European Maritime Safety Agency


# POTENTIAL OF AMMONIA AS FUEL IN SHIPPING

## BY ABS, CE DELFT & ARCSILEA

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# Executive Summary

The maritime industry faces a number of substantive challenges, mostly driven by increasingly stricter air emissions and climate legislation. Among the broad spectrum of technologies and fuel solutions ship designers, builders, owners and operators, anhydrous ammonia ($NH_3$) has been identified as a potential long-term fuel that could enter the market relatively quickly and offer a zero, or a near-zero, carbon solution (on a tank-to-wake basis and in some cases on a well-to-wake basis) irrespective of the origin of the fuel.

While there is little recent marine experience with using ammonia as a fuel – and some of the key machinery technologies (such as engines) are under development – extensive land-based experience with the production and use of ammonia for the petrochemical and fertiliser industries forms a sound basis for increasing its use as a marine fuel. Experience with the carriage of ammonia in liquefied-gas carriers – and the specific requirements for storage, distribution, personal protective equipment (PPE), etc. in the International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code) – provide some of the statutory requirements to guide its application on ammonia-fuelled ships.

However, the toxicity challenges and related risks are significant and, while manageable, they will add complexity to ship designs (compared to those for conventional and other low-flashpoint fuels and gases) and will potentially limit the ships for which it is a suitable fuel. Ammonia ultimately may prove to be a more appropriate solution for deep-sea cargo ships rather than short-sea, passenger, or inland waterway craft.

By examining the current production capacity for ammonia, the existing regulatory landscape, fuel storage options, supply and power generation technologies – along with techno-economic analyses and risk-based case studies – this study has identified the key challenges for adopting ammonia as fuel.

It has also identified a number of advantages that ammonia would have over other low-flashpoint fuels or gases, technology and regulatory gaps that would prevent its immediate application, and some incentives that would encourage its adoption.

**Availability**

Ammonia is currently produced in large quantities as an input for products in the fertiliser and chemical industries. To realise the large-scale production of 'green ammonia' (see 2.1.2 for its definition) for maritime shipping, its production capacity, along with that of renewable electricity and green hydrogen, will need to grow tremendously; the current global installed capacity of wind and solar farms, and especially the electrolysers needed to produce the necessary green hydrogen for ammonia production, are dwarfed by the capacity required.

Renewable electricity for the electrolysers will need to be produced at locations around the globe that have favourable conditions for wind and solar irradiation (or other low carbon power generation). It should be noted that it is generally cheaper and more efficient to use the electricity directly, in electrolysers, and to synthesise ammonia (i.e., co-location of hydrogen and ammonia production) for use and further distribution, than it would be to transport hydrogen itself.

Current projections for the growth in global production would appear to indicate there will be enough renewable electricity to produce the volumes of green ammonia needed for the maritime fleet alone by 2040. However, by that time shipping will also be competing with many other industries for renewable electricity and green hydrogen necessary to produce ammonia, as well as with other sectors that also depend currently on the consumption of ammonia such as agriculture.

In addition, there are constraints as to the speed at which solar and wind farms, ammonia plants and transport and distribution infrastructure can be deployed, which may potentially limit the availability of green ammonia, especially in the short and medium term.

**Suitability**

Although ammonia is not currently used as a fuel by oceangoing ships, recent analysis of the required land storage and distribution, onboard storage, and conversion to energy – in either an internal combustion engine or in a fuel cell – have revealed no insurmountable barriers to the use of ammonia as a marine fuel. While it is toxic and harmful to the environment, the related health, safety, and environmental challenges can be managed. So, it is reasonable to conclude that ammonia can be a suitable marine fuel.

Several research-and-development projects are ongoing, developing standards for the use of ammonia as a fuel. When those standards have been fully developed, the conditions under which ammonia can be used as a fuel will become clearer.

**Sustainability**

Ammonia can be produced with renewable electricity, a process that is capable of generating almost no greenhouse gas (GHG) emissions on a well-to-wake basis. Most of the ammonia produced to date is ‘grey ammonia’, which has higher GHG emissions than conventional marine fuels on a well-to-wake basis.

When using ammonia as a fuel in a marine internal combustion engine, the emissions of sulphur dioxide, carbon monoxide, heavy metals, hydrocarbons, and polycyclic aromatic hydrocarbons (PAH) drop to zero; harmful particulate matter (PM) emissions would also be substantially lower than for conventional fossil fuels, this is because ammonia has no carbon, sulphur and other contaminants typically seen in conventional residual or distillate fuels. Particulate matter emissions will mainly come from the combustion of pilot fuel and cylinder lubrication oil.

Engine developments related to the use of ammonia are ongoing. Issues related to concerns on nitrogen oxide (NOx) and nitrous oxide ($N_2O$) emissions, as well as the detrimental effects of ammonia slip from engines would need to be addressed.

Using ammonia in an onboard fuel-cell system would reduce emissions even more than when using 2 or 4-stroke engines as no combustion products are formed during the process. Yet, this technology is still not mature.

**Techno-Economic Aspects**

With many challenges related to producing and using green ammonia, it is important to analyse the case for the expected total cost of ownership (TCO) for a blue and green ammonia-fuelled ship. For the analysis, different ship types have been evaluated. In 2030, blue or green ammonia-fuelled vessels (see 2.1.2 for definition) are expected to still have relatively high TCO (considering carbon pricing, for green ammonia 2.5 to 3 times higher and for blue ammonia 1.5 times higher than for conventional fuelled ships). The cost gap between ammonia powered vessels and conventional fossil fuelled vessels may, however, be closed by 2050, due to expected reduced ammonia production costs, a lower CAPEX for ammonia installations and higher carbon prices for fossil fuels. This, however, will also depend on the development of global fuel oil prices.

**Regulations**

There exist regulations applying to some parts of the ammonia supply chain, including inland production, distribution, storage, and usage; the IGC Code also covers its transportation by ships. This framework would however require adaptations to extend the use of ammonia as a marine fuel; in the meantime, in absence of harmonised international rules, class societies have at their hand the use of well-established, risk-based ‘alternative design’ approval methodologies which have been used for alternative fuels to support shipowners.

There are ongoing regional initiatives being developed, such as the EU’s ‘Fit-for-55’ package of measures, which are expected to provide incentives and impetus for shipping to adopt alternative low- and zero-carbon fuels such as (green) ammonia with the aim of reducing GHG emissions from shipping.

International and regional GHG reduction regulations coupled with market-based measures have the potential to encourage the uptake of ammonia as a fuel as demonstrated by the techno-economic analyses presented in this study. In particular, work at the IMO is currently ongoing to develop fuel lifecycle analysis guidelines for calculating fuel well-to-wake emissions and considering other technical and market-based measures under which ammonia and its renewable production pathways would be considered.

Strengthening the existing regulatory framework possibly including amendments to the NOx Technical Code, developing ISO standards for bunkering and couplings, together with further work on unified requirements by IACS where needed, would also contribute to the adoption of ammonia as a marine fuel.

### Risk and Safety

This study assesses several designs for ammonia-fuelled ships from the risk and safety perspectives. In particular, two cargo ships (an oil tanker and a bulk carrier) and a Ro-Pax ship have been analysed. The analysis conducted has demonstrated that the main safety concern in relation to ammonia is associated with its toxicity and gas-dispersion properties. While solutions are available, additional research and studies are needed to further reduce or fully mitigate the associated risks.

Safeguards and recommendations for the above ship types have been identified to reduce the risks and the consequences of potential hazards. While some safeguards stem from the IGF Code and for methane as a marine fuel, many more have been added due to the inherent and specific risks associated to using ammonia onboard ships.

Ammonia is not new to shipping; it is currently transported as a cargo in gas carriers. There is considerable industry experience and so some safety procedures for handling ammonia are already in place. However, the prospect of using ammonia as a fuel would mean an increase in the operations and human interaction with it, which would require careful implementation of dedicated and unified training regimes.

Additional regulations would need to be developed to reduce the risk and safety concerns. These should include rules for the detection of ammonia leakages, definition of ammonia concentration thresholds, requirements for protective equipment, toxicity zones, the handling of ammonia, bunkering procedures, safe discharge of ammonia or water contaminated with ammonia, fire protection, firefighting, ventilation, procedures for emergencies, alarms, etc.

As ship designs and associated technologies (engines, fuel gas supply systems, etc.) are further developed, more knowledge will be acquired on the use of ammonia as a marine fuel. This study identifies a number of additional studies, analyses and developments that should be considered, such as dedicated dispersion analysis, ventilation studies, review and development of dedicated firefighting procedures, new training requirements need to be put in place both for onboard and onshore operations, etc.

### Concluding Remarks

Ammonia presents a series of advantages which make it a promising fuel to support the decarbonisation of shipping. Naturally carbon-free, it can drastically reduce the GHG emissions on a well-to-wake basis, provided it is produced using sustainable energy sources. Ammonia is produced and has been used in large quantities in other industries for decades, where there is available knowledge on its handling, storage and operation. The production of ammonia based on the Haber-Bosch process and electrolysis is well-known and established. As a cargo, ammonia is well known product to the shipping industry where is has been transported in LPG carriers subject to already existing regulations such as the IGC code. Based on the growing interest for ammonia fuelled vessels and on announced projects to produce green ammonia, it is fair to conclude that the uptake of ammonia as a marine fuel will likely take place.

However, there are still barriers which the industry, engine manufacturers, producers, and other industry segments, as well as policy makers and regulators, need to address in a collaborative manner. Despite the extensive experience in its handling, there is little knowledge on using ammonia as a fuel. Given that it is toxic and corrosive, there are some concerns related to the safety of using ammonia as fuel onboard ships and their engines. Therefore, further work on understanding these risks and their possible mitigation is needed. Additional guidelines and regulations are needed, bearing in mind the increased number of operations (such as bunkering) and human interaction, when the uptake of ammonia takes place.

