk assessment, dispersion and consequence modelling, and other safety studies which can be used to inform the design.

The hazard identification process should be used to identify the causes and consequences of a loss of control of a hazards, including possible domino effects. This is critical to identifying measures for preventing the loss of control of a hazard, as well as measures to control or mitigate the consequences of a loss of control should it occur.

The use of guidewords during the hazard identification process is recommended to stimulate discussion and ensure a thorough approach to the identification of potential hazards, causes and consequences that may be outside the direct experience of those involved. Several examples of possible guidewords for use in HAZIDs are available in standards (e.g. ISO 17776) or online and can be adapted to suit the specific application. Once details of the design and operation of the ship are available, these guidewords may include those for the identification of potential human errors (e.g. incorrect operations, checks or information/communication) and performance influencing factors (e.g., workload, equipment, training, complexity, working environment).

Guidewords for use in HAZOP workshops are provided in IEC 61882.

6.4. Risk Assessment

Two main types of risk assessment are typically used, namely qualitative risk assessment and quantitative risk assessment (QRA).

6.4.1. Qualitative Risk Assessment

A risk assessment matrix should be used during HAZID/HAZOP studies described in Section 6.3 to provide a risk scoring for each hazard. This is a simple matrix used to define the level of risk by considering the category of likelihood against the category of consequence severity to provide a qualitative assessment of the risk. This enables the most significant risks to be prioritised and assessed in more detail. Further risk assessment using Layers of Protection Analysis (LOPA) may also be used, in conjunction with a HAZOP study, to determine the requirements for additional risk reduction measures based on the existing risk.

A simple illustration of a typical risk-assessment matrix is shown in Figure 10. Clear definitions should be provided for the likelihood, consequence, and risk categories to ensure consistency within and between assessments. For example, likelihood (or frequency) categories may range from events that are considered credible but have not been experienced in the industry to those that occur several times per year at the location. Consequence categories may be defined in terms of the number and severity of the harms caused, such as multiple fatalities or minor injuries or health effects. The use of subjective terms, such as very likely or significant harm, should be avoided.

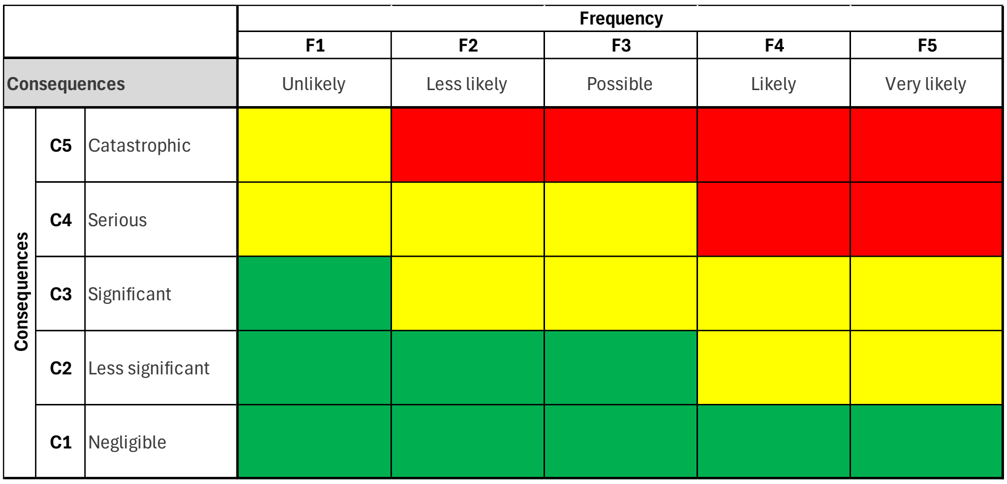


Figure 10. Typical Risk Assessment Matrix

6.4.2. Consequence Modelling and QRA

While qualitative assessment described in the previous section can enable the most significant risks to be prioritised and provide an indication of whether risks have been reduced to an acceptable level, major accident hazards may be subject to detailed consequence analysis or quantitative risk assessment (QRA).

QRA is a systematic approach to assessing the frequency and consequences of hazardous events and expressing the results quantitatively (numerically) in terms of risk to workforce, third parties and members of the public. The QRA shall evolve during the design process, to provide contours showing the consequences and risk at all locations both inside and outside the ship boundary.

6.4.2.1. Consequence Modelling

Modelling of the potential consequences of significant hazardous events (including gas dispersion, heat radiation, explosion overpressure etc.), should be undertaken at an early stage in a project to determine possible impact on the ship crew, as well as port facilities and neighbouring infrastructure and third party workers, and members of the public, and used to optimise the layout and orientation of the ship (including spacing of equipment, location of muster points and escape routes, location of ventilation inlets etc.), and provide early indication of the requirements for, and location of, fire and gas detection and fire and explosion protection. Various approaches are available for consequence analysis from the use of simple fire dynamics equations to use of modelling tools. Software is available to model the effects contours on plans to illustrate the consequences at different locations, both on board and offsite, based on temperatures and pressures, release sizes and atmospheric conditions. These contours can be translated into effects on humans, on assets or equipment, based on harm criteria, e.g. the effect of heat radiation or overpressure at different levels. Both empirical and Computational Fluid Dynamics (CFD) modelling tools are available, depending on the accuracy required.

Empirical modelling may be used during feasibility, concept selection and early in project design to give quick indicative results but is less accurate than CFD and does not account for differences in elevation, topography or obstructions dominating the layout of the area. Care should also be taken to ensure the validity of the software for specific application (e.g. some software may not be valid for modelling of liquid hydrogen releases).

CFD modelling is more accurate and takes account of the actual 3D layout but may be time-consuming and sensitive to changes to design. It is therefore more suitable for use during detailed design and to model areas where there are dominant obstacles which adding the congestion of the layout. A hybrid approach, in which CFD approach is used to look at the 'zoom in' on areas where more detailed modelling is required, may also be used.

6.4.2.2. Quantitative Risk Assessment

As the design evolves, QRA can be developed to combine the consequences of a hazardous event, as described in the previous section, with its frequency and the probabilities that an event escalates leading to different consequences, to assess the overall risk to crew or to third parties. Various means are available for assessing this, from simple spreadsheets to more complex tools for modelling logical combinations of failures, errors or conditions, such as fault and event tree assessment. Data may be based on actual operating data, operational experience, industry databases for component failures, etc. Task analysis techniques may also be used to estimate the likelihood of human errors. Software is available to create risk contour maps showing the risks in different locations. The results of a QRA may be expressed in terms of individual risk to specific crew groups, or the risk at specific locations (including port facilities).

As well as informing the design, the QRA can be used to demonstrate that the risks associated with the project are within defined risk acceptance criteria. These criteria specify the acceptable levels of risk to workforce, third parties or members of the public, and may be defined by legislation, by the company or for specific projects.

6.5. Risk Control and Mitigation

Once hazards have been identified and the associated risk assessed, it is necessary to ensure that the associated risks are reduced as far as reasonably practicable. Risks shall be managed using the following hierarchy of controls, arranged from the most effective to the least, to identify risk reduction measures:

1. Eliminate: Remove the hazard completely.
2. Substitute: Replace the hazard with something less dangerous (for example, lower volumes, pressures, or temperatures).
3. Isolate / Separate: Keep people away from the hazard (such as through remote operations).
4. Engineering Controls: Use technical measures or safeguards to control the hazard or limit its consequences.
5. Administrative Controls: Change the way work is carried out through procedures, training, signage, or emergency plans.
6. Personal Protective Equipment (PPE): Provide equipment that offers individual protection.

6.5.1. Inherently Safer Design (ISD)

The principles of ISD should be applied early in the design process to reduce the need for significant changes and implementation of potentially more costly and less effective controls later. There are four main ISD principles, which focus on the top of the hierarchy of controls, namely:

1. Minimise: reduce inventory of hazardous material.
2. Substitute: replace a material with a less hazardous substance.
3. Moderate: operate under less hazardous conditions (e.g. pressures, temperatures).
4. Simplify: eliminate unnecessary complexity.

ISD measures shall consider good engineering practice and industry standards, e.g.

- Minimisation of leak sources, including piping joints, small bore connections, flanges,
- Selection of material suitable for fuel containment (e.g. For methanol, ammonia or hydrogen),
- Minimisation of piping length by effective layout,
- Minimisation of operating pressures,
- Optimisation of layout and spacing.

The layout, spacing and orientation of the ship and its equipment can have a significant effect on the consequences of fires and explosions, including the possibility of domino effects both onboard and on neighbouring facilities, as well as the availability and effectiveness of risk reduction measures. The possible layout options should therefore be evaluated, including the use of consequence modelling and QRA, to ensure that the risk of fire and explosion is minimised as far as reasonably practicable.

6.5.2. Engineering Controls

Engineering controls are the next layer of protection. These include leak detection, fire and gas detection, alarms, hazardous area classification and ignition source control, overpressure protection, emergency shutdown and isolation, active fire protection, passive fire and explosion protection, escape routes and emergency access. Again, the use of consequence modelling and risk assessment can be used to inform the design and location of such measures.

6.5.3. Emergency Response

An emergency response plan shall be developed based on the identified hazardous scenarios and required response. It shall describe the specific actions to be taken by different roles, contact information, as well as details of escape routes, emergency access, and available emergency equipment. It shall also describe the emergency drills to be conducted (including involvement of emergency services) based on the identified hazardous scenarios and identify any training requirements for specific roles.

It must be ensured that all persons involved in emergency response, including external emergency services, are aware of the specific hazards onboard and their specific roles and responsibilities following a hazardous event.

6.6. Risk Acceptance and ALARP Demonstration

Some risk is inherent to a ship's design and operation and cannot be eliminated entirely. It is therefore necessary to determine whether the risk is acceptable, or whether further risk reduction is required. To do this, the estimated risk should be compared to the defined risk acceptance criteria. These criteria may be defined by applicable legislation, by the operating company or for a specific project, and may be expressed qualitatively (using a risk acceptance matrix) or quantitatively, in terms of risk to the individual (for workers) or location specific risk (for third parties or members of the public), in units of number of fatalities per unit time. If the risk does not meet the defined criteria, then further risk reduction measures must be implemented to reduce the risk further.

Even if the risk does meet these criteria, it shall also be considered whether it is As Low As Reasonably Practicable (ALARP). For a risk to be ALARP, it must be demonstrated that the cost of implementing further Risk Reduction Measures (RRMs), in terms of money, time and effort, is grossly disproportionate to the benefit gained, in terms of lifetime risk reduction (i.e. the benefit gained does not justify the cost). Compliance with applicable legislative requirements and following of best engineering practice must also be demonstrated for a risk to be ALARP.

In simple terms, if the assessment has been through the process of identifying risk reduction measures in line with the hierarchy of controls described in Section 6.5 and no further risk reduction measures can be identified, then the risk may be considered ALARP. If there is doubt as to whether a risk reduction measure is justified on safety cost benefit grounds, then detailed QRA and cost benefit analysis may be required.

6.7. Risk Review

The final step in the risk management process is the continued monitoring and review of the risk reduction measures during the lifecycle of the ship to ensure that they remain operational and able to meet their requirements effectively. They should also be reviewed in the event of any changes to the site and its operation, as part of a robust MoC process. This applies to non-technical systems for prevention and mitigation of accident scenarios (e.g. processes and instructions, competency and training of personnel) as well as technical systems (e.g. layout, equipment, safeguarding systems).

7. HUMAN FACTORS ENGINEERING

7.1. Purpose of the Chapter

Human Factors Engineering (HFE) assesses the interaction between crew, equipment, alarms, procedures, and the physical environment when handling methanol, ammonia, or hydrogen. For alternative fuels, the human element is often the dominant contributor to risk because:

- Some hazards are not visible (e.g., methanol flames, hydrogen plumes).
- Some hazards cannot be tolerated even briefly (e.g., ammonia toxicity).
- Actions must be rapid, precise, and coordinated (e.g., hydrogen isolation, emergency evacuation).

This chapter explains how Human Factors Engineering (HFE) helps crews work safely with the alternative fuels considered in this study. HFE is concerned with what people must notice, decide, and do in both normal operations and emergencies, and how alarms, camera systems, ventilation, and procedures support or challenge those actions. The goal is not to make work more complicated, but to make it easier to understand and minimise the likelihood of human error.

7.2. Why Human Factors Matter More for Alternative Fuels

7.2.1. Complexity of New Systems

Alternative fuel technologies introduce unfamiliar and interdependent systems such as fuel conditioning units, cryogenic tanks, vaporizers, and complex venting and purging arrangements. These systems generate a larger volume of data, alarms, and control logic, increasing the cognitive workload for crews not yet fully accustomed to such configurations.

7.2.2. Higher Information Demands

Unlike conventional fuels, many alternative fuels have invisible or imperceptible hazards. They may be odourless, colourless, or exhibit effects that are not visually detectable. Safe operations therefore depend heavily on reliable detection systems, alarms, and accurate feedback from instrumentation rather than direct sensory cues.

7.2.3. Lower Tolerance for Error

The margin for human error is significantly narrower. Hydrogen ignites almost instantly, ammonia can become life-threatening within seconds at high concentrations, and methanol fires may go unnoticed until secondary effects appear. Effective safety depends on procedural discipline, situational awareness, and clarity in system design.

7.2.4. High Workload During Bunkering

Bunkering operations for alternative fuels add complexity through shore-side coordination, variable PPE requirements, and real-time monitoring of multiple parameters. The result is a high workload environment where decisions must be made rapidly under stress, emphasizing the need for clear roles, structured communication, and robust human–machine interface design.

7.3. Methodology for HFE Assessment

As part of this project, DBI visited a methanol-fuelled ship for a guided walk-through (including the engine room and related systems) and held casual discussions with ship crew members, including the chief engineer, who explained how the crew handle methanol in their day-to-day work or when things go wrong. It was noted how alarms, ventilation and procedures are used in practice, and how layout or access can affect human actions and responses. These practical insights feed directly into this chapter. Methanol is an illustration of why the focus on HFE is important, as its flames can be hard to see, vapours spread quickly, and leaks are not always obvious without proper detection [23]. It was noted that leak detection in the fuel treatment room can be difficult, as ventilation moves the vapour and that one of the riskiest stages of bunkering operations is disconnection, when small errors can have serious consequences.

Training for handling of alternative fuels can be time-consuming, and not always targeted towards specific fuel properties, which makes it harder for crews to prepare. Over time, people may feel less cautious as they become familiar with the fuel, but it makes it even more important that systems and procedures stay clear and simple, so that safe habits are maintained. The focus is on the operational environment on board, including work on the bridge, in the engine room, and on deck during preparation, daily operation, abnormal situations, and emergencies. Human factors include how crews share tasks, make decisions under time pressure, and coordinate during high-risk operations such as bunkering [24, 25]. HFE also covers how controls and alarms are presented so they can be understood and used quickly and correctly [21, 22]. Physical conditions such as lighting, noise, vibration, temperature, and airflow affect attention, communication, and reaction, especially when wearing PPE in tight spaces. Training and procedures are effective when they are practical and match how work is really done.

These factors connect with METAFUEL’s aims of prevention, detection, containment, and response. Human performance can create risks, but it can also be the strongest tool for safety when it is supported in the right way. Prevention means ensuring that high-risk tasks, such as bunkering, are as simple and clear as possible, that roles and responsibilities are clearly defined and understood. Detection and interpretation improve when signals are reliable and clearly visible, and when crews can confirm an alarm quickly using camera systems or local checks [23]. Containment and safe action depend on clear access and exit routes, good visibility when wearing PPE, and layouts that make isolation points obvious. Ventilation should help the crew, not make leaks or vapours harder to detect and to manage. Resilience grows when experiences and near misses are fed back into training, procedures, and small system changes. Training should reflect the specific properties of the fuel, and the reality of working under pressure in noisy and stressful environments.

7.4. Human-Centred Risk Management

Risk on a ship depends on how people notice weak signals, understand uncertain situations, and act under time pressure [23, 26]. The same actions that can cause delay can also stop escalation and restore control. Procedures may not correspond to how work is really done in spaces like fuel treatment rooms, bunkering stations, and engine control rooms. The use of alternative fuels adds challenges due to their unique properties and new instrumentation with which crew may not be as familiar than with that for conventional fuels.

Leak localisation is harder when airflow changes. The use of camera systems helps, but blind spots and complicated infrared tools can slow checks, and disconnection during bunkering remains one of the most hazardous steps. Time-consuming and overly generic training may also give a false sense of confidence if it is not targeted towards specific fuel properties.

Tasks, equipment, and the work environment should help crews take the right action, even under pressure [21, 23, 26]. Human errors can take several forms. Slips and lapses are execution problems: for example, leaving a valve partly open or missing a step because of distraction. Mistakes are planning problems, such as applying assumptions from conventional fuels to methanol or misreading an alarm because of poor labelling. Violations occur when people intentionally take shortcuts, like skipping a procedural step that feels awkward or unnecessary.

Each type of error requires a different approach. Clearer labels, better task design, and procedures that reflect real working conditions all help reduce failures. Alarm reliability is especially important: when alarms are inconsistent, crews become slower to react [24]. Improving alarm quality and making verification quick and obvious prevents “check before act” from turning into a passive “wait and see” response [23, 24].

Working conditions on board also influence performance. Fatigue and shift patterns reduce alertness. Time pressure can push people toward unsafe shortcuts, especially when procedures are unclear. Noise, heat, vibration, confined spaces, and even PPE can add stress by limiting dexterity and visibility. Ventilation can also complicate leak detection if airflow disperses vapours before they reach sensors. Confusing labels and shared tasks across teams add further risk.

Finally, training must be practical and fuel specific. Short, scenario-based drills linked to real tasks, such as connecting, disconnecting, or performing emergency isolation, help develop safe and reliable habits.

These factors often combine. A small leak with shifting ventilation, poor visibility, and heavy radio traffic is not one problem but several that contribute to slow detection and delay isolation. Managing risk requires looking at the whole system, not just a checklist [23, 25]. The following steps play a significant role in ensuring that risks are kept ALARP:

- Removing hazards where possible, for example by reducing manual disconnections and improving components at weak points.
- Simplify tasks so that the safe path is the easiest one, for example with clear valve indication and guarded controls.
- Strengthen recovery, for example with quick verification that combines gas detection with camera and infrared views, isolation points that can be reached while wearing PPE, and rehearsed call-out.

7.5. Operational Roles and System Interaction

As with conventional fuels, working safely with alternative fuels depends very much on how people and systems come together in daily work and in emergencies [23, 25]. On board a ship there are three main groups who take part in methanol operations, namely the crew on the bridge, the engineers in the engine room, and the crew working on deck [26]. Each of these groups has clear duties, but there are also overlaps and dependencies between roles.

