Concept design of a 3,500 TEU ammonia-fueled container vessel

With a focus on safety and cargo capacity

Mærsk Mc-Kinney Møller Center
for Zero Carbon Shipping

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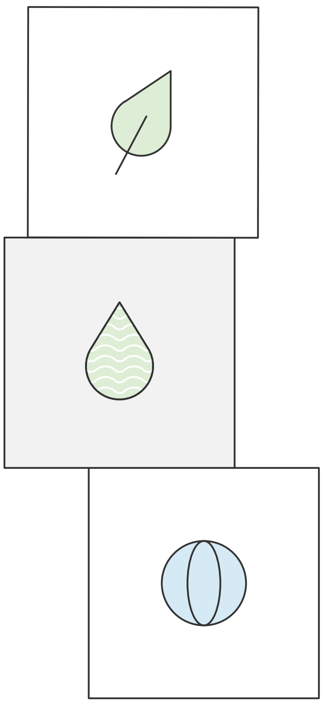
Executive summary

As an emerging maritime fuel, ammonia has advantages in scalability and potential for low greenhouse gas (GHG) intensity. When sustainably produced, ammonia is a viable candidate for low carbon operation of future vessels. However, the toxicity and corrosiveness of ammonia also brings challenges and risks. In the ongoing maritime green transition, detailed guidance on vessel design will increase confidence for shipowners/operators and shipyards and help enable the safe adoption of ammonia and other alternative fuels.

This report describes a concept design of a technically viable and safely designed 3,500 TEU container feeder vessel integrating cutting-edge ammonia fuel technology. Previous work by the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS) and partners on the design and safety of ammonia-fueled vessels (see page 7) has been instrumental in creating a safe design concept considering key risks, such as ammonia exposure, toxicity, and structural integrity. Accordingly, in this project we placed focus on safety and cargo capacity. Further, the design process focused on early vessel deployment with available two-stroke propulsion engines, increased ammonia storage space requirements, and uncertainties related to bunkering infrastructure and limited bunkering options.



This report details safety and technical design considerations, including ammonia safety barriers, vessel performance, fuel system interactions, and our risk management approach. Our aim with this report is to share an example of a safe and viable design for an ammonia-fueled vessel that can be deployed in the near term, creating confidence in the maritime green transition.

In particular, we hope that the insights from the report will be useful to shipowners/operators and shipyards looking to build, own, or operate ammonia-fueled vessels in the near term.

Risk management and safety measures

As prescriptive regulations for ammonia-fueled vessels were not available at the time of our project, our design process relied on alternative design processes and risk assessments to ensure an adequate safety level. Our systematic risk management approach allowed us to identify and implement design criteria early in the concept design process. One fundamental criterion was to minimize the risk of crew exposure to ammonia by minimizing access to areas containing ammonia equipment or ventilation outlets. We therefore strategically positioned key components of our vessel concept design accordingly.

3,500 TEU feeder concept design

The general arrangement of the feeder design includes a midship location of ammonia bunker station, storage tank, reliquefaction plants, and tank connection space

(TCS). The accommodation and bridge are located aft, above the engine room, to optimize space utilization and minimize the risk of crew exposure during a potential leak in the bunker station, storage tank, or TCS. The configuration of the general arrangement enhances crew safety, simplifies operations, and minimizes pipe lengths. Another crucial safety feature is the inclusion of the bridge as a gas-tight refuge during emergencies.

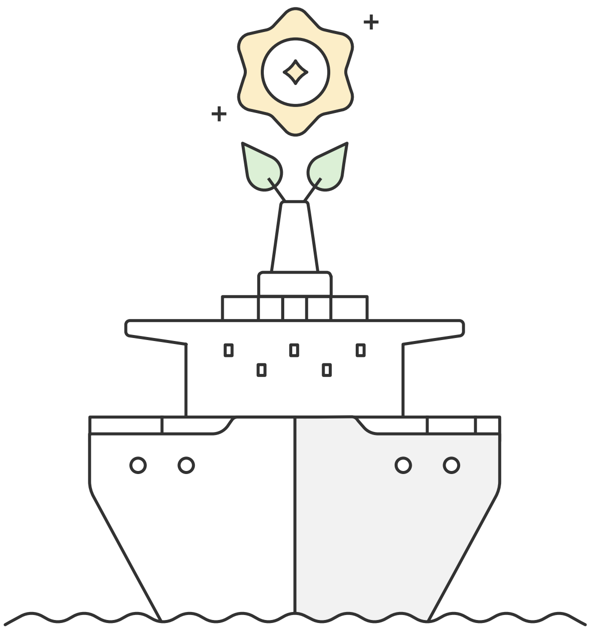
To ensure maximum flexibility for bunkering, the bunker station is positioned midship. This placement allows for efficient interfacing with various sizes of bunker vessel. The semi-enclosed bunker station incorporates advanced safety features to enhance operational safety and manage leaks. These safety features include a gas-tight passage to prevent exposure to toxic zones. The position of the fuel storage tank below the bunker station enables a short bunker line routing and a space-efficient tank geometry. To balance safety, efficiency, and space considerations while enabling future scalability, the ammonia storage tank is a Type A tank with a full secondary barrier. The innovative tank design features an insulated tank inter-barrier space, minimizing the evaporation of ammonia during a leakage. Furthermore, the tank hold space structure can be constructed using standard steel. We designed an efficient tank pressure control system incorporating two independent reliquefaction plants and redundant pressure management. The reliquefaction plants are close to the bunker station and TCS, which gives a short pipe routing to the storage tank.

Another innovative design feature is the strategic position of the fuel preparation room (FPR) close to the engine room, and the division of FPRs for main and auxiliary engines into smaller, independent rooms. The short distance between the FPR and engine room minimizes the fuel pipe length and ammonia purging volume. Gas-tight structures in the FPR enhance safety, and the ventilation ensures that any potential ammonia leaks are led away from areas accessed by the crew. The FPR contains a remote-controlled filter unit with integrated double block-and-bleed separation of fuel supply system and engine, further enhancing the safety during operation and maintenance.

Ventilation outlets from the TCS and reliquefaction rooms are directed to a midship ventilation mast. The vent mast is positioned as far forward as possible to ensure that vented gas is diluted and dispersed before potentially reaching the accommodation. Ventilation outlets from the FPRs and filter room are combined in a ventilation mast at the aft part of the ship. Computational fluid dynamics (CFD) studies confirmed the safe location of the aft ventilation mast.

Future directions

This ammonia-fueled feeder vessel design has received Approvals in Principle from two classification societies, demonstrating its readiness for practical application. We encourage readers with interest in the ammonia fuel pathway – including ship designers, shipyards, technical managers, ship operators, and regulators – to consider the design principles embodied in this concept design. In doing so, they can support a safe green transition for the maritime industry.



01
Introduction

The maritime industry is undergoing a green transformation driven by the urgent need to reduce GHG emissions in line with the Paris Agreement. Among the various alternative fuels under exploration to replace conventional fossil-based fuels, ammonia is a promising candidate because of its long-term potential for zero carbon emissions.[1] As a carbon-free molecule, ammonia offers numerous advantages as a maritime fuel. When produced with renewable energy (e.g., e-ammonia), ammonia reduces well-to-wake GHG emissions by up to 97% compared to low-sulfur fuel oil.[1] With that said, emissions from the combustion of ammonia are still under study, and their environmental impact is uncertain.[2]

Despite these advantages, the adoption of ammonia as a maritime fuel poses several challenges, including:

- Ammonia toxicity, corrosivity, flammability, and significant safety risks to humans and the environment.
- The need to understand and evaluate the various risks, including those associated with human factors. This evaluation enables the implementation of appropriate design and operational safeguards early in the design process, which encompasses both engineering and administrative controls, to reduce risk to 'as low as reasonably practicable' (ALARP).
- Careful handling of ammonia onboard, together with robust safety measures and procedures to manage risks.
- Technological infrastructure and equipment onboard are still under development, and key components, like auxiliary combustion, need further advancement.
- Larger space allocation for ammonia fuel storage (2.94 times higher volumetric ratio per unit heating) because of ammonia's lower volumetric energy density (0.696 t/m^3) compared to marine gas oil.[3]

In this context, the ship design process plays a vital role in technically qualifying the ammonia pathway across the value chain by highlighting areas that require focus. At the MMMCZCS, we leverage ship design case studies to address technical challenges and opportunities and to help drive regulatory policymaking and verification.

Together with our partners, we have conducted several studies to explore the technical feasibility of ammonia-fueled vessels.

In particular, we wish to highlight:

Our Concept design of a 15,000 TEU ammonia-fueled container vessel included assessments of technical, regulatory, and environmental considerations necessary for the successful deployment of such a vessel.[4] The study highlights the importance of integrating safety measures and robust design principles to mitigate the risks identified in a hazard identification (HAZID) study, pointing to early considerations in the design to cater for challenges such as leakages and releases.[4]

In cooperation with the Lloyd's Register Maritime Decarbonisation Hub (Decarb Hub), we published Recommendations for design and operation of ammonia-fueled vessels based on multi-disciplinary risk analysis which used a systematic, data-driven quantitative risk assessment (QRA) to evaluate risks to the crew onboard ammonia-fueled vessels.[5] The study highlighted a series of important findings that collectively aim to mitigate risks and ensure safe operation. High-priority actions included lowering storage temperatures, dividing FPRs, minimizing access to ammonia equipment areas, safely placing ventilation outlets, and installing multiple leak detection sensors. Additional findings highlight the importance of secondary containment, gas-tight enclosures, effective ventilation, and reliable leak alarms. The fuel system must support rapid shutdowns, and distinctive toxicity alarms must be implemented.[5]

A human factors study relating to ammonia[6] pointed to the development of comprehensive change management plans to address operational and safety impacts on seafarers and shoreside personnel through competence training, ergonomics and enhanced safety, and maintenance management. This study indicated that, if the maritime industry ensures the implementation of adequate technical barriers and administrative safeguards, addresses human factor considerations, and applies existing experience with gas fuels and ammonia handling from other industries, risks to the crew when using ammonia as a maritime fuel can be kept at an acceptable level.[6]

Our publication Emerging ship design principles for ammonia-fueled vessels provides comprehensive guidance on design considerations for key aspects of the ammonia-fueled ship. These design principles help ship designers and owners navigate key decisions by highlighting the interconnections between onboard systems.[3]

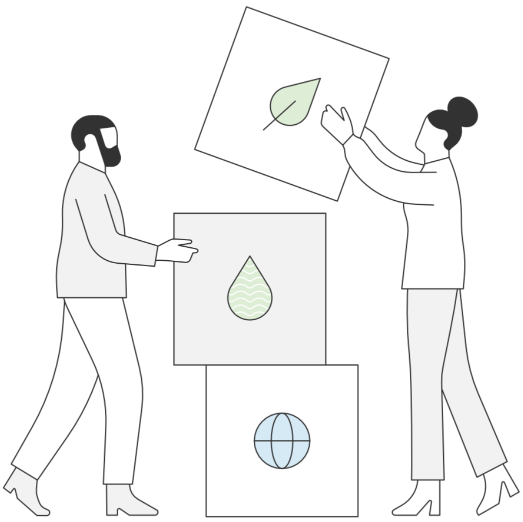
This report builds on our previous efforts and introduces a concept design for an ammonia-fueled container feeder vessel, incorporating modular knowledge acquired from these previous studies. The report addresses two principal questions about the design of an ammonia-powered vessel:

What are the key technical considerations when designing an ammonia-fueled container feeder vessel?	→ Ammonia tank capacity and location of key items (accommodation, bunker station, ammonia tank, FPR, vent mast, and ventilation outlets from ammonia spaces)
What are the technical safety barriers needed to make the vessel safe enough for the crew?	→ Separation of ammonia spaces → Safe distance to outlet of ammonia vapor if a leak occurs → Physical barriers → Drain systems → Water screens and ammonia release management systems (ARMS)

Considering these factors, this report presents a detailed concept design of a 3,500 TEU container feeder, developed with a focus on ammonia system design principles. The concept design was optimized to achieve the required safety level while also limiting reductions in cargo capacity. As a result, this design concept marks an advancement in technically qualifying ammonia as a viable maritime fuel.

Although the concept design is an important first step in qualifying a fuel pathway, the final design and operational details must ultimately deliver a safe vessel. We addressed this aspect early in our design process with reference to the technical safety barriers listed above. We confirmed the concept design's ability to achieve an acceptable safety level through a HAZID, hazard and operability study (HAZOP), and QRA. These processes have resulted in two Approvals in Principle of the concept design awarded by ABS and Lloyd's Register (LR).

This report explains our design objectives (Section 3), applicable rules and regulations (Section 4), and design methodology (Section 5). Subsequently, we present an overview of our design philosophy (Section 6), focusing on different areas of the vessel or ammonia fuel system in turn. Finally, we highlight some key results from our safety assessments (Section 7). For readers interested in demonstrating the viability of the ammonia pathway, our concept feeder design can provide a successful case study of what is technically possible in the early phases of vessel deployment. For ship designers, technical managers, ship operators, shipyards, and regulatory bodies involved in designing ammonia-fueled vessels, we aim to provide guidance on the main technical considerations for a feeder vessel.



02 About the project

The concept design was developed through a collaborative effort between the MMMCZCS and our partners.

MAN Energy Solutions (MAN ES) and Maersk participated in the development of the concept design, while classification societies ABS and Lloyd's Register through the Decarb Hub provided statutory and design expertise throughout the project. In particular, ABS led the HAZID and HAZOP facilitation and supported with the gas dispersion studies, while LR led the QRA. Deltamarin was the ship design house for the detailed concept design, and Eltronic FuelTech designed the detailed ammonia fuel system.

Two flag administrations – the Danish Maritime Authority and the Maritime Port Authority of Singapore – also followed the risk assessment in observational roles.

03 Design objectives and requirements

The key objective of the project was to design a safe container feeder integrating state-of-the-art ammonia fuel technology. As an important design parameter, the container feeder design must demonstrate an adequate level of safety quantified by rigorous risk assessment (see also Section 7).

As a new fuel, designing for ammonia introduces uncertainty about ammonia technology availability and the development of bunkering infrastructure. Our intention with the current feeder design is early deployment, targeting the earliest available two-stroke engine size (60-bore) from MAN ES. The available engine size limits the vessel size to around 3,500 TEU.