The development of relevant effective and clear decarbonisation policies to promote the uptake of green fuels in general needs to be fostered, in the absence of which green ammonia may not be commercially competitive. Indeed, without further market demand for green transportation or implementation of market-based measures, the use of green ammonia as a fuel may remain very onerous. At the same time, as green ammonia production will highly depend on green electricity, which will also be in very high demand by all other industrial sectors, there will be a need to ensure that sufficient certified green electricity is available for and used by all industrial sectors.

Ammonia shows a good and promising potential, but to become the alternative fuel to support the decarbonisation of shipping, early action is needed to unblock all the barriers opposing its uptake.

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# 1. Introduction

## 1.1 Background

The marine industry faces a number of substantive challenges, mostly driven by increasingly strict legislation with regard to gaseous air emissions and global warming. Uncertainties related to globalisation, geopolitical influences, digitalisation and cyber risks are complicating an already increasingly complex operating landscape as shipping searches for the most effective propulsion and fuel strategies for the global fleet.

However, the most serious threat to the planet may be the rising global temperatures caused by anthropogenic emissions; as shipping is estimated to be the source of 3% of the world's carbon-dioxide ($CO_2$) emissions, the industry needs to shoulder its share of the responsibility for delivering a more sustainable future.

In April 2018, the industry took the first big step towards the levels of commitment and ambition that will be required when the IMO Marine Environment Protection Committee (MEPC) agreed to align with the goals of the UN's Paris Agreement and reduce the GHG emissions from shipping.

The IMO Initial GHG-reduction strategy (Resolution MEPC.304(72)(1)) included an ambition to reduce annual emissions by at least 50% by 2050 (compared to 2008), signalling an international shift for maritime industry towards the use of zero-carbon and low-carbon fuels.

As the typical marine asset has a lifetime of more than 20 years, it is clear this transition needs to begin sooner rather than later, particularly as decisions for new ships are pending.

Recent regulatory developments in the European Union clearly indicate that the IMO's timetables for regulatory development -- and the 'business-as--usual' approach taken by large sectors of the marine industry are being challenged, nor will they meet societal expectations.

Among the broad spectrum of technology and fuel-solution pathways currently in front of ship designers, builders, owners and operators, anhydrous ammonia ($NH_3$) is seen as a potential marine fuel that could enter the market relatively quickly and offer a zero-carbon solution (on a tank-to-wake basis) regardless of the origin of the fuel, although further consideration will be needed when considering a well-to-wake basis.

To provide regulators and stakeholders with the information required to make informed regulatory and investment decisions, this study provides information on the properties, production, suitability and sustainability of using ammonia as a marine fuel. Furthermore, an examination of the current regulatory instruments is presented, as are a techno-economic assessment and a series of detailed risk-based case studies that examine the commercial and safety implications of using ammonia as a marine fuel.

## 1.2 Scope and Objectives

The scope and objectives of this report are to consider the technical issues, regulatory framework and state of play for application of ammonia as a fuel. It addresses the 'Potential of Ammonia as fuel in shipping', which was part of EMSA tender EMSA/OP/43/2020 for 'Studies on Alternative Fuels/Power for shipping', and detailed in the ABS, CE Delft and Arcsilea proposal of 27 January 2021.

The scope specifically addresses the tasks of the EMSA tender by:

- **Task 1:** Providing a state of play on the use of alternative fuel/power in the shipping sector. See Section 2 of this report for the findings under this task.
- **Task 2:** Providing a detailed description of the existing safety and environmental standards/regulations/guidelines on the production, transport and distribution, bunkering and onboard storage, handling and use of alternative fuels/power for shipping, as well as those currently under development. See Section 3 of this report for the findings under this task.
- **Task 3:** Providing a safety assessment of the fueled/powered cargo and passenger ships, engaged in the short-sea (coastal) or deep-sea trades. In total, four safety assessments are offered. If a ship can accommodate cargo and passengers (for example, a Ro-Pax ship), only one safety assessment is needed (for short-sea), without prejudice of conducting two remaining assessments for a cargo ship. Consideration should be given whenever simultaneous transport and usage of the fuel (or energy carrier)

is possible, e.g., for future hydrogen or ammonia ships/carriers. See Section 4 of this report for the findings under this task.

## 1.3 Symbols, Abbreviations and Acronym List

See Appendix I – Symbols, Abbreviations and Acronyms of this report.

# 2. State of play on the use of Ammonia in the shipping sector

This section provides an overview of the state of play for using ammonia as a fuel in the shipping sector. This is divided into the following sections:

- Overview of ammonia properties alongside a description of production pathways, level of maturity and further developments
- Sustainability aspects including an overview of GHG performance, air pollution and other effects
- Availability aspects including an overview of availability in Europe and worldwide and the link with other sectors of the industry
- Suitability aspects, including storage and production, onboard fuel supply, internal combustion engines, machinery spaces, fuel cells and related emissions and air pollution.

## 2.1 Ammonia Properties and the Ammonia Production

Anhydrous ammonia is a compound of nitrogen and hydrogen and is a widely used, commercially available chemical. It is a building block for many chemical and pharmaceutical products, notably as fertiliser for food production. Although common in nature, ammonia is corrosive and toxic in concentrated form. It is typically traded as aqueous ammonia (usually 28% ammonia in water), or as anhydrous ammonia.

Current global production is approximately 235 million tonnes (Mt) and for comparison, the annual consumption of conventional residual and distillate fuels by international shipping is currently estimated at 285 Mt per year (equivalent to about 650 Mt of ammonia on an energy basis).

This section of the report examines ammonia's properties, pathways to sustainable production, the level of maturity of production technologies and current pilot projects.

### 2.1.1 Ammonia Properties and the Ammonia Production

At atmospheric temperature and pressure, ammonia is a colourless gas with a characteristically pungent smell. At higher pressures, ammonia becomes a liquid, making it easier to transport and store.

Ammonia has a relatively narrow range of flammability compared with some other fuels being considered for the shipping industry; however, it is toxic and very reactive.

In addition, in low concentrations ammonia can be irritating to the eyes, lungs and skin; at high concentrations, or in the case of direct contact, it is immediately life threatening. Symptoms include: difficulty breathing, chest pain, bronchospasms and, at its worst, pulmonary oedemas, where fluids fill the lungs and result in respiratory failure.

If ammonia contacts the skin in high concentrations, it can cause severe chemical burns. Exposure to the eyes can cause pain, excessive tearing, redness, swelling of the conjunctiva, injury to the iris and corneas, glaucoma and cataracts. Acute exposure to ammonia in liquid form can cause redness, swelling, ulcers on the skin and frostbite.

Due to these toxicity issues, ammonia is classified as a hazardous substance, with exposure levels and time of exposure controlled by several national standards, typically setting Permissible Exposure Limits (PEL) at approximately 50 ppm (parts per million), Recommended Exposure Limits (REL) at 25 ppm and identifying the Immediate Danger to Life or Health (IDLH) limit at 300 ppm. See Appendix II– Acute Ammonia Exposure Limits for a tabulation of ammonia's acute exposure limits and Appendix III – Ammonia Safety Data Sheet (SDS) for a typical Material Safety Data Sheet (MSDS).

For use as a marine fuel, the toxicity represents the most significant safety hazard to mitigate, as further discussed in section 4.2.6.

The risk of fire and explosion is reduced when compared with other hydrocarbon fuels and gases, particularly in open air, ammonia has a flammability range in dry air from 15.2% to 27.4%. However, under certain conditions, there can be a risk of fire and explosion, so safety concepts must consider both toxicity and fire/explosion risks (see section 4.2.6 for firefighting aspects in relation to ammonia).

When attempting combustion in an engine, ammonia is hard to ignite. It requires a high-ignition energy in the form of either a pilot fuel or another 'hot' source to ignite the ammonia. It also has a high auto-ignition temperature and low cetane number, so it will be challenging to develop for marine combustion without a pilot fuel. However, many different fuels can be used as pilot fuels. The best igniters are fuels such as marine gas oil (MGO), marine diesel oil (MDO) and dimethyl ether (DME); different types of biofuels and very low sulphur oils (VLSFO) also can be used.

In addition, ammonia is incompatible with various industrial materials; in the presence of moisture, it reacts with and corrodes copper, brass, zinc and other alloys, forming a greenish/blue colour. Ammonia is an alkaline-reducing agent and reacts with acids, halogens and oxidising agents. These properties add challenges related to the selection of materials for onboard equipment and tanks.

The key properties of ammonia are shown below in Table 1.

Table 1. Key properties of ammonia in comparison to MGO

| Item | Ammonia | MGO |
|---|---|---|
| Energy density (MJ/L) | 12.9 | 35.95 |
| Latent heat of vapourisation (LHV) (MJ/kg) | 18.8 | 42.8 |
| Heat of vapourisation (kJ/kg) | 1371 | 250-450 |
| Autoignition temperature (ºC) | 651 | 250 |
| Liquid density (kg/m3) | 696 (at -33 ºC) | 840 (at 15 ºC) |
| Adiabatic flame temperature at 1 bar (ºC) | 1800 | 2000 |
| Molecular weight (g/mol) | 17.031 | 54 |
| Melting point (ºC) | -77.7 | -26 |
| Boiling point (ºC) | -33 | 154 |
| Flash point (ºC) | 132 | 60 |
| Critical temperature (ºC) | 132.25 | 654.85 |
| Critical pressure (bar) | 113 | 30 |
| Flammable range in dry air (%) | 15.15 to 27.35 | 0.7 - 5 |
| Minimum ignition energy (mJ) | 8 | 0.23 |
| Cetane number | 0 | 40 |
| Octane number | ~130 | 15-25 |

As described in more detail later in this report, because ammonia is produced from the same process as hydrogen it is reasonable to question whether hydrogen could be used directly as a marine fuel instead of ammonia. However, to use hydrogen as a fuel it would have to be stored in a highly compressed form (from 250-700 bar) or as a liquid in order to minimise the storage space it would require onboard a ship: even in the liquid form at -253 $^{o}$C, it would still take up about four times more volume than fuel oil.