On the bridge the officers keep overall responsibility. They supervise the bunkering operation, monitor safety and maintain contact with both the engine room and the deck. The bridge often relies on camera systems, gas detection alarms, and constant radio traffic to understand what is happening in areas they cannot see directly. When alarms are many or unclear, or when the camera view is poor, the officers may lose valuable time trying to understand the situation.

In the engine room, the engineers must keep a close eye on the fuel treatment systems. They need to act quickly in the event of an alarm and decide if it is a true warning or a false signal. Operational confidence in alarms is important, because a slow response can allow a small leak to grow larger. Engineers also control isolation valves, pumps, and ventilation. If they do not receive clear information from the deck or the bridge, their decisions can become harder.

On the deck the crew carry out physical tasks. They connect and disconnect hoses during bunkering, they handle couplings and valves, and as such they are often located in the areas with the highest risk. Small errors here can have serious results, especially during disconnection when pressure and residual fuel can create leaks. Deck crew also carry personal protective equipment, which makes visibility and communication more difficult.

Complexity grows when all three groups act together. For example, a leak in the fuel treatment room may involve the deck reporting an unusual odour or the presence of vapour, the bridge personnel checking alarms and giving instructions, and the engine room confirming system readings. When communication is slow, or when responsibilities are not clear, mistakes are more likely. It is therefore important to map which crew member is responsible for each task, and to define communication protocols and practise how information should be communicated between teams. Clear task ownership prevents contradictory actions or unsafe assumptions on task responsibility.

Stress factors during operations make the work harder. Time pressure, high radio traffic, and fatigue from shift work all reduce concentration. Crew members may try to take shortcuts when they feel overloaded. If procedures are too long or complex, people may skip steps that seem less important. HFE shows that the design of work should guide the crew into the correct action without requiring unnecessary effort.

The way alarms, displays, and controls are designed is also critical. Alarms should be reliable so that the crew can trust them [24], and prioritised to prevent information overload. Controls must be within easy reach and simple to understand [21]. A valve should show clearly if it is open or closed. Buttons should be protected to prevent them being pressed by mistake. Information should be consistent across the ship, so that an alarm in the engine room means the same as an alarm on the bridge. If procedures use one word but the label on the equipment uses another word, confusion and delay can result.

Crew members also build their own understanding, or mental model, of how a fuel system works. If equipment behaves in a way that is not expected, or if procedures are different from daily practice, people may hesitate or take incorrect actions. Consistency between systems, procedures, and training helps build confidence. When people are sure that the system will react consistently, they can act faster in an emergency.

By looking closely at how roles interact, and designing tasks, interfaces, and procedures with the crew in mind, fuel handling operations can be made simpler and safer. This reduces risk not only during normal operations but also during stressful situations, such as emergency isolation or bunkering under time pressure.

7.6. Physical and Environmental Considerations

7.6.1. Environmental Ergonomics and Crew Wellbeing

The physical environment on board plays a direct role in how well crews work with alternative fuels [23, 25]. High levels of noise, strong vibration, and fluctuating temperatures are common in engine rooms and fuel treatment spaces. These conditions reduce alertness, make communication harder, and increase fatigue during long shifts. Lighting also matters, both for everyday tasks and emergencies. Poor lighting or glare can make it harder to see small leaks, read alarms, or judge the position of valves [21, 24]. Good ergonomics mean reducing unnecessary strain, keeping the climate as stable as possible, and making sure crews can stay focused without being overloaded by the environment around them.

7.6.2. Access, Visibility, and Spatial Layout

The way spaces are arranged influences how quickly and safely crews can respond [21]. Access routes should allow people to reach isolation points and exits without delay, even when using PPE [23, 26]. Visibility is equally important. Clear sightlines make it easier to supervise operations, detect unusual events, and coordinate actions across different parts of the ship. Crews need layouts that support both early detection and safe escape. Simple design choices, such as keeping pathways free from obstacles and marking critical equipment clearly, improve both day-to-day work and emergency response.

7.6.3. Stress Factors in Confined or Dynamic Environments

Confined spaces and constantly changing conditions increase stress levels. Engine rooms and treatment spaces are often cramped, with little room to move, especially when crews are wearing PPE that limits dexterity and visibility [23, 26]. Vibration, heat, and strong airflow patterns can also interfere with attention and decision making. In dynamic situations such as bunkering or emergency isolation, these factors can slow down reaction time and complicate teamwork. Recognising these factors is essential for realistic training and for procedures that match the actual challenges on board [25].

7.6.4. Design Implications for Physical Resilience

Physical and environmental conditions shape how resilient a crew can be during both routine operations and emergencies [25]. Spaces should be arranged so that crews can navigate them quickly and safely under pressure, with or without full visibility [21, 23]. Alarms and indicators must be positioned where they can be seen and acted upon without confusion [24]. Ventilation systems should balance the need to dilute vapour with the need to support leak detection and fire control. Above all, the layout onboard should make critical tasks straightforward: moving safely through tight spaces, isolating fuel systems, and exiting in an emergency. By addressing these physical and environmental factors, HFE supports crews in maintaining clear judgement and coordinated action, even under stress.

7.7. Training and Procedures

Good training and clear procedures are the basis for safe work with alternative fuels [23, 25, 26]. Training must be focused, practical, and repeated often enough to become habit. Learning is made easier when the information is explained step by step and without unnecessary complexity. Crew members should first see how the system is arranged, then practise each task in a simple way, and later combine the steps into full operations. For example, before practising full bunkering, the crew should practise small parts such as valve isolation, hose connection, or alarm confirmation. This builds confidence and avoids overload.

Scenario-based training is especially important. Drills should not only be classroom lessons, but real practice under the same conditions as on board. Bunkering simulations, leak detection with real gas detectors, and emergency shutdown exercises prepare the crew for what they will face. Training should include PPE, high noise levels, and radio traffic, so that people get used to working with reduced visibility and hearing. This makes drills more realistic and improves crew preparedness.

Procedures must be short, simple, and clear. Long lists and technical language are difficult to follow when a person is under stress. A procedure that can be read quickly and understood in one glance is much more useful and the use of visual aids can provide clarity. Diagrams that show valve positions, colour markings on pipes, and laminated cards with the most important steps are practical and support quick action [21].

Repetition is also an aid to effective learning. When drills are repeated, the body remembers the actions so that they become instinctive. This muscle memory can save time in an emergency. Repeated practice also makes sure that safe actions become natural habits and not something that is forgotten after the training course is completed.

Competence must be checked regularly. Short tests or practical demonstrations can show if a crew member still remembers the correct way to act and enable incorrect actions to be corrected before a real operation. It is essential to collect feedback from the crew following drills and real-life incidents. If something did not work as expected, or if a procedure was too long, this experience should be recorded and action taken to improve training and procedures.

Training should also be fuel-specific and reflect the fuels actual properties and specific system requirements. Training should include these specific considerations so that crews understand the risks and are prepared to handle them.

By keeping training practical, procedures simple, and competence checked, the crew is much more ready to act correctly under pressure. When knowledge is matched to real conditions, and when feedback is used to improve the system, human performance becomes a strong defence instead of a weak point.

7.8. Conclusions

HFE aims to make work clearer and mistakes less likely. It does this by shaping tasks, tools, spaces, and training so crews can observe what is important, make timely decisions, and act safely. It does not remove all risk. Conditions change at sea, people get tired, and systems can fail. HFE helps by reducing confusion and by improving the chances of a safe outcome.

The use of alternative fuels adds specific challenges. These do not call for more complexity but for simple solutions that reflect the fuel’s specific properties and fit the way the work is really done.

Safe operation depends on coordination between bridge, engine room, and deck. While each group has defined duties, they also share information and rely on each other. Clear task ownership and timely handovers reduce delays and prevent omissions. Regular practice of the handovers is as important as practice of the technical actions.

Alarms must be meaningful and trusted. Crews respond faster when false or unclear alarms are rare and when messages match the language in procedures. Verification should be quick and clear (e.g. through use of cameras without blind spots and handheld checks that are usable in PPE). If the first check is easy to perform, people are less likely to delay decision making.

The physical layout should support action under pressure. Isolation points and exits need to be reachable in poor visibility and while wearing PPE. Indication should show quickly whether a valve is open or closed. Controls should be protected to prevent them being operated by mistake. Sightlines should help both supervision and escape. These details shorten decision time and reduce the chance of error.

Ventilation needs careful balance. It should dilute vapour and support fire control yet not move a leak away from detectors or people who are trying to locate it. Where airflow makes localisation difficult, detector placement and verification steps should be adjusted. Camera and infrared options can help, but only if they are positioned and maintained for real use.

Training and procedures work best when they match real conditions. Short, repeated, scenario drills are more useful than long, general courses. Focus should be on connection, disconnection, alarm confirmation, isolation, and evacuation, and should take account noise, radios, heat, and PPE. Procedures should be short, use simple language, and make use of visual information. Diagrams should mirror the actual layout. Words on the page should be consistent with those used on equipment and workstations. Competence checks, followed by quick refreshers where needed, help maintain skills and competence.

Ensuring risk is maintained at a level which is ALARP is an ongoing effort, and eliminating hazards where possible, simplifying tasks and strengthening recovery can all play a significant role in achieving this.

Error types point to practical fixes. Clear labelling, job aids at the point of use, and layouts that guide the hand can reduce the likelihood of slips and lapses. Fuel-specific training and consistent interfaces can reduce the risk of planning errors or errors due to incorrect information. Having clear practical and unambiguous procedures can remove the awkwardness to staff and reduce the likelihood of procedural violations

Lessons learned from drills and actual incidents should feed back into design and practice. After drills and real events, note what helped and what hindered. Fix small items quickly, such as a label, a camera angle, or a line in a checklist. Many small corrections build resilience over time. Uncertainty will remain, so crews benefit from a habit of review and refinement.

8. REGULATORY AND STANDARDS FRAMEWORK

8.1. Purpose of the Chapter

This chapter provides a clear overview of the regulatory landscape governing the use of methanol, ammonia, and hydrogen as marine fuels, including international regulations, interim guidelines, class society rules, and regional policy drivers.

The chapter is structured to allow easy cross-fuel comparison, ensuring that maritime stakeholders e.g. designers, shipowners, and authorities can see how regulatory requirements differ, where they overlap, and critically where gaps exist that must be addressed using Risk-Based Design (Chapter 6) and Safety Functions (Chapter 9).

8.2. The Current Regulatory Framework

8.2.1. Methanol

The regulatory and standards framework for methanol as a marine fuel is advancing but remains less mature than for LNG, which forms the prescriptive foundation of the IGF Code. For methanol, ship designs still rely on interim guidelines, classification society rules, and the alternative design process, though IMO work is progressing toward formal incorporation into the Code.

At the international level, methanol is addressed through the International Convention for the Safety of Life at Sea (SOLAS) and the International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels (IGF Code). While LNG has a dedicated prescriptive chapter in the IGF Code, methanol and other alcohols do not. Instead, stakeholders must follow MSC.1/Circ.1621 – Interim Guidelines for the Safety of Ships Using Methyl/Ethyl Alcohol as Fuel. These guidelines cover containment systems, fuel supply arrangements, ventilation, fire safety, and toxicity considerations unique to methanol. Approval is pursued under SOLAS II-1/55 and MSC.1/Circ.1455 (Alternative Design and Arrangements), where compliance is demonstrated against the safety objectives of the IGF Code. This pathway is now well-established, with several methanol-fuelled ships in operation under these arrangements. The IGC Code (gas carriers) is not the governing instrument for methanol projects, because methanol is a liquid chemical, not a liquefied gas. When methanol is carried as cargo in bulk, the ship and cargo arrangements are governed by the IBC Code (chemical tankers), which lists methanol ("methyl alcohol") in its product tables and prescribes ship type, containment, ventilation, PPE, and transfer requirements for carriage; the fuel system on the same ship remains under the IGF code and MSC.1/Circ.1621 regime. Packaged methanol moves under the International Maritime Dangerous Goods Code (IMDG).

On the regional level, the European Union creates strong incentives for methanol adoption through climate regulation. The FuelEU Maritime Regulation imposes limits on greenhouse gas intensity of energy used on board from 2025 onwards, rewarding renewable methanol (bioethanol or e-methanol) that meets the Renewable Energy Directive (RED III) sustainability criteria. Conventional fossil-based methanol, by contrast, will not provide significant compliance benefits. At the same time, the EU Emissions Trading System (EU ETS) applies to CO_2 emissions from methanol combustion, which underlines the importance of renewable production pathways to deliver real decarbonisation advantages.

At the national flag administration level, methanol projects are handled as alternative designs using the IGF code framework, with MSC.1/Circ.1621 providing the technical benchmark. National authorities, working with classification societies, require structured risk assessments (HAZID/HAZOP, QRA) covering methanol's particular hazards: toxicity (inhalation/skin exposure), low flashpoint, potential for invisible flames, and spill/fire scenarios. The approval process closely resembles that used for hydrogen, though methanol benefits from the fact that its interim guidelines are already widely applied and tested.

The standards environment provides practical references for methanol systems and bunkering. While a dedicated ISO standard for methanol bunkering is under development, existing frameworks such as ISO 20519 (LNG bunkering) are often applied by analogy, with adaptations for methanol's toxicity and fire behaviour. International Electrotechnical Commission (IEC) electrical standards for electrical systems (IEC 60092 series) remain applicable, while EU ATEX and Seveso III directives apply to bunkering and shore-side facilities. These frameworks ensure consistency in safety measures for both shipboard and port operations.

Formal IMO work to include methanol as a prescriptive chapter in the IGF Code is underway, but the schedule has shifted beyond 2025. The aim remains to move from the current Interim Guidelines for Methyl/Ethyl Alcohol-Fuelled Ships (MSC.1/Circ.1621) to mandatory IGF requirements.

At the 11th session of the Sub-Committee on Carriage of Cargoes and Containers (CCC-11) in September 2025, member states and industry observers reaffirmed the goal of integrating methanol into the Code. However, other priorities—especially finalising the hydrogen guidelines—delayed progress. As a result, CCC-11 extended the work plan and assigned a correspondence group to refine the draft structure and technical content of the revised methanol guidelines.

The updated methanol provisions will first appear as a revision of MSC.1/Circ.1621. This will act as a transitional step between today's alternative design approval process and future prescriptive IGF requirements. A consolidated draft is now expected for review at CCC-12 in September 2026. The longer-term goal is to develop a full prescriptive chapter for potential adoption around 2027, depending on the timing of the next MSC session.

Once adopted, these provisions will reduce reliance on the Alternative Design and Arrangements pathway under SOLAS II-1/55 and streamline approval for methanol-fuelled vessels, bringing methanol in line with other fuels already regulated under the IGF Code.

Together, this framework gives methanol a clear but transitional regulatory pathway: mandatory international conventions enforced via the Alternative Design route, interim IMO guidelines providing technical direction, EU legislation shaping the commercial case, and class rules and standards filling technical gaps. Stakeholders thus have a workable, though evolving, foundation for methanol projects, with greater regulatory certainty expected once methanol-specific IGF Code provisions are formally adopted.

8.2.2. Ammonia

The framework for ammonia as a marine fuel has advanced markedly in the last year. While the IGF Code does not yet contain a fully prescriptive ammonia chapter, the IMO has issued interim guidelines specific to ammonia and has also amended gas-carrier rules to enable "cargo-as-fuel" on appropriate ship types.
In parallel, EU climate policy and class rules shape how ammonia projects are designed, approved, and operated.

At the international level, ammonia is governed by SOLAS and the IGF Code. Because the IGF Code remains prescriptive primarily for natural gas, ammonia projects proceed under Alternative Design & Arrangements to demonstrate “equivalent safety” against IGF code safety objectives. The IMO’s Interim Guidelines for the Safety of Ships Using Ammonia as Fuel (MSC.1/Circ.1687) now provide the primary technical reference for containment, fuel supply, ventilation, toxic- and hazardous-area concepts, detection, shutdowns, and crew protection; Administrations and class apply these guidelines during plan approval. In addition, MSC 109 (Dec 2024) adopted amendments to the IGC Code to allow ammonia cargo to be used as fuel on gas carriers, creating a clear path for cargo-as-fuel configurations on those ships.

At the regional level, the EU adds strict operational requirements and reporting obligations. The EU Emissions Trading System (EU ETS) for shipping applies from 2024, and from 2026 it will also include methane and nitrous oxide. This means that ammonia-fuelled engines must minimise both unburned ammonia released to the atmosphere (known as "ammonia slip") and the formation of nitrous oxide, which is a very potent greenhouse gas, to avoid additional compliance costs.

FuelEU Maritime will also introduce progressively stricter limits on greenhouse gas intensity starting in 2025. Whether ammonia meets these limits depends mainly on how it is produced, for example whether it is made using renewable electricity, often referred to as "e-ammonia.

At the national flag administration level, approvals are issued within the IGF code framework using the Alternative Design process: proponents submit structured risk assessments (HAZID/HAZOP, QRA), define acceptance criteria, and show equivalent safety versus conventional fuels, with MSC.1/Circ.1687 as the core technical benchmark. Administrations rely on classification societies (ROs) to verify compliance through plan approval and surveys; class rules now include ammonia-specific options and guidance to translate the interim goals into concrete engineering requirements.

The standards landscape for ammonia as a marine fuel is still taking shape. There is not yet a final ISO standard for ammonia bunker quality or bunkering procedures. As a result, current projects rely on emerging guidance, such as the ABS Ammonia Bunkering Technical and Operational Advisory, which covers transfer operations, sampling, and interim fuel-quality specifications.

On the shore side, EU regulations such as ATEX (relating to equipment and workplaces in explosive atmospheres) and Seveso III (covering major accident hazards) apply to bunkering and storage facilities. In addition, IEC electrical standards and EU pressure-equipment directives guide the detailed design of the bunkering interface

With MSC.1/Circ.1687 already approved at MSC 109, ammonia now has an IMO-endorsed safety baseline. The IMO has also adopted IGC code amendments (entry into force expected 1 July 2026) to permit ammonia cargo-as-fuel on gas carriers. Further refinements to ammonia guidance and eventual incorporation into the IGF Code are expected through upcoming CCC/MSC cycles; stakeholders should align current designs to the interim guidelines to ease future compliance.

Together, this framework gives ammonia projects a practical path: mandatory conventions (SOLAS/IGF) applied via Alternative Design, interim IMO ammonia guidelines for technical direction, EU climate instruments that influence engine and after-treatment choices, class rules that operationalize requirements, and developing standards and port-readiness tools to ensure safe bunkering and shore interfaces. This combination provides sufficient legal certainty and technical detail for decision-makers to advance ammonia-fuelled ships while the prescriptive code text matures.