Furthermore, we developed our design with the expectation that ammonia bunkering infrastructure will not be fully developed when the vessel begins operation. The bunkering arrangement should allow for bunkering from a handy-sized gas carrier (approximately 20,000 m^3). We have developed the feeder design to the best of our knowledge and abilities without having access to any specific ammonia bunkering guidelines at the time of design.

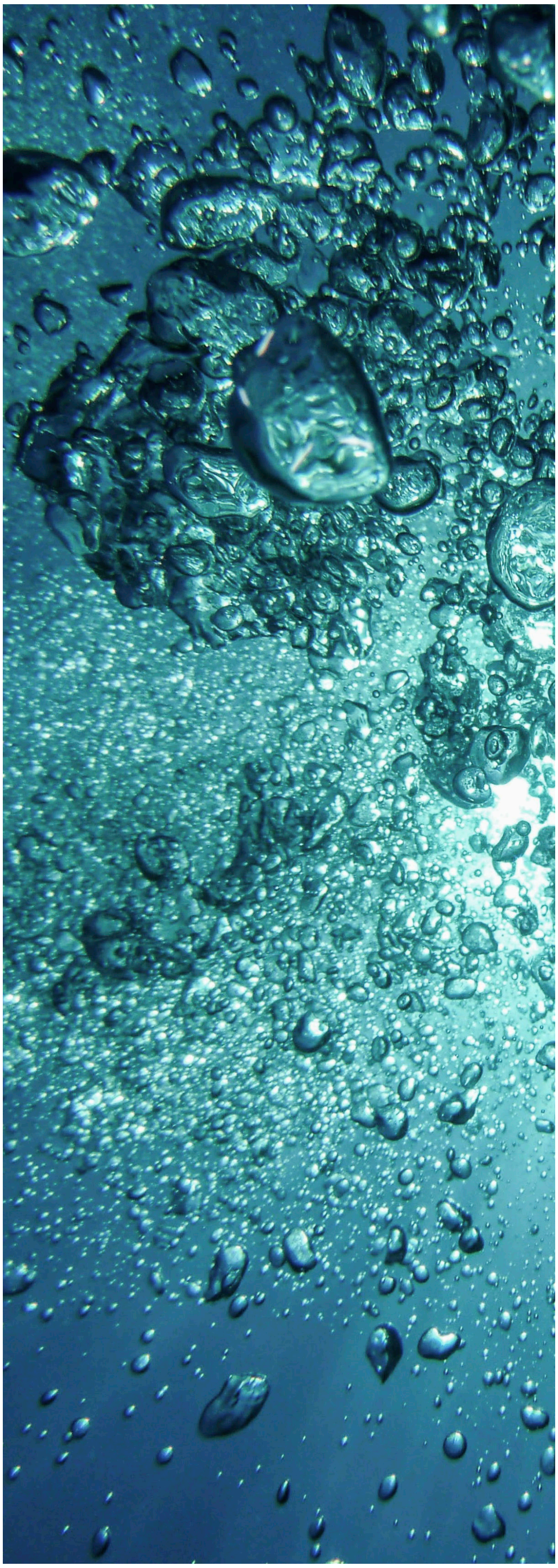
Finally, even though boilers and ammonia-fueled auxiliary engines are still under development, we explored a full-scope ammonia-fueled machinery design. This approach enabled us to explore all risks pertinent to a full-scope design, which can be reduced by considering a hybrid between ammonia-fueled and other technology when the former is fully available. As an example, combining an ammonia-fueled main engine with batteries for auxiliary power can significantly reduce the risks of ammonia leaks.

04 Rules and regulations

At the time of the design, no detailed prescriptive regulations were in place. Hence, the design was based on the International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels (IGF Code)[7] and the International Convention for the Safety of Life at Sea (SOLAS) alternative design process[8] and class requirements of ABS and LR.

In September 2024, the tenth Sub-Committee on Carriage of Cargoes and Containers (CCC10) discussed the latest revision of interim guidelines with technical provisions for the safety of ships using alternative fuels, including ammonia. These interim guidelines were approved during MSC109 in December 2024 – after our vessel design had been completed. In anticipation of finalized interim guidelines for the safety of ships using ammonia as fuel at the time of the design process, the feeder design was based on the classification requirements for ammonia-fueled vessels from ABS and LR. Furthermore, we verified the concept design against the latest interim guidance to ensure that it remains relevant and compliant.

Generally, the issuance of an Approval in Principle requires that the level of safety of the ship is equivalent to that of a ship using conventional fuel. To quantify the safety level of the developed feeder design, we have used the risk assessments outlined in Section 7 and the risk matrix in Appendix A1.



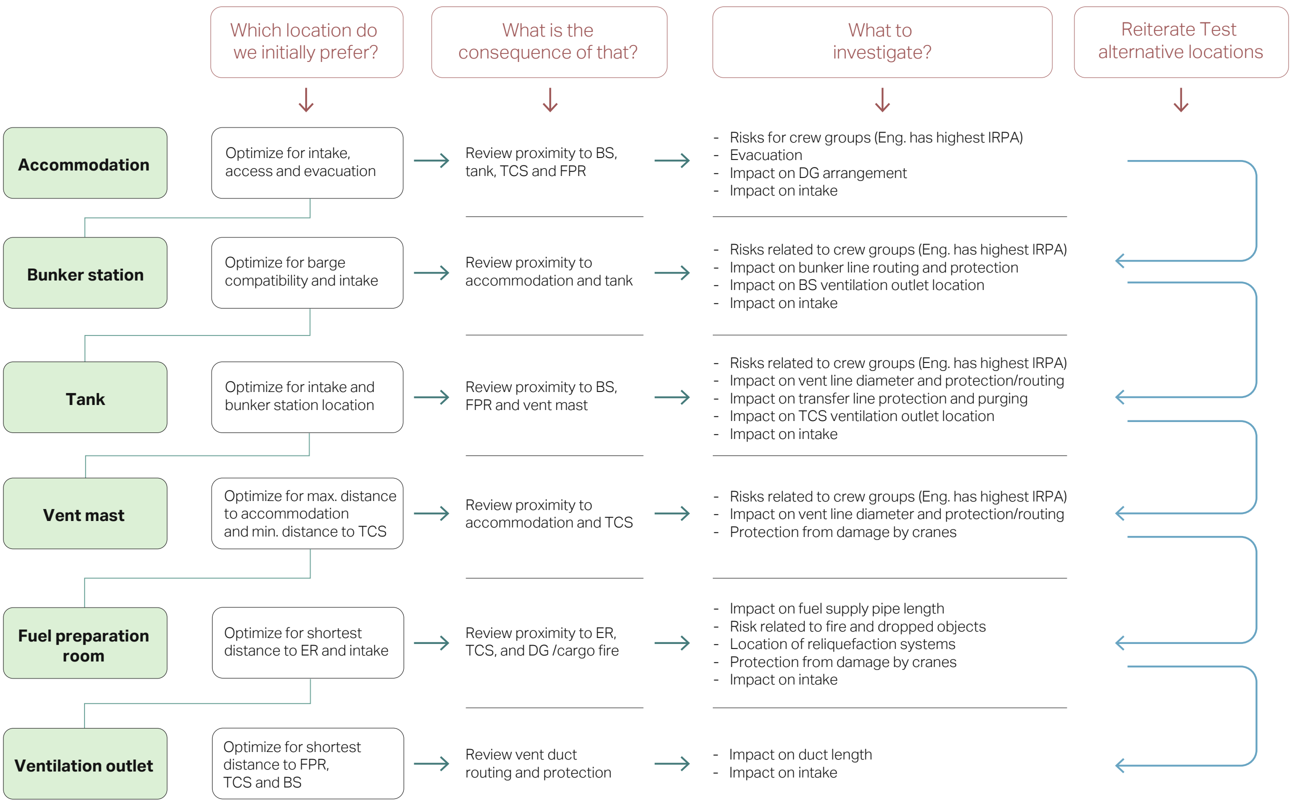
05 Design methodology

To achieve a robust starting point for the design process, we defined a baseline vessel design by incorporating modular knowledge from past studies, as listed in the Introduction. The detailed ammonia-fueled design comprises main interactions between systems and interconnections between components that need to be considered early in the design phase. Throughout our design process, and with guidance from the Emerging ship design principles for ammonia-fueled vessels,[3] we evaluated the impact of the locations of fuel storage, bunker station, FPR, accommodation, ventilation, and vent mast on the overall design. Figure 1 gives an overview of the design decision process applied.

To ensure the highest level of safety in the feeder design, we systematically integrated safety and risk assessments into the design process. These assessments consisted of:

- HAZID and HAZOP qualitative assessments with a multidisciplinary group of experts
  - A HAZID study to identify potential hazards early in the design phase – see Section 7 and Appendix A2 for more details
  - A HAZOP study involving a detailed examination of the fuel system design and systematic review of each aspect of the ship's systems to identify possible causes, effects, and mitigations – see Section 7 and Appendix A3 for more details
- A QRA to quantify the risks at an individual or group level – see Section 7
- Dispersion studies to verify the design of the vent mast and ammonia ventilation outlet – see Section 6.6

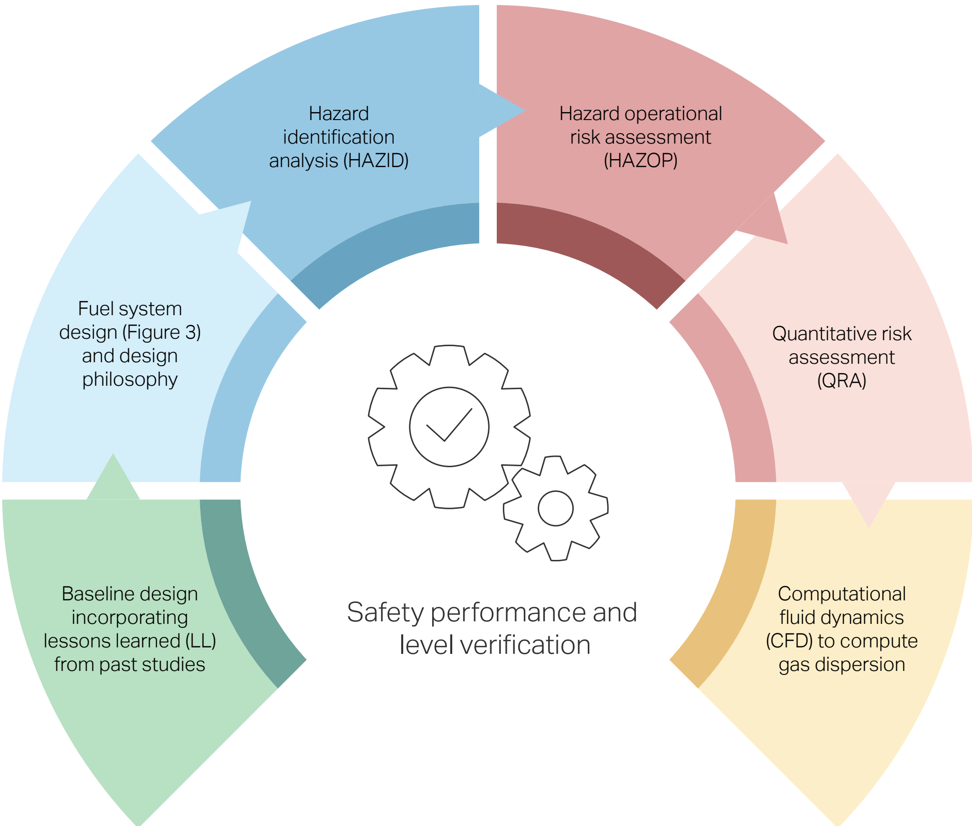
Figure 1: Applied design decision process for the concept design.



BS = bunker station, TCS = tank connection space, FPR = fuel preparation room, ER = engine room, DG = dangerous goods, IRPA = individual risk per annum.

This comprehensive and systematic approach enabled us to prioritize safety measures effectively, ensuring that the final ship design not only met but exceeded industry safety standards. Figure 2 illustrates the process rationale behind the concept design development.

Figure 2: Process rationale for concept design development.



06 Design philosophy

Recommendations from our past studies have been integral in shaping the design philosophy for the design of the ammonia-fueled feeder vessel. In more detail, we used the following design philosophy as a guide:[4,5]

- Reduce the impact of a leak

Storage at a lower temperature (tends to give lower risk/ less risk mitigation effort required).

- Reduce exposure to leak sources

Divide the FPR into two or more separate rooms containing different groups of equipment.

- Reduce the exposure time

Minimize, monitor, and control access to and time spent in spaces containing ammonia equipment.

- Safe by location

Place ventilation outlets from spaces containing ammonia equipment in a safe location adequately separated from areas accessed by crew.

- Rapid reliable leak detection and isolation

Install multiple sensors of different types to detect ammonia leaks.

Figure 3 shows a 3D rendering of the feeder design with a traditional layout, with the accommodation located aft to optimize cargo intake for this vessel size. Additionally, the figure shows the arrangement of ammonia fuel system components.

Figures 4 and 5 show the final general arrangement of the feeder design and a top view, respectively, indicating the main feature arrangement, including positions of the FPR, reliquefaction rooms, filter room, and auxiliary engine rooms. Table 1 gives main particulars of the ammonia-fueled feeder vessel.

Figure 3: 3D rendering of the feeder concept, visualizing the prismatic tank (in green) and reliquefaction spaces (in yellow).

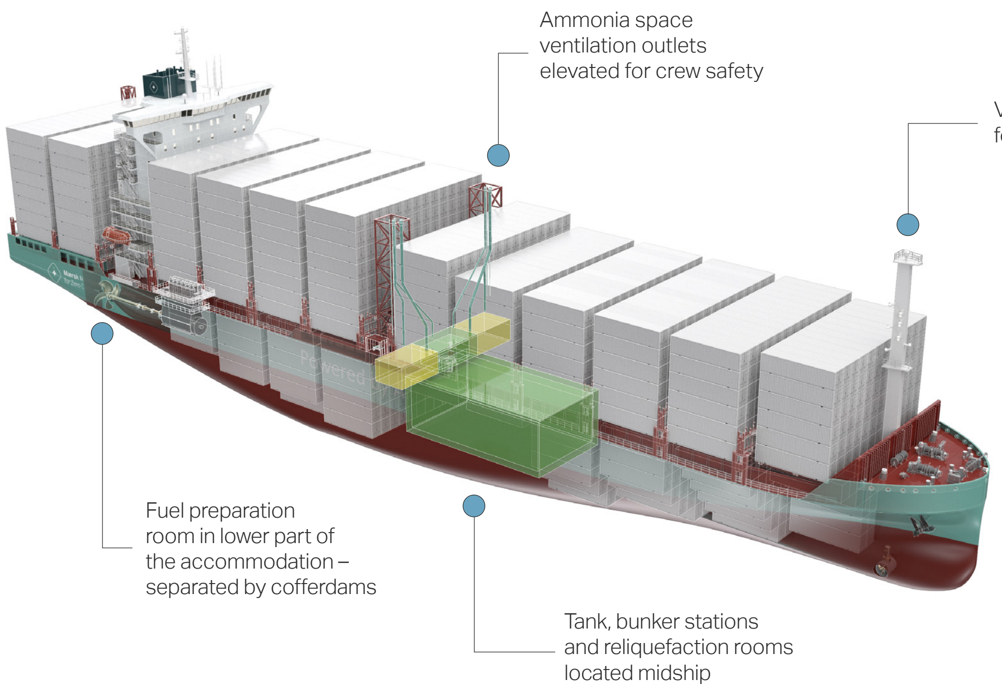


Figure 4: Final general arrangement of the feeder design.