In addition, liquid hydrogen needs to be stored in insulated spherical tanks to minimise the heat ingress. This takes even more volume. When it is transported in a liquid form on ships, or when it is stored at terminals, a substantial amount of energy is therefore required to keep the hydrogen in cryogenic conditions. Consequently, hydrogen boil off can be expected when in transit, management of which may result in further energy losses. These losses reduce the overall cost-efficiency of using hydrogen as a marine fuel for shipping.

As a result, there is near consensus that ammonia is a preferred energy carrier compared to hydrogen. It provides a higher energy density by volume than hydrogen and has a much higher boiling temperature. Marine engines are being developed to burn ammonia with a similar efficiency as hydrogen engines.

These facts, combined with the challenges associated with the storage of liquid hydrogen, give ammonia a better chance for widespread adoption as a marine fuel. Also, turning hydrogen into ammonia using the well-established and efficient Haber-Bosch process results in a relatively low energy loss, another feature that favours ammonia as a marine fuel.

### 2.1.2 Technical options

Currently, hydrogen for ammonia production is typically produced by means of steam methane reforming (SMR) or autothermal reforming (ATR) of natural gas (grey ammonia) (Yusef Bicer, 2017). If the $CO_2$ emissions from the process of converting natural gas are captured and stored, the ammonia is typically referred to as 'blue'. However, methane (which is a much more potent greenhouse gas than $CO_2$ – 82.5 times that of $CO_2$ on a 20-year basis and 29.8 times on a 100-year basis, as per the IPCC AR6 report) may leak at the production plant or at any point along the distribution chain. Also, the $CO_2$ capture rate of SMR and ATR are lower than 95%.

Moreover, the production of blue ammonia retains a dependency on fossil fuels. Therefore, 'green ammonia', which is produced from hydrogen made from renewable energy sources (green hydrogen), is generally considered to be the end-solution for the decarbonisation of ammonia production and use; blue ammonia is seen to have an intermediate role. Consequently, green ammonia is the focus of this report.

### 2.1.3 Production pathways

Five production pathways for green ammonia production have been identified (see Figure 1) and described separately below. Most pathways start with the production of renewable hydrogen. The first three pathways (1 to 3) combine renewable hydrogen-production technologies with the Haber-Bosch synthesis process. Pathway 4 combines a renewable hydrogen technology with an innovative synthesis process (non-thermal plasma synthesis), while Pathway 5 (electrochemical ammonia synthesis) does not require a separate hydrogen production step.

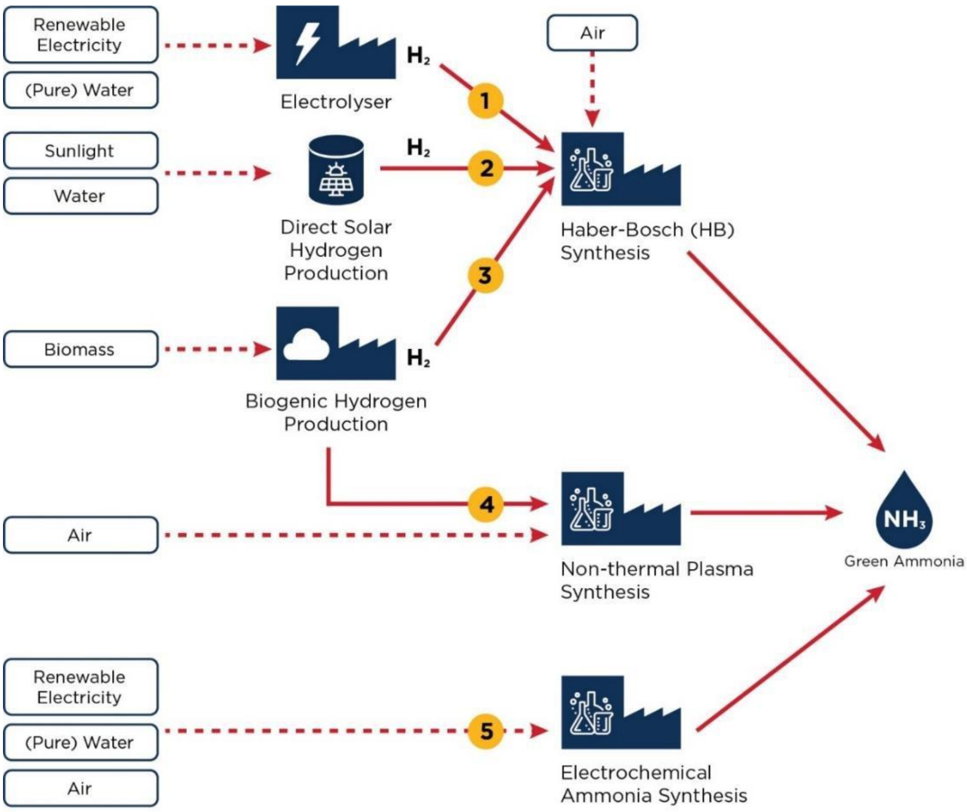


Figure 1. Production pathways for producing green ammonia
(Note: Air is used to produce nitrogen for the ammonia synthesis process)

**<u>Electrolysis and Haber-Bosch synthesis (pathway 1)</u>**

The main process that for decades has been used to produce fertiliser from (grey) ammonia involves converting fossil fuels into hydrogen and extracting nitrogen from atmospheric air using cryogenic air separation, pressure swing absorption or membrane permeation (Rouwenhorst, et al., 2019).

The hydrogen and nitrogen are then converted to (grey) ammonia using the Haber-Bosch ammonia synthesis process.

The main pathway for 'green' ammonia is to produce green hydrogen through water electrolysis using renewable electricity, and then use the green hydrogen (e-hydrogen) in the Haber-Bosch synthesis process (see Figure 2).

Currently, a few production plants make use of partially green hydrogen (see section 2.1.6). The use of e-hydrogen for ammonia production is not new. Until the 1960s, most fertilisers sold in Europe were produced using hydropower-based electrolysis and ammonia production in Norway.

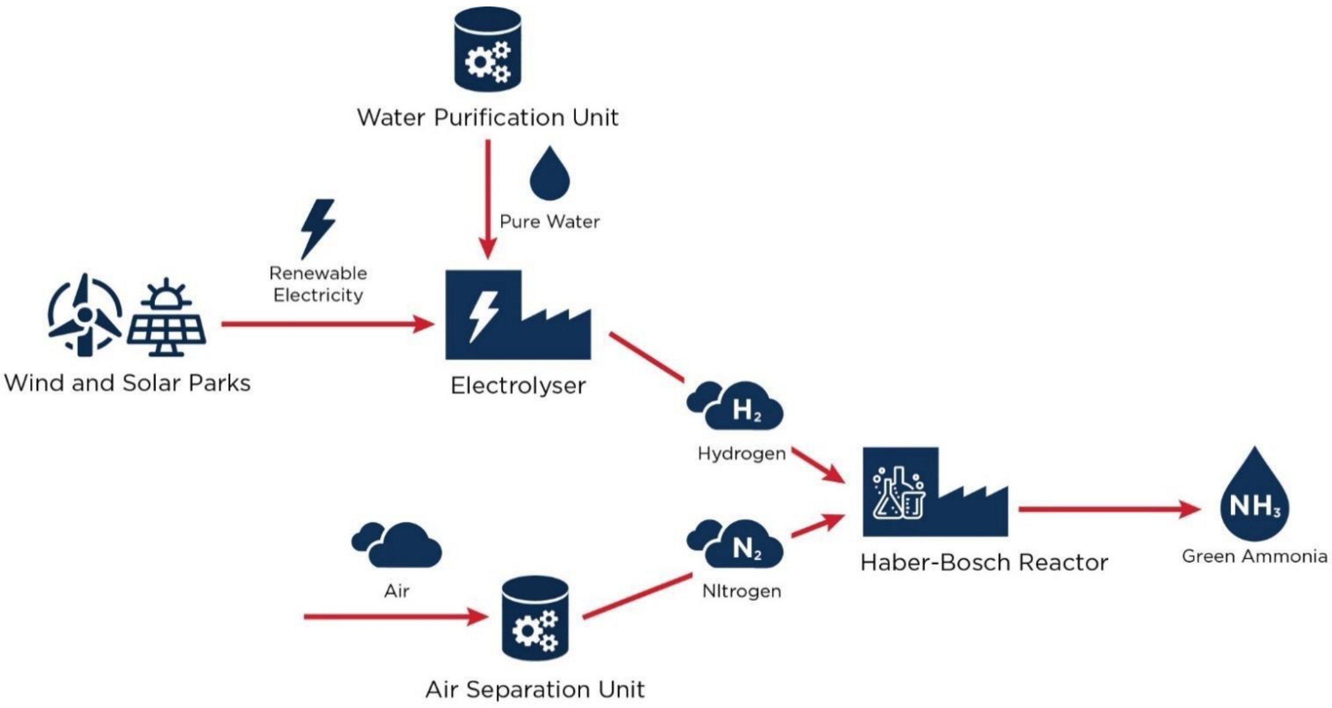


Figure 2. Production process of green ammonia using electrolysis and Haber-Bosch synthesis

Haber-Bosch synthesis is an exothermic process which uses high operating temperatures (400-500 °C) and pressures (150-300 bar). In the process, nitrogen and hydrogen are directly combined. This process is accelerated by the presence of a metal catalyst.

Two main types of synthesis reactors that can be used are the fixed-bed reactor and the fluidised-bed reactor, both of which are mature technologies. Even though the Haber-Bosch process is an established technology, it can be improved; for example, improving the catalysts can increase the production yield.

There are a couple of electrolyser technologies to consider. The alkaline technology is currently the most advanced and cheapest option. The Polymer Electrolyte Membrane (PEM) electrolyser is less developed and more expensive, but it is expected to be more operationally flexible than the alkaline version.