8.2.3. Hydrogen

The regulatory and standards framework for hydrogen as a marine fuel is evolving rapidly, reflecting both global decarbonisation goals and the safety challenges associated with this fuel. While there is not yet a single prescriptive code for hydrogen, a comprehensive pathway exists by combining international conventions, regional regulations, and classification society guidance.

At the international level, hydrogen is addressed through the International Convention for the Safety of Life at Sea (SOLAS) and the International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels (IGF Code). Since the IGF Code currently provides detailed requirements only for natural gas, hydrogen-fuelled ships must follow the Alternative Design and Arrangements process, demonstrating equivalent safety under SOLAS Regulation II-1/55 and MSC.1/Circ.1455. Interim guidelines developed at the International Maritime Organization (IMO) offer technical direction on system design, gas handling, ventilation, and hazard management for hydrogen installations, and are increasingly used as reference points in approval processes. These requirements are supplemented by existing provisions in the IGF Code for gaseous fuels, which are applied by analogy to hydrogen, particularly in areas such as double-walled piping, ventilation rates, hazardous area zoning, and explosion protection.

On the regional level, the European Union sets strong drivers through instruments such as the FuelEU Maritime Regulation, which imposes progressive limits on the greenhouse gas intensity of energy used on board, and the EU Emissions Trading System (EU ETS), which applies to shipping emissions. These instruments shape the economic case for hydrogen, especially where renewable hydrogen can qualify as a Renewable Fuel of Non-Biological Origin (RFNBO) under the Renewable Energy Directive (RED III). Compliance at the operational level therefore depends not only on shipboard systems but also on the certification and traceability of the hydrogen supply chain.

At the national flag administration level, approvals are granted within the framework of the IGF Code but require early engagement with authorities and classification societies. Hydrogen projects are processed as alternative design cases, where the proponent must present a structured risk assessment (HAZID/HAZOP, quantitative risk analysis), define acceptance criteria, and demonstrate that safety objectives equivalent to conventional fuels are achieved. This process is supported by class society rules and guidelines—for example, ABS and DNV have both published hydrogen-specific requirements addressing fuel supply systems, materials, ventilation, leak detection, and explosion prevention.

The standards environment for hydrogen is evolving, but several mature references already guide engineering practice. ISO standards for gaseous and liquid hydrogen storage, transfer systems, and fuelling protocols (for example ISO 19880-1 for gaseous fuelling and ISO 21012 for cryogenic hoses) are already applied to marine bunkering designs. Shore-side safety and electrical equipment are covered by IEC standards for explosive atmospheres as well as the EU ATEX and Seveso regulations. Together, these frameworks help ensure that ship and port systems follow recognised best practice for handling hydrogen.

IMO guidance is also advancing quickly. Interim IMO guidelines specific to hydrogen were finalised at CCC-11 in September 2025 and are now moving to the Maritime Safety Committee for approval, expected at MSC 111 in May 2026. Their scope covers both liquid hydrogen and compressed hydrogen concepts, including portable and fixed installations, with requirements focused on open-deck arrangements. Once approved, these guidelines will provide a consistent basis for design and approval and will reduce the need for case-by-case alternative design justifications while future amendments to the IGF Code are developed.

For now, projects still need to follow the alternative design process. However, aligning new designs with the forthcoming hydrogen guidelines will make approval smoother and help ensure compliance once the rules become mandatory.

The International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (the IGC Code) applies to hydrogen only in specific situations. It becomes relevant when liquid hydrogen is carried in bulk as cargo. At present, such carriage is permitted under the Revised Interim Recommendations for the Carriage of Liquefied Hydrogen in Bulk and a tripartite agreement, which act as the technical framework until a full Chapter 19 entry is adopted.

Regarding the use of cargo as fuel, there is currently no dedicated IGC amendment that broadly allows liquid hydrogen carried as cargo to be used as fuel on gas carriers. These cases are handled individually, using the interim recommendations, the hydrogen interim guidelines, and acceptance from the flag state and classification society.

By combining mandatory conventions, evolving interim guidance, regional climate legislation, and detailed technical standards, stakeholders can make informed design and investment decisions while ensuring that safety and regulatory compliance are maintained from ship design through to operation and bunkering.

With the applicable governing references established; the IGF Code, the relevant IMO interim guidelines (methanol/alcohols, ammonia), and the leading classification society rules, this report now moves from mapping “what exists” to testing “what suffices.” Chapter 9, 10 and 11 apply these references across all fuel handling areas to identify where requirements are insufficiently prescriptive, ambiguous, inconsistent, or silent, prioritise risk-based mitigations for methanol, ammonia, and hydrogen and derive recommendations for concrete gap-closure actions for stakeholders and demonstrate selected remedies through targeted tests and simulations.

9. SAFETY FUNCTIONS

9.1. Purpose of the Chapter

This chapter summarises the application of the risk-based approach to safety in design, described in Chapter 6, to identify the safety functions required to manage the hazards associated with the use of alternative fuels, the mapping of the impact of the inherent hazardous properties of each type of fuel (see Chapter 4) on those safety functions, and the development of requirements for safety functions for each fuel type and each fuel handling zone. This collected information has been used to inform the decision support logic described in Chapter 10.

9.2. Identification of Safety Functions

The term 'safety function' in this study refers to the function of a system in place to prevent, control or mitigate the risk associated with major accidents such as fire, explosion and toxic release. Each safety function is fulfilled by a combination of technical (physical equipment, systems and structures), operational (e.g. procedures and information required to perform safety-related actions) and organisational (e.g. competences and training, lines of reporting and communication) elements. As an example, the safety function of fire detection is fulfilled by the combination of the following:

- Smoke, heat or flame detectors and associated control panels and alarms (technical),
- Information (e.g. Cause and effect diagrams) needed to interpret and respond to a fire alarm (operational)
- The competence of personnel required to respond to a fire alarm (organisational).

9.2.1. Hazard Identification

A high-level hazard identification workshop was carried out by DBI to identify the major accident hazards explicitly associated with the use of alternative fuels, along with potential causes of a loss of control of each hazard leading to a hazardous event (e.g. loss of containment), the consequences of such an event and the systems in place to prevent a loss of control or mitigate its consequences. The HAZID considered the findings of the methanol ship visit described in Chapter 7. Several existing studies (including other HAZID studies) undertaken by other industry stakeholders were also reviewed to provide further information. These included:

- Safe Bunkering of Biofuels – HAZID and Risk Assessment Report, EMSA, Rev 2.0, July 2024
- Emerging Ship Design Principles for Ammonia-Fuelled Vessels, Maersk McKinney Møller Center, October 2024
- Potential of Ammonia as Fuel in Shipping, EMSA, September 2022
- Hazard Identification of Generic Hydrogen Fuel Systems, EMSA, March 2025.

9.2.2. Bowtie Analysis

The information gathered from these studies was used to undertake bowtie analysis of the major accident hazards for each fuel type and develop a set of bowtie diagrams to provide a clear visual representation of the relationship between the major accident hazards, and the systems in place to in place to prevent a hazardous event or mitigate against its escalation (safety functions). For each fuel type, bowties were developed for a loss of fuel containment (with the potential to result in a fire, explosion or toxic release) in each of the four fuel handling zones of a ship defined in Chapter 5, namely:

1. Bunkering (inc. pipework to storage)
2. Storage (including tank connection space and LP piping to pre-treatment/engine room)
3. Preparation / mixing room (including HP piping to the engine room)
4. Engine Room.

The bowtie diagrams are presented in Annex A to this report.

The objective of the bowties is to identify the safety functions applicable for all ship types and thus the bowties are, by definition, generic and do not model details of the different systems used to provide the safety functions. Furthermore, they are not intended to be exhaustive in showing details of all possible causes and consequences of a loss of containment, but to focus on modelling the safety functions whose requirements are dependent on the type of fuel and its hazardous properties. For this reason, causes for which the prevention measures do not depend on type of fuel (such as dropped loads) have not been included. Generic causes such as 'Maintenance error' have not also been included, as again, the controls in place do not depend on the type of fuel.

Based on the bowtie analysis, a set of safety functions required for the prevention and mitigation of major accidents has been defined, and these are listed below, together with a short description of what is included in each Safety Function (SF).

Table 6. List of Safety Functions

No.	Safety Function	Description
SF1	Layout and arrangement	Ship structure, impact protection, overall layout.
SF2	Fuel primary containment	Primary containment of fuel – e.g. storage tanks, piping, vacuum insulation, cofferdams), includes requirements for pipework leak detection, valves, pumps, joints, flanges, bunkering pipework and couplings, material specification and compatibility.
SF3	Secondary containment and drainage	Secondary containment of spills (bunds, drip trays, etc.) (inc. level indication), drainage systems, boil-off gas capture.
SF4	Purging / inerting	Purging / inerting systems and procedures.
SF5	Gas/vapour detection	Flammable and toxic gas detectors and associated control panels and alarms. ESD actions on gas detection are covered by SF11.
SF6	Fire detection	Smoke, heat and flame detectors and associated control panels and alarms.
SF7	Ignition source control	Hazardous area classification, Ex-rating of permanent and portable equipment. Earthing and bunding (static control). Shutdown of non-essential systems is covered by SF11.
SF8	Pressure relief	Pressure relief valves, rupture discs etc.
SF9	Ventilation	Ventilation systems (inc. inlets/outlets, fans, dampers), airlocks.
SF10	Process control and monitoring	Pressure, temperature, level monitoring and process control. Emergency shutdown is covered by SF11.

No.	Safety Function	Description
SF11	Emergency Shutdown (ESD)	Manual and automatic shutdown systems and associated executive actions (inc. isolation of non-essential systems, actuation of shutdown valves).
SF12	Active fire protection	Fixed and portable systems for fire suppression and extinguishing (e.g. foam, CO_2, dry powder, water mist systems). This SF also includes water curtains for use in the event of an ammonia release.
SF13	Passive fire and explosion protection	Fire and blast-rated walls, explosion relief, etc. Flame arrestors and deflagration protection.
SF14	Emergency response	Muster, escape routes, emergency lighting/signage, rescue, LSA. Emergency response plans and environmental/spill response.
SF15	Personal Protective Equipment (PPE)	Protective clothing, personal gas detectors, breathing apparatus. Eye wash stations and emergency showers.

Safety functions which are required for the prevention and mitigation of major accidents, but which are not affected by the properties of the fuel (e.g. emergency communications, emergency power), have not been included in the list above.

9.2.3. Mapping of Safety Functions against Hazardous Properties

To identify the key safety issues associated with the use of each of the alternative fuels under consideration in this report and thus provide the first step in identifying the gaps in existing Codes and Standards when applied to such fuels, the impacts of the specific hazardous properties (see Chapter 4) of each type of fuel on each of the Safety Functions have been mapped. The results of this mapping are presented In Annex B to this report.

9.3. Safety Considerations and Safety Function Requirements

This section collects the safety considerations for methanol, ammonia, and hydrogen and shows how the inherent properties of each fuel translate into risks across the four fuel handling zones identified in Chapter 5 (i.e. bunkering, storage tank/TCS, FPR, engine room). The hazardous properties described in Chapter 4 (e.g., methanol's low flashpoint and low-luminous flame; ammonia's toxicity and corrosivity; hydrogen's buoyancy and low ignition energy, as well as the cryogenic effects of liquid nitrogen) are outlined and mapped against the requirements for controls and mitigation. The goal is to clarify and explain the differences from conventional fuels, using concise implementation notes and performance targets that feed directly into the gap analysis and the subsequent scenario evidence. This section builds on the safety functions derived in the bowtie analysis (and listed in Table 6) and provides a detailed description of the requirements for these in Annex C.

9.3.1. Methanol

Figure 11 gives an overview of the main hazards associated with methanol identified in this study and the Risk Reduction Measures (RRMs) that can be applied in the ship design stage to manage them. Table 1 in Annex C provides a full list of the safety considerations and detailed safety function requirements which can be applied for each ship fuel handling zone.

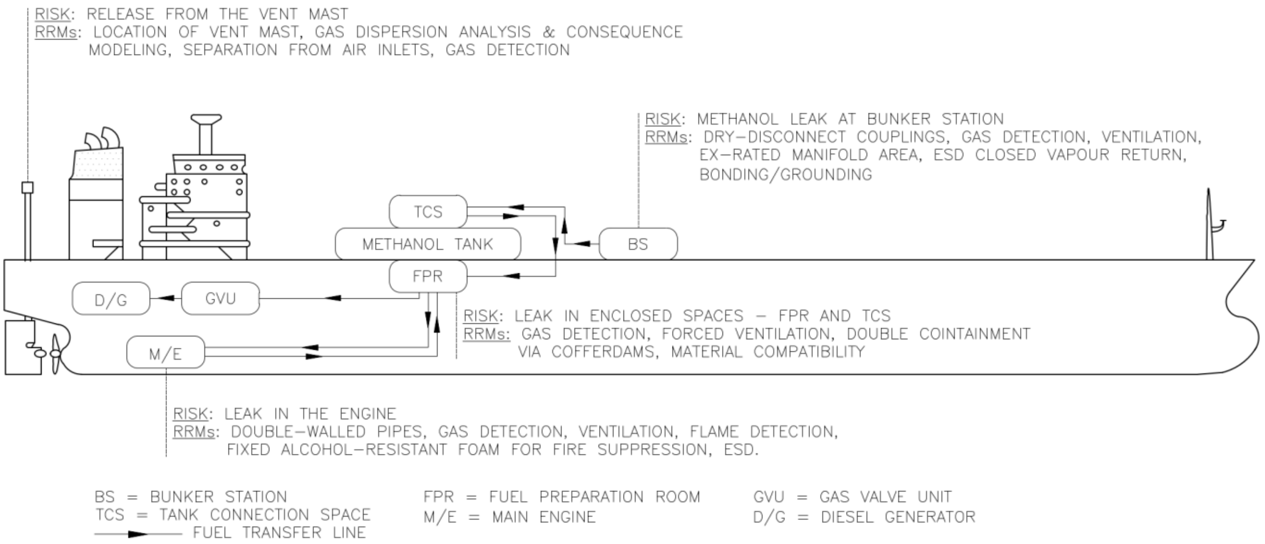


Figure 11. Overview of methanol onboard hazards and RRMs

9.3.2. Ammonia

Figure 12 gives an overview of the main hazards associated with ammonia identified in this study and the RRMs that can be applied in the ship design stage to manage them. Table 2 in Annex C provides a full list of the safety considerations and detailed safety function requirements which can be applied for each ship fuel handling zone.

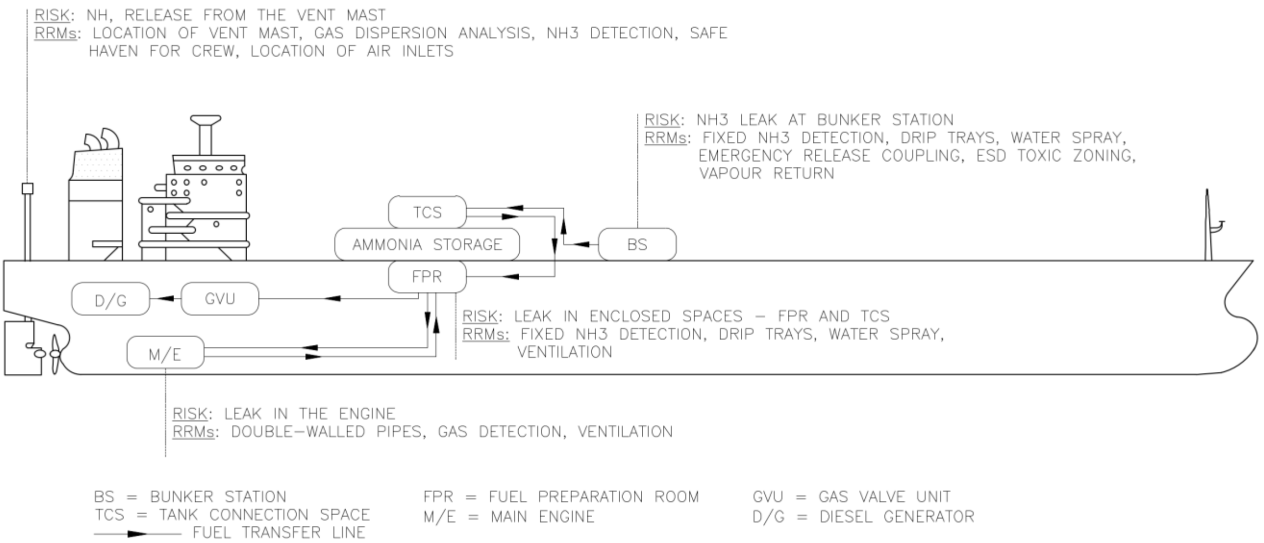


Figure 12: Overview of ammonia onboard hazards and RRMs

9.3.3. Hydrogen

Figure 13 gives an overview of the main hazards associated with hydrogen identified in this study and the risk reduction measures (RRMs) that can be applied in the ship design stage to manage them. Table 3 in Annex C provides a full list of the safety considerations and the detailed safety function requirements that can be applied for each ship fuel handling zone.

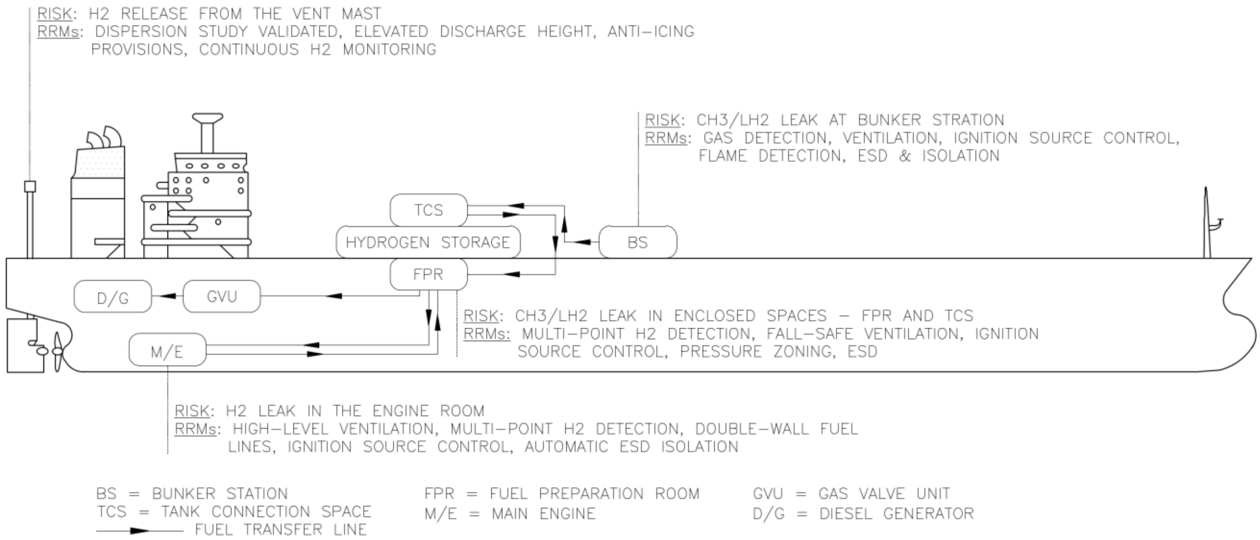


Figure 13: Overview of hydrogen onboard hazards and RRMs

10. INTEGRATED DECISION SUPPORT FRAMEWORK

10.1. Purpose of This Chapter

The purpose of this chapter is to present the Integrated Decision Support Framework that forms the backbone of the METAFUEL approach to evaluating the safety of methanol, ammonia, and hydrogen. The framework provides a structured, evidence-based method for interpreting hazards, applying Safety Functions, identifying regulatory gaps, and guiding design and operational decision-making from concept to approval.