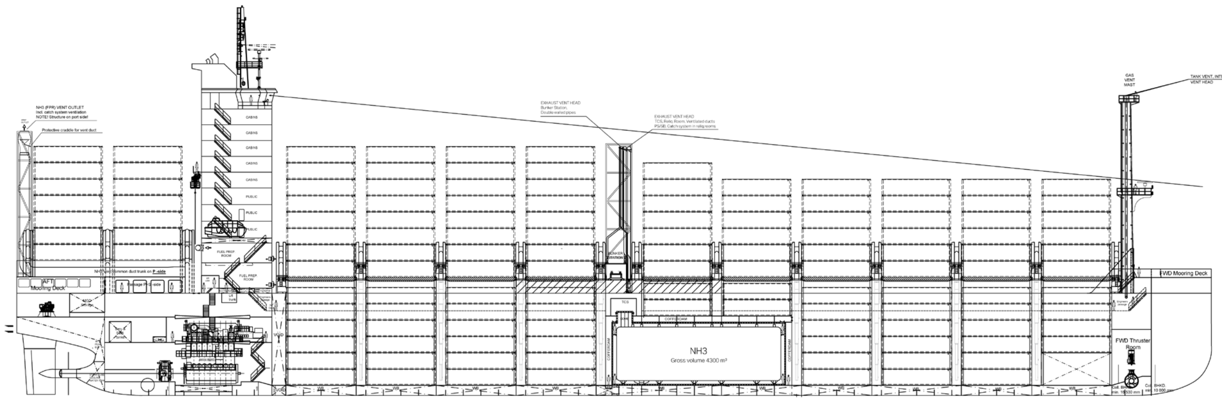


Figure 5: Feeder top view indicating the main feature arrangements.

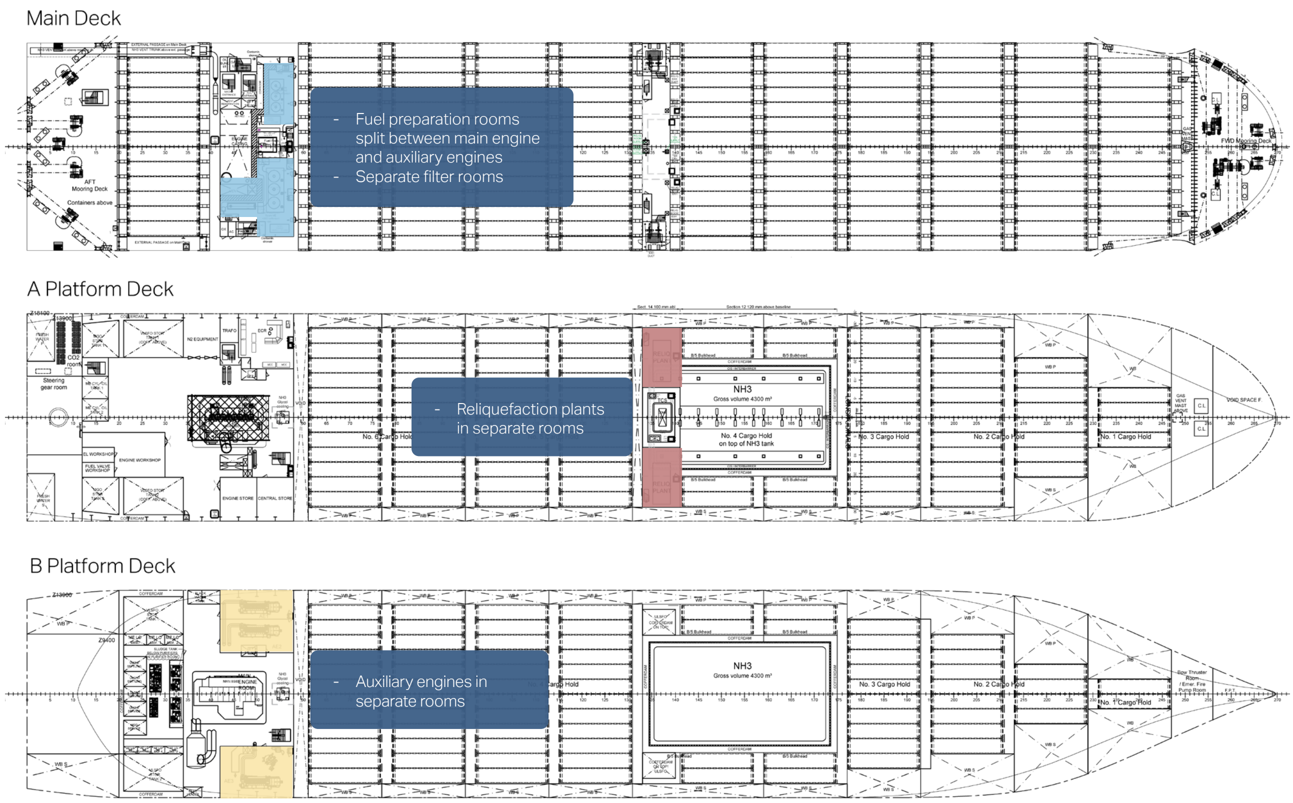


Table 1: Main particulars of the ammonia-fueled feeder vessel.

Length overall (m)	211.90
Length, between perpendiculars (m)	206.60
Breadth, molded (m)	35.20
Depth, molded (m)	18.10
Draft, design (m)	11.40
Draft, scantling (m)	12.40
Equivalent High Cube (TEU)	3,374
Reefers (TEU)	400
Ammonia tank capacity (m^3)	4,300
Fuel oil (FO) capacity (m^3)	2,000
Marine gas oil (MGO) capacity (m^3)	270
Main engine	MAN ES, ammonia dual-fuel, 8 cylinders, 60-bore
Maximum continuous rating (kW)	c. 18,500
Auxiliary engines	3 x 1,935 kW, ammonia dual-fuel
Shaft generator	2,000 kW
Boil-off gas (BOG) management	2 x 100% redundant reliquefaction units

The following list highlights key considerations for the main parts of the ammonia fuel system and related systems, which are explored in more detail in the specific sections of this document.

Section 6.1 – Fuel storage

A midship location of the bunker station, storage tank, and TCS creates a distance to the accommodation, which reduces the risk of crew exposure during a potential leak in one of these areas.

Section 6.2 – Tank pressure management

The reliquefaction plants are in separate rooms close to the bunker station and TCS to maintain a short pipe routing to the storage tank. The FPR is in the lower part of the accommodation close to the engine room, the FPR is gas-tight towards the accommodation, and the only entrance is from the open deck.

Section 6.3 – Bunker station

Ventilation outlets from the TCS and reliquefaction rooms are located midship, forward of the accommodation. The ventilation mast is placed as far forward as possible to allow dilution and dispersion of any vented gas before it can reach the accommodation.

Section 6.4 – Fuel preparation room

The fuel storage tank and bunker station are located midship to ensure a flat side for safe mooring and alignment of the manifold of a handy-sized bunker vessel. The storage tank is placed below the bunker station to maintain a short bunker line routing and a space-efficient tank geometry.

Section 6.5 – Accommodation and bridge

An important purpose of the bridge design is to keep the bridge as a safe space during a major gas leak. Therefore, the design incorporates a separate ventilation system with a gas filter on the air intake, which enables a continuous supply of air and overpressure in the bridge. For a vessel of this feeder size, a single-island layout is normal (as opposed to twin-island concepts). It is advantageous to keep a single section/area of the ship safe, from which the ship control, propulsion, and evacuation can take place during a major leak or fire.

Section 6.6 – Ventilation and vent mast

An important safety measure is to lead ventilation outlets from spaces with ammonia equipment to a vent mast in a safe location not accessed by the crew. Ventilation outlets from the TCS and reliquefaction rooms are located midship, forward of the accommodation. Ventilation outlets from the main engine and auxiliary engine FPRs and filter room are combined in a common duct placed at the aft part of the ship.

6.1. Fuel storage

Figure 6 shows the two tank types considered (IMO tank types A and C) in the concept design study for storage of fully refrigerated ammonia at -33°C. Due to the more extensive design requirements for Type B tanks, and since Type A tanks have been used to date for large ammonia carriers, we did not consider a Type B tank for this design. We evaluated a Type C tank configuration given the advantage of possible pressure buildup and a higher safety margin before venting during an emergency. With the same space allocated for the tank system, the Type C tank resulted in a limited reduction in tank volume compared to the Type A tank, as Figure 6 shows. Despite both tank types resulting in the same loss of cargo volume, we selected the IMO Type A tank with a full secondary barrier for the concept design because of the space efficiency, which we anticipate will be favored in larger vessels (see Figure 7).

Structurally, the tank insulation is mounted on the ship structure outside the secondary barrier and combined with a membrane inside the insulation. On traditional Type A tanks, the insulation is mounted on the tank itself. The benefit of the new configuration is that the inter-barrier space between the secondary barrier and the tank is insulated and cold, and evaporation of ammonia leaked into this space will be low. Furthermore, the structure supporting the secondary barrier will not be exposed to low-temperature liquid and normal steel can be used. The cold surface of the tank means that nitrogen is needed in the inter-barrier space to avoid ice formation on the tank surface. A transfer pump can return any leaked ammonia from the inter-barrier space to the storage tank.

Figure 6: Application, section design, and cargo loss for a prismatic Type A tank (left) and a Type C tank (right).

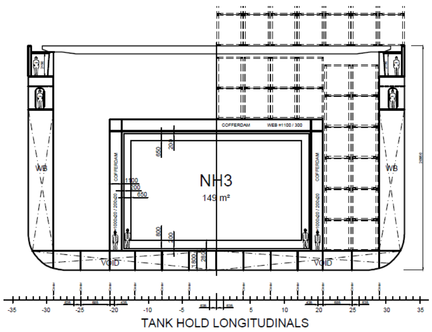
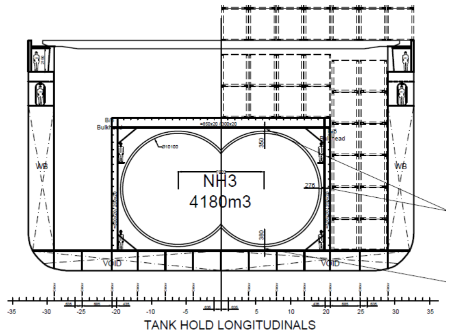
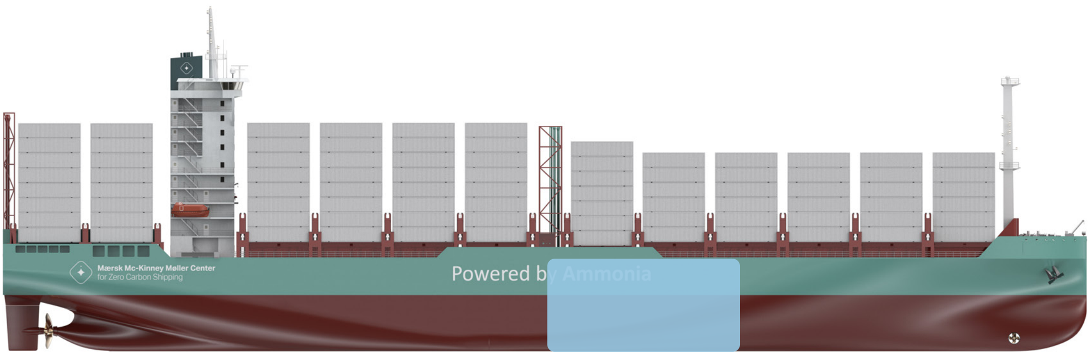
	Type A tank	Type C tank
		
Cargo loss	128 TEU	128 TEU
Ammonia tank volume	4,300 m³	4,180 m³

Figure 7: Position of ammonia storage tank on the feeder vessel.



6.2. Tank pressure management

The process of reliquefaction re-condenses the vapor phase in the storage tank and can support the tank pressure management during bunkering, depending on system capacity, bunkering rate, and temperature.

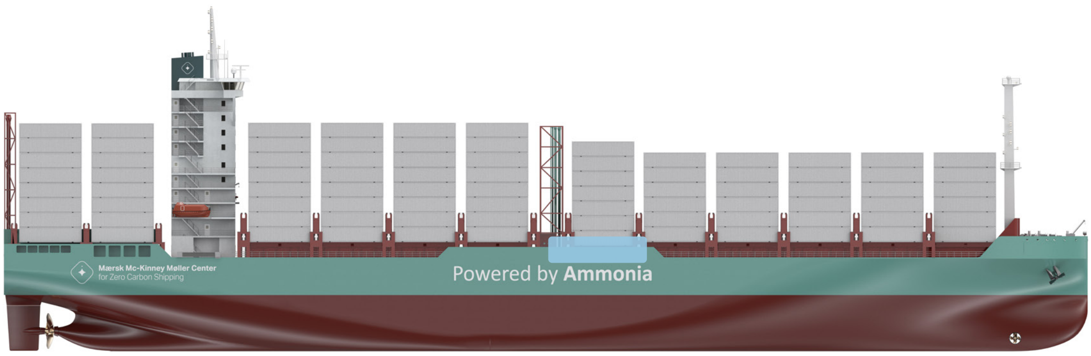
The feeder has two reliquefaction plants (with hot gas production capability) in two independent rooms, which are in the same midship area as the TCS (see Figures 5 and 8). The two reliquefaction plants maintain the storage tank pressure at 0–0.24 bar. This setup provides the option for two separate tank pressure controls for a single failure condition. The pressure relief value (PRV) is set at a tank design pressure of 0.7 bar.