The solid oxide electrolyser cell (SOEC) technology is not yet commercially available and therefore further from implementation on a larger scale. It works at a high temperature and has the potential to offer the highest energy efficiency, especially when integrated with ammonia-synthesis or concentrated-solar plants, enabling heat utilisation. (IEA, 2017). These different electrolyser technologies are detailed in Figure 3.

Further, PEM electrolysers use a proton exchange membrane which uses a solid polymer electrolyte. (Hence, they are also referred to as polymer electrolyte membrane electrolysers.) When current is applied, the water splits into hydrogen and oxygen, and the hydrogen protons pass through the membrane to form $H_2$ gas on the cathode side.

The increased current density enables a more rapid system response to fluctuations in energy input, which can be a great benefit when working with intermittent renewable energy sources. They operate at temperatures between 50°C and 80°C, but at higher pressures than alkaline electrolysers.

Typical PEM electrolysers are constructed using more rare earth metals than alkaline electrolysers and require more precise construction techniques for their catalysts, which makes them more expensive to produce and maintain.

Alkaline electrolysers use a liquid-electrolyte solution, such as potassium hydroxide (KOH) or sodium hydroxide (NAOH), and water. When current is applied, the hydroxide ions (OH-) move through the electrolyte from the cathode to the anode of each cell, with hydrogen gas bubbles generated on the cathode side of the electrolyser and oxygen gas at the anode, as represented in Figure 3.

These can be either unipolar or bipolar in design. Unipolar designs, also known as monopolar or tank designs, have their electrodes suspended, in parallel, in alternating tanks separated by thin membranes that allow for the transfer of ions, but restrict the movement of the gases that are produced. Bipolar designs position the electrodes very close to each other, separated by a thin non-conductive membrane.

Unipolar designs have the advantage of being cheaper and easier to build and maintain, but they are typically less efficient than bipolar designs. Alkaline electrolysers operate best near their design loads, and they experience a drop in efficiency when operating under lower loads. Both designs for alkaline electrolysers are more durable and contain fewer expensive rare earth metals than PEM and solid oxide electrolysers.

Solid oxide electrolysers use solid ceramic material as the electrolyte. Electrons from the external circuit combine with water at the cathode to form hydrogen gas and negatively charge ions. Oxygen then passes through the solid ceramic membrane and reacts at the anode to form oxygen gas and generate electrons for the external circuit. Solid oxide electrolysers are less likely to see use, as they typically require 700+°C temps to operate.

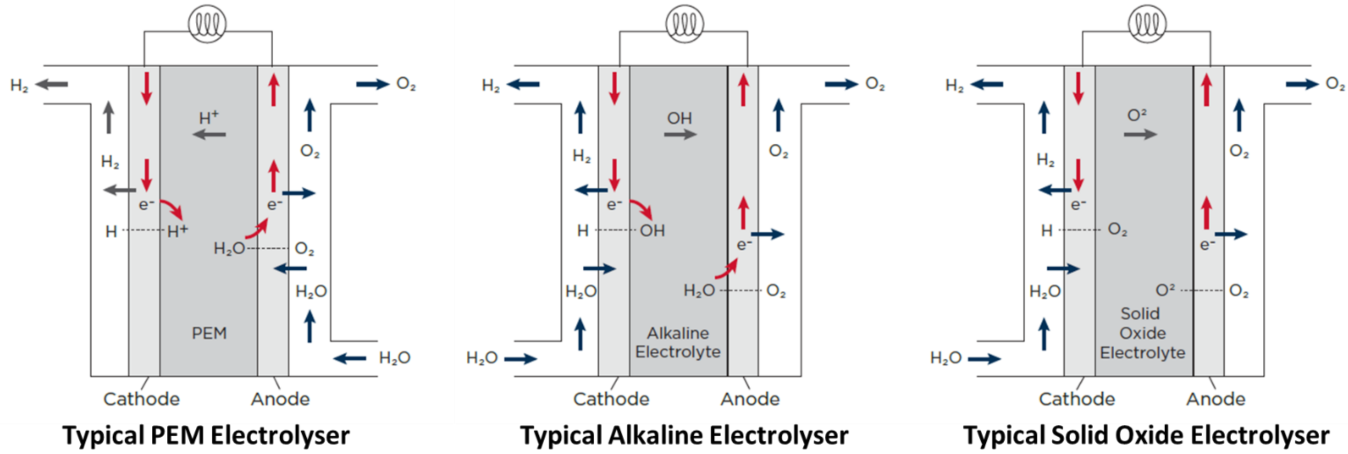


Figure 3. Electrolyser technologies currently available or under development

The electrolyser requires pure, deionised water to split into hydrogen and oxygen. To produce this, freshwater could be purified, using filtration, deionisation and/or reverse osmosis processes. If access to freshwater is a challenge, seawater could be desalinated and purified. As a summary, **Table 2** provides a summary comparing the different electrolysers.

Table 2. Summary comparing different types of electrolysers

| Name | PEM Electrolyser | Alkaline Electrolyser | Solid Oxide Electrolyser |
|---|---|---|---|
| Electrolyte | Solid Polymer | Aqueous Alkaline Solution (KOH or NaOH) | Solid Oxide, Yttria-stabilized Zirconium Oxide |
| Current Density [A/m$^2$] | 10,000-20,000 | 2,000-4,000 | 3,500-5,500 |
| Operating Temperature [°C] | 50-80 | 60-90 | 500-850 |
| Input Component(s) | Deionized Water | Deionized Water and Alkali Material | Deionized Water (Steam) |

To turn a grey ammonia plant into an e-ammonia plant, the SMR unit can be replaced by an electrolyser, decreasing the $CO_2$ emissions from ammonia production by 78% (noting that this is dependent on the grid's $CO_2$ intensity). Furthermore, using today's electrolysis technology would result in higher energy losses from the hydrogen-production process, but lower losses from the ammonia-synthesis process[1].

The net result is it takes more energy to produce green ammonia compared with producing grey ammonia using steam-methane to reform natural gas, but the former source of energy is renewable. SOEC technology has the potential to reduce the total energy used to produce green ammonia compared with the amount used to produce grey ammonia. (Smith, et al., 2020)

Ammonia made from e-hydrogen is only considered 'green' if the electricity used in the electrolysis process is renewable. This would require the direct use of electricity produced from, for examples, wind turbines or solar panels, or electricity from the grid that is considered 'green' after purchasing renewable electricity certificates.

A reliable certificate market would need to be in place. This would allow the electrolyser to be located elsewhere, potentially providing cost benefits at the energy-system level[2], but removing the opportunity to use the residual heat from it in the synthesis process.

The renewable electricity input of this pathway is about 1.85 times the lower calorific value of the fuel, or, in other words, this pathway has an efficiency of about 54% (Ghavam, et al., 2021). However, according to a comparative analysis of green ammonia production methods by Rouwenhorst et al. (Rouwenhorst, et al., 2020), an energy efficiency of 72% (LHV) could potentially be reached after the technology has developed further.

**Direct solar hydrogen production (pathway 2)**

An alternative way to produce renewable hydrogen is through 'direct solar hydrogen' (also called photoelectrochemical hydrogen), a process where hydrogen is directly produced from water without using an electrolysis unit. This technology make use of a photoelectrochemical cell, which drives water-splitting redox (reduction-oxidation) reactions. The electrical energy for this process could be generated using concentrated solar power (which bundles sunlight using mirrors or lenses) (IEA, 2017), photovoltaic (PV) cells (Bellini, 2021), or photoactive material (Radowitz, 2021). This technology is in the research and development phase and will have the highest hydrogen yield in areas with high solar-irradiation factors and clear skies.

This process is still in an early stage of development which makes it hard to present reliable figures on its energy efficiency. In the analysis of Rouwenhorst et al. (Rouwenhorst, et al., 2020), a potential energy requirement of 200 MJ per kg of produced ammonia is given, which translates to an energy efficiency of 9% (LHV). This low figure may be explained by the low conversion efficiency of solar irradiation to energy, which makes it hard to compare this production pathway to the other ones. However, considering the "in-development" nature of this technology, it is important to continuously assess its efficiency and readiness as it may evolve to reach an efficiency up to 70% (Rouwenhorst, 2022).

**Biogenic hydrogen production (pathway 3)**

Another way to produce renewable hydrogen is to decompose hydrocarbon molecules from biomass. There are different technological processes to do this. Dark fermentation is an anaerobic process (in the absence of oxygen) in which biomass is decomposed into hydrogen, $CO_2$ and other intermediate products, using bacteria.

A wide range of bacteria types, which may be active at different temperature ranges, could be used. Anaerobic bacteria that are active between 25 and 70 °C can be used to convert biomass compounds such as sucrose, cellulose, glucose and starches. The technology of dark fermentation is still in an early stage of development and the main challenge is the low hydrogen concentration (40-60%) of the product gas.

[1] The lower energy losses in the ammonia-synthesis process are caused by the electrolyser producing pressurised hydrogen (which reduces the energy use from compression), high purity of the hydrogen and nitrogen (avoiding the need to purge gas containing inerts), and the use of efficient electric motors instead of steam turbines to drive compressors. (Smith, et al., 2020)

[2] Locating the electrolysers close to renewable electricity-production facilities, such as wind and solar parks, can be beneficial because this allows for the direct use of surplus electricity (reducing electricity-balancing tasks), transportation of energy in the form of hydrogen (which is cheaper than electricity transport) and large-scale underground hydrogen storage (which is cheaper than local hydrogen storage).

One area of research looks at improving the hydrogen yield by coupling the dark-fermentation process with other processes and technologies, such as photo-fermentation, methanogenesis, microbial electrolysis cells and microbial fuel cells (Ghavam, et al., 2021).