The transition toward green maritime fuels demands structured, evidence-based decision-making tools that can interpret complex safety, regulatory, and operational interdependencies. Within the METAFUEL project, this need is addressed through the development of an integrated Decision Support Tool (MAFSKE), a matrix-based system that synthesizes technical knowledge, safety functions, and regulatory insights into actionable guidance for diverse maritime stakeholders.

Unlike traditional rule-based checklists, this framework operates as a black box: it draws upon validated mappings of hazards, controls, and requirements developed in previous chapters, but does not expose the detailed computational or comparative mechanisms that underpin its assessments. This preserves the intellectual integrity of the model while emphasizing its purpose—to enable consistent, transparent, and defensible decision support across varying fuel types and ship configurations.

The framework integrates:

- Fuel properties and hazards (Chapter 4)
- The four-zone reference architecture (Chapter 5)
- Design risk principles (Chapter 6)
- Human factors (Chapter 7)
- The regulatory baseline (Chapter 8)
- The Safety Functions (Chapter 9)
- Technology maturity (Chapter 11)
- Scenario-based evidence (Chapter 12)
- Bowtie logic (Annex A), fuel-property mapping (Annex B), and zone safety function requirements (Annex C)

It provides a traceable, evidence-informed method for aligning system design and operational decisions with fuel properties and regulatory intent.

10.2. Gap analysis

The integrated Decision Support Tool (MAFSKE) conducts a gap analysis that helps identify where existing rules are missing, incomplete, or inconsistent between different authorities and classification societies. These gaps often mean that projects must rely on risk-based design approaches and alternative design justifications rather than clear prescriptive standards.

As described in Chapter 8, prescriptive safety requirements for methanol, ammonia, and particularly hydrogen remain incomplete or uneven across the IMO and Class landscape.

- The gap analysis identifies where existing standards:
- Lack detailed guidance (e.g., ammonia ventilation rates, hydrogen PRD routing)
- Are ambiguous (e.g., methanol flame detection coverage)
- Require case-by-case justification (e.g., double-wall piping for hydrogen)
- Do not capture fuel-specific human factors challenges
- Rely heavily on “goal-based” intent rather than performance criteria

These gaps directly affect hazard identification, Safety Function selection, evidence pathways and approval timelines. The Decision Support Framework is designed to help stakeholders navigate these gaps transparently.

10.3. Structure of the Decision Framework

The Decision Support Tool is constructed around four key input dimensions that represent the main determinants of safety and compliance in alternative fuel adoption:

1. Maritime Stakeholder Type (e.g. Shipowner, Shipyard, Classification Society, Port Authority, or Regulator)
2. Fuel Type (e.g. Methanol, Ammonia, or Hydrogen)
3. Ship Build Type (e.g. New Build or Retrofit)
4. Fuel Handling Zone (e.g. Bunkering Station, Storage System, Fuel Preparation Room, Engine Room)

These inputs feed into a central decision engine that aligns safety functions, performance requirements, and regulatory frameworks in real time. The process culminates in a tailored set of outputs relevant to the user’s profile.

10.4. Outputs and Application

The tool’s outputs are structured to provide decision-grade insights that stakeholders can directly integrate into design, operational, or regulatory processes. The results are grouped into five categories:

- Safety Considerations: Key design or operational themes specific to the selected fuel and handling area.
- Regulatory References: Extracts from the IGF Code, interim IMO guidelines, and classification society rules most relevant to the selected configuration.
- Guideline Chapters: Cross-links to best-practice sources or standards providing more prescriptive implementation detail.
- Gap Analysis:
    - The tool internally interprets areas where existing frameworks remain non-prescriptive or ambiguous but does not display this detail externally.

- This mechanism ensures that users receive compliant, forward-aligned guidance without direct exposure to evolving or contested regulatory gaps.

- Stakeholder-Specific Recommendations: Actionable recommendations derived from the synthesis of the above layers. For example:
  - *Shipowners* may receive direction on detection system thresholds or material compatibility.
  - *Classification societies* may be prompted to apply specific verification procedures.
  - *Port authorities* may be guided toward emergency response or safety zoning considerations.

Figure 14 shows the functional representation of the MAFSKE decision support tool.

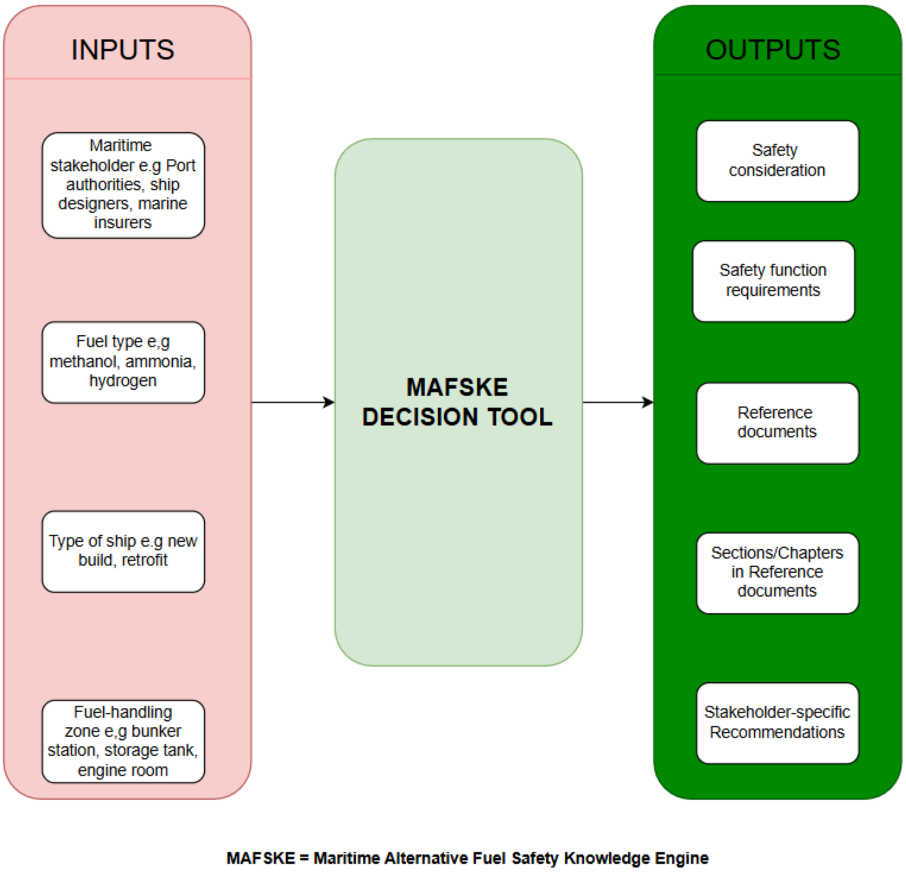


Figure 14: MAFSKE Decision Support Framework

10.5. Operating Philosophy

The Decision Support Tool is underpinned by three guiding principles:

1. Evidence-Based Alignment: All outputs stem from validated mappings of safety functions and regulatory sources described in prior chapters.

2. Analytical Core: The computational and comparative logic is integrated within the engine to preserve

methodological integrity. It is based on a structured and systematic regulatory gap analysis.

3. Dynamic Adaptability: The tool architecture allows future updates to accommodate regulatory evolution, new fuels, or refined safety data without altering the core structure.

10.6. Strategic Role in Maritime Decarbonization

The Decision Support Tool acts as a bridging mechanism between research and regulation. By embedding knowledge from hazard identification, safety function mapping, and regulatory review, it provides a stable reference model that can evolve alongside IMO and class developments.

For maritime stakeholders, this means:

- Streamlined project approval and design review.
- Enhanced clarity in interpreting safety expectations.
- A consistent pathway for aligning new fuel projects with global regulatory progression.

The approach enables decision-making that is proactive rather than reactive, ensuring that safety and regulatory compliance evolve in tandem with innovation.

10.7. Path Forward

The next phase of this decision tool will focus on refining and validating this framework through user testing and case-based evaluation. Future iterations may incorporate probabilistic risk weightings, automated document referencing, and integration with digital twin environments.

Ultimately, the Decision Support Tool provides a foundation for a continuous-learning safety ecosystem—one that empowers maritime stakeholders to make informed, confident decisions in an increasingly complex regulatory and technical landscape.

10.8. Examples of how the decision tool can be used:

In this section, five examples of how the decision tool can be used by the stakeholder is highlighted. This is just on a basic level. More detailed output information is obtained when the tool itself it used.

10.8.1. Example 1: Fire Suppression in the Engine Room (Methanol Case)

10.8.1.1. Inputs to the Decision Tool

Table 7. Example 1 Input Parameters Used to Demonstrate the MAFSKE Integration Decision-Support Process.

Parameter	Input
Maritime stakeholder	Shipowner / Operator
Fuel type	Methanol
Type of ship build	Retrofit
Fuel handling Zone	Engine Room

10.8.1.2. Outputs (as presented Shipowner / Operator)

Table 8. Example 1 Outputs Generated by the MAFSKE Tool for Illustrative Integration Decision Support.

Output Category	Example Output
Safety Consideration	Methanol has a low flash point (~11 °C) and produces a nearly invisible flame. Detection and suppression systems must be able to respond despite limited visual confirmation.
Safety Function Requirement	Fire detection in the engine room should integrate optical and infrared flame sensors. Fixed water-mist or foam-based suppression must eliminate potential ignition sources.
Regulatory References	IMO Interim Guidelines for Methanol (MSC.1/Circ.1621); Classification Society Rules (DNV, BV, ABS, LR); SOLAS II-2/10 (Fire-Extinguishing Systems).
Guideline Chapters	Interim Guidelines: Ch. 15.5, 8.3, 13.5, 11.6, 17.4.3, 7.3.10; DNV Pt.6 Ch.2 Sec.6 §3 (Fire Protection).
Stakeholder-Specific Recommendation	Shipowners should verify compatibility between fire-detection sensors and methanol combustion properties. Retrofit design should integrate ventilation shutdown with automatic suppression activation.

10.8.2. Example 2: Ammonia Leak During Bunkering (Hypothetical Danish Port)

10.8.2.1. Inputs to the Decision Tool

Table 9. Example 2, First Input Parameters Used to Demonstrate the MAFSKE Integration Decision-Support Process.

Parameter	Input
Maritime stakeholder	Port Authority / Emergency Responder
Fuel type	Ammonia
Type of ship build	New Build
Fuel handling Zone	Bunkering Station

10.8.2.2. Outputs 01 (as presented to the Port Authority / Emergency Responder)

Table 10. Example 2, First Outputs Generated by the MAFSKE Tool for Illustrative Integration Decision Support.

Output Category	Example Output
Safety Consideration	Ammonia is highly toxic and corrosive. Vapour release can cause severe inhalation hazards, requiring rapid leak detection and effective emergency dispersion management.
Safety Function Requirement	Continuous gas monitoring based on AEGL-1/2 thresholds; automatic activation of emergency shutdown (ESD) valves upon detection; establishment of controlled exclusion zones during bunkering operations.
Regulatory References	IMO IGF Code, Chapter 15 (Fuel Containment); MSC.1/Circ.1647 (Interim Guidelines for Ammonia as Fuel, where applicable); IGC Code, Chapter 17 (Toxic Cargo Handling); Classification Society Rules (DNV, BV, ABS, LR).
Guideline Chapters	Interim guideline Section 5.9.2, 7.2.1.5, 5.7.3.2 15.8.2, 13, 5.2.1.2, 6.7.2, 8.3.1.2, 8.5, 5.8, 5.7.3.3 | ABS Section 7 4.3-4.7, 8 7, Section 15, Table 1, 12.4, Section 13 6; Section 17; BV Section 2 5.2 2 13.2, Section 2 11.2.2, 3.8
Stakeholder-Specific Recommendation	Port authorities should validate dispersion modelling under local meteorological conditions and define temporary safety perimeters. Coordination with port emergency services should ensure PPE availability and decontamination capability.

10.8.2.3. Input 02 to the Decision Tool

Table 11. Example 2, Second Input Parameters Used to Demonstrate the MAFSKE Integration Decision-Support Process.

Parameter	Input
Maritime stakeholder	Marine insurer
Fuel type	Methanol
Type of ship build	Retrofit
Fuel handling Zone	Engine Room

10.8.2.4. Outputs 02 (as presented to the Port Authority / Emergency Responder)

Table 12. Example 2, Second Outputs Generated by the MAFSKE Tool for Illustrative Integration Decision Support.

Output Category	Example Output
Safety Consideration	Methanol has a low flash point and produces a low-luminous flame, increasing reliance on detection and automatic suppression due to delayed visual confirmation.
Safety Function Requirement	Safety functions include fire detection, active fire protection systems, ignition-source control, ventilation management, emergency shutdown (ESD), and process monitoring—applied as defined in the project's safety-function set.
Regulatory References	IMO Interim Guidelines for Methanol (MSC.1/Circ.1621); Classification Society Rules (DNV, BV, ABS, LR); SOLAS II-2/10 (Fire-Extinguishing Systems).
Guideline Chapters	Interim guideline Section 10 11.6.5, 15.8; ABS Section 10, 15 8; BV Section 8 1.1, 9 2.1.4
Stakeholder-Specific Recommendation	• Require dual-phenomenology flame detection suitable for low-luminous methanol fires, with integration to ESD and ventilation cutback. • Verify fixed-system suitability for alcohol fuels (water-mist configuration and/or AR-foam if required) and align evidence with project laboratory testing and findings from Chapter 11. • Ensure cause-and-effect linkages (detector → alarm → shutdown → suppression) are fully documented and functionally tested. Evidence Checklist to Request *(bind these to pricing/terms)*: • Fire-detection design basis and placement rationale specific to methanol, including commissioning function tests. • Test reports for fixed systems or analogue evidence aligned with Chapter 11 methanol pool-fire results (time-to-control/extinguishment, visibility effects). • Cause-and-Effect (C&E) matrix and FAT/SAT records (detector → ESD → ventilation → local application firefighting systems). • Maintenance and re-test intervals for detectors and nozzles, plus spare-parts provisions for critical components. Insurer Policy Levers (Examples): • Warranty: “Maintain detection and fixed suppression per approved C&E; test quarterly with records available to underwriters.”

Output Category	Example Output
	• Pricing credit: Demonstrated use of dual-tech flame detection and successful suppression testing under methanol-representative conditions. • Deductible loading: Applied if AR-foam or equivalent measures for open-pool scenarios are absent despite design-basis need. KPIs to Track • Mean alarm-to-ESD time (target: ≤ X s). • Nozzle availability at inspection (percentage within tolerance). • Quarterly detector proof-test pass rate (≥ 99%)

10.8.3. Example 3: Cold-temperature hazards at bunker station

10.8.3.1. Inputs to the Decision Tool

Table 13. Example 3 Input Parameters Used to Demonstrate the MAFSKE Integration Decision-Support Process

Parameter	Input
Maritime stakeholder	Marine Insurer
Fuel type	Ammonia
Type of ship build	New Build
Fuel handling Zone	Bunker Station

10.8.3.2. Outputs (as presented to the user)

Table 14. Example 3 Outputs Generated by the MAFSKE Tool for Illustrative Integration Decision Support

Output Category	Example Output
Safety Consideration	Refrigerated or semi-pressurized NH_3 can drive steels into brittle fracture below the minimum design temperature (MDT). Low-temperature operation also promotes icing and frosting that impair valve actuation, couplings, emergency release couplers (ERC/BRC), and sensor accuracy at the bunker station.
Safety Function Requirements	• Materials & MDT: All pressure parts, supports, and quick-connect fittings must be certified for the lowest credible metal temperature at the bunker interface (impact-tested steels or equivalent alloys). • Instrument winterization: Temperature-rated gas/toxic detectors, pressure/level transmitters and ESD devices, with heated enclosures where required; diagnostic logic for "sensor fail-low in cold" conditions. • Icing control: Heat tracing and insulation on critical lines and actuator housings; adequate drainage to prevent ice bridging; anti-icing procedures for ERC/BRC and dry-break couplings. • Emergency Shutdown (ESD): Low-temperature-rated shutdown valves with demonstrated closure performance under frosting/icing; periodic functional testing. • Containment & spill control: Curbed or graded surfaces and low-temperature-compatible trays to prevent ice sheets; wash-down and neutralization plans for ammonia residues.

Output Category	Example Output
	• Detection & ventilation: Toxic-gas detection around manifolds and air intakes with alarm/ESD setpoints; ventilation paths maintained to avoid obstruction from ice buildup. • Human factors & PPE: Cold-burn protection (face shields, cryogenic gloves); eyewash/showers accessible without icing; lighting/visibility preserved during frosting events.
Regulatory References	IMO IGF Code (fuel systems, detection/ventilation, ESD fundamentals applicable to low-flashpoint fuels); IMO Interim Guidance for Ammonia as Fuel (MSC.1/Circ.1687 — ammonia-specific design and approval baseline, adopted at MSC 109); Classification Society Rules (DNV, BV, ABS, LR).
Guideline Chapters	Interim Guideline Section 8; ABS Section 8; BV Section 2 6,
Stakeholder-Specific Recommendation	Underwriting terms should be linked to evidence of cold-service fitness at the bunker station: • MDT verification dossier for manifolds, valves, ERC/BRC and supports, including Charpy impact data or equivalent evidence. • Cold-proof ESD functional-test records (closure performance under induced frost/ice). • Instrument winterization plan with low-temperature setpoint validation and failure-mode alarm logic. • Icing-management SOPs (pre-bunkering anti-icing checks; post-operation de-icing and inspection). • Drill logs for cold-spill response and ammonia exposure scenarios, including PPE readiness and access-route clearing under icing. • Requirement for periodic site validation (witness test or third-party survey) prior to granting favourable premiums/deductibles. Optional Performance Indicators (for policy conditions): • Percentage of cold-rated critical devices with validated MDT certification. • Mean time to ESD closure under icing (acceptance criterion ≤ X seconds). • Detector availability under sub-zero conditions (≥ 99% during bunkering windows). • Corrective-action closure time for any low-temperature “fail-low” sensor incidents.