The fuel system design includes an ammonia-fired boiler, which can consume free-flow (not supplied by compressor) ammonia boil-off gas (BOG), even though this technology has not yet been developed. The boiler is in the same room as one of the auxiliary engines in the engine room.

Another option for BOG handling is to sub-cool the liquid ammonia in the tank. This requires a simpler system consisting of a refrigeration unit with a separate cooling medium. The subcooling principle implies a slow reaction time, and will not be able to manage the increased BOG amount when bunkering ammonia at the higher end of the accepted temperature range.

Additionally, a gas combustion unit (GCU), or a boiler with GCU function, can be used to control the tank pressure by consuming the BOG. Such technology was not yet readily available at the time the design was developed, but, once available, combining a boiler with a single reliquefaction system can protect against pressure buildup and unintended venting. However, if a non-heated pilot and back-up fuel is used onboard, the need for steam production can be significantly reduced.

Figure 8: Two independent reliquefaction plants (in blue) in two rooms which are in the same midship area as the tank connection space.



6.3. Bunker station

The interaction with the bunker vessel/barge during bunkering essentially determines the optimal positioning of the bunker station. A midship location for the bunker station provides the maximum flexibility for mooring of the bunker vessel (Figure 9). Bunkering from handy-sized ammonia carriers with a length around 160–180 m may be required to offer high flexibility during the initial steps of adopting ammonia as a fuel. The mooring arrangement and manifold location must be designed and arranged accordingly.

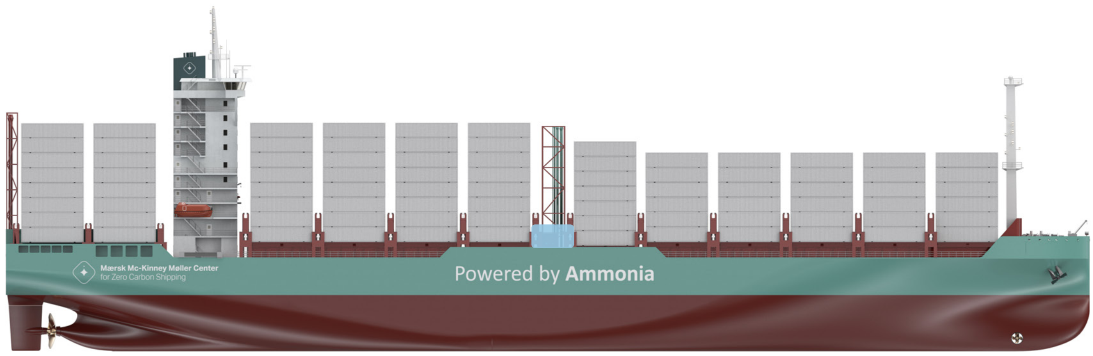
General properties of the bunker station design are as follows:

- Installation of a 1 x 8" liquid line and a 1 x 6" vapor line connection
- Semi-enclosed arrangement with access from a door on both sides
- Drip tray must contain the maximum credible leak volume determined during detailed design (currently, we use the volume in the hose and manifold)
- Connection from the drip tray to the ammonia bilge tank and to the sea, since we expect the valves from the drip tray to be open at sea
- Combination of gas detectors (location based on gas dispersion study and smoke test) for the gas and leak detection system, high-level alarms in the ammonia space bilge wells, and temperature sensors in the drip tray
- A gas-tight tunnel on the upper deck and in the bunker station allows passage past the bunker station without exposure to the toxic zone

Further safety measures

Water screen systems placed outside the bunker station can capture gas escaping from the bunker station. However, to avoid increased evaporation by mixing liquid ammonia with water, it is necessary to keep a safe distance between the water screen and the bunker station drip tray, which may contain liquid ammonia.

Figure 9: The traditional midship bunker station design provides maximum flexibility for mooring and interfacing with various sizes of bunker vessels.



6.4. Fuel preparation room

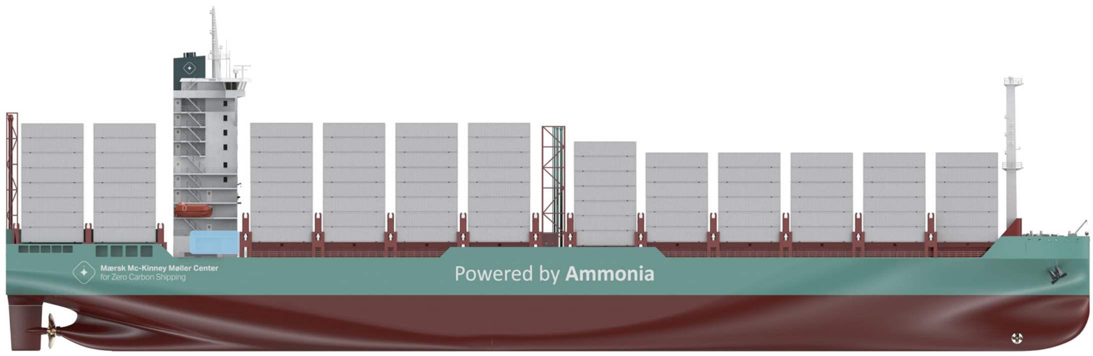
The position of the FPR in the lower part of the accommodation, close to the engine room, minimizes the pipe length and the purged ammonia volume to be treated when engines are stopped or switched to fuel oil (FO) (Figure 10).

A cofferdam surrounds the FPR, which is gas-tight towards the accommodation, and the only entrance to the FPR is from an open deck. In this location, the FPR is well protected from cargo fires and dropped objects. The ventilation systems direct any gas from leaks in the room to a location in the aft part of the ship at a safe distance from areas accessed by crew.

The FPR is split into five smaller rooms to ensure limited exposure to potential ammonia leakages. The division entails two rooms, each with an FPR for the main engine (upper deck and A deck), FPR for auxiliary engines, supply units for the boiler and SCR, and the fuel supply system drain tank.

The filter unit is designed for remote changeover and double block-and-bleed separation, allowing for minimum attendance in the filter room and maximum flexibility for running on ammonia. The intent was to develop the most flexible design by providing a design for the full system. For simplification, parts can be removed if not required. Self-cleaning filters for ammonia require a further study of additional systems for draining filter sludge. The FPR and the filter room must be remotely monitored by sensor systems and CCTV.

Figure 10: The fuel preparation room is in the lower part of the accommodation, close to the engine room.



6.5. Accommodation and bridge

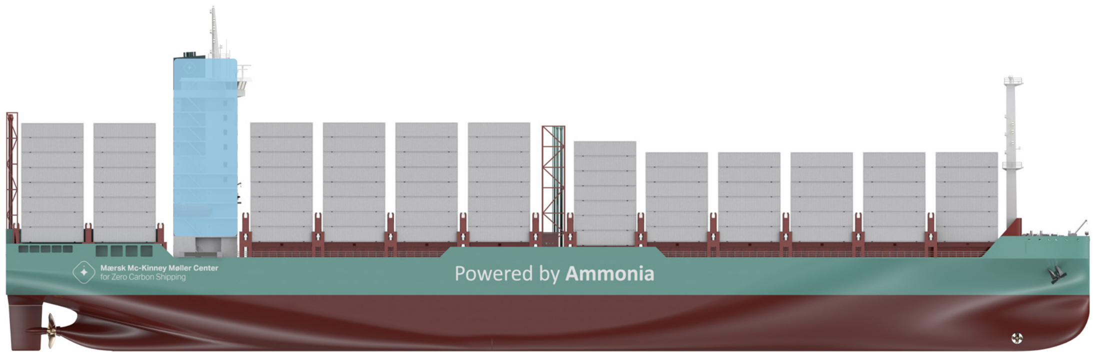
Adhering to the classic design for feeders of this size, the accommodation is placed aft above the engine room to optimize the space for containers (see Figure 11). This position enables a short passageway from the engine room to the bridge, and direct access from the accommodation to lifeboats, protected by a water screen.

Generally, it is possible to maintain overpressure in accommodation areas, including the bridge. If ammonia gas is detected at the accommodation ventilation inlets, the ventilation system switches to full recirculation.

The bridge is designed to act as a 'safe refuge' area for the crew. An independent air supply system equipped with a suitable gas filtration system is able to maintain overpressure and fresh air supply to the bridge. Finally, the accommodation design has closed windows, or gas-tight openable windows with rapid closing.

If there is a fire in the cargo area, the position of the accommodation allows the ship to maneuver and position itself so that the wind pushes the fire away from both accommodation and engine room. As such, the crew can maintain full control of the vessel.

Figure 11: The position of the accommodation and bridge above the engine room.



6.6. Ventilation and vent mast

Correctly positioning the ventilation outlets from spaces with ammonia equipment is an important safety measure. These ventilation outlets must lead to a safe location separated from areas accessible by the crew. Relevant outlets include:

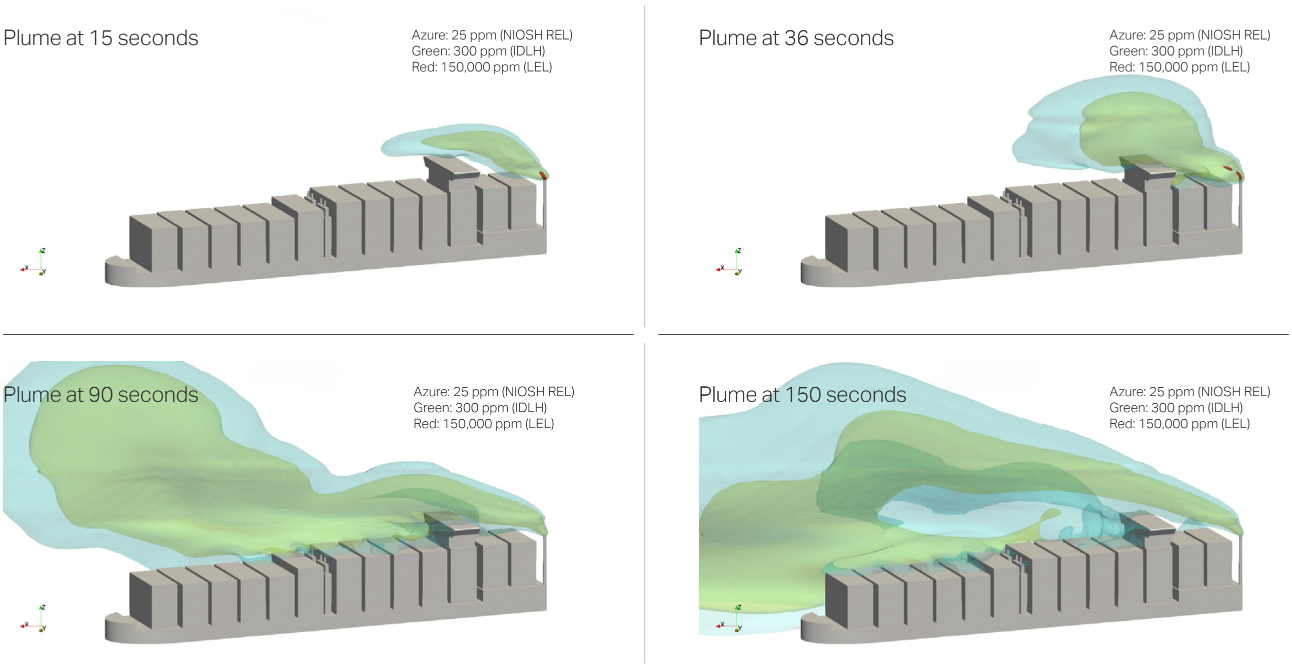
- Ventilation outlets from TCS and reliquefaction rooms are placed midship, forward of the accommodation.
- Combined ventilation outlets from main engine FPR, auxiliary engine FPR, and filter room in a common duct at the aft part of the ship.

We conducted a CFD gas dispersion analysis to evaluate the location of the aft ventilation mast and its proximity to the accommodation. The analysis investigated the worst-case leak scenario with gas dispersed through the aft ventilation outlet from the FPR, assuming:

- 2″ full-bore rupture in the FPR
- Wind of 5 knots from stern to bow
- Ambient temperature assumed to be 25°C
- Ammonia release time of 150 seconds

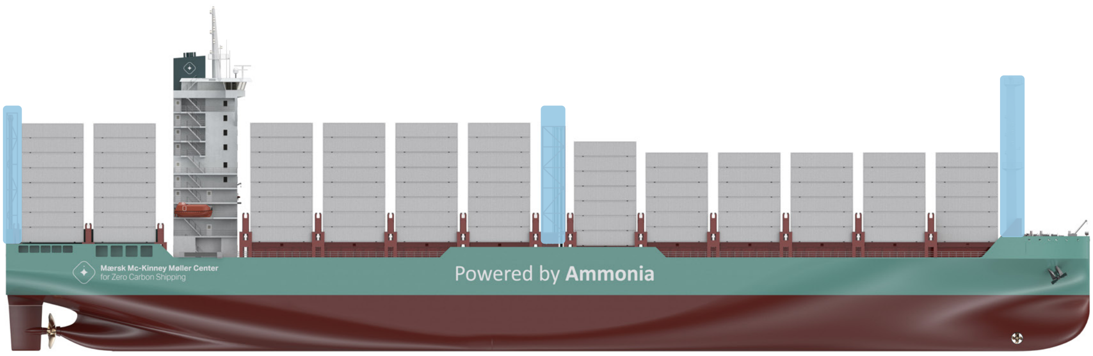
According to the US Centers for Disease Control and Prevention National Institute for Occupational Safety and Health (NIOSH), the recommended exposure limit for ammonia is 25 ppm, and a concentration of 300 ppm is defined as immediately dangerous to life or health.[9] Based on the results in Figure 12, a large area of the vessel, including the bridge and accommodation, could be exposed to ammonia concentrations exceeding 25 ppm (azure) and 300 ppm (green) in the event of a 'worst-case' leak. This exposure is likely due to the low ammonia release velocity (6–9 m/s), even though the release is vertically upward. This analysis considers one of the worst wind directions; we expect actual operational conditions to be less severe. We expect that the vessel can steer in the appropriate direction to ensure that the gas dispersion is directed away from the accommodation. The application of a scrubber system in the ventilation system should be further investigated.

Figure 12: Computational fluid dynamics (CFD) gas dispersion study of ammonia dispersion from the fuel preparation rooms through the aft ventilation outlet on port side for a worst-case scenario with wind blowing from stern to bow.