With thermal biomass gasification technology, woody biomass can be decomposed into hydrogen, carbon monoxide and $CO_2$, after which the hydrogen can be separated from the gas mixture using a method such as membrane separation.

With supercritical water gasification technology, wet biomass feedstocks such as organic waste and sewage sludge can be 'gasified' to form hydrogen and methane. The methane produced can be converted into hydrogen in an additional reforming step.

Thermal gasification has been demonstrated commercially, but not on a large scale. Supercritical water gasification has not yet been demonstrated in the market.

This process is still in an early stage of development which makes it hard to present reliable figures on its energy efficiency. In the analysis of Rouwenhorst et al. (Rouwenhorst, et al., 2020), a potential energy requirement of 33 MJ per kg of produced ammonia is given of biomass-based ammonia production including CCS, which translates to an energy efficiency of 57% (LHV).

**Non-thermal plasma synthesis (pathway 4)**

A second alternative to the Haber-Bosch process is non-thermal plasma synthesis. This synthesis process, which is also in the research-and-development stage, operates at low temperature (around 50°C) and pressure (around 1 bar), does not operate on fossil fuels, has a low capital cost and is suitable for small-scale ammonia production.

However, the three challenges to developing this technology are nitrogen-gas fixation, back reactions and improving conversion and energy efficiencies. A related plasma technology developed by the Virginia University Research Corporation can convert renewable electricity, water and air into ammonia by means of plasma excitation. This makes use of a microwave plasma process that activates nitrogen and hydrogen to produce ions and free radicals that react over a catalyst, forming ammonia. This process also can take place at low temperatures and pressures and is flexible in operation (Ghavam, et al., 2021).

This process is still in an early stage of development which makes it hard to present reliable figures on its energy efficiency. In the analysis of Rouwenhorst et al. (Rouwenhorst, et al., 2020), an energy requirement of 150 MJ (reported value) to 50 MJ per kg of produced ammonia (potential value) is given, which translates to an energy efficiency of 12% to 37% (LHV). There is a potential to increase this efficiency as the technology develops and 40-45% efficiency may be reachable (Rouwenhorst, 2022).

**Electrochemical ammonia synthesis (pathway 5)**

A pathway for producing green ammonia that does not require a separate process is electrochemical ammonia synthesis. This technology, which is still in the research-and-development phase, makes use of an electrochemical cell to produce ammonia from nitrogen, water and electricity.

Voltage is applied to the electrodes of the cell, releasing ions that pass through a separation membrane and an electrolyte to the electrode of opposite charge. This induces a chemical reaction in which either the water is broken into oxygen and hydrogen, after which the hydrogen reacts with nitrogen to form ammonia, or in which hydrogen ions ($H+$) are transferred to nitrogen and form ammonia without having to first form hydrogen molecules ($H_2$).

Four main types of electrolytes that can be used for electrochemical ammonia synthesis are: 1) liquid (operating near room temperature); 2) molten salt (operating at 180-500 °C); 3) composite membrane (300-700 °C) and; 4) solid-state (10-800 °C, depending on the type of membrane). The composite membrane electrolyte consists of a solid electrolyte mixed with a low melting salt.

Compared with the Haber-Bosch process, electrochemical ammonia synthesis is thought to have these advantages: higher energy efficiency; higher selectivity (reducing the need for purification); lower temperatures and pressure; and modularity. On the other hand, electrochemical synthesis suffers from low rates of ammonia production and membrane instability. (Ghavam, et al., 2021)

Solid state ammonia synthesis (SSAS) – i.e., electrochemical synthesis using a solid-state electrolyte – promises lower energy use compared to the electrolyser and Haber-Bosch synthesis combination (pathway 1): 7,000-8,000 kWh per tonne of ammonia instead of 12,000 kWh per tonne, or 33-42% less (Bartels & Pate, 2008).

The molten-salt electrolyte has the potential to reduce electricity consumption by up to 30% but avoiding the formation of hydrogen is a technical challenge that must be overcome (IEA, 2017). A general challenge for electrochemical synthesis is developing catalysts that improve the performance (i.e., ammonia production rate) of the process.

This process is still in an early stage of development which makes it hard to present reliable figures on its energy efficiency. In the analysis of Rouwenhorst et al. (Rouwenhorst, et al., 2020), an energy requirement of 135 MJ (reported value) to 30 MJ per kg of produced ammonia (potential value) is given, which translates to an energy efficiency of 14% to 62% (LHV). The high range reflects the early stage of development that the technology is in and the uncertainty on the energy efficiency that will be realised in the future, making it hard to rank pathways in terms of energy efficiency. In principle, this technology could reach efficiencies in the range of 90%, but there is a need for further technological developments before reaching this stage (Rouwenhorst, 2022).

### 2.1.4 Impurities and Ammonia Production

Ammonia relies on the use of water that is further decomposed into hydrogen. This hydrogen is then combined with nitrogen, resulting in ammonia. Impurities may appear during the process of ammonia production and need to be removed. Typically, oxygenates ($O_2$ and $H_2O$) need to be removed from the hydrogen, as these can have detrimental effects on the iron-based ammonia synthesis catalyst. Other impurities, such as natural gas, are removed when hydrogen is produced from natural gas.

When hydrogen is produced via electrolysis, no further impurities are expected to appear that could require further modifications to the Haber-Bosch process (Rouwenhorst & Vrijenhoef, 2022). Therefore, only deoxidisers are needed to remove the oxygenates from the hydrogen for the synthetises of ammonia.

Argon in small amount will be present when ammonia is being produced from natural gas. If electrolysers are used to produce hydrogen, the production can be made purer, given that argon also is removed to a larger extent in a nitrogen separation unit. Removing argon will improve the production efficiency; however, it is only a minor improvement.

### 2.1.5 Level of maturity of technologies

*Ammonia production technology*

Scientific literature and market information indicate a large gap in technology readiness between the established ammonia production process of Haber-Bosch synthesis and the innovative synthesis technologies, which are in various phases of research – and development. Therefore, in the short term, it is more feasible to improve the Haber-Bosch process and replace the SMR unit with a renewable hydrogen production system than to introduce new synthesis technologies.

With regard to electrolysis technologies, alkaline and PEM electrolysers are fully proven in an operational environment. The SOEC has yet to leave the laboratory. The technology readiness levels (TRLs) of the different technologies are shown in Table 3 (below).

Table 3. Technology readiness level of green ammonia production technologies

| Production pathway | Technologies | Remarks | Technology readiness level | Sources |
|---|---|---|---|---|
| 1. Electrolysis and Haber-Bosch synthesis | Cryogenic air separation | Alternative technologies to separate nitrogen from air. Used in all production pathways. | 9 | (Rouwenhorst, et al., 2019) |
| | Pressure swing adsorption | | 9 | |
| | Membrane permeation | | 8-9 | |
| | Haber-Bosch synthesis reactor | Also used in pathways 2 and 3. | 9 | (Cerulogy, 2018) |
| | Alkaline electrolyser | Alternative technologies to split pure water into hydrogen and oxygen using electricity. Also can be part of pathway 4. | 9 | (Rouwenhorst, et al., 2019), (Smith, et al., 2020) |
| | PEM electrolyser | | 8-9 | (Smith, et al., 2020) |
| | SOEC electrolyser | | 3-5 | (Rouwenhorst, et al., 2019), (Smith, et al., 2020) |
| 2. Direct solar hydrogen production | Direct solar conversion | Can also be part of pathway 4. | 1-3 | (Smith, et al., 2020) |
| 3. Biogenic hydrogen production | Thermal gasification | | 7-8 | (LBST and Hinicio, 2015) |
| | Supercritical water gasification | | 4 | |
| | Dark fermentation | | 4 | |
| 4. Non-thermal plasma synthesis | Non-thermal plasma synthesis | - | 1-3 | (Smith, et al., 2020) |
| 5. Electrochemical ammonia synthesis | Electrochemical ammonia synthesis | - | 1-3 | (Smith, et al., 2020), (The Royal Society, 2020) |

Note: TRL 1 = Basic principles observed; TRL 2 = Concept formulated; TRL 3 = Experimental proof of concept; TRL 4 = Validated in lab; TRL 5 = Validated in relevant environment; TRL 6 = Demonstrated in relevant environment; TRL 7 = System prototype demonstration in operational environment; TRL 8 = System complete and qualified; TRL 9 = Actual system proven in operational environment.

*Vessel technology*

There are no ammonia-powered ships sailing. Only recently has maritime shipping begun to test ammonia-powered engines and fuel-cell systems for vessels. So far, these tests have taken place in a laboratory environment. One engine manufacturer has successfully tested an Otto cycle engine running on a fuel mix containing higher than 70% ammonia and has ongoing tests operating on the diesel cycle and these tests are expected to continue throughout 2023. Further, Diesel cycle engines running on ammonia will also be tested in Copenhagen during the summer of 2022; at the time this report was written, these tests were being prepared.

Although no ammonia-powered demonstration vessel has yet sailed, several shipping-related consortia have initiated projects that should lead to ammonia-powered vessel demonstrations by 2023/2024. A list of these projects is presented in Appendix IV - Pilots with ammonia-powered ships.

### 2.1.6 Developments in production capacity of green ammonia

In 2019, the worldwide production of ammonia was 235 Mt. About 4% of the required hydrogen was produced from electricity, which in turn was partly produced by combustion of fossil fuels (Ghavam, et al., 2021). To produce green ammonia, existing ammonia plants could switch to using green hydrogen, or new plants could be built.

A global overview of large green-ammonia projects is presented in Table 4 (below). The announced green ammonia projects add up to a total production capacity of 133 Mt per year. The overview shows that a lot of production capacity for green ammonia is in the pipeline, which reflects its widely accepted potential to become a convenient energy carrier to transport renewable energy over longer distances.