10.8.4. Example 4: CH_2—Embrittlement of Storage Systems (Hydrogen, Marine Insurer, Newbuild)

10.8.4.1. Inputs to the Decision Tool

Table 15. Example 4 Input Parameters Used to Demonstrate the MAFSKE Integration Decision-Support Process

Parameter	Input
Maritime stakeholder	Marine Insurer
Fuel type	Hydrogen
Type of ship build	New Build
Fuel handling Zone	Storage Tank + Tank Connection Space (TCS)

10.8.4.2. *Outputs (as shown to the user)*

Table 16. Example 4 Outputs Generated by the MAFSKE Tool for Illustrative Integration Decision Support

Output Category	Example Output
Safety Consideration	Hydrogen can embrittle susceptible metallic materials, reducing toughness and promoting crack initiation in pressure parts, fittings, supports, and welded areas in storage and TCS service. This hazard is explicitly addressed in the report deliverables and in the hydrogen fuel-properties mapping.
Safety Function Requirements	Fuel primary containment (materials & design): • Select steels/alloys and welding procedures qualified for hydrogen service at relevant pressures and temperatures; document fracture toughness and crack-growth resistance. • Apply liners or surface treatments where appropriate; control hardness to avoid hydrogen-affected regions; qualify NDE for hydrogen-susceptible defects. Process control & monitoring: • Continuous pressure/temperature monitoring with trending to identify abnormal permeation or slow leaks; integrate alarm logic with ESD where applicable. Pressure relief & venting: • Relief devices sized for credible upset conditions; vent masts positioned to achieve safe dispersion (accounting for hydrogen buoyancy and rapid vertical rise). Inspection & testing regime: • Baseline pre-commissioning NDE plus periodic in-service inspections focused on weld toes, supports, and nozzles; defined acceptance criteria for micro-cracking and hydrogen-assisted cracking. Emergency shutdown (ESD) & isolation: • Remote-operated isolation on abnormal readings; proof of valve actuation under design-extreme conditions. Layout & arrangement: • Protect TCS boundaries; maintain required separations and airflow paths; avoid confinement that could increase consequences should loss of containment occur due to cracking.
Regulatory References	IGF Code with Alternative Design provisions for non-LNG fuels: hydrogen projects proceed via structured risk assessment and equivalence demonstration (HAZID/HAZOP, QRA) under SOLAS/IGF. Interim hydrogen guidelines: finalized at IMO CCC-11 and moving toward MSC approval, covering gaseous and LH_2 concepts—particularly relevant for open-deck storage and TCS design expectations.
Guideline Chapters	IGF Code: Chapter 7, 6.7.2; BV: Section 5, Section 13, Section 7 1.1.1; ABS: Section 7, Section 16.

Output Category	Example Output
Safety Consideration	Hydrogen can embrittle susceptible metallic materials, reducing toughness and promoting crack initiation in pressure parts, fittings, supports, and welded areas in storage and TCS service. This hazard is explicitly addressed in the report deliverables and in the hydrogen fuel-properties mapping.
Stakeholder-Specific Recommendation	Underwriting terms should be linked to verified embrittlement-control measures: • Materials dossier: fracture-mechanics test data (e.g., K_IC, J-integral, slow-strain-rate or constant-load H_2 tests), weld procedure qualifications, hardness maps, and PWHT records. • Crack-management plan: defined inspection intervals, qualified NDE methods (TOFD/PAUT), and acceptance criteria for hydrogen-assisted cracking. • Operating envelope: clearly defined pressure/temperature cycling limits with alarms for excursions; evidence of fatigue and thermal-cycle assessments. • Relief & venting validation: design calculations and commissioning test records for PRDs and vent-mast dispersion. • Change control: any material or vendor change in the storage/TCS system triggers re-qualification for hydrogen service. Optional Performance Indicators (for policy conditions) • Percentage of storage/TCS pressure parts with hydrogen-service qualification on file (target: 100%). • Crack-indication rate per 1,000 weld-meters per inspection cycle (target ≤ X). • Alarm-to-isolation time for abnormal pressure/temperature trends (target ≤ Y seconds). • Relief-system functional-test pass rate (target: 100%). • Corrective-action closure time for any sensor anomalies.

10.8.5. Example 5: Ammonia leak during bunkering

10.8.5.1. Inputs to the Decision Tool

Table 17. Example 5 Input Parameters Used to Demonstrate the MAFSKE Integration Decision-Support Process

Parameter	Input
Maritime stakeholder	Marine insurer
Fuel type	Ammonia
Type of ship build	New build
Fuel handling Zone	Bunkering station

10.8.5.2. Outputs (as presented to the user)

Table 18. Example 5 Outputs Generated by the MAFSKE Tool for Illustrative Integration Decision Support

Output Category	Example Output
Safety Consideration	Ammonia presents toxicity, corrosivity, and significant operational dispersion risk. Safe operations require credible AEGL-linked alarm and

Output Category	Example Output
	response thresholds, together with managed exclusion zones during bunkering and abnormal-condition scenarios.
Safety Function Requirement	• Gas detection: AEGL-based alarm setpoints with redundancy and calibration coverage for expected concentrations. • Emergency shutdown (ESD): Automatic isolation on toxic-gas triggers; proof of valve action under expected flow/pressure conditions. • Ventilation & air-intake control: Maintain clean-air paths; automatic closure or redirection when toxic gas is detected near intakes. • Spill/effluent handling: Low-temperature-compatible containment, drainage, and neutralization provisions. • Active mitigation: Water curtains or equivalent measures to suppress or redirect vapour clouds. • Emergency response & PPE: Site readiness for toxic exposure, including respiratory protection, decontamination capability, and trained response teams.
Regulatory References	IMO IGF Code, Chapter 15 (Fuel Containment); MSC.1/Circ.1647 (Interim Guidelines for Ammonia as Fuel, where applicable); IGC Code, Chapter 17 (Toxic Cargo Handling); Classification Society Rules (DNV, BV, ABS, LR).
Guideline Chapters	Interim guideline Section 15.8.2, 13, 5.2.1.2, 6.7.2, 8.3.1.2, 8.5, 5.8, 5.7.3.3 | ABS Section 8 7, Section 15, Table 1, 12.4, Section 13 6; Section 17, BV Section 2 13.2, Section 2 11.2.2, 3.8
Stakeholder-Specific Recommendation	Underwriting terms should be linked to demonstrated toxic-exposure control: • AEGL-based detection setpoints and ESD trip logic fully documented and validated; exclusion-zone management shown for bunkering periods. • Scenario evidence (study outputs or site-specific analysis) demonstrating that detection + ESD timing achieves toxic-exposure objectives under local wind conditions—aligned with your simulation chapter. • Verified PPE and decontamination readiness and integration with port emergency services. Evidence Checklist to Request: • Detector layout, calibration ranges, and AEGL-linked alarm logic. • ESD functional-test records under realistic flow/pressure conditions, including proof of shutdown timing. • Bunkering SOPs (hot/cold checks, ERC/BRC verification, communications). • Dispersion and exclusion-zone assessments for active berths (wind roses, air-intake positions). • Drill logs for toxic exposure, over-water plume scenarios, and shelter-in-place protocols. Insurer Policy Levers (Example Wording): • Sub-limit for toxic-release events unless AEGL-based design and drills are evidenced.

Output Category	Example Output
	• Premium credit for annual scenario validation (table-top + live drill) and detector uptime ≥ 99%. • Deductible loading if ERC/BRC cold-function tests are not completed before first-fuel operations. **KPIs to Track:** • Detector availability during bunkering windows (≥ 99%). • Alarm-to-ESD activation time (target ≤ Y seconds). • Toxic-exceedance events above AEGL-1/2 per 1,000 bunkering hours (target: 0).

11. GAP ANALYSIS MATRIX — DEVELOPMENT STAGE OF FUEL HANDLING VALUE CHAIN

11.1. Purpose of This Chapter

The purpose of this chapter is to present a maturity assessment of the key components in the fuel-handling value chain for methanol, ammonia, and hydrogen. Using a structured Technology Readiness Level (TRL) approach, the chapter identifies:

- Where technologies and procedures are already mature
- Where prescriptive guidance is missing or incomplete
- Where risk-based justification is still required
- Where additional testing, modelling, or standardisation is needed

This assessment supports the Decision Support Framework (Chapter 10) by showing which safety functions, systems, and operational arrangements are ready for widespread adoption and which require further development.

11.2. Purpose of the Gap Analysis Matrix

The development of methanol, ammonia, and hydrogen as alternative marine fuels introduces new technical, safety, and regulatory challenges across the fuel handling chain. While the IMO's IGF Code and interim guidelines provide the functional safety foundation, prescriptive design and verification rules remain incomplete for these fuels.

This chapter presents a Gap Analysis Matrix designed to evaluate the readiness and maturity of each segment of the fuel handling value chain. The goal is to provide a clear picture of which areas are technically mature, and which require further standardization, testing, or regulatory development before widespread adoption can occur.

The analysis supports the decision support framework developed in this project by linking technical readiness, regulatory maturity, and stakeholder preparedness across the entire fuel system from bunkering to engine room integration.

11.3. Scope of the Value Chain

The analysis covers all critical fuel-handling zones found on board a ship that operates on methanol, ammonia, or hydrogen:

1. Bunker Station and Transfer to Tank: The ship–shore interface for fuel delivery.
2. Storage Tank (including Tank Control System): Onboard containment and tank safety systems.
3. Fuel Preparation Room (FPR): Fuel conditioning, heating, pressure regulation, and leak management.
4. Engine Room / Utilization System: Final fuel use in engines

Each zone represents a critical safety boundary with different technical and regulatory demands depending on the fuel characteristics for instance flammability for methanol, toxicity for ammonia, and cryogenic/explosive potential for hydrogen.

11.4. Methodology: Technology Readiness Level Assessment

To assess the development stage of each fuel system, the Technology Readiness Level (TRL) scale is used as a consistent, objective measure of maturity.

Originally developed by NASA and adopted widely in maritime innovation and EU R&D programs, TRL provides a common language for comparing different technologies and identifying gaps between concept and commercial application. Table 19: Technology Readiness Level for shipping alternative fuelsTable 19 summarizes how TRL methodology is applied to readiness and maturity of shipping alternative fuels.

Table 19: Technology Readiness Level for shipping alternative fuels

TRL Range	Description	Interpretation for Alternative Fuels
1–3	Basic principles & early concept formulation	Early-stage lab research; safety concepts under study
4–6	Validation in lab or prototype environment	Demonstration projects, test rigs, prototype systems
7–9	Demonstrated and operational systems	Approved, certified systems in commercial operation

In this project, TRLs are assigned based on technical maturity, regulatory framework completeness, and operational experience from pilot or commercial ships.

Readiness is evaluated for each fuel handling zone and plotted in both tabular (matrix) and graphical (heat map) form to enable quick comparison and prioritization of development focus.

11.5. Gap Analysis Matrix

The matrix illustrates how each part of the fuel system currently stands in terms of readiness for methanol, ammonia, and hydrogen.

It highlights where stakeholders like ship designers, operators, classification societies, port authorities, and emergency responders etc., must still rely on risk-based justification instead of prescriptive requirements.

Table 20: Gap Analysis Matrix — Development Stage of Fuel Handling Value Chain

Fuel Handling Zone	Readiness & Key Gaps		
	Methanol	Ammonia	Hydrogen
Bunker Station & Transfer to Tank	**Readiness:** High (≈ TRL 8–9). **Gaps:** Standardization of bunkering interfaces; harmonized safety zones; port-specific variations; operator training.	**Readiness:** Low–medium (≈ TRL 5–6). **Gaps:** No global bunkering standard; toxicity management (water curtains, scrubbers); ESD-link integration; emergency procedures not harmonized.	**Readiness:** Low (≈ TRL 4–5). **Gaps:** Cryogenic LH_2 bunkering infrastructure limited; H_2 detection/venting not standardized; interface and coupler technology under qualification.

Storage Tank (incl. TCS – Tank Control System)	**Readiness:** High (≈ TRL 8). **Gaps:** Material compatibility for long-term exposure; leak detection calibration; inerting management for double barriers.	**Readiness:** Medium (≈ TRL 6–7). **Gaps:** Design for toxic release containment; material compatibility (no Cu alloys); boil-off control for refrigerated NH_3; integration of TCS with toxicity alarms.	**Readiness:** Low–medium (≈ TRL 5–6). **Gaps:** LH_2 cryogenic tank standards still evolving; vacuum integrity and insulation safety; venting and PRD harmonization; embrittlement-resistant materials.
Fuel Preparation Room (FPR)	**Readiness:** Medium–high (≈ TRL 7–8). **Gaps:** Alcohol-resistant materials; hazardous zoning and ESD configurations differ by class; ventilation redundancy under review.	**Readiness:** Medium (≈ TRL 6). **Gaps:** Toxic gas management and dilution standards incomplete; separation distances for dual-fuel systems unclear.	**Readiness:** Low (≈ TRL 5). **Gaps:** Integration of engine systems and compressors; explosion risk quantification; overpressure protection validation.
Engine Room / Utilization System	**Readiness:** High (≈ TRL 8–9). **Gaps:** Ignition control for low-flashpoint liquid; visibility of methanol flames; fuel leak isolation near hot surfaces.	**Readiness:** Medium (≈ TRL 6–7). **Gaps:** Engine performance validation still ongoing; toxicity in confined spaces; dual-fuel safety verification.	**Readiness:** Low–medium (≈ TRL 5–6). **Gaps:** Limited experience with marine hydrogen engines; flame detection and ventilation layout not prescriptive.

11.6. Heat Map Visualization

The heat map visually communicates the maturity contrast between fuels:

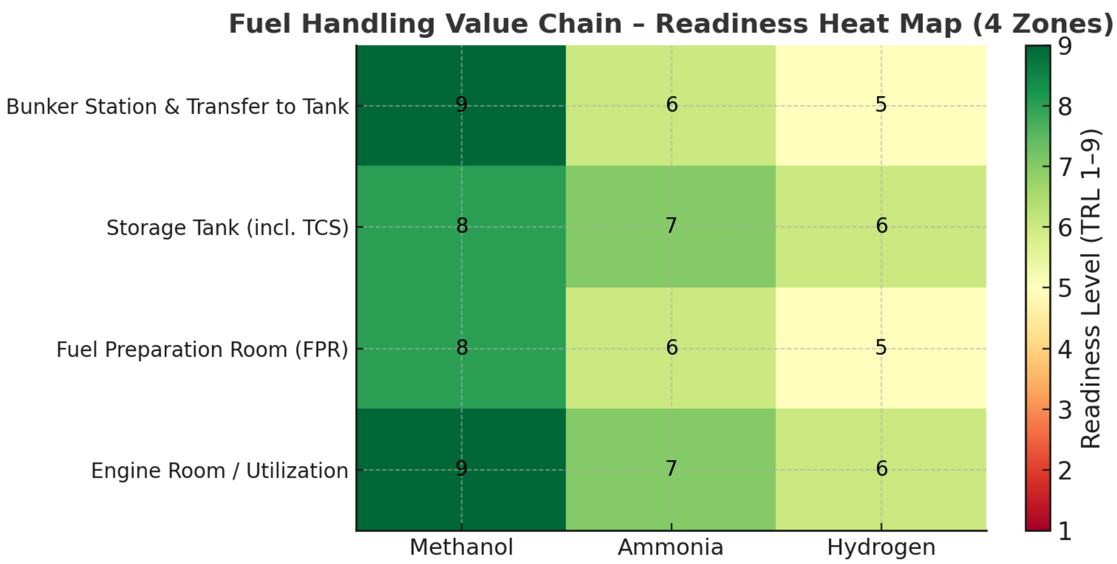


Figure 15: Maturity heat map for each fuel handling zone

- Methanol systems show high readiness (TRL 8–9) with established designs and approval pathways under interim guidelines.

- Ammonia systems are in mid-development (TRL 6–7), reflecting ongoing validation of toxicity management and bunkering practices.
- Hydrogen, especially in liquid form, remains at lower readiness (TRL 5–6), where cryogenic containment, material compatibility, and standardization are still in early development.

This visualization helps decision-makers quickly identify where technology and regulation are aligned and where targeted R&D and regulatory harmonization are most urgently needed.

11.7. Interpretation and Strategic Use

The Gap Analysis Matrix and Heat Map serve multiple purposes within the decision framework:

- Benchmarking: Establishes a baseline readiness profile for each fuel system.
- Prioritization: Identifies areas needing R&D investment, testing, or new standards.
- Risk Communication: Translates technical uncertainty into a structured view for regulators, class, ship owners and operators.
- Regulatory Pathfinding: Supports the case for prescriptive development under IMO or IACS by highlighting recurring technical gaps.
- Decision Support: Integrates directly with the project's decision tool to assist stakeholders—from ship designers and class societies to insurers, port authorities, and emergency response agencies—in making risk-informed choices during the design and approval process.

The Gap Analysis Matrix consolidates the industry's current understanding of where methanol, ammonia, and hydrogen technologies stand in terms of technical and regulatory readiness. It allows the wider maritime community to navigate uncertainty methodically and to target collaborative development efforts where they will have the most impact. By integrating this analysis into the decision support framework, the project provides a strategic tool for aligning technical innovation, safety assurance, and regulatory evolution—a vital step toward the safe, scalable, and harmonized adoption of alternative marine fuels.

12. SCENARIO-BASED TESTING AND SIMULATION

12.1. Purpose of This Chapter

This chapter demonstrates how empirical testing and scenario-based simulation can be used to close regulatory gaps and provide the quantitative evidence needed to support safe design decisions for methanol, ammonia, and hydrogen fuel systems. Two representative scenarios are presented:

1. Suppression of a methanol pool fire
2. Dispersion of ammonia following a bunkering leak in a hypothetical Danish port

These scenarios were selected because they reflect areas where current regulations remain high-level or incomplete. They show how targeted testing and CFD simulation can produce decision-grade evidence to strengthen Safety Function performance, refine design assumptions, and support equivalency demonstration under the Alternative Design pathway.

12.2. Suppression Test of Methanol Pool Fires

12.2.1. Introduction

Methanol is gaining rapid traction as a marine fuel, which makes it essential to understand its fire behaviour and how active fire suppression systems perform against alcohol-fuel fires. Previous work by Survitec [27] and the RISE proFLASH program [28] underscores that design assumptions used for diesel protection are unreliable for methanol and that focused, empirical evaluation is therefore required. This report presents results from controlled tests using methanol as the fuel and water mist as the active protection method, intended to form a basis subsequent design choices in evidence.