REL = recommended exposure limit, IDLH = immediately dangerous to life or health, LEL = lower explosive limits

Figure 13: Location of vent mast (forward), ventilation outlets from tank connection space and reliquefaction rooms (midship), and ventilation outlets from main engine fuel preparation room, auxiliary engine fuel preparation room, and filter room (combined in a common duct in the aft ventilation mast).



Vent mast

Placing a vent mast in front of the accommodation can be risky, since the gas may drift towards the accommodation (Figure 13). It should be noted that venting from the tank requires that both tank pressure controls fail, causing the tank pressure to increase. In a situation where both reliquefaction units have failed, information from the tank designer indicates that the holding time until the PRV starts releasing gas through the vent mast is a minimum 5 days and up to 30 days, depending on the filling level of the tank. The release of gas through the vent mast is, therefore, known in advance and precautions can be taken in due time, such as positioning the ship such that the wind direction will lead the gas away from the vessel.

We conducted a venting study to investigate the behavior of vent mast release. We used the PHAST software (version 8.9) from Det Norske Veritas (DNV) to model the ammonia gas dispersion, considering a range of weather conditions and wind speeds. The results showed that the vent mast is tall enough to reduce the risk to the crew next to the accommodation and to ensure a low likelihood of a gas cloud being dragged down to the container stacks.

6.7. Ammonia drain systems

Ammonia bilge tank

The bilge from ammonia spaces and the bunker station is drained to a separate ammonia bilge tank that also contains the drainage from the engine water catch system. If the bunker station drip tray contains a mixture of ammonia and water, it can be drained to the bilge tank. The ventilation of the ammonia bilge tank connects to the ammonia catch system for the main engine.

Ammonia drain tank – fuel supply system

A separate drain tank is installed for the ammonia supply system with a capacity corresponding to the content in the ammonia supply system. If an ammonia leak occurs in the supply system, the liquid content of this system can be drained to the tank and stored fully pressurized until it is returned to the supply system. The purpose of this design is to limit the amount that eventually can leak into the drip trays, and the drip trays are therefore not connected to a separate liquid ammonia drain tank. However, the drip trays for relevant ammonia equipment should be sized to allow for the maximum credible leak volumes.

Although the supply system drain tank could be used as a common liquid ammonia drain tank, the ammonia from drip trays and bilges may be contaminated, and therefore reusing the ammonia in the supply system will no longer be possible. Furthermore, if the tank is filled with leaked ammonia, it will no longer be available for draining the supply system.

Leaked ammonia should be evaporated by the ventilation system, and ARMS for the ventilation system needs further assessment. The ARMS could use a water spray scrubber system, combustion in a GCU, or other strategies.

6.8. Summary of design philosophy

This section summarizes the design choices and highlights the novelty for the main parts of the ammonia fuel system and related systems.

The midship location of the storage tank is distant from the accommodation, which reduces the risk of crew exposure during a potential leak. A novel aspect of the design is the use of an IMO Type A tank with a fully insulated secondary barrier and a supporting structure of normal steel. The inter-barrier space remains insulated and cold, minimizing ammonia evaporation if a leak occurs.

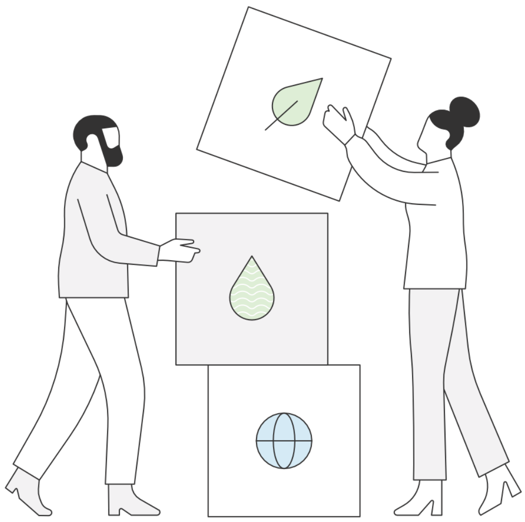
The novelty in the tank pressure management design lies in the inclusion of two independent reliquefaction plants (in blue on Figure 8) and the redundancy for pressure management, which enables safe operations during bunkering and system failures. The future integration of an ammonia-fueled boiler may maintain safety by managing BOG and preventing pressure buildup, while simplifying the reliquefaction system.

The traditional midship bunker station design (Figure 9) provides maximum flexibility for mooring and interfacing with various sizes of bunker vessel, an essential feature during the early adoption phase of ammonia as fuel. The semi-enclosed bunker station includes advanced safety features like a gas-tight passage to prevent exposure to toxic zones, which is an innovative approach to enhance operational safety and manage leaks.

The novelty in the FPR design is the strategic placement of the FPR near the engine room. This position minimizes ammonia purging and the pipe length, while also ensuring safety through a gas-tight structure and ventilation directing any gas leaks away from crew-accessible areas. Another innovative feature is the division of the FPR into smaller, independent rooms for the main and auxiliary engines combined with a remote-controlled filter unit that allows double block-and-bleed separation, enhancing operational flexibility and reducing maintenance requirements when running on ammonia.

The bridge provides a 'safe refuge' area with an independent air supply system equipped with a gas filtration system. If ammonia is detected in the accommodation ventilation inlets, the air supply switches to full recirculation. The aft position of the accommodation above the engine room provides easy, water-screen-protected access to the lifeboats and allows the ship to maneuver to keep a potential fire in the cargo area away from both accommodation and engine room.

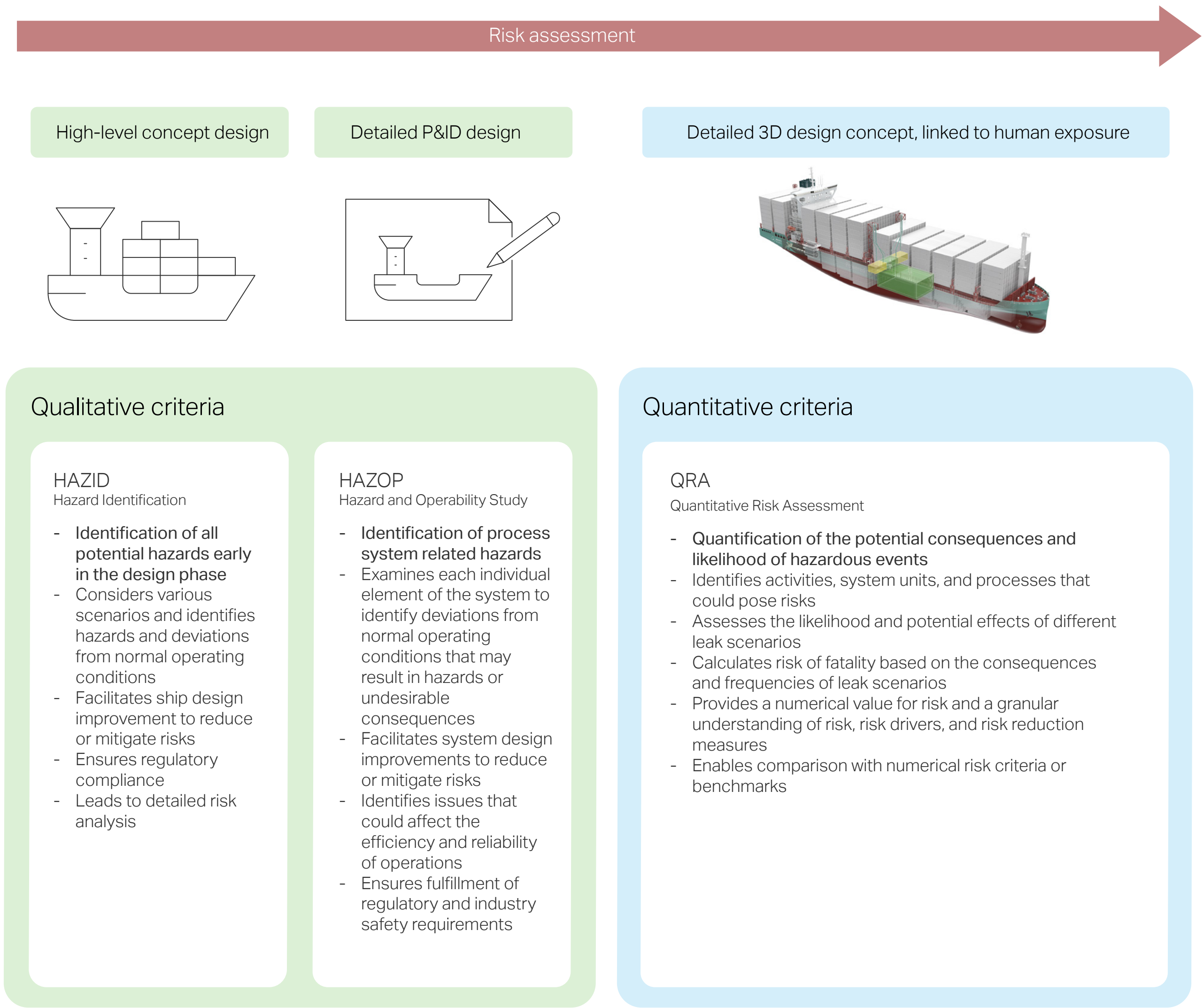
The application of CFD and gas dispersion analysis significantly enhances optimization of ventilation outlet locations to minimize ammonia exposure for critical areas of the ship, such as the bridge and accommodation, and for the crew. The vent mast height is sufficient to prevent harmful ammonia concentrations from reaching the accommodation and container stacks, while also providing a long lead time to manage any potential venting incidents, ensuring safe operational responses.



07 Safety verification

To verify the safety level of the feeder concept design, we have used two qualitative risk assessment methods (HAZID, HAZOP) and one quantitative risk assessment (QRA), which provided feedback about risk reduction measures applicable to the design process. Figure 14 illustrates our risk assessment approach, and the upcoming subsections provide an overview of the results of these assessments.

Figure 14: Overview of our risk assessment approach when developing the concept design.



P&ID = piping and instrumentation diagram

7.1. HAZID

The HAZID study was conducted to identify appropriate safeguards that can prevent or mitigate risks. Early identification and assessment of hazards during the initial stages of design, or procedural development, provides critical input for making informed decisions based on risk assessment. This approach allows implementation of changes with the lowest possible cost implications. The magnitude of the risks was assessed based on the risk classification matrix in Appendix A1.

Hazards identified and mitigation measures

In total, the study identified 142 hazards, including 24 categorized as unmitigated extreme risks, and 77 as unmitigated high risks (Table 2). After we implemented risk mitigation measures, all extreme risks were mitigated, and 42 high risks remained but were deemed controllable. In this section, we highlight some of the mitigation measures implemented to address the highest risks identified in the study. For further details, see Appendix A2. Table 2 illustrates the key hazards identified and how risks were reduced to ALARP.

Ventilation and vent masts

Proper design of vent masts and ventilation outlets, verified by CFD analysis, and safe positioning of ventilation outlets, will reduce the exposure to ammonia to acceptable levels as defined in applicable class rules (e.g., ABS).

Ammonia storage

Risks to crew members, such as explosions or ammonia exposure resulting from leaks into the inter-barrier space, are controlled by inerting the inter-barrier space, eliminating ignition sources, and connecting the inter-barrier space to the vent mast. Insulating the secondary barrier prevents excessive evaporation. The integrity of the tank and secondary barrier system is ensured through an appropriate design that accounts for relevant internal and external pressure loads, as well as through thorough design reviews.

The crew must manage the risk of fire near the tank by strategically planning stowage to avoid placing dangerous cargo next to the tank.

Pressure relief valves and vent lines are appropriately dimensioned to handle fire scenarios.

Positioning the tank according to prescriptive rules in the IGF Code to ensure the required distance to the side and bottom shell will mitigate the risk of tank damage and subsequent releases due to collisions or grounding.

Bunkering

Experienced personnel should supervise vapor handling related to the first-time bunkering process, including controlling the cool-down and ramp-up phases.

FPR and reliquefaction rooms

Risks to the crew from leaks in the FPR or reliquefaction rooms, such as explosions or exposure, are managed by minimizing time spent in these rooms, eliminating ignition sources, ensuring proper ventilation, and positioning the ventilation outlets in safe locations.

Piping

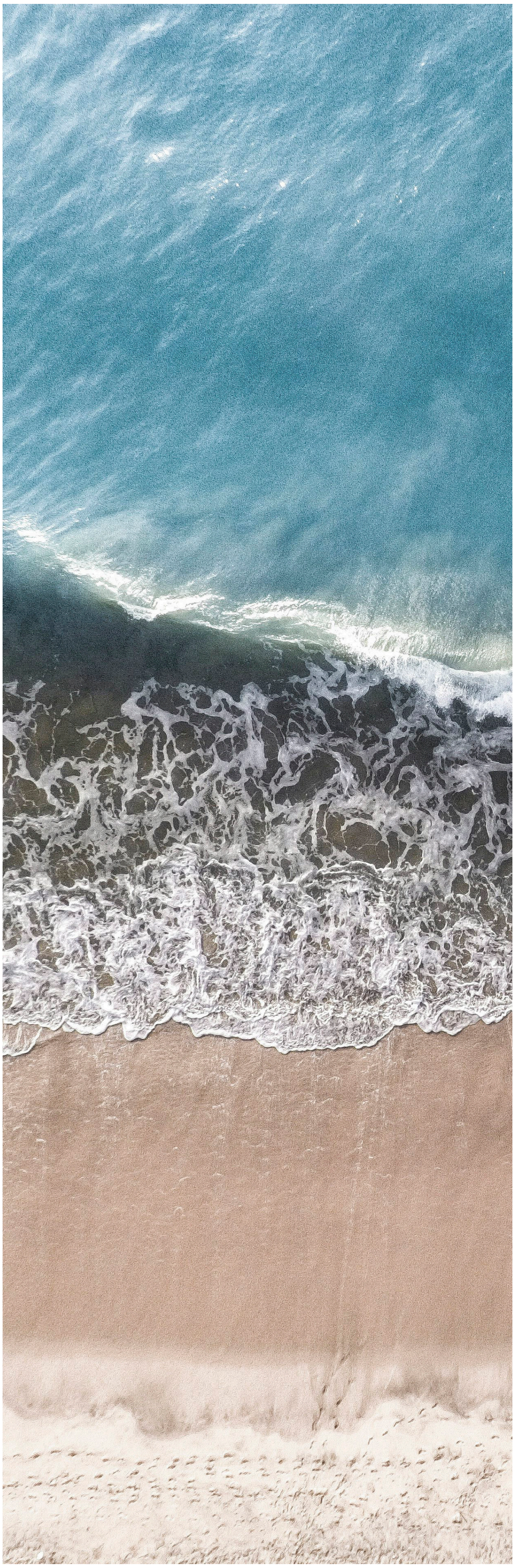
Structural protection and purging of ammonia pipes before heavy items are lifted above them will mitigate the potential for ammonia pipe damage and rupture in the engine room. Detailed instructions must be developed by classification societies for structural pipe protection and pipe purging procedures.