Table 4. Green ammonia projects worldwide

| Project | Stakeholders | Production location | Ammonia production volume (ktonnes/year) | Project stage | Start of operation | Remarks |
|---|---|---|---|---|---|---|
| NEOM (Brown, 2020) | Air Products, ACWA Power, NEOM | Saudi Arabia | 1,200 | Announced | 2025 | Intended use: hydrogen trucks and buses |
| Western Jutland plant (Hydrocarbon Processing, 2021) | Skovgaard Invest, Vestas and Topsoe | Denmark | > 5 | Announced | Not specified | Electrolyser directly coupled to solar/wind |
| Herøya plant (Yara, 2021) | HEGRA (established by Aker, Yara and Statkraft) | Norway | 530 | Announced | 2026-2028 | Decarbonisation of existing grey ammonia plant |
| Oruro plant (Atchison, 2021) | H2 Bolivia and the Government of Oruro | Bolivia | 500 | Announced | Not before 2025 | Electrolysers at plant, powered by solar farm |
| HNH project (Austria Energy, 2021) | AustriaEnergy, Ökowind | Chile | 850 | Announced | Not specified | - |
| Porto Central project (AmmPower Corp., 2021) | AmmPower, Porto Central | Brazil | Not specified | MOU signed | Not specified | Intended as shipping fuel and for fertiliser production |
| H2-Hub Gladstone project (Brown, 2020) | Hydrogen Utility (H2U) | Australia | 1,750 | Land purchased, detailed planning and feasibility study started. | 2025 | Up to 3 GW electrolyser capacity |
| Yara Pilbara plant (Blackbourn, 2021) | Yara, ENGIE | Australia | 3.7 (first phase) | Planned | 2023 | Green hydrogen production for existing ammonia plant |
| HyDeal España (Atchison, 2022) | ArcelorMittal, Enagás, Grupo Fertiberia, DH2 Energy | Spain | > 1,500 | Planned | 2025 | 7.4 GW of installed electrolysers by 2030 |
| Puertollano plant (Atchison, 2021) | Fertiberia | Spain | 6.1 | Announced and contracts for electrical works awarded | 2021 | On-site production, 20 MW of electrolysers |
| Donaldson-ville project (CF Industries, 2022) | CF Industries | United States | 20 | Planned | 2023 | - |
| Asian Renewable Energy Hub (AREH) project (Intercontinental Energy, 2022) | InterContinen-tal Energy, CWP Asia, Vestas, Pathway Investments | Australia | 9,900 | Major Project Status granted, 2025 FID target | 2031 (first phase) | 26 GW of electrolysers |
| Catalina project (Atchison, 2022) | Copenhagen Infrastructure Partners, | Spain | 900 | Construction of Phase 1 is | Not before 2025 | 2 GW of electrolysers |

| Project | Stakeholders | Production location | Ammonia production volume (ktonnes/year) | Project stage | Start of operation | Remarks |
|---|---|---|---|---|---|---|
| | Fertiberia, Vestas, Enagás, Naturgy | | | due to start end of 2023 | | |
| ACME Duqm project (Atchison, 2022) | ACME, Scatec | Oman | 1,200 | Project launched | No timelines have been set | 300 MW of electrolysers |
| SalalaH2 project (Prabhu, 2021) | OQ, Marubeni, Linde, Dutco | Oman | 365 | Joint Development Agreement signed | Not specified | 400 MW of electrolysers, which will feed an existing ammonia plant |
| Ain Sokhna project (OCI, 2021) | Fertiglobe, Scatec, the Sovereign Fund of Egypt | Egypt | 90 | Agreement signed, FID expected in 2022 | 2024 | 50-100 MW electrolysis plant |
| Garner plant (Maire Tecnimont, 2021) | Maire Tecnimont Group, Greenfield Nitrogen LLC | United States | 83 | Agreement signed | Not specified | Use of in-house green ammonia technology |
| (Minbos Resources, 2021) | Minbos Resources, Angola Ministry of Agriculture | Angola | 84 | Announced | | Newbuild |
| (Fortescue Future Industries, 2021) | Fortescue Future Industries | Argentina | 197 | Announced | 2024 | Newbuild |
| (Fortescue Future Industries, 2021) | Fortescue Future Industries | Argentina | 1,208 | Announced | 2027 | Newbuild |
| (Fortescue Future Industries, 2021) | Fortescue Future Industries | Argentina | 12,360 | Announced | 2030 | Newbuild |
| AREH (Intercontinental Energy, 2020) | Intercontinental Energy | Australia | 3,000 | Announced | 2030 | Newbuild |
| Eyre Peninsula Gateway™ (H2U, Mitsubishi, SA Government, ThyssenKrupp, 2018) | H2U, Mitsubishi, SA gov, ThyssenKrupp | Australia | 40 | Announced | 2022 | Newbuild |
| Eyre Peninsula Gateway™ (H2U, Mitsubishi, SA Government, ThyssenKrupp, 2018) | H2U, Mitsubishi, SA gov, ThyssenKrupp | Australia | 1,058 | Announced | - | Newbuild |
| Fortescue Metals Group green | Fortescue Future Industries | Australia | 250 | Announced | 2025 | Newbuild |

| Project | Stakeholders | Production location | Ammonia production volume (ktonnes/year) | Project stage | Start of operation | Remarks |
|---|---|---|---|---|---|---|
| hydrogen and ammonia (Fortescue Future Industries, 2021) | | | | | | |
| GERI (BP, GHD, ARENA, 2020) | BP, GHD, ARENA | Australia | 20 | Announced | - | Newbuild |
| GERI (BP, GHD, ARENA, 2020) | BP, GHD, ARENA | Australia | 1,000 | Announced | - | Newbuild |
| H2Perth (Woodside Energy, 2021) | Woodside Energy | Australia | 590 | Announced | 2023 | Newbuild |
| H2Perth (Woodside Energy, 2021) | Woodside Energy | Australia | 2,949 | Announced | - | Newbuild |
| H2TAS (Woodside Energy, 2021) | Woodside Energy | Australia | 200 | Announced | 2025 | Newbuild |
| Murchison Renewable Hydrogen Project (MRHP, Copenhagen Infrastructure Partners, 2020) | MRHP, Copenhagen Infrastructure Partners | Australia | 1,900 | Announced | 2028 | Newbuild |
| Origin Energy Bell Bay Green Hydrogen and Ammonia (Origin, 2020) | Origin | Australia | 420 | Announced | 2025 | Newbuild |
| Pacific Solar Hydrogen (Austrom Hydrogen, 2020) | Austrom Hydrogen | Australia | 1,125 | Announced | - | Newbuild |
| Port Adelaide green hydrogen (AEMC, 2020) | | Australia | 310 | Announced | - | Newbuild |
| Portland Renewable Hydrogen (Countrywide Energy, Glenelg Shire Council, Port of Portland, 2020) | Countrywide Energy, Glenelg Shire Council, Port of Portland | Australia | 56 | Announced | - | Newbuild |
| WGEH (Intercontinental Energy, CWP Global, 2021) | Intercontinental Energy, CWP Global | Australia | 20,000 | Announced | - | Newbuild |
| (CAC-H2, 2021) | CAC-H2 | Australia | 75 | Announced | 2023 | Newbuild |

| Project | Stakeholders | Production location | Ammonia production volume (ktonnes/year) | Project stage | Start of operation | Remarks |
|---|---|---|---|---|---|---|
| (Province Resources, Total-Eren, 2021) | Province Resources, Total-Eren | Australia | 2,400 | Announced | 2030 | Newbuild |
| (CAC-H2, Clean Holdings, 2021) | CAC-H2, Clean Holdings | Australia | 30 | Announced | - | Newbuild |
| (HyEnergy, 2021) | HyEnergy | Australia | 300 | Announced | - | Newbuild |
| (Queensland Nitrates, Incitec Pivot, Wesfarmers JV, Neoen, Worley, 2020) | Queensland Nitrates, Incitec Pivot, Wesfarmers JV, Neoen, Worley | Australia | 20 | Announced | - | Newbuild |
| (Proton Ventures, Trammo, Global Energy Storage, VARO, 2021) | Proton Ventures, Trammo, Global Energy Storage, VARO | Brazil | 2,500 | Announced | - | Newbuild |
| (Fortescue Future Industries, 2021) | Fortescue Future Industries | Brazil | 250 | Announced | - | Newbuild |
| Hy2Gen Canada (Hy2Gen, 2021) | Hy2Gen | Canada | 183 | Announced | 2025 | Newbuild |
| H2 Magallanes (Total Eren, 2021) | Total Eren | Chile | 4,400 | Announced | 2027 | Newbuild |
| HyEx (Enaex, ENGIE, 2020) | Enaex, ENGIE | Chile | 18 | Announced | 2024 | Newbuild |
| HyEx (Enaex, ENGIE, 2020) | Enaex, ENGIE | Chile | 700 | Announced | 2030 | Newbuild |
| Hy-Fi (CORFO, N/A) | CORFO | Chile | 1,278 | Announced | 2025 | Newbuild |
| (Copenhagen Infrastructure Partners, Maersk, DFDS, 2021) | Copenhagen Infrastructure Partners, Maersk, DFDS | Denmark | 650 | Announced | 2026 | Newbuild |
| (Haldor Topsoe, Aquamarine, 2021) | Haldor Topsoe, Aquamarine | Germany | 105 | Announced | 2024 | Newbuild |
| (RWE, 2020) | RWE | Germany | 972 | Announced | | Newbuild |
| (EI-H2, Zenith, 2021) | EI-H2, Zenith | Ireland | 489 | Announced | 2028 | Newbuild |
| (FREA, JGC Corporation, 2018) | FREA, JGC Corporation | Japan | 0 | Operational | 2018 | Demonstrator |
| (Maire Technimont S.p.A, 2021) | Maire Technimont S.p.A | Kenya | 45 | Announced | 2025 | Newbuild |
| AMAN (CWP Global, 2021) | CWP Global | Mauritania | 11,425 | Announced | - | Newbuild |
| Tarafert-1 (Tarafert, N/A) | Tarafert | Mexico | 850 | Announced | 2025 | Newbuild |