The technical obstacles are well understood. RISE shows that water-based systems (spray or mist) suppress methanol but often do not achieve prompt extinguishment in open-pool scenarios; effective extinguishment typically requires alcohol-resistant foam injection, while relying on dilution alone can demand water contents approaching ~90% in the surface layers. These effects are compounded by the low-visibility flame, made even less visible as dilution increases, which elevates operational risk. Consistently with these findings, Survitec reports that a “standard” diesel-type water mist Local Application Firefighting (LAFF) arrangement has little or no effect on methanol, highlighting the need to rethink discharge rates, nozzle placement, and additives for this fuel.

Additionally, to the previous description, neither reference offers a unified, formal test protocol tailored to methanol and fire suppression or fire extinction solutions. Survitec explicitly notes the absence of pre-existing requirements or protocols and the need to devise testing from scratch, while RISE bases its full-scale benchmarks in MSC/Circ.1165 scenarios developed around diesel and heptane which illustrates a standards gap for alcohol fuels. Now, DBI’s main purpose is to develop a proper protocol for methanol fire suppression evaluation: defining representative scenarios, clear pass/fail and time-to-extinguishment criteria, instrumentation and sampling methods, and repeatability measures so that results are objective, comparable, and decision-grade for design and class engagement.

12.2.2. Testing Methodology

Two groups of tests were conducted for this campaign:

1. Free-burn series (no discharge): Methanol was burned in a steel pan and allowed to burn freely to full consumption. The objectives were to
    a. characterise methanol behaviour in the MOBAT compartment
    b. verify the correct operation of all instruments: thermocouples (TC/TT), weigh scale, oxygen meter, and FLIR camera.
2. Water mist discharge series: After ignition and stabilization (~30 seconds free burn), a water mist nozzle was activated for 5 min. The fire size was held constant, while fire location (centre/side/corner) and nozzle type (2125 vs 2307) were varied to compare performance as the primary means of suppression/extinction. Test conditions are summarized in Table 21.

Table 21. Test Conditions Considered for Methanol Pool Fires.

Date (YY.MM.DD)	Test No.	Nozzle Type	Fire Position	K-Factor (L/min/bar½)	Fire Pan Diameter (m)	Density (kg/m³)	Fuel volume (kg)	Volume (m³)	Volume (l)
25.08.20	1	2125[1]	Centre	1.43	0.70	796.00	4.50	0.0057	5.65
25.08.20	2	2125[1]	Side	1.43	0.70	796.00	3.50	0.0044	4.40
25.08.20	3	2125[1]	Corner	1.43	0.70	796.00	3.50	0.0044	4.40
25.08.20	4	2125[1]	Centre	1.43	0.70	796.00	3.50	0.0044	4.40
25.08.21	1	2307[2]	Corner	2.75	0.70	796.00	3.50	0.0044	4.40
25.08.21	2	2307[2]	Side	2.75	0.70	796.00	3.50	0.0044	4.40
25.08.21	3	2307[2]	Centre	2.75	0.70	796.00	3.50	0.0044	4.40

[1]SEM-SAFE-2125-K=1.43-100-P
[2]SEM-SAFE-2307-K=2.75-100-S

The following methodology was considered for the test series. For the detailed procedure refer to Annex E:

1. Confirm MOBAT is safe, and the steel tray is in place.
2. Fill the tray to the required methanol depth; record all measurements.
3. Ignite and allow 30 s of free burn.
4. Close the MOBAT door, controlling oxygen during the discharge.
5. Discharge water mist for 5 min.
6. Monitor behaviour during/after discharge (minimum 480 s observation).
7. Assess extinguishment via thermal data, flame visibility, and IR/FLIR.
8. If extinguished, monitor for re-ignition and stabilize before reopening.
9. If not extinguished and safe, smother with fitted lids or allow full consumption.

12.2.3. Results

Free-burn series (no water mist)

This series focused on system shakedown and on estimating peak temperatures in MOBAT with methanol. Peak compartment temperatures typically ranged 700–800 °C, providing a baseline to quantify suppression (and, when applicable, extinguishment) during water mist discharges.

Water mist discharge series

Two signal sets were tracked: (i) local thermocouples (TC1, TC2, TC5, TC6 in the plume; TC3 in the fuel; TC4 on the pan), and (ii) ambient TC tree (TT1–TT4) for the compartment field, complemented with visible and FLIR video to mark ignition, stabilization (30 s), start/stop of the 5-min discharge, and the final state (extinguished or not).

- Fire at centre (below the nozzle): best outcomes. Average temperature dropped to ~42 °C with 2125 and ~21 °C with 2307. With 2125 there was suppression without extinguishment (temperature rose once water stopped); with 2307 extinguishment was achieved—the only full-extinguishment case of the campaign—consistent with dilution to non-flammability (see ProFLASH).

- Fire at side: smaller temperature reductions; averages ~398 °C (2125) and ~123 °C (2307), illustrating loss of effectiveness when application does not directly impact the fire area.

- Fire at corner: reductions around 548 °C (2125) and 605 °C (2307). Two conclusions follow: (i) higher flow (higher K-factor at the same pressure) improves cooling/suppression, and (ii) spray geometry/coverage matters; distribution, not only quantity, drives performance.

Even without extinguishment, ambient cooling in the compartment was consistent: TT1–TT4 readings stayed below ~48 °C in all cases—operationally relevant for human intervention. Thus, while a given system may not ensure extinguishment in every scenario, it can meaningfully improve tenability and safety for response teams (See Figure 16 and Figure 17).

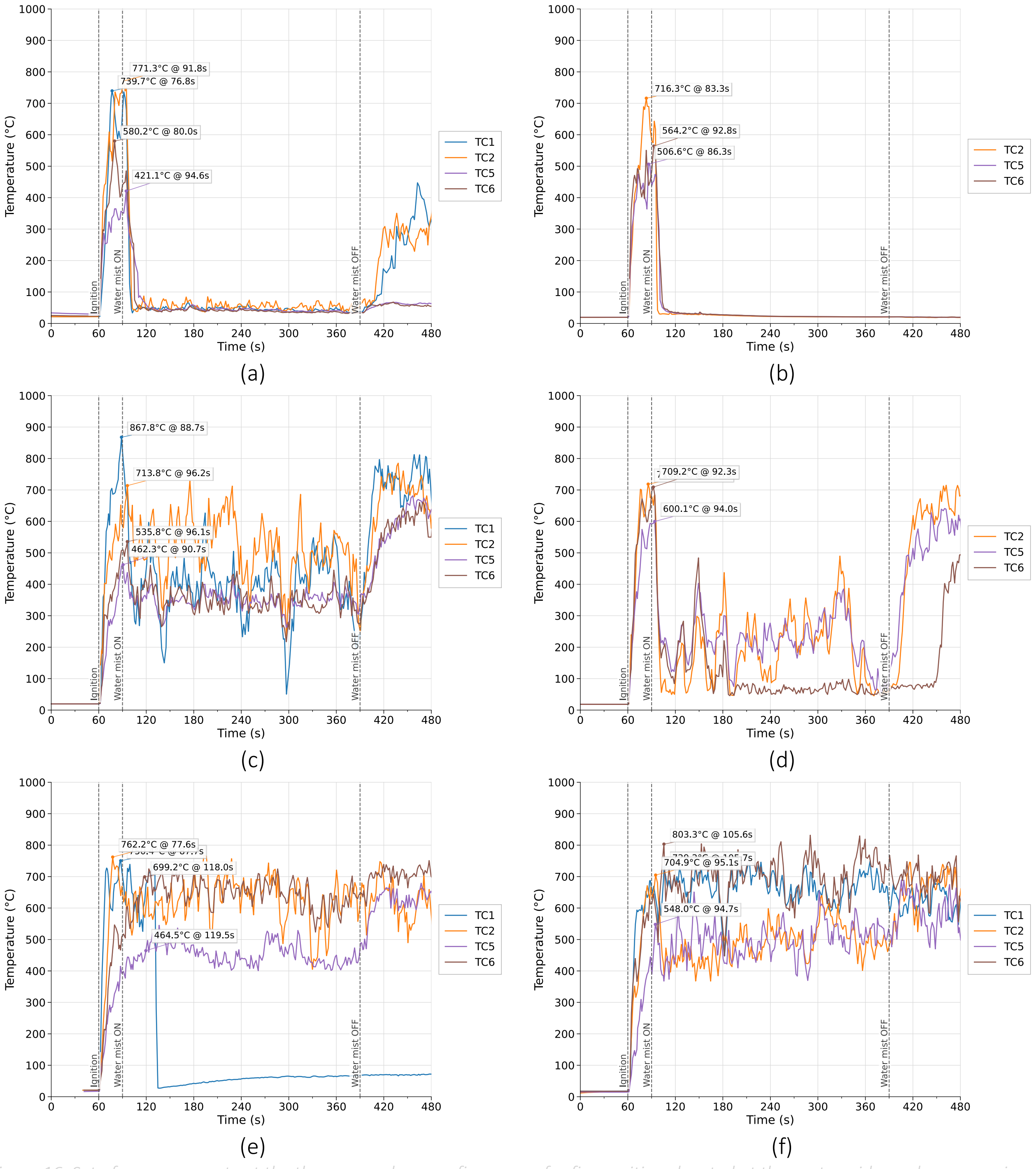


Figure 16. Set of measurements at the thermocouples near fire source for fire positions located at the centre, side, and corner, using two different nozzles. The plots in the left column correspond to nozzle SEM-SAFE-2125, while those in the right column show the results with nozzle SEM-SAFE-2307. The first row presents the results for fire at the centre (a, b), the second row for fire at the side (c, d), and the third row for fire at the corner (e, f).

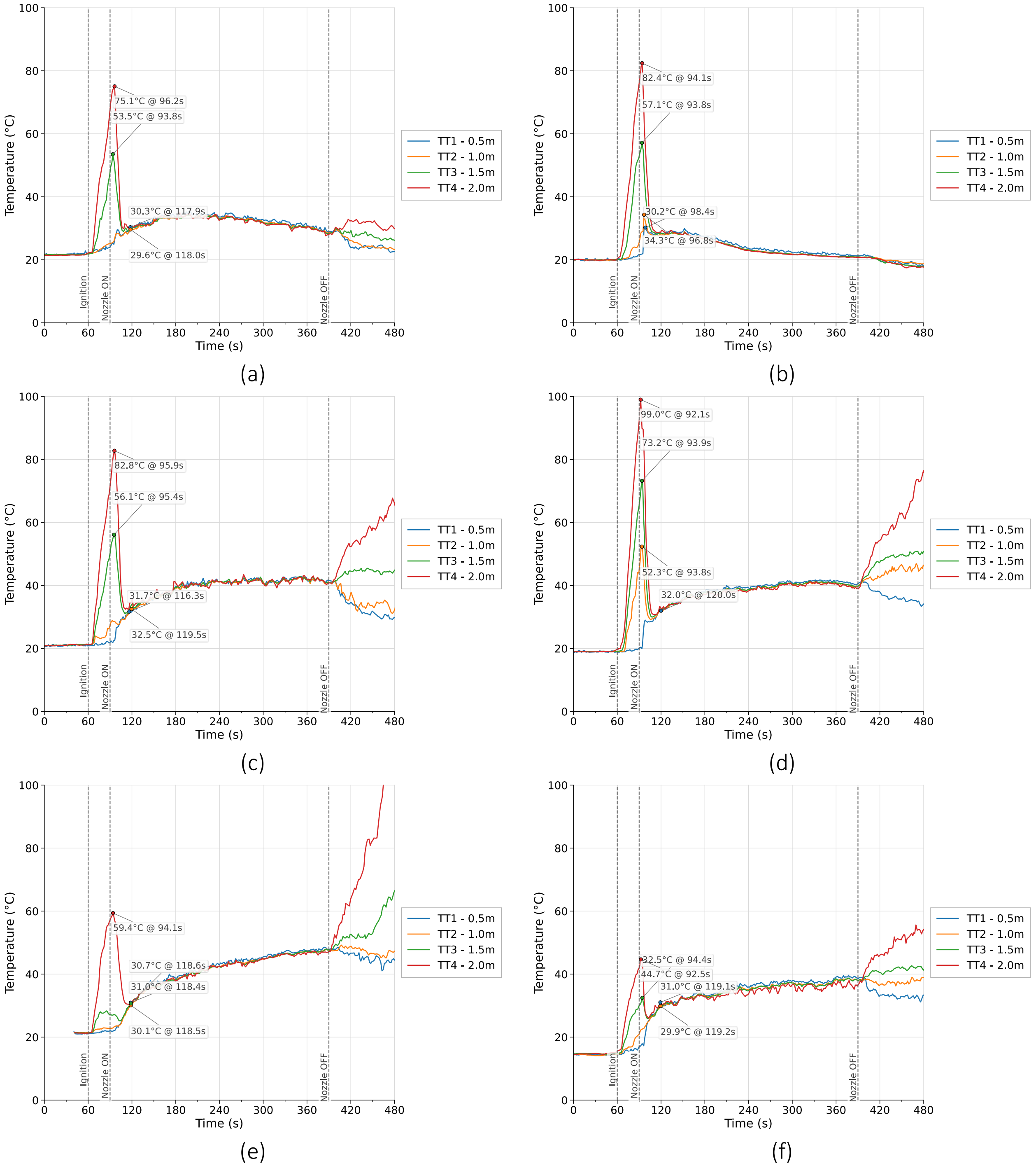


Figure 17. Set of measurements at the thermocouple trees inside the room for fire positions located at the centre, side, and corner, using two different nozzles. The plots in the left column correspond to nozzle SEM-SAFE-2125, while those in the right column show the results with nozzle SEM-SAFE-2307. The first row presents the results for fire at the centre (a, b), the second row for fire at the side (c, d), and the third row for fire at the corner (e, f).

12.2.4. Analysis and Evaluation

When reviewing the graphs obtained from the tests performed with both nozzle types (SEM-SAFE-2125 and SEM-SAFE-2307) it becomes clear that, although the numerical results vary, the overall behaviour patterns and the order of magnitude remain comparable. From these observations, several meaningful insights can be drawn.

Three key factors directly affect the suppression or potential extinction of the fire:

1. The amount of water distributed by the nozzle,
2. The orientation of the nozzle, and
3. The relative position of the water distribution points with respect to the pool fire.

As illustrated in Figure 16, for Cases A and B, where the pool fires were located at the centre of the MOBAT, a significant temperature drop was recorded above the flame. Temperatures stabilized between 20–40 °C, which indicates an effective heat absorption by the water mist.

In Case A, the temperature remained around 40 °C, showing a balanced cooling effect that reduced heat intensity without complete extinction. This condition is favourable in real scenarios: it provides a safer environment for firefighting teams to intervene without facing critical thermal exposure.

In contrast, Case B reached lower temperatures (approximately 20 °C) achieving full fire extinction. This result suggests that water droplets not only absorbed radiant heat but successfully penetrated the flame zone, reaching the fuel surface and disrupting combustion by dilution and cooling.

For Cases E and F, the results were markedly different. The tests showed almost no suppression effect, with the fire remaining stable throughout the discharge. The nozzle in these cases was positioned farther from the fire and at an angle not properly directed toward the source. Consequently, heat levels remained uncontrolled. This emphasises that directionality and coverage are just as critical as discharge rate when designing suppression layouts.

Moving to Cases C and D, results presented a mild variation. Temperatures dropped to 300–400 °C in Case C and to 200–300 °C in Case D. The only parameter changed between these two tests was the nozzle type. The SEM-SAFE-2307 (used in Case D) delivers nearly twice the water flow of the SEM-SAFE-2125 used in Case C — as shown in Table 21. This confirms that water delivery rate plays a significant role in mitigating thermal effects, particularly when fire proximity and nozzle orientation remain constant.

Another essential aspect of the analysis involves the Thermocouple Tree (TT) readings. The TT was installed halfway along the MOBAT room length, 15 cm from the right wall, opposite the fire inside and corner configurations, with thermocouples positioned at 0.5 m, 1.0 m, 1.5 m, and 2.0 m above floor level.

From these measurements, temperatures remained between 20–30 °C for Cases A and B (centre fires, closest to the TT), around 40 °C for Cases C and D (side position), and between 40–50 °C for Cases E and F (corner position).

Although not all fires were fully suppressed, the ambient conditions within the compartment remained within acceptable limits, ensuring survivable environments for firefighting personnel and reducing the escalation risk compared to uncontrolled free-burn scenarios.

Finally, even though not the main objective of this study, the use of FLIR cameras represents an important element for the analysis and evaluation of methanol fire behaviour. Due to the combustion characteristics of methanol, which produces low-visibility, almost colourless flames, FLIR cameras can assist in visualising and characterising flame development under specific compartment conditions. Traditional smoke detectors or standard video surveillance systems are often unable to detect these flames effectively. Therefore, FLIR technology can be considered a valuable complementary tool within a hybrid detection or emergency monitoring system, especially when integrated with CCTV or multi-spectrum sensors to enhance situational awareness and detection reliability.

12.2.5. Evaluation of Methanol Fire Tests

Comparative effectiveness: 1.4 vs. 2.75 K-factor water mist nozzles

Generally, fires attacked with the higher K = 2.75 nozzle showed lower temperature profiles than those with K = 1.4. However, further testing with additional nozzle types would help determine the precise threshold where this difference becomes significant or negligible.

Suppression dynamics in enclosed environments

As noted earlier, suppression efficiency depends on the combined influence of flow rate, nozzle orientation, and relative positioning within the compartment. This reinforces the importance of performance-based testing prior to implementing such systems in real projects.

Relevance to shipboard conditions

The objective of these tests is to develop a concept scalable to marine engine-room environments. Although extrapolation is not linear — not a simple “rule of three” — these results provide a valuable foundation for understanding how solutions behave in smaller-scale scenarios before being applied to IMO-compliant or any kind of full-scale tests (whether for methanol or other low-flashpoint fuels). This approach can significantly reduce preliminary testing costs and prevent large-scale failures.

12.2.6. Gap Analysis, Conclusions and Future Work

This project contributes to defining several of the fundamental parameters that govern the performance of water mist suppression systems, the delivered water rate, nozzle orientation, and their relative positioning with respect to the potential fire source.

However, understanding fire suppression cannot be limited to flame behaviour alone. The compartment conditions like temperature, oxygen availability and air circulation, play an equally critical role. A well-designed system must not only extinguish or suppress flames but also maintain tenable conditions for emergency personnel to intervene safely.

Beyond the direct findings, the integration of test results with numerical simulations proved essential. This cross-analysis enabled the identification of technical and behavioural gaps, revealing where current models under-predict or over-estimate system performance. Such integration strengthens the decision-making process for future designs, guiding the refinement of methodological matrix and helping distinguish between active suppression, containment, and preventive approaches within enclosed spaces.