Boiler

Risks associated with the boiler can be addressed once the development of the ammonia boiler design is finalized.

Table 2: Overview of hazards identified in the HAZID study, with risk ratings before and after mitigation.

		Unmitigated risk rankings of hazards identified				Mitigated risk rankings of hazards identified			
Node	Key system level HAZID nodes	Low	Moderate	High	Extreme	Low	Moderate	High	Extreme
1	Generic recommendations	1	3	1	1	1	13	2	-
2	Ammonia fuel storage tank, option no. 1 (Type A)	1	8	20	9	3	18	16	-
3	Ammonia fuel storage tank, option no. 2 (Type C)	-	4	11	9	2	8	14	-
4	Bunkering stations & manifold arrangement	-	2	6	1	2	5	2	-
5	Arrangement of tank connection space (TCS)	-	4	6	-	1	9	-	-
6	Reliquefaction plant and boil-off gas (BOG)	1	4	8	-	3	9	1	-
7	Ammonia fuel supply system	-	1	8	1	-	10	-	-
8	Fuel supply arrangements from fuel supply system to machinery space	-	1	1	-	-	2	-	-
9	Venting arrangement	-	-	1	-	-	-	1	-
10	Ventilation arrangement	-	2	2	1	1	2	2	-
11	Main engine room arrangements	-	6	1	1	3	3	2	-
12	Generator set	-	-	-	-	-	-	-	-
13	Boiler/gas combustion units (GCU)	-	-	-	1	-	-	1	-
14	Safety systems, gas detection, fire fighting	-	2	-	-	-	2	-	-
15	Inerting & purging system	-	-	-	-	-	-	-	-
16	Bilge water and drainage system	-	-	-	-	-	-	-	-
17	Escape routes, muster stations and evacuation	-	1	-	-	-	1	-	-
18	Simultaneous operations (SIMOPS)	-	1	1	-	-	2	-	-
19	Maintenance	-	-	1	-	-	1	-	-
20	Dry docking	-	-	-	-	-	-	-	-
Total		2	39	77	24	16	85	41	0



7.2. HAZOP

Besides the HAZID study, we performed a HAZOP study to investigate operational and process hazards by examining different modes of operation and failure cases. The HAZOP analysis highlighted several high-risk scenarios related to ammonia handling and the bunker system, primarily focused on potential leaks, high pressure, and crew exposure to ammonia during maintenance. Key risks included high flow in the bunker system, ammonia leakage in the reliquefaction system, and leaks from relief valves during maintenance. The severity of these risks is classified as major; however, the likelihood of occurrence is significantly reduced with proper controls, such as system design, procedural measures, gas detection, and maintenance protocols.

As shown in Table 3, a total of 76 hazards were identified in the HAZOP, entailing five unmitigated extremes and 43 unmitigated high risks. After we implemented the risk mitigation measures identified in the HAZOP, these were reduced to zero extreme, eight high, 49 moderate, and 19 low risks. Among the top contributors to hazards were ammonia bunkering, reliquefaction, and fuel supply and drain system.

The main risk mitigation measures were proper pressure monitoring and control of the bunker line, together with further design review and implementation of maintenance procedures for the reliquefaction plant. Risk related to maintenance of the fuel supply systems was reduced by draining the system to the drain tank before maintenance. The risks related to the drain system were mitigated by leading overflow to knockout drum and proper design for maximum pressure.

Overall, the HAZOP analysis concluded that while the severity of potential hazards remains significant, the likelihood is effectively minimized, resulting in a manageable risk profile for the fuel system. For further details, see Appendix A3.

Table 3: Overview of the hazardous areas and the number of hazards identified in the HAZOP study, with risk ratings before and after mitigation.

		Unmitigated risk rankings of hazards identified				Mitigated risk rankings of hazards identified			
#	HAZOP node	Low	Moderate	High	Extreme	Low	Moderate	High	Extreme
1	Bunker system	2	3	9	-	3	10	1	-
2	Fuel tank system	-	-	-	-	-	-	-	-
3	Reliquefaction system	1	4	9	2	4	9	3	-
4	Fuel supply (LP)	1	1	7	-	2	7	-	-
5	Filtration skid	-	4	5	-	-	8	1	-
6	Fuel supply (HP)	-	4	4	1	4	4	1	-
7	Fuel valve train supply & return	-	-	-	-	-	-		-
8	Nitrogen separator	2	1	4	-	2	5	-	-
9	Knockout drum supply	-	-	-	-	-	-	-	-
10	Drain system	-	1	1	2	-	2	2	-
11	Purging system	-	-	-	-	-	-	-	-
12	Cooling circuit	-	2	3	-	2	3	-	-
13	Main engine knockout drum & recovery tank	-	-	-	-	-	-	-	-
14	Catch system	-	-	-	-	-	-	-	-
15	Auxiliary consumer	-	-	-	-	-	-	-	-
16	Auxiliary fuel valve train	-	-	-	-	-	-	-	-
17	Nitrogen purging system	-	-	-	-	-	-	-	-
18	Ammonia drain & bilge system	-	2	1	-	2	1	-	-
19	Ventilation space room	-	-	-	-	-	-	-	-
20	Vent system	-	-	-	-	-	-	-	-
21	Ventilation system – double wall	-	-	-	-	-	-	-	
22	Safety system	-	-	-	-	-	-	-	
Total		6	22	43	5	19	49	8	0

LP = low-pressure, HP = high-pressure

7.3. QRA

QRA is a rigorous assessment tool that can be used to highlight the main risk contributors and test the effectiveness of proposed mitigation measures, or modifications, leading to design improvements. Previous studies[6] have demonstrated the benefits of QRA analysis for ammonia-fueled vessels. We compared the base case of the concept design presented in the previous sections with two additional cases that incorporate different design changes.

We used location-specific individual risk (LSIR) and individual risk per annum (IRPA) as metrics for individual risks. Specifically, LSIR compares the risk level at different locations on the vessel, while IRPA shows the level of risk experienced by a hypothetical person who is a member of the crew. The target risk level from fuel (both ammonia and FO) were defined as 1 in 10,000 risk of fatality per year in the same manner as a past study (see especially Appendix 1).[5]

For our concept design, the highest LSIR levels were observed in the main engine and auxiliary engine FPRs, as might be expected due to the presence of ammonia-containing equipment and the associated connections. In terms of the crew, the engineers with access to these spaces, albeit infrequently, generally experience the highest IRPA risks. We observed that the risks from ammonia were dominated by the toxic effects of leaks, with the effects of fires and explosions making only a small contribution.

Base case

Table 4 shows the LSIR for the base case. The highest LSIR values are in the FPR (main engine), FPR (auxiliary engines and boiler), filter room, and reliquefaction rooms, due to the presence of ammonia-containing equipment. Since the ammonia boiler is placed in auxiliary engine room 3, this room has a higher LSIR than the other auxiliary engine rooms. In the engine room, nearly 70% of the risk is associated with fire due to FO leaks, while the risk from ammonia is low due to the double walls and barriers placed on the ammonia pipes and equipment.

The LSIR at the accommodation in the base case (Table 4) is relatively high due to the location of the FPR and filter room at the base of the accommodation structure with only a single gas-tight bulkhead towards the accommodation, and the risk of potential ammonia leaks penetrating the accommodation. As a result, the IRPA is high for all crew groups, since all groups spend a high proportion of their time in the accommodation. This contributes to the IRPA for some crew groups exceeding the target value (see Figure 15, base case).

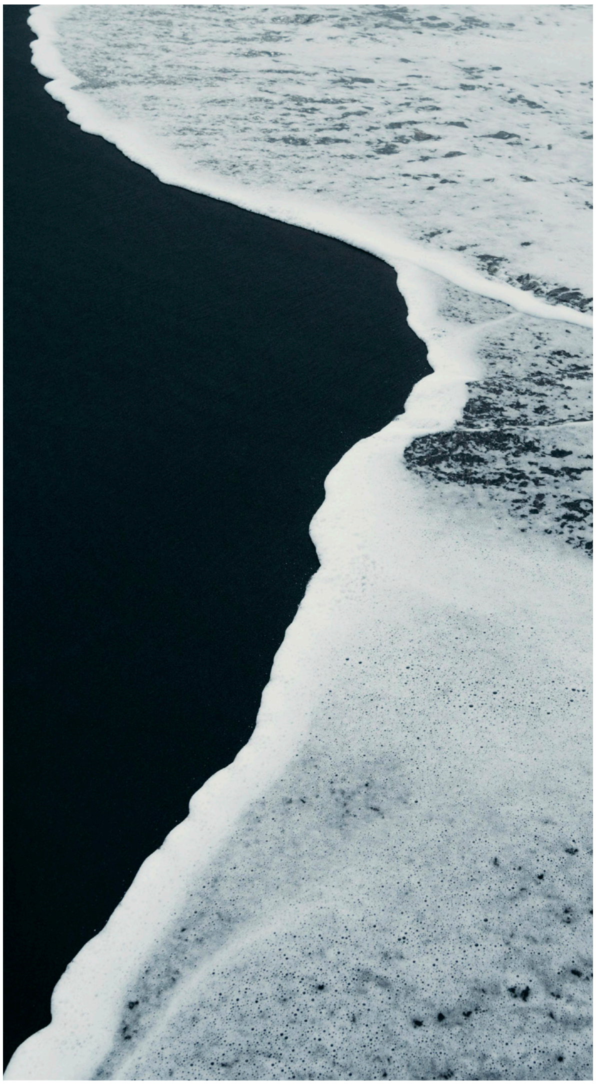
Table 4: Location-specific individual risk (LSIR) heat map (base case). Red indicates high risk, green lower risk

Location	LSIR (1 in N per year)	% LSIR from ammonia
Fuel preparation room (main engine)	(1 in 50)	100%
Filter room	(1 in 130)	100%
Fuel preparation room (auxiliary engine)	(1 in 50)	100%
Accommodation	(1 in 7,200)	100%
Bunker station	(1 in 55,000)	99.60%
Reliquefaction room	(1 in 100)	100%
Tank connection space	(1 in 160)	100%
Cargo hold	(1 in 220,000)	100%
Tunnel	(1 in 50,000)	100%
Deck aft	(1 in 4,370,000)	100%
Passageway main deck	(1 in 17,000)	100%
Lashing bridge 3	(1 in 10,000)	100%
Deck forward	(1 in 2,300,000)	100%
Engine room	(1 in 5,000)	27.63%
Engine control room	(1 in 3,240,000)	100%
Auxiliary engine room 1	(1 in 13,000)	59.08%
Auxiliary engine room 2	(1 in 26,000)	100%
Auxiliary engine (and boiler) room 3	(1 in 1,000)	97.14%
Bridge	(1 in 7,200)	100%

Risk reduction case (RR case)

In view of the risk to some crew groups exceeding the target IRPA value, we recommend separating the accommodation from the adjacent high-risk FPRs with a cofferdam (the risk reduction, or RR, case – see Figure 15). This change led to a significant decrease in LSIR at the accommodation (99%), with decreases in IRPA values to below the target level for all crew members (Figure 15, RR case). This reduction can be attributed to the elimination of boundary failure risk from the accommodation.

In the RR case, the decrease in IRPA for the engineers is less marked than for other groups. Engineers are still exposed to significant risks by spending time in the FPRs or reliquefaction rooms, even though these stays are assumed to be short. In addition, the IRPA for the engineering ratings in the RR case is only just below the target level. Therefore, further risk mitigation may be required before risks for this group can be considered ALARP.



Alternative design case (AD case)

We also assessed an alternative design case (AD case) where only the main engine was ammonia-fueled, batteries replaced auxiliary engines, and the boiler was a traditional FO boiler (Figure 15, AD case).

In the AD case, we observe the greatest reduction in IRPA for the crew groups who previously spent part of their time in the FPR for the auxiliary engines (Chief Engineer, Second Engineer, Third Engineer, and engineering ratings). The IRPA reduction for the other crew groups is primarily due to the removal of the boiler supply piping, which previously passed through the duct keel and cargo hold of the vessel, and thus no longer contributes to the risk in outdoor deck areas.