| Project | Stakeholders | Production location | Ammonia production volume (ktonnes/year) | Project stage | Start of operation | Remarks |
|---|---|---|---|---|---|---|
| Tarafert-2 (Tarafert, N/A) | Tarafert | Mexico | 500 | Announced | 2026 | Newbuild |
| HEVO (Fusion Fuel, 2021) | Fusion Fuel | Morocco | 3 | Announced | 2022 | Newbuild |
| HEVO (Fusion Fuel, 2021) | Fusion Fuel | Morocco | 20 | Announced | 2023 | Newbuild |
| HEVO (Fusion Fuel, 2021) | Fusion Fuel | Morocco | 40 | Announced | 2024 | Newbuild |
| HEVO (Fusion Fuel, 2021) | Fusion Fuel | Morocco | 60 | Announced | 2025 | Newbuild |
| HEVO (Fusion Fuel, 2021) | Fusion Fuel | Morocco | 183 | Announced | 2026 | Newbuild |
| (OCP, Fraunhofer IMWS, 2018) | OCP, Fraunhofer IMWS | Morocco | 1 | Announced | - | Demonstrator |
| Southern Corridor Development Initiative Green Hydrogen project | Hyphen Hydrogen Energy | Namibia | 1,037 | Announced | 2026 | Newbuild |
| Southern Corridor Development Initiative Green Hydrogen project | Hyphen Hydrogen Energy | Namibia | 2,592 | Announced | 2030 | Newbuild |
| (Varanger Kraft, 2018) | Varanger kraft | Norway | 90 | Announced | 2025 | Newbuild |
| GEO (OQ, Intercontinental Energy, EnerTech, 2021) | OQ, Intercontinental Energy, EnerTech | Oman | 10,450 | Announced | 2038 | Newbuild |
| HYPORT® (DEME Concessions, 2020) | DEME Concessions, OQ | Oman | 150 | Announced | 2026 | Newbuild |
| HYPORT® (DEME Concessions, 2020) | DEME Concessions, OQ | Oman | 520 | Announced | | Newbuild |
| (ACME, Tatweer, 2021) | ACME, Tatweer | Oman | 105 | Announced | 2022 | Newbuild |
| (ACME, Tatweer, 2021) | ACME, Tatweer | Oman | 840 | Announced | | Newbuild |
| FFI project (Fortescue Future Industries, Papua New Guinea Government, 2021) | Fortescue Future Industries, Papua New Guinea Government | Papua New Guinea | 11,500 | Announced | - | Newbuild |
| ATOME Energy project (AEA, 2021) (ATOME Energy, 2021) | ATOME Energy | Paraguay | 219 | Announced | 2023 | Newbuild |

| Project | Stakeholders | Production location | Ammonia production volume (ktonnes/year) | Project stage | Start of operation | Remarks |
|---|---|---|---|---|---|---|
| Alto Paraná plant (AEA, 2021) (ANDE, MET Development, FerSam Uruguay, 2021) | ANDE, MET Development, FerSam Uruguay | Paraguay | 213 | Announced | 2026 | Newbuild |
| (HEVO, N/A) | HEVO | Portugal | 55 | Announced | - | Newbuild |
| SAREH (Saudi Aramco, Intercontinental Energy, Modern Investment Group, 2021) | Saudi Aramco, Intercontinental Energy, Modern Investment Group | Saudi Arabia | 10,000 | Announced | - | Newbuild |
| (Eneus Energy, 2020) | Eneus Energy | Scotland | 7 | Announced | | Newbuild |
| (Hive Hydrogen Linde, 2021) | Hive Hydrogen, Linde | South Africa | 780 | Announced | 2026 | Newbuild |
| Green Wolverine (Argus Media, 2021) | Fertiberia | Sweden | 520 | Announced | 2026 | Newbuild |
| NewGen (Energy Chamber of Trinidad and Tobago, 2021) | NewGen (BP, Shell) | Trinidad & Tobago | 163 | Announced | 2024 | Newbuild |
| (KIZAD, Helios Industry, 2021) | KIZAD, Helios Industry | United Arab Emirates | 40 | Announced | 2024 | Newbuild |
| (KIZAD, Helios Industry, 2021) | KIZAD, Helios Industry | United Arab Emirates | 200 | Announced | 2026 | Newbuild |
| (KIZAD, Helios Industry, 2021) | TAQA Group, Abu Dhabi Ports | United Arab Emirates | 1,200 | Announced | | Newbuild |

Note: In the scope of many projects, ammonia is considered to function as a hydrogen carrier, i.e., to transport hydrogen more efficiently by ship. However, selling this ammonia to meet rising demand for green ammonia, such as from the maritime sector, would prevent the need reconversion to hydrogen in an ammonia cracker, saving on energy use and capital investments. Various green ammonia plant feasibility studies have been announced as well, and high-level memoranda of understanding have been signed, which could lead to concrete projects at a later stage.

### 2.1.7 Production Conclusions

Ammonia can be stored in a liquefied condition at atmospheric pressures or fully pressured at approximately 18 bar, which makes it easier to transport and store than other gases. It is a widely used and available chemical, notably used for fertiliser production. With a current global ammonia production of approximately 235 Mt per year, the production capacity would need to increase significantly to provide fuel for maritime shipping and other purposes.

Currently, ammonia is produced using hydrogen made from fossil fuels (mostly natural gas), which are converted to ammonia in a Haber-Bosch synthesis reactor. Five production pathways for green ammonia production have been identified. The first three pathways combine different renewable hydrogen production technologies with the Haber-Bosch synthesis process: electrolysis (using renewable electricity), direct solar hydrogen production; and biogenic hydrogen production.

Pathway 4 combines renewable hydrogen technology with an innovative synthesis process (non-thermal plasma synthesis), while pathway 5 (electrochemical ammonia synthesis) does not require a separate hydrogen production step.

There is a large gap in technology readiness when comparing the established ammonia production process of Haber-Bosch synthesis with innovative synthesis technologies, many of which are in the research and development phase. In the short term, it is more feasible to replace the grey hydrogen-production system with a renewable hydrogen-production system than to try to introduce new ammonia synthesis technologies into the market.

The different production pathways as outlined can potentially yield high efficiency. However, at this stage and with the information at hand, it seems that in the long term the Haber-Bosch process will continue to provide the highest efficiency. This is summarized in the table below, where we provide both numbers that are documented in literature and values that can be reached ([up to] in Table 5) based on discussions with industry experts. The numbers in brackets are highly dependent on the technological development to be followed in the coming years.

Table 5. Comparison of expected efficiency for different ammonia production pathways.

| Process Type | Expected Efficiency [up to] |
|---|---|
| Pathway 1<br>Electrolysis and Haber-Bosch synthesis | ~72% |
| Pathway 2<br>Direct solar hydrogen production | 9%<br>[up 70%] |
| Pathway 3<br>Biogenic hydrogen production | ~57% |
| Pathway 4<br>Non-thermal plasma synthesis | 12-37%<br>[up to 45%] |
| Pathway 5<br>Electrochemical ammonia synthesis | 14-62%<br>[up to 90%] |

## 2.2 Sustainability

In this section, the sustainability of green ammonia production (using grey ammonia as a reference) and its use as a fuel in maritime ships is discussed. Greenhouse gas (GHG) emissions (subparagraph 2.2.1), air pollutant emissions (subparagraph 0) and other environmental impacts (subparagraph 2.2.3) are also examined. It is summarised in subparagraph 2.2.4.

### 2.2.1 GHG performance

Because ammonia does not contain carbon, $CO_2$ emissions from the combustion of ammonia only arise if pilot fuel is used (which is not the case if a ship is propelled by fuel cells). This holds true for both grey and green types of ammonia. However, there are other GHG gases produced from the combustion of ammonia such as nitrous oxide, $N_2O$. The formation of $N_2O$ is a potential risk as it is an even more potent GHG than methane and $CO_2$. It is 264 times more potent than $CO_2$ on a 20-year basis (GWP20) and 265 times on a 100-year basis (GWP100), according to the IPCC AR5 report (Myrhe, G., et al., 2014) (see Table 6). Even a small amount of $N_2O$ emissions formed during combustion and emitted to the atmosphere can limit or reverse the positive impact of ammonia on GHG emissions. The $N_2O$ levels from the combustion of ammonia and the ammonia slip itself (due to potentially incomplete combustion) are expected to play an important role in the further development of the engines.

Other GHG emissions are produced during the production and transportation of ammonia. These emissions represent much higher volumes for grey ammonia than for green ammonia, which uses natural gas as a feedstock for SMR to produce hydrogen for the ammonia-synthesis process, and as a fuel to reach the required operating temperature.

On the other hand, green ammonia, produced with green hydrogen from water electrolysis using renewable electricity, creates GHG emissions that are close to zero. This is because the Haber-Bosch synthesis process is exothermic (does not require an external heat source) and because the reaction heat can be used to satisfy the process's demand for heat (Liu, et al., 2020).

If the electricity used for nitrogen production and the HB synthesis is from the grid, the GHG emissions are more than zero. Also, the provision of heat for a high-temperature electrolyser may contribute to the GHG emissions of green ammonia.

Liu et al (2020) estimate the well-to-wake GHG emission of green ammonia to be 91% lower than grey ammonia (Liu, et al., 2020), and 85% lower than heavy fuel oil (HFO) and MGO (Ghavam, et al., 2021).