The outcome is a practical evaluation framework for assessing water mist systems, one that can be expanded to other suppression technologies, such as clean agents, inert gases, CO_2, or hybrid systems. By doing so, the methodology begins to close the regulatory gap surrounding low-flashpoint fuels like methanol, where international standards remain limited.

This framework introduces structured test conditions with clear pass/fail criteria, allowing for repeatable and scalable results that may ultimately support the development of harmonized guidelines.

Further work is needed on several fronts. Additional tests with different nozzle geometries, flow rates, and configurations should be carried out under performance-based design conditions, adjusting parameters such as discharge density and nozzle placement. Likewise, extending the matrix to encompass other suppression systems will help establish standardized pre-scale evaluation protocols, reducing the waste of resources (time, materials, and budget) while enhancing the quality of data available to manufacturers, clients, insurers, and regulatory bodies.

Finally, this study does more than evaluate a set of fire tests. It lays a foundation and framework for smarter suppression design, more informed engineering decisions, and a safer path forward for ships and facilities that handle methanol and other low-flashpoint fuels.

12.3. Simulation of leakage during ammonia bunkering

12.3.1. Introduction

Denmark's strategic position between Scandinavia and the rest of Europe makes its ports critical conduits for freight and passenger movement. This strategic role is enhanced by the country's footprint in global shipping and logistics, positioning Denmark to influence how maritime decarbonization unfolds across the region.

Among candidate alternative fuels, green ammonia is gaining traction as a potential marine energy carrier due to its carbon-free combustion. As of September 2025, however, Denmark has no established infrastructure or regulatory framework for ammonia bunkering. This absence of standards, facilities, and permitting pathways is a barrier for pilot projects.

At the same time, the safety evidence base for ammonia bunkering remains thin, especially for port settings and traffic patterns relevant to Danish waters. There is limited location-specific analysis of both operational and accidental releases. Without such analysis, authorities and operators lack the risk picture needed to guide design choices, siting, emergency planning, and regulatory development.

This study addresses that gap by outlining a representative ammonia bunkering concept tailored to Danish port contexts and evaluating the potential consequences of ammonia releases through a set of illustrative scenarios in the port of Rønne. The impact in terms of dispersion envelopes and lethality is quantified, and the safety implications are discussed.

12.3.2. Methodology

The consequence modelling software was developed using DNV's PHAST (Process Hazard Analysis Software Tool) to simulate accidental releases of ammonia that could occur during bunkering operations. The main objective of these simulations is to estimate how far ammonia could disperse at harmful concentrations and to assess the potential impact on people living or working near port areas.

The analysis is based on a representative Danish port where ammonia bunkering is assumed to take place. The site layout reflects a typical port environment surrounded by urban and industrial areas. Two representative bunkering configurations were considered:

- Ship-to-Ship (STS), where a bunker vessel supplies ammonia directly to a receiving vessel; and
- Terminal/Pipeline-to-Ship (PTS), where ammonia is transferred from a shore-based storage tank through a dedicated pipeline system.

The main characteristics and parameters defined for both bunkering methods are summarised in Table 22.

Table 22: Characteristics of Ammonia Bunkering Methods

Parameter	Ship-to-ship (STS)	Terminal/pipeline-to-ship (PTS)
Bunker supply	Bunker vessel	Storage tank
Receiving vessel	Container ship	Bunker vessel
Shore tank capacity (m^3)	-	10,000
Working bunker vessel capacity (m^3)	2,925	-
Connection (in)	8” flexible hose, 27.3 m	8” fixed pipeline 500 m 8” flexible hose, 27.3 m
Orifice size (in)	8”	8”
Release direction	Horizontal	Horizontal
High release elevation (m)	4.3	4.3
Low release elevation (m)	0	0
Phast scenario simulated	Pressure vessel – short pipe release	Long pipeline – location specific breach

For the Ship-to-Ship (STS) ammonia bunkering method, four potential locations were evaluated:

- Alongside the shore, at one of the following quays (See Figure 18):
  - The future quay
  - Quay 34 and 35
  - Quay 33 (Hypothetical location)
- Offshore, approximately 2 nautical miles west of the Port of Rønne.

For the Terminal/Pipeline-to-Ship (PTS) configuration, only one location was considered – alongside Quay 33.

For both bunkering methods, two weather conditions were analysed; summer and winter, to reflect seasonal variations in atmospheric stability and dispersion potential. Also, two operating conditions were evaluated for each case: fully refrigerated and semi-refrigerated ammonia.

A total of 20 scenarios were simulated, grouped into five scenario categories based on bunkering configuration and location. The scenarios are summarised in Table 23 and visualized in Figure 18.

Table 23: Scenarios Considered for Simulation of Ammonia Release during Bunkering.

Scenario ID	Bunkering method	Location	Weather condition	Operating condition
Scenario 1				
1.1	Ship-to-Ship (STS)	Alongside the future quay	Summer	Fully refrigerated
1.2	Ship-to-Ship (STS)	Alongside the future quay	Summer	Semi-refrigerated
1.3	Ship-to-Ship (STS)	Alongside the future quay	Winter	Fully refrigerated
1.4	Ship-to-Ship (STS)	Alongside the future quay	Winter	Semi-refrigerated
Scenario 2				
2.1	Ship-to-Ship (STS)	Alongside Quay 34 and 35	Summer	Fully refrigerated
2.2	Ship-to-Ship (STS)	Alongside Quay 34 and 35	Summer	Semi-refrigerated
2.3	Ship-to-Ship (STS)	Alongside Quay 34 and 35	Winter	Fully refrigerated
2.4	Ship-to-Ship (STS)	Alongside Quay 34 and 35	Winter	Semi-refrigerated
Scenario 3				
3.1	Ship-to-Ship (STS)	Alongside Quay 33	Summer	Fully refrigerated
3.2	Ship-to-Ship (STS)	Alongside Quay 33	Summer	Semi-refrigerated
3.3	Ship-to-Ship (STS)	Alongside Quay 33	Winter	Fully refrigerated
3.4	Ship-to-Ship (STS)	Alongside Quay 33	Winter	Semi-refrigerated
Scenario 4				
4.1	Ship-to-Ship (STS)	2 nautical miles west of the port	Summer	Fully refrigerated
4.2	Ship-to-Ship (STS)	2 nautical miles west of the port	Summer	Semi-refrigerated
4.3	Ship-to-Ship (STS)	2 nautical miles west of the port	Winter	Fully refrigerated
4.4	Ship-to-Ship (STS)	2 nautical miles west of the port	Winter	Semi-refrigerated
Scenario 5				
5.1	Terminal/Pipeline-to-Ship (PTS)	Alongside Quay 33	Summer	Fully refrigerated
5.2	Terminal/Pipeline-to-Ship (PTS)	Alongside Quay 33	Summer	Semi-refrigerated
5.3	Terminal/Pipeline-to-Ship (PTS)	Alongside Quay 33	Winter	Fully refrigerated
5.4	Terminal/Pipeline-to-Ship (PTS)	Alongside Quay 33	Winter	Semi-refrigerated

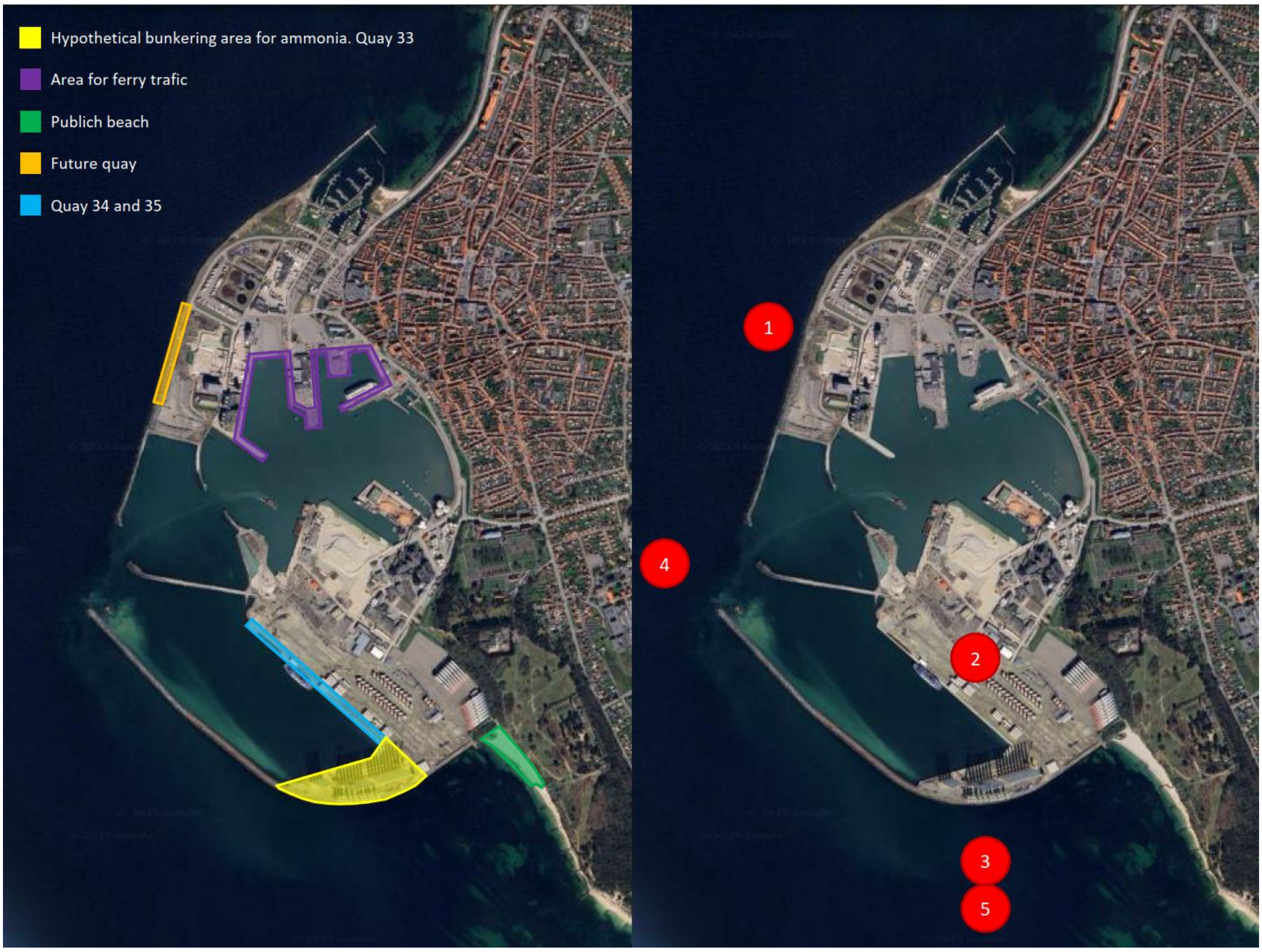


Figure 18. Port of Rønne with hypothetical ammonia bunkering areas (left) and the hypothetical simulation scenarios (right)

12.3.3. Results

All dispersion footprints were evaluated at a reference height of 1.5m above the ground level. The cloud concentration maps illustrate 10-minute AEGL contours for ammonia at the following threshold levels:

- AEGL-2 (220 ppm) – corresponding to potentially harmful but non-lethal exposure, and
- AEGL-3 (2700 ppm) - corresponding to potentially life-threatening exposure.

For each simulated release, the probit function was applied to estimate lethality probabilities (0–100%) based on the relationship between ammonia concentration, exposure time, and toxic response. This statistical model converts exposure doses into the probability of fatal effects, allowing direct assessment of potential human impacts. For each simulated release, a probit approach is used to estimate lethality probabilities by calculating a probit value for the toxic dose using internal parameters for ammonia and converting this to a probability of death. These lethality contours are reported for probabilities of 3%, 10%, 50%, and 99% and the associated downwind distances and footprints are then used to support consequence evaluation and to enable consistent comparison across scenarios.

During the initial release phase, the release of fully refrigerated ammonia is consistently dominated by liquid pooling, regardless of location, terrain or season. In contrast, releases of semi refrigerated ammonia are vapour dominated. Most of the semi refrigerated inventory appears directly as a vapour cloud and only a smaller fraction forms a pool, which is always smaller and shorter lived than the pool from fully refrigerated ammonia. After one hour, releases of fully refrigerated ammonia retain a clearly larger liquid inventory than semi refrigerated ammonia scenarios, providing a more sustained evaporation source.

For releases over land at a height of 4.3 m, semi refrigerated ammonia produces the longer footprints at early times, while fully refrigerated ammonia produces clouds that persist for longer. The semi refrigerated cloud is more intense near the source and reaches farther downwind in the first minutes because most of the inventory appears directly as vapour, but it then dilutes below the concentration thresholds relatively quickly. Fully refrigerated ammonia produces shorter footprints initially, yet the large pool continues to evaporate after the discharge ends and feeds vapour into the atmosphere. As a result, the cloud remains detectable at both AEGL 2 and AEGL 3 thresholds for longer than the semi refrigerated cloud.

Increasing the release height from 4.3 m to 15.8 m makes the dispersion cloud more airborne and increases its downwind reach for both storage modes. Early footprints become longer, with a stronger effect for semi-refrigerated ammonia, which can develop exceptionally long footprints. For fully refrigerated ammonia, the clouds also extend further at early times, while retaining a similar pattern of persistence in time as at the lower release height.

Changing the terrain from land to open water increases dispersion footprints at both AEGL thresholds for all release types, with the strongest increase for semi refrigerated ammonia.

For maximum dispersion footprints, winter generally stretches fully refrigerated clouds farther than summer at the lower concentration level, as colder, denser air and stronger winds carry the cloud further downwind before it falls below the threshold. For semi refrigerated ammonia, winter often dominates on land, while over water summer can give the longest maximum footprints at the lower threshold because summer conditions and the smooth sea surface favour long range persistence of a vapour dominated cloud.

Lethality outcomes are governed primarily by the storage condition of the ammonia.

- Semi-refrigerated ammonia releases produce the longest lethal ranges in both summer and winter, as a greater fraction of the ammonia is airborne immediately after release and forms a large vapour cloud that carries significant dose farther downwind.

- Fully refrigerated ammonia releases, in contrast, result in shorter lethal distances, as a larger portion of the release remains pooled and the vapour source is more localised around the pool area.

As illustrated in Figure 19 -Figure 28, the lethality contours associated with fully refrigerated releases remain confined within the Port of Rønne, without extending into nearby populated areas. Overall, fully refrigerated ammonia operation remains both the safer and the more plausible bunkering mode for the Port of Rønne.

Legend:

Fully refrigerated @ 2700 ppm	Semi refrigerated @ 2700 ppm
Fully refrigerated @ 220 ppm	Semi refrigerated @ 220 ppm

a) b)

Figure 19. a) Maximum dispersion footprint for scenario 1.1 and 1.2 b) Maximum dispersion footprint for scenario 1.3 and 1.4

a) b)

Figure 20. a) Maximum dispersion footprint for scenario 2.1 and 2.2 b) Maximum dispersion footprint for scenario 2.3 and 2.4

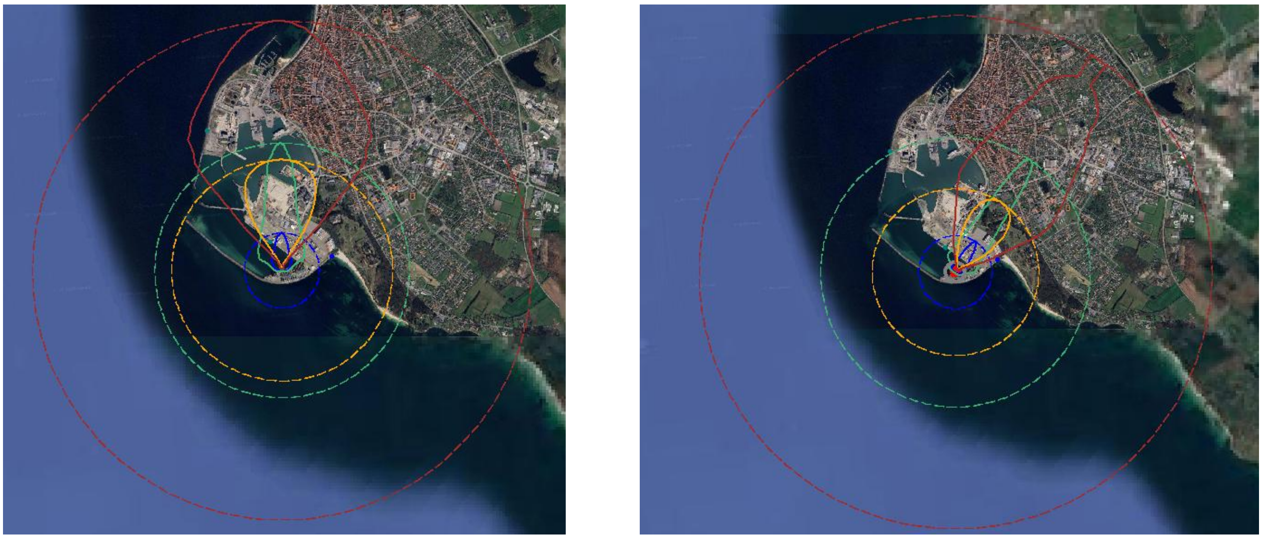
Legend:

Fully refrigerated @ 2700 ppm

Semi refrigerated @ 2700 ppm

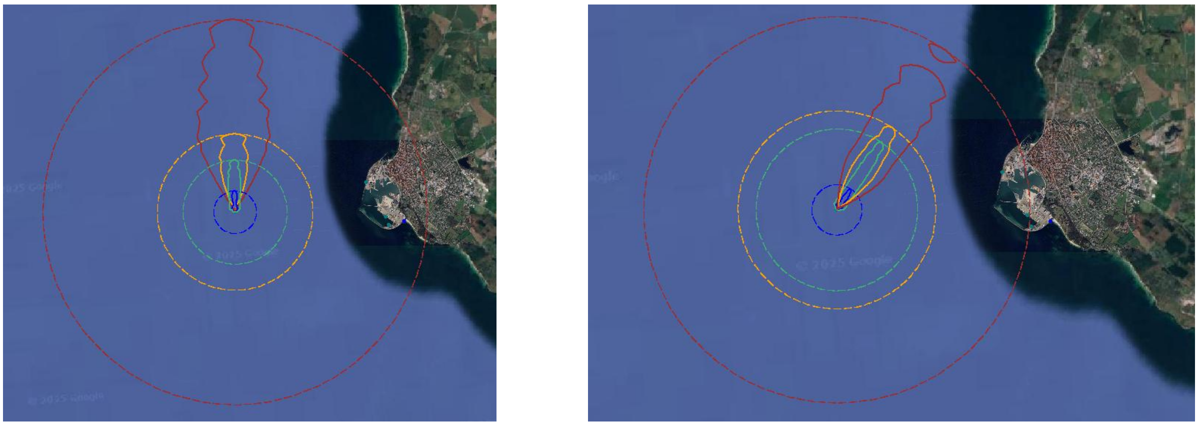
Fully refrigerated @ 220 ppm

Semi refrigerated @ 220 ppm



a) b)