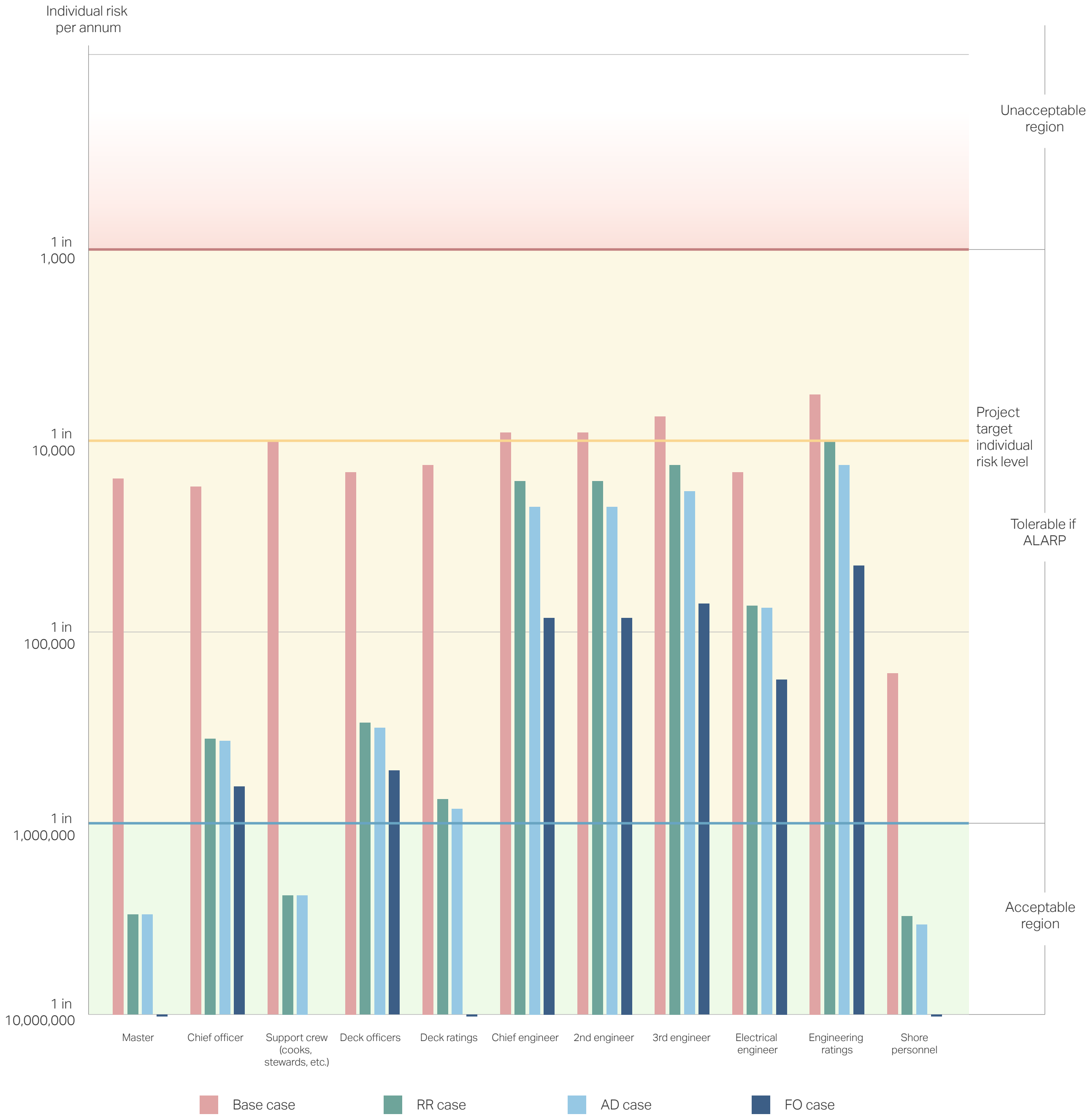
The AD case results indicate that replacing auxiliary engines with batteries and operating the boiler on FO could potentially reduce the IRPA values for the engineering team. However, the uncertainties are large, and we recommend further research on this subject.

FO case

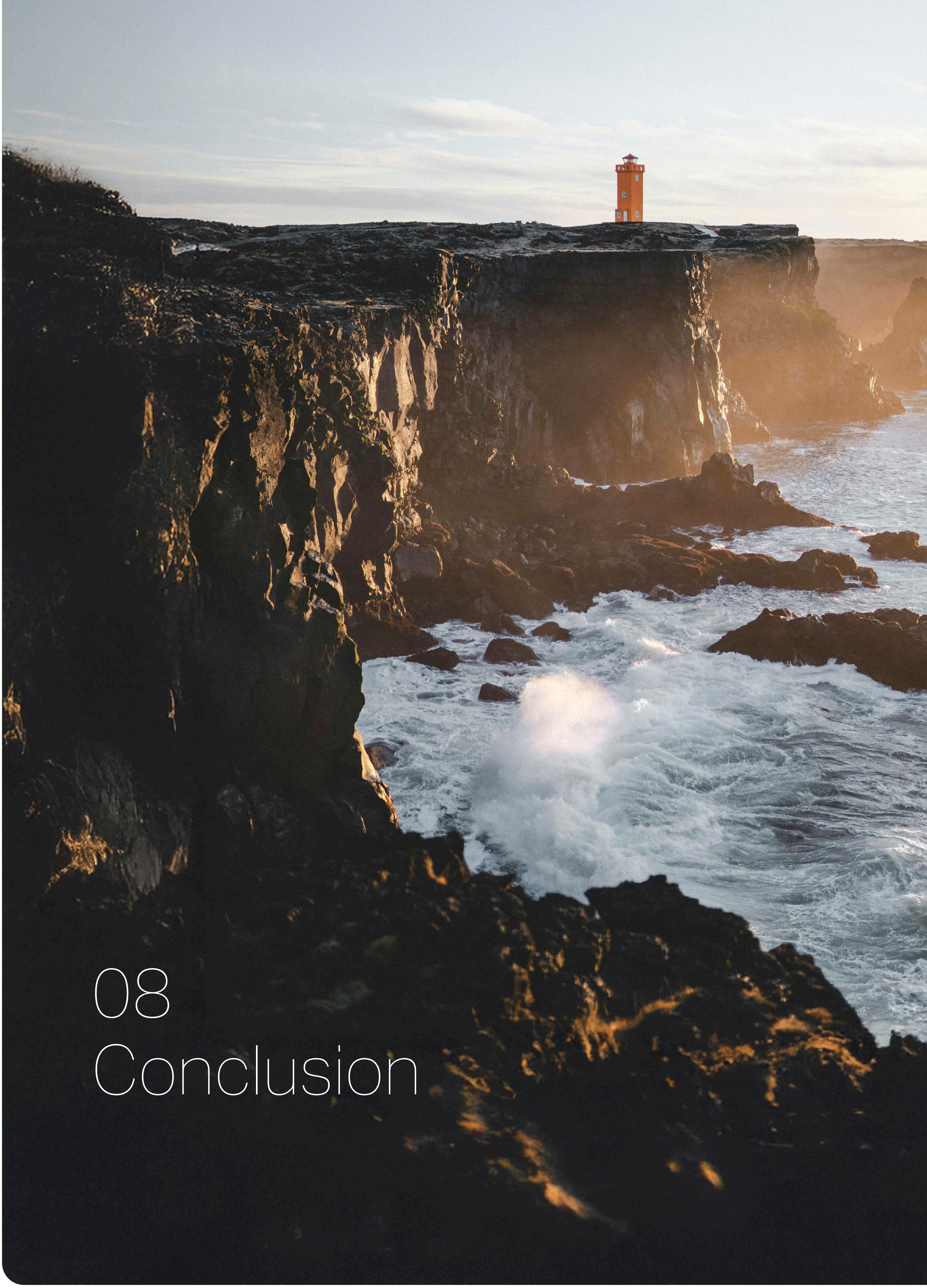
As a point of reference, we also calculated risks for the vessel assuming it was fueled only by FO, i.e., a conventionally powered vessel. The IRPA is lower for all crew groups in the FO case than in any of the ammonia cases (Figure 15). For example, the IRPA values for the Master, support crew, deck ratings, and shore personnel in the RR case are 2-5 times lower when operating solely on FO.

In summary, our risk assessments showed that risks identified in the HAZID and HAZOP were deemed manageable and the calculated IRPA values were below the project target. However, further risk reduction measures should be identified to further reduce the individual risk level for the engineering ratings.

Figure 15: Summary of IRPA results for the base case in light red, RR case in green (cofferdam between accommodation and high-risk spaces), AD case in light blue (auxiliary engines replaced by batteries, conventional boiler), and FO case in dark blue (conventional vessel fueled by FO, no ammonia). Please refer to Appendix 1 in our previous publication for explanations of our QRA methodology and definitions of the risk regions and project target risk level.[5]



RR = risk reduction, AD = alternative design, FO = fuel oil, IRPA = individual risk per annum, ALARP = as low as reasonably practicable, QRA = quantitative risk assessment



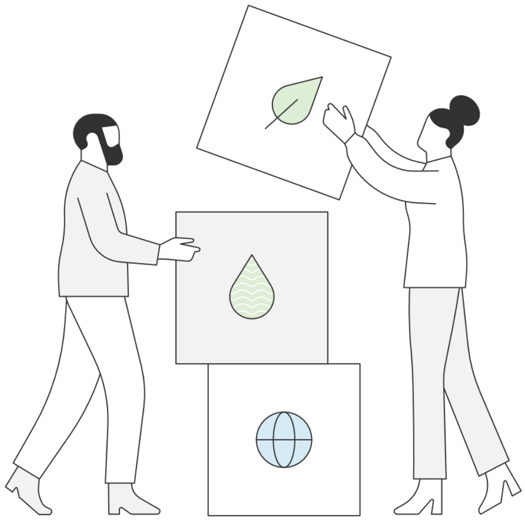
08 Conclusion

Amid the maritime industry's drive to reduce GHG emissions, ammonia is emerging as a promising alternative to conventional fuel. When produced from renewable sources, ammonia fuel could offer shipping with significant emissions reductions. However, ammonia poses challenges due to its toxicity, corrosiveness, flammability, and increased storage space requirements.

Building on extensive studies by the MMMCZCS, including design assessments and quantitative risk analyses, we have devised a technically viable and safely designed 3,500 TEU ammonia-fueled feeder vessel. This report outlines the design process and provides a comprehensive guide for stakeholders on the ammonia fuel pathway, covering key technical considerations, design principles, and safety barriers. It aims to inform and assist in the development and operational planning of ammonia-fueled vessels.

Our goal was to develop a 3,500 TEU container feeder design integrating cutting-edge ammonia fuel technology. As ammonia is an emerging fuel, the concept design had to address the limited bunkering options. Furthermore, the concept design focused on early deployment using available 60-bore two-stroke engines.

Given the lack of prescriptive regulations for ammonia-fueled ships available at the time of project work, the design process relied on alternative design processes and risk assessments to ensure an equivalent level of safety to conventional fuels. We employed a systematic risk management approach incorporating HAZID, HAZOP, and QRA analyses to identify and mitigate risks. Key risks, such as ammonia exposure, fire, and structural integrity, were addressed, ensuring that the vessel's design adheres to industry best practices and safety requirements. As part of the extensive safety considerations, the feeder design incorporates critical safety measures. The bunker station, storage tank, and ventilation outlets were strategically placed to minimize exposure risks to the accommodation area and enhance safety by ensuring proper dispersion of vented gases.



Here we summarize some benefits of our key design decisions:

- The choice of a Type A tank for ammonia storage balances safety and space efficiency, and allows future scalability. The inclusion of reliquefaction plants and a boiler for BOG management ensures robust control of tank pressure and prevents unintended venting.
- The midship bunker station offers flexibility for mooring and safe ammonia transfer, supported by a leak detection system.
- The FPR placement close to the engine room, with gas-tight separation from the accommodation, reduces risks and allows for safe handling of ammonia fuel, with remote monitoring systems ensuring continuous oversight.
- The aft placement of the accommodation and bridge above the engine room ensures optimal cargo space utilization and enhances safety during emergencies. The design of the bridge as a gas-tight safe refuge with independent ventilation systems provides a critical safety measure against ammonia exposure.
- The ventilation system design, including the forward-located vent mast, ensures that ammonia gases are safely dispersed away from crew areas.
- The ammonia drain system effectively manages leaked ammonia, with provisions for storage, evaporation, and potential system enhancements to mitigate risks further.

The final feeder design complies with the IGF Code, SOLAS, and class requirements from ABS and LR. The application of HAZID, HAZOP, and QRA analyses confirmed that the design meets high safety standards. However, we recommend considering further risk reduction measures to ensure that the goal of ALARP is met. The concept design has received Approvals in Principle from ABS and LR, demonstrating its readiness for practical application. Our next step is to further our efforts to technically qualify ammonia as a maritime fuel with a focus on integrating human factors in ship design.

09 The project team

This report was prepared by MMMCZCS with assistance from our partners. Team members marked with an asterisk (*) were seconded to the MMMCZCS from their home organizations.

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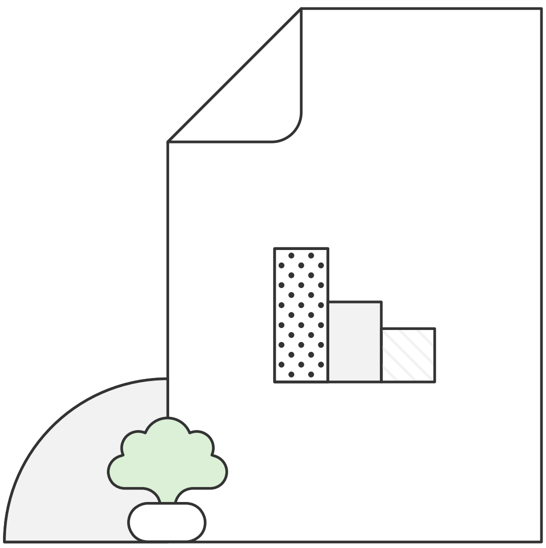

Abbreviations

ALARP	As low as reasonably practicable
ARMS	Ammonia release management system
BOG	Boil-off gas
CFD	Computational fluid dynamics
Decarb Hub	Lloyd's Register Maritime Decarbonisation Hub
FO	Fuel oil
FPR	Fuel preparation room
GCU	Gas combustion unit
GHG	Greenhouse gas
HAZID	Hazard identification
HAZOP	Hazard and operability
IGF Code	International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels
IRPA	Individual risk per annum
LR	Lloyd's Register
LSIR	Location-specific individual risk
MAN ES	MAN Energy Solutions
MMMCZCS	Mærsk Mc Kinney Møller Center for Zero Carbon Shipping
PRV	Pressure relief valve
QRA	Quantitative risk assessment
SOLAS	International Convention for the Safety of Life at Sea
TCS	Tank connection space

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Appendices

A1. Risk matrix

Figure 16: Risk matrix with definitions of likelihood and severity used in HAZID and HAZOP assessments (source: ABS, 2024).