Table 6. Well-to-wake GHG emission factors for green ammonia vs. fossil marine fuels

| Fuel | Production pathway | GHG emission factor (g/MJ) | Source | Remarks |
|---|---|---|---|---|
| Grey ammonia | SMR | 100-137 | (Liu, et al., 2020) | Electricity source for $N_2$ production for green ammonia and HB loop for grey/green ammonia: 2019 US grid generation mix. |
| Green ammonia | Low-temperature electrolysis | 0-12 | | |
| Green ammonia | High-temperature electrolysis | 0-13 | | |
| VLSFO | - | 92 | (CE Delft, 2021) FuelEU Maritime proposal | Upstream emissions depend on crude oil source and refinery |
| MGO | - | 91 | | |

## 2.2.2 Air pollution

Burning conventional fossil fuels in ships results in the emission of air pollutants, which can be damaging to the health of the crew or the local environment. When using ammonia in a marine internal combustion engine, the emissions of sulphur dioxide, carbon monoxide, heavy metals, hydrocarbons and polycyclic aromatic hydrocarbons (PAH) drop to zero. The emission of PM is substantially reduced due to the lack of carbon, sulphur and other contaminants in the ammonia compared to the typically used conventional residual or distillate fuels.

However, the volume of emissions released will depend on the engine-combustion concept, design features and, critically, the amount and type of pilot fuel used to burn ammonia. The sulphate, hydrocarbon and PM emissions are expected to be dominated by the pilot fuel and combustion of the cylinder oil applicable to the specific engine design.

Using ammonia as a fuel for an onboard fuel-cell system would reduce these emissions even more, because no combustion products are formed. In Solid Oxide Fuel Cells (SOFC), it is possible to avoid the formation of $NO_x$, although at high temperatures a small amount of NO will be produced (Valera-Medina, et al., 2021). Furthermore, there is a risk of ammonia emissions from leaks or incomplete ammonia combustion because ammonia is an aerosol precursor that contributes to PM concentrations (Ash & Scarbrough, 2019). This will be influenced by the engine design and combustion concept; it is likely that an operator can expect engines that apply Otto combustion to suffer similar issues with ammonia slip issues as those seen with methane slip on dual and single fuel Otto gas (methane) engines.

Considering ammonia's toxicity and excluding the difficulties with initiating ammonia combustion that the Otto process may experience, this may practically exclude those engine designs without significant levels of ammonia slip control by aftertreatment systems. Also, there is a risk of $NO_x$ formation in the case of ammonia combustion, but with good control of the combustion conditions and after-treatment $NO_x$ emissions can be mitigated (Cerulogy, 2018).

However, a high combustion temperature will limit the production of $N_2O$, so it is expected that using ammonia in the diesel cycle process (which involves high combustion temperatures) will result in less $N_2O$ being produced than the Otto cycle process.

In short, the emission levels of gaseous and particulate air pollutants when using (grey and green) ammonia as a shipping fuel are generally lower than those from conventional fossil fuels (see Table 8 in subparagraph 2.2.4).

Table 7. GWP for different GHG emissions

| | Lifetime (years) | GWP time horizon | | | Report Reference |
|---|---|---|---|---|---|
| | | 20 years | 100 years | 500 years | |
| Carbon Dioxide($CO_2$) | Complex | 1 | 1 | N/A | IPCC 2013-AR5 (Myrhe, G., et al., 2014) |
| | | 1 | 1 | 1 | IPCC 2007-AR4 (Forster, P., et al., 2007) |
| Methane($CH_4$) | 12.4 | 84 | 28 | N/A | IPCC 2013-AR5 (Myrhe, G., et al., 2014) |
| | 12 | 72 | 25 | 7.6 | IPCC 2007-AR4 (Forster, P., et al., 2007) |
| Nitrous Oxide($N_2O$) | 121 | 264 | 265 | N/A | IPCC 2013-AR5 (Myrhe, G., et al., 2014) |
| | 114 | 289 | 298 | 153 | IPCC 2007-AR4 (Forster, P., et al., 2007) |

### 2.2.3 Other environmental impacts

Ammonia causes severe skin burns and eye damage and is toxic if inhaled. Therefore, onboard fuel storage, energy-conversion systems and safety regulations for ammonia should be designed to guarantee the safety of the crew. Ammonia is toxic for marine organisms and direct exposure can create long-term adverse effects (Hansson, et al., 2020). It also indirectly depletes the ozone layer by forming nitrous compounds in the atmosphere. Although scientists presently think its contribution to ozone depletion is negligible, large-scale use of ammonia as a shipping fuel could change that (Valera-Medina, et al., 2018). The emission of ammonia into the atmosphere through leaks or incomplete combustion would contribute to acid deposition and eutrophication, which could damage soil and water quality. With careful operation and control of the combustion system, however, those emissions should be preventable (Ash & Scarbrough, 2019).

The production of green hydrogen by means of electrolysis requires pure, deionised water. The amount of water required to produce green ammonia can increase water scarcity, if freshwater is used; whereas the intake of seawater for desalination and the rejection of brines can be detrimental to ocean biodiversity and marine life (Ghavam, et al., 2021).

The generation of renewable electricity requires land or sea area. The amount varies widely across regions, depending on the incoming solar radiation and prevailing wind speeds.

Land-usage is a point of concern for the implementation of renewable energy production for the synthesis of ammonia. The need for large quantities of energy implies that installation of solar plants and wind farms, if onshore, would require large portions of land. However, the production of solar energy should avoid competing for land used for production of food crops. There are arid regions around the world where this would be possible (e.g., northern Chile, western Australia, northeast Brazil, northern Africa, parts of the U.S. and China, etc.); the same applies for wind farms. For the latter, in some regions of world, offshore wind farms are a good candidate to lower the impact of land use.

Ammonia spills could occur during bunkering or as the result of damage to the hull (extending beyond 1/5th of the beam dimension) and the fuel tanks. Ammonia dissolves in water, in which case it is partly ionized. Dissolved non-ionised ammonia ($NH_3$(aq)) exists in equilibrium with ionized ammonia ($NH_4^+$(aq)) and with its vapour ($NH_3$(g)). The concentration of $NH_3$(aq) increases with water temperature and pH (Franklin & Edward, 2019). The pH of seawater ranges from 7.4 to 9.6 (Marion, et al., 2011). At pH 8 (the average alkalinity of seawater), the share of $NH_3$(aq) in the equilibrium between $NH_3$(aq) and $NH_4^+$(aq) ranges from 0.8% at 0ºC to 7.4% at 30ºC. At 15ºC, $NH_3$(aq) in the equilibrium between $NH_3$(aq) and $NH_4^+$(aq) ranges from 0.9% at pH 7.5 to 46% at pH 9.5 (Franklin & Edward, 2019).

Non-ionised ammonia is toxic to marine life (Gregory D. Boardman, 2004) (ionised ammonia is not toxic). The acute toxicity level at which 50% of a species dies varies by species. Values have been reported ranging from 17 mg NH3/litre for sea bass to 510 mg/L for south African abalone (Batley & Simpson, 2009). In general, toxicity tends to be less in highly saline waters (Franklin & Edward, 2019). Still, it appears that seawater species are more sensitive to ammonia than freshwater species (Eddy, 2005). Combined with the fact that a larger fraction of spilled ammonia will be dissolved as $NH_3$ rather than as $NH_4^+$, this means that ammonia spills in seawater are potentially more harmful than ammonia spills in freshwater. Ammonia spills could be addressed by spraying with a mild acid, so that more ammonia is dissolved in its ionised form. A reduction of the pH locally to 6 would push the equilibrium between $NH_3$(aq) and $NH_4^+$(aq) towards $NH_4^+$(aq) so that less than 0.1% of the ammonia remains in its toxic non ionized form (Franklin & Edward, 2019).

A long-term result of any ammonia spill would be increased eutrophication of the receiving waters, depending on the presence of other nutrients. The additional nutrient levels could stimulate noxious blooms of algae, which would cause the continuous degradation of water quality.

#### 2.2.3.1 Pollution prevention

When and if ammonia emerges as a viable marine fuel, its potential to pollute must be closely considered. The risks associated with the potential release of large quantities of ammonia is addressed in Section 4 of this report; these relate typically to events where there is low risk, but when consequences are the highest.

The probability of these accidents happening is higher when the vessel operates close to or in port areas, so prevention and mitigation plans will need to be developed with local authorities and regulatory bodies. Industry experience with other potentially hazardous cargoes/fuels, such as LNG, can be used to lessen those risks and build response strategies. When LNG carriers are operating in port under a local jurisdiction, a mitigation plan is usually in place. This can include procedures such: as strict escort services; restricted navigation zones (to minimize collision and grounding); traffic watches; marine channel announcements before entering; pre inspection by authority; emergency plans for minor to major spills with pollution-reduction measures; minor to major fire/explosion responses; support from local emergency services, etc.

These measures help to move the probability and potential consequences of events to extremely low levels. Similar or higher measures for mitigation plans are expected to be implemented for ammonia in the initial stages of implementation. As experience grows on handling ammonia as a fuel, these measures will need to be continuously updated.

As an example, for hazardous cargo transportation in the U.S., strategies required by the Coast Guard for especially hazardous cargoes have four main pillars, requiring practitioners to: (1) work with port partners, contributing to real-time awareness of the location of the vessels transporting especially hazardous cargoes and the potential threats and consequences associated with an accident, such as spillage; (2) assess the vulnerability and potential consequences of accidents; (3) improve the response time and coordination with local authorities to mitigate the impact of an accidental spillage and (4) promote local authorities to develop plans, infrastructure, etc., to handle hazardous cargoes. See (USCG, 2015).

### 2.2.4 Sustainability Conclusions

The well-to-wake GHG emissions of green ammonia are estimated to be around 91% lower than for grey ammonia, because the reformer does not create emissions from using natural gas used as a feedstock for SMR, or as a fuel in the ammonia-production process.

Green ammonia, produced with green hydrogen from water electrolysis using renewable electricity, creates almost no GHG emissions. Compared with HFO and MGO, its GHG emissions are around 85% lower.

When using ammonia as a fuel for a marine internal combustion engine, the emissions of sulphur dioxide, carbon monoxide, heavy metals, hydrocarbons and PAHs drop to zero (or close to zero, in case pilot fuel is used); PM emissions are substantially reduced compared to conventional