Figure 21. a) Maximum dispersion footprint for scenario 3.1 and 3.2 b) Maximum dispersion footprint for scenario 3.3 and 3.4



a) b)

Figure 22. a) Maximum dispersion footprint for scenario 4.1 and 4.2 b) Maximum dispersion footprint for scenario 4.3 and 4.4

Legend:

Fully refrigerated @ 2700 ppm

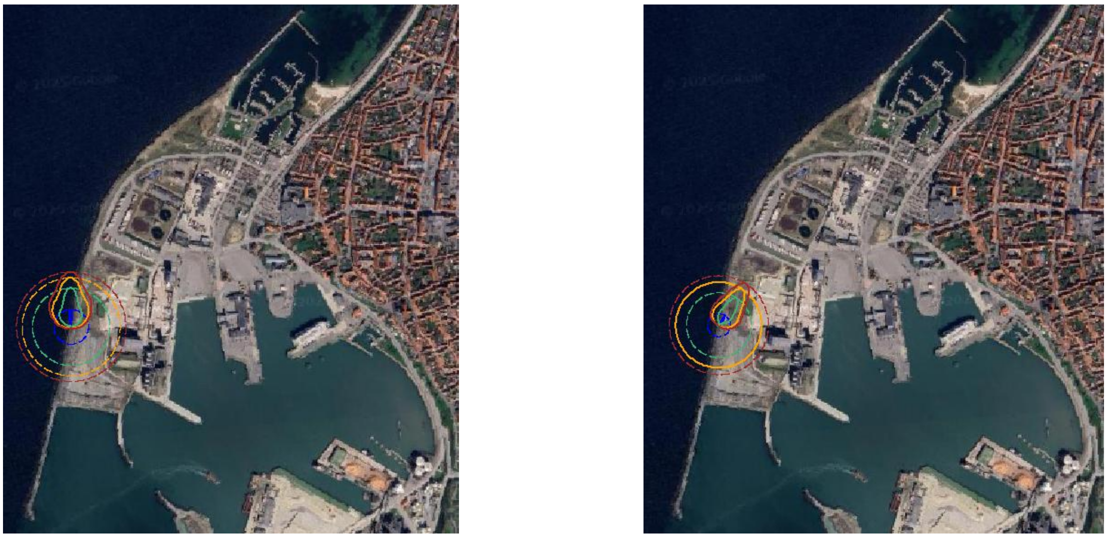
Fully refrigerated @ 220 ppm

Semi refrigerated @ 2700 ppm

Semi refrigerated @ 220 ppm

a) b)

Figure 23. a) Maximum dispersion footprint for scenario 5.1 and 5.2 b) Maximum dispersion footprint for scenario 5.3 and 5.4



a) b)

Figure 24. a) Toxic outdoor probit footprint for scenario 1.1 b) Toxic outdoor probit footprint for scenario 1.3

Legend:

Fully refrigerated @ 2700 ppm	Semi refrigerated @ 2700 ppm
Fully refrigerated @ 220 ppm	Semi refrigerated @ 220 ppm

a) b)

Figure 25. a) Toxic outdoor probit footprint for scenario 2.1 b) Toxic outdoor probit footprint for scenario 2.3

a) b)

Figure 26. a) Toxic outdoor probit footprint for scenario 3.1 b) Toxic outdoor probit footprint for scenario 3.3

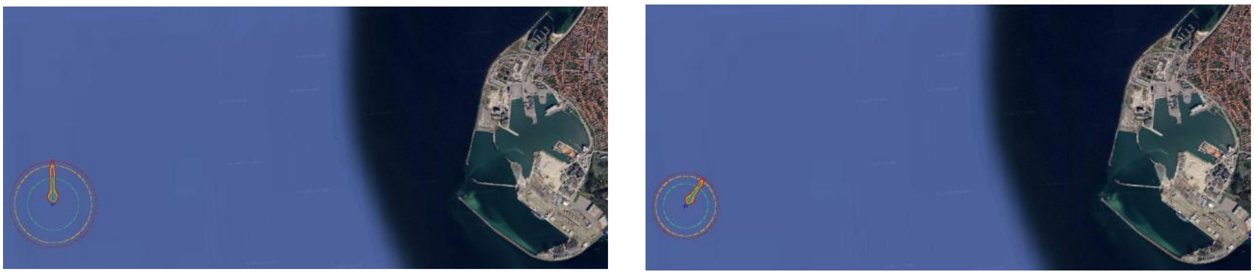
Legend:

Fully refrigerated @ 2700 ppm

Semi refrigerated @ 2700 ppm

Fully refrigerated @ 220 ppm

Semi refrigerated @ 220 ppm



a) b)

Figure 27. a) Toxic outdoor probit footprint for scenario 4 for fully refrigerated ammonia during summer b) Toxic outdoor probit footprint for scenario 4 for fully refrigerated ammonia during winter

a) b)

Figure 28. a) Toxic outdoor probit footprint for scenario 5.1 for fully refrigerated ammonia during summer b) Toxic outdoor probit footprint for scenario 5.3 for fully refrigerated ammonia during winter

12.3.4. Gap Analysis, Conclusions and Future Work

Ammonia bunkering today sits in a regulatory grey zone: the IMO's interim guidance and most class rules (DNV/LR/ABS/BV) outline high-level risk-based processes under the IGF-Code umbrella, but leave gaps on quantitative siting/stand-off criteria driven by toxicity (e.g., AEGL-based acceptance limits and how to apply them at specific ports), harmonized detection/alarm setpoints and shutdown logic for open-air bunkering, consistent requirements for release height control and breakaway systems, over-water vs. over-land dispersion treatment, SIMOPs at berth (public interface, traffic and shelter-in-place triggers), and verification of mitigation effectiveness (water curtains/scrubbers) via scenario-tested performance metrics rather than generic ALARP language.

Section 11.2 directly begins to fill these gaps by converting generic prescriptions into decision-grade, location-specific consequence evidence: it compares STS and PTS concepts at multiple quays and offshore, spans seasons and storage modes, and expresses outcomes in AEGL-2/AEGL-3 and probit lethality contours at 1.5

m—showing, for example, that semi-refrigerated releases drive the longest lethal ranges while fully refrigerated cases are pool-dominated and spatially contained, and that open water and higher source elevations enlarge footprints, which in turn informs practicable stand-off distances, preferred operating modes, and when offshore STS offers risk advantages.

To close the remaining gaps, future work should couple frequency analysis with consequence (full QRA) and deepen physics fidelity: transient CFD with site geometry and metocean to resolve jet/flash-boil behaviour and obstacle channelling; parametric studies of release height, hose/pipeline breach sizes and ERC/BRC performance; mitigation modelling (water curtains, dry fog, mobile scrubbers) with pass/fail criteria tied to AEGL targets; SIMOPs-aware crowd/traffic exposure and evacuation timelines; uncertainty/sensitivity analysis to bound decisions; and validation against scaled field trials where feasible. By sequencing scenario-resolved dispersion now and probabilistic, mitigation-verified simulation next, IMO can be provided with the necessary evidence to tighten interim guidance (explicit AEGL-linked siting, alarm/shutdown, offshore-use triggers) and provide classification societies a defensible framework for port-specific approval of ammonia bunkering.

13. RECOMMENDATIONS AND ROADMAP

13.1. Purpose of this chapter

This chapter presents a set of recommendations and a phased roadmap to support the safe and scalable adoption of methanol, ammonia, and hydrogen. The roadmap synthesises insights from hazard characterisation, Safety Functions, regulatory review, human factors, and scenario-based evidence to guide stakeholders through:

- Current risk-based approval pathways
- Emerging opportunities for standardisation
- Potential areas for future prescriptive rulemaking

The overarching intent is to provide evidence-informed guidance, while recognising that the long-term regulatory landscape for alternative fuels is still developing and may evolve as knowledge matures.

13.2. Near-Term Priorities - “Approve Safely Now”

In the near term, the priority is to maintain project momentum while ensuring that safety approvals remain credible and transparent under existing regulatory mechanisms. The goal is to strengthen the consistency and traceability of equivalency demonstrations by using quantifiable, evidence-driven criteria.

13.2.1. Key Recommendations

1. Strengthen Risk-Based Approval Documentation

Develop approval packages that explicitly link identified hazards to the corresponding safety barriers and control measures. Each safety function — such as gas detection, ventilation, isolation, pressure relief, or firefighting should have defined setpoints, activation logic, and performance criteria. This ensures that equivalency demonstrations are measurable, traceable, and technically defendable. Using the METAFUEL Decision Support Tool and Technology Readiness Matrix provides a defensible, systematic basis for such documentation.

2. Translate ALARP into Quantifiable Evidence

Reduce subjective risk language by providing quantifiable parameters that show risks are ALARP. Examples include:

- Detector alarm and shutdown thresholds (e.g., ammonia 25/50 ppm or hydrogen 20% LFL).
- ESD activation time limits (typically < 5 s).
- Minimum ventilation rates and fan redundancy.
- Verified vent mast dispersion performance and pressure relief design basis.

By specifying numerical criteria, ALARP becomes tangible and verifiable, not interpretive.

3. Integrate Experimental and Simulation Evidence

Incorporate validated test data from fuel-fire suppression testing and gas dispersion simulations into design calculations and risk justification. Quantified suppression performance, toxicity exposure distances, and system response times provide the technical evidence needed to support risk equivalence claims under the Alternative Design route.

4. Enhance Collaboration Between Stakeholders

Establish early and close coordination between shipyards, class societies, and port authorities during design development. Early engagement allows alignment on acceptance criteria, bunkering procedures, toxic-zone management, and emergency response plans therefore reducing uncertainty and delays in project approval.

13.3. Medium-Term Priorities - "Standardize the Evidence"

In the medium term, the industry must consolidate project-level lessons into consistent methodologies and data frameworks that can be referenced across class societies and regulatory bodies.

13.3.1. Key Recommendations

1. Develop Standard Evaluation Criteria

Identify recurring conditions and design parameters that have proven effective in previous approvals and standardize them into Recommended Practices or Class Guidelines. Areas for standardization include:

- Detector spacing and calibration requirements.
- Minimum ventilation rates for enclosed spaces.
- ESD zone definitions and sequencing logic.
- Vent mast and pressure relief configurations.
- Water curtain or foam system performance benchmarks.

2. Advance Quantitative Risk Assessment (QRA) Methods

Strengthen the integration of frequency analysis and consequence modelling to quantify both individual and societal risk. The development of validated models for fuel leaks, ignition probability, and toxic cloud dispersion will improve the repeatability and acceptance of QRA results for alternative-fuel vessels.

3. Establish Unified Testing and Certification Protocols

Introduce unified type-approval tests for alternative-fuel safety systems, including:

- Alcohol-resistant foam and water-mist suppression systems for methanol fires.
- Water-curtain and scrubber systems for ammonia leak mitigation.
- Cryogenic venting and hydrogen flame detection systems.

Certified testing procedures will form the basis for prescriptive design verification.

4. Expand Knowledge-Sharing Networks

Formalize collaboration between ship designers, operators, ports, classification societies, and research institutions. Establish open databases of validated test results, failure modes, and QRA outcomes to support consistent decision-making and accelerate rule development.

13.4. Long-Term Priorities - "From Goal-Based to Targeted Prescriptive rules"

In the long term, the objective is to embed the validated findings and risk-based methodologies into the regulatory framework, allowing future ship designs to rely on prescriptive, harmonized standards rather than individual equivalency demonstrations.

13.4.1. Key Recommendations

1. Integrate Evidence into IMO and IACS Rulemaking

Use the body of experimental, analytical, and operational data developed through projects like METAFUEL to inform future IGF Code amendments and IACS Unified Requirements specific to methanol, ammonia, and hydrogen fuels. This will ensure a globally consistent safety baseline for new fuel technologies.

2. Define Quantitative Performance Benchmarks

Translate validated test and simulation results into quantitative criteria, such as:

- Maximum allowable concentration exposure (AEGL/IDLH limits).
- Required gas-detection sensitivity and response times.
- Minimum fire suppression efficiency and system reliability.
- Prescribed separation distances and venting configurations.

These metrics will form the measurable foundation for prescriptive design rules.

3. Implement Digital, Continuous-Learning Tools

Transform the decision-support framework into a digital platform capable of continuous learning and feedback. By incorporating real operational data and incident learning, the platform can guide future updates of standards and best practices dynamically.

4. Institutionalize Cross-Sector Collaboration

Establish long-term partnerships across the maritime ecosystem including shipyards, operators, ports, research institutes, and regulators to support continuous validation and improvement of new fuel technologies. This cooperative model ensures that prescriptive rules evolve alongside technology maturity.

13.5. Summary

The METAFUEL roadmap provides a realistic trajectory for the maritime industry:

- Short term: Apply risk-based methods consistently and transparently for immediate project approvals.
- Medium term: Standardize evaluation methods and develop shared test protocols to harmonize decisions.
- Long term: Translate validated performance data into prescriptive, globally aligned regulations.

Through this stepwise approach, METAFUEL provides a structured path from research and demonstration to regulatory adoption, accelerating the safe and scalable transition toward carbon-neutral marine fuels.

14. CONCLUSIONS

14.1. Overview

The METAFUEL project provides a structured, evidence-informed framework for supporting the safe uptake of methanol, ammonia, and hydrogen as alternative marine fuels. These fuels are central to international decarbonisation pathways, yet their hazardous properties differ substantially from conventional fuels and from each other.

This report synthesises hazard understanding, system architecture, Safety Functions, regulatory analysis, scenario-based evidence, and technology maturity into a coherent methodology that can support shipowners, designers, regulators, and port authorities as they navigate the transition to low- and zero-carbon fuels.

14.2. Key Findings

14.2.1. Structured Risk Management Framework

The project demonstrated that a systematic link between identified hazards, preventive barriers, and mitigating controls can be established across all fuel-handling stages — bunkering, storage, fuel preparation, and engine room operations. This structured approach allows stakeholders to quantify and visualize safety performance, improving both design confidence and regulatory transparency.

14.2.2. Safety-Function Validation and Performance Evidence

Comprehensive analysis and testing confirmed the performance of key safety functions such as gas detection, ventilation, emergency shutdown, pressure relief, and fire suppression.
Quantified performance metrics provide a foundation for measurable design verification and future prescriptive requirements.

14.2.3. Technology Readiness and Gap Mapping

The Gap Analysis Matrix and Heat Map identified the relative maturity of safety technologies:

- Methanol: High readiness (TRL 8–9), requiring standardization of fire suppression and spill management.
- Ammonia: Medium readiness (TRL 6–7), requiring validation of toxicity management and bunkering safety protocols.
- Hydrogen: Early readiness (TRL 5–6), requiring advancement in cryogenic systems, embrittlement-resistant materials, and ventilation standards.

These insights help prioritize research, investment, and standardization efforts.

14.2.4. Quantitative and Qualitative Integration

The project successfully merged qualitative tools such as HAZID and bowtie analysis with quantitative assessments including CFD, QRA, and testing.
This integration created a defensible chain of evidence that supports both immediate approvals and future rulemaking.

14.2.5. Human Factors and Operational Safety

Human reliability remains central to the safe operation of alternative-fuel ships. The project emphasized ergonomic control design, clear alarm hierarchies, and fuel-specific training as essential components of holistic risk reduction.

14.3. Implications for the Maritime Industry

The outcomes of the METAFUEL project indicate a broader shift in how safety, regulation, and technology readiness are managed across the maritime sector. The integration of risk-based evidence, quantitative analysis, and human factors establishes a replicable model for future low- and zero-carbon fuel initiatives. Moving from case-by-case approval to harmonized rulemaking will require coordinated action between regulators, class societies, shipyards, operators, and port authorities.

14.3.1. Regulatory and Governance Implications

The transition toward prescriptive frameworks depends on validated, quantitative data that can support consistent interpretation of risk and performance across jurisdictions. Classification societies and flag administrations will need to align early with ongoing IMO and IACS processes to incorporate results from experimental testing and simulation. Establishing permanent, shared evidence registries or data platforms could strengthen regulatory transparency and reduce the time required for new-fuel approvals.

14.3.2. Digitalization and Knowledge Integration

The Decision Support Tool developed in METAFUEL can evolve into a digital platform for continuous learning. Integrating operational data, simulation outputs, and incident feedback would allow dynamic updates to risk models and facilitate periodic refinement of safety benchmarks. Such tools can support digital twins for validation and enable consistent data exchange between stakeholders, ensuring traceability in future regulatory developments.

14.3.3. Infrastructure and Port Readiness

Port and fuel infrastructure will increasingly determine the feasibility of large-scale deployment. Adoption of structured frameworks, such as the Port Readiness Level for Marine Fuels (PRL-MF), can help align onshore and onboard safety systems. Embedding METAFUEL's findings into permitting procedures, bunkering standards, and emergency planning will support consistent risk management across different port environments.

14.3.4. Human and Operational Readiness

The introduction of multiple fuel types increases operational complexity and demands ongoing competency management. The findings on Human Factors Engineering confirm that procedural clarity, environmental design, and realistic training are key safety barriers. Incorporating human performance validation into design reviews and audits will help ensure that alternative-fuel vessels remain safe and operable under both normal and degraded conditions.

14.3.5. Economic and Policy Drivers

Quantified safety performance provides a more predictable foundation for investment and policy design. Insurers and financial institutions can use validated safety metrics to assess project risk, while regulators can align incentives and compliance milestones with proven readiness levels. This evidence-based approach supports a stable transition toward carbon-neutral fuels by linking technological maturity with financial and regulatory confidence.

14.4. Pathway to Prescriptive Rules

The project outcomes demonstrate a practical and traceable route from current goal-based regulation to prescriptive safety standards:

1. Functional Stage: Identify hazards and define high-level control objectives.
2. Performance Stage: Validate barrier effectiveness through simulation, testing, and quantitative metrics.
3. Prescriptive Stage: Codify verified parameters (e.g., detection limits, exposure thresholds, suppression performance) into formal rules and standards.

This staged approach ensures that regulatory evolution keeps pace with technology maturity and operational experience.

14.5. Summary

The METAFUEL project provides the maritime industry with a defensible, data-driven pathway to safe and sustainable fuel adoption. By uniting quantitative evidence, functional safety mapping, and human-centred design, the project moves the sector from risk acceptance to rule definition. METAFUEL lays the groundwork for future prescriptive regulations by ensuring that the next generation of methanol, ammonia, and hydrogen fuelled ships are designed, operated, and regulated with verified, harmonized safety performance.

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