Category		Consequence severity				
Asset		No shutdown, costs less than $10,000 to repair	No shutdown, costs less than $100,000 to repair	Operations shutdown, loss of day rate for 1-7 days and/or repair costs of up to $1,000,000	Operations shutdown, loss of day rate for 7-28 days and/or repair costs of up to $10,000,000	Operations shutdown, loss of day rate for more than 28 days and/or repair more than $10,000,000
Environmental Effects		No lasting effect. Low level impacts on biological or physical environment. Limited damage to minimal area of low significance.	Minor effects on the biological or physical environment. Minor short-term damage to small area of limited significance.	Moderate effects on biological or physical environment but not affecting ecosystem function. Moderate short-medium term widespread impacts e.g. oil spills causing impacts on shoreline.	Serious environmental effects with some impairment of ecosystem function e.g. displacement of species. Relatively widespread impacts.	Very serious effects with impairment of ecosystem function. Long term widespread effects on significant environment e.g. unique habitat, national park.
Community/ Government/ Media/ Reputation		Public concern restricted to local complaints. Ongoing scrutiny/ attention from regulator.	Minor, adverse local public or media attention and complaints. Significant hardship from regulator. Reputation is adversely affected with a small number of site focused people.	Attention from media and/ or heightened concern by local community. Criticism by NGO's. Significant difficulties in gaining approvals. Environmental credentials are moderately affected.	Significant adverse national media/public/ NGO attention. May lose license to operate or not gain approval. Environment/ management credentials are significantly tarnished.	Serious public or media outcry (international coverage). Damaging NGO campaign. License to operate threatened. Reputation severely tarnished. Share price may be affected.
Injury and Disease		Low level short-term subjective inconvenience or symptoms. No measurable physical effects. No medical treatment required.	Objective but reversible disability/impairment and/or medical treatment, injuries requiring hospitalization.	Moderate irreversible disability or impairment (<30%) to one or more persons.	Single fatality and/or severe irreversible disability or impairment (>30%) to one or more persons.	Short- or long-term health effects leading to multiple fatalities, or significant irreversible health effects to >50 persons.
		Low (1)	Minor (2)	Moderate (3)	Major (4)	Critical (5)
Likelihood	Almost Certain (E) Occurs 1 or more times a year	High	High	Extreme	Extreme	Extreme
	Likely (D) Occurs once every 1-10 years	Moderate	High	High	Extreme	Extreme
	Possible (C) Occurs once every 10-100 years	Low	Moderate	High	Extreme	Extreme
	Unlikely (B) Occurs once every 100-1000 years	Low	Low	Moderate	High	Extreme
	Rare (A) Occurs once every 1000-10000 years	Low	Low	Moderate	High	High

Action Key		
	Low	No action is required, unless change in circumstances
	Moderate	No additional controls are required, monitoring is required to ensure no changes in circumstances
	High	Risk is high and additional control is required to manage risk
	Extreme	Intolerable risk, mitigation is required

A2. HAZID, risk control, and conclusion

Table 6: Summary of high-risk hazardous events identified in the HAZID study.

High-risk hazardous events	Consequence	Controls	Conclusion Reference: Figure 6
Ventilation or venting of ammonia	Contamination of cargo (smell).	- Final design ventilation masts to be based on CFD dispersion study. - Review reefer storage plan based on CFD results.	Final design based on CFD expected to reduce severity to minor, reducing the risk to moderate. - Severity: Moderate - Likelihood: Possible
	Fire and explosion.	Develop storage plans to avoid reefers and ignition sources in hazardous zones.	Removal of ignition sources from a hazardous zone combined with CFD studies, and the fact that ammonia requires higher-energy ignition sources than other gaseous fuels (e.g., LNG), should reduce the risk to a lower or similar level than that accepted by existing LNG-fueled designs. - Severity: Major - Likelihood: Rare
Primary barrier ammonia leak from fuel tank into tank hold space (inter-barrier space)	Fire and explosion.	- Inerting inter-barrier space with nitrogen. - Elimination of ignition sources. - Gas detection system.	Inerting and gas detection systems are deemed sufficient. Likelihood will be extremely rare. For comparison, it is not required to inert inter-barrier spaces on ammonia gas carriers. - Severity: Major - Likelihood: Rare
	Crew exposure to ammonia.	- The inter-barrier space is insulated and connected to the vent mast. - The vent mast is designed for safe release of ammonia.	The insulated inter-barrier space will prevent violent evaporation of ammonia and ensure a controlled release to vent. - Severity: Major - Likelihood: Unlikely.
Damage to tank in case of external pressure from hold space	Damage to fuel tank.	The tank will be designed for max. pressure in the inter-barrier space that will be limited by the pressure relief valve connected to the inter-barrier space.	Proper design of the tank will eliminate this risk. - Severity: Major - Likelihood: Unlikely

High-risk hazardous events	Consequence	Controls	Conclusion Reference: Figure 6
Breakdown of secondary barrier insulation	Cold spots on the ship structure.	Design and approval of secondary barrier and insulation system. Inspection and approval of installation work. The insulation is protected by the secondary barrier. To get -30°C on the ship inner hull will require: 1) leak from primary barrier, 2) collapse of secondary barrier, or total collapse of the PU insulation panel protection. Periodical test scheme of barrier integrity will be developed.	Multiple failures are required, and it is deemed possible to eliminate the risk with proper quality control of the installation process and review of type approval and tests. Periodical test scheme of barrier integrity will ensure continuous condition control. - Severity: Moderate - Likelihood: Possible. Until further studies have been made.
Fire in cargo hold	High thermal load on structure around tank.	Dangerous cargo plan to be developed to avoid the risk of fire in containers close to the tank area. Fire load analysis and consequence analysis to be conducted. PRV valves are designed for fire cases.	The risk should be limited to mis-declared containers catching fire. Risk level is comparable with risk level on similar LNG-fueled vessels. - Severity: Major - Likelihood: Unlikely
Fire in containers above tank	Collapse of structure around the tank and tank failure.	Dangerous cargo plan to be developed to avoid the risk of fire in containers above the tank area. Fire load analysis and consequence analysis are to be conducted. PRV valves are designed for fire cases.	The risk should be limited to mis-declared containers catching fire. Risk level is comparable with risk level on similar LNG-fueled vessels. - Severity: Major - Likelihood: Unlikely
Grounding	Tank damage and leakage.	The tank is located according to prescriptive rules in the IGF Code. (B/5 from the side and 2 m, or B/15, above the bottom).	It is unlikely that grounding impact at midship will penetrate 2 m into the hull. However, deformation of the hull structure could impact the tank structure. A finite element (FEM) analysis to be made on the specific design. Hull damage - Severity: Moderate - Likelihood: Possible. Tank failure - Severity: Major - Likelihood: Rare

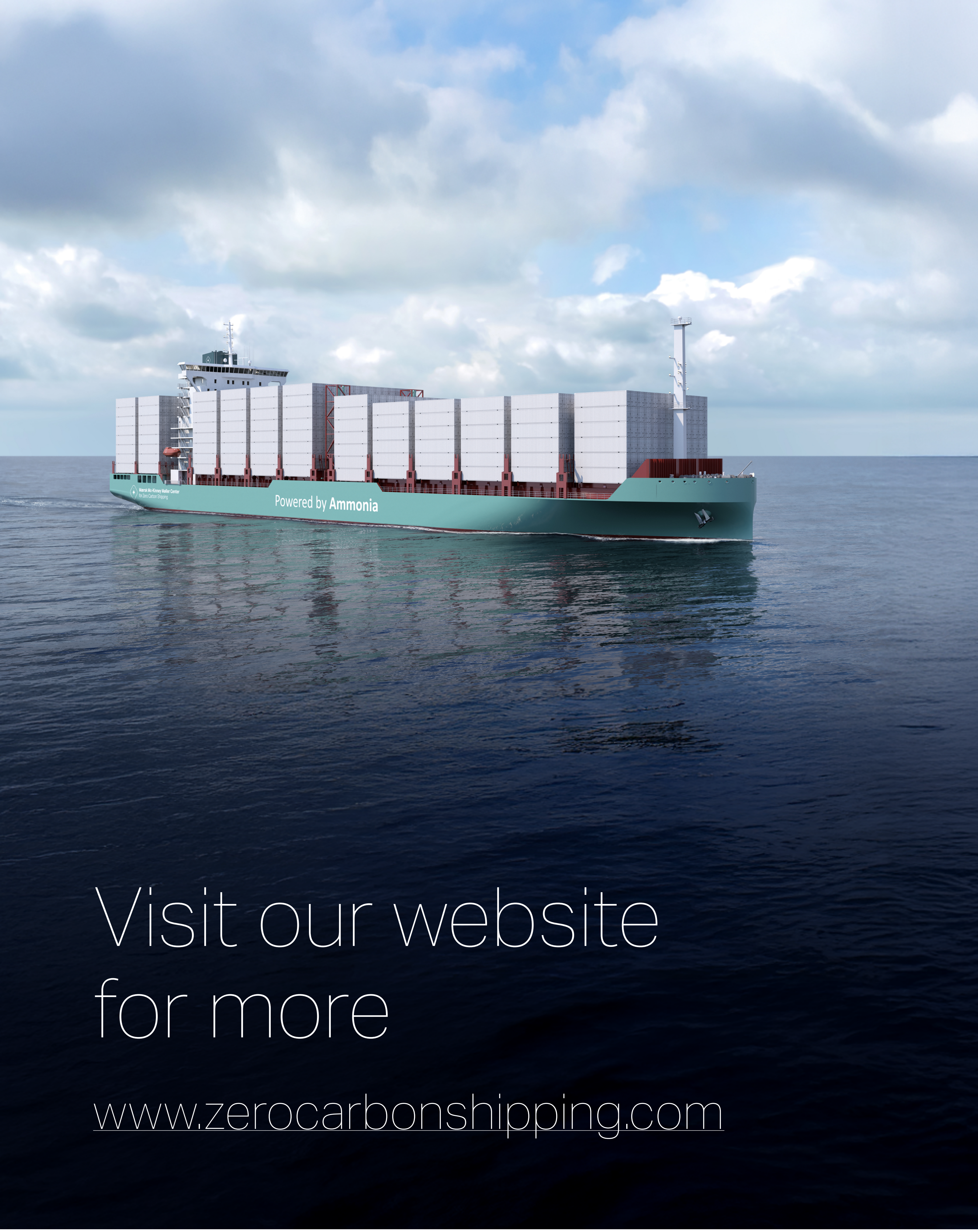
High-risk hazardous events	Consequence	Controls	Conclusion Reference: Figure 6
Allision and collision	Damage to hull and tank. Ammonia leakage.	The tank is located according to prescriptive rules in the IGF Code. (B/5 from the side and 2 m, or B/15, above the bottom).	With tank location B/5 from the side and given that allisions and collisions very rarely penetrate both outer and inner hull, the design is considered sufficiently safe according to IGF rules. Hull damage: - Severity: Moderate - Likelihood: Possible Tank failure: - Severity: Major - Likelihood: Rare
First-time bunkering	Venting and related risks. Exposure from vent mast and fire and explosion risk.	Trained and experienced gas engineer/ superintendent should attend and supervise first-time bunkering. Pressure management devices are in place protecting the tank from overpressure by venting, and from vacuum by the vacuum relief valve.	First-time bunkering is considered manageable with experienced personnel in place, combined with pressure relief systems on the tank and safe location of vent mast. Surrounding area exposed to ammonia: - Severity: Moderate - Likelihood: Possible Fire and explosion: - Severity: Major - Likelihood: Rare
Reliquefaction plant	Fire and explosion due to leaks.	Ex-proof equipment is installed in the reliquefaction room.	By avoiding ignition sources, and having forced ventilation, the risk is deemed manageable. - Severity: Major - Likelihood: Rare
Tank relief system	Overpressure in tank.	A redundant relief valve is installed on the tank and two redundant vent lines running on each side of the ship.	The installed redundancy in both valves and vent line is deemed sufficient to control the risk. - Severity: Major - Likelihood: Rare
Ammonia release in FPR	Ammonia in ventilation outlet. Exposure to lashing crew.	The location of the ventilation outlet from the FPR is a safe distance from areas with crew presence.	Any leak in the FPR will be released to a safe location. - Severity: Moderate - Likelihood: Possible
Ammonia absorption in cylinder oil /drain	Exposure to crew when in contact with oil.	Engine test center to determine if an actual risk/ issue is present.	Not expected to be a problem from engine manufacturer. - Likelihood: Possible

High-risk hazardous events	Consequence	Controls	Conclusion Reference: Figure 6
Piston crack, ammonia in lubricating oil	Exposure to crew when in contact with oil.	Further studies needed. Ammonia will be combusted. If misfiring happens, one injection volume will expose the crack to ammonia.	Potential amount of ammonia accumulation in the system oil is deemed small. - Severity: Moderate - Likelihood: Possible
Dropped object on pipe in engine room	Ammonia leak in engine room.	Pipe routing to be arranged outside crane reach and mechanically protected from dropped objects. Operational procedure to be developed. If heavy items are to be lifted above fuel pipes, the pipes are to be purged before lifting.	Proper structural protection of piping combined with procedures/instructions/training. The risk should be manageable. - Severity: Major - Likelihood: Unlikely
Cylinder cover lift	Exposure to ammonia.	Only one misfire will happen before shutting down. Ammonia will be combusted during a cylinder cover lift.	Potential amount of ammonia exposure by cylinder cover lift is deemed small. - Severity: Moderate - Likelihood: Possible
Boiler malfunction – blow-by	Blow-by.	Depending on boiler design. To be further studied. Type approval of boiler will ensure correct design.	Approved design will ensure an acceptable risk level. - Severity: Major - Likelihood: Unlikely

A3. HAZOP, risk control, and conclusion

Table 7: Summary of high-risk hazardous events identified in the HAZOP study.

High-risk hazardous events	Consequence	Controls	Conclusion
High flow in bunker system	Damage to in-line components.	Pressure measurements and procedural communication with bunker barges. Further design of control logic.	The risk can be controlled in the same way as bunker flow of other fuel types. - Severity: Major - Likelihood: Rare
Reliquefaction system – high pressure	Ammonia leakage in reliquefaction room.	The system is designed for the pressure in the system.	The risk is controlled by design for maximum pressure. - Severity: Major - Likelihood: Rare
Reliquefaction system – leak from relief valve arrangement in economizer during maintenance	Exposure of crew from 3-way valve and back-flow from header.	3-way valve design to be reviewed and further risk assessment with supplier. Maintenance procedure to be developed.	The design is well proven, and risk will be managed by further design review with designer and establishment of maintenance procedures to reduce the risk of leaks. - Severity: Major - Likelihood: Unlikely
Filtration skid – leakage from filter seals, etc.	Ammonia leakage in filter room.	Gas detection in filter room will inform crew if ammonia is present in the room before entering. The room is ventilated, and crew are to wear PPE during maintenance of the system. The filter is isolated with double block-and-bleed valves.	With proper design, gas detection systems, and maintenance procedures, the risk is manageable. - Severity: Major - Likelihood: Rare
Fuel supply system – leak during maintenance	Exposure of crew working on the system.	Proper draining of the system to the drain tank before working on it.	By draining the system before maintenance, the risk is manageable. - Severity: Major - Likelihood: Unlikely
Drain system – high-level overflow	Overflow of ammonia.	All overflow is led to the knockout drum and the tank is designed for max. pressure. Drain tank is equipped with level sensors.	Overflow of the drain tank will not lead to direct leaks – it will be contained in the system. - Severity: Major - Likelihood: Rare
Drain system – high pressure	Damage to equipment and piping.	The system is designed for maximum pressure in the system.	Damage to equipment due to high pressure should be eliminated by proper safety margin in design. - Severity: Major - Likelihood: Rare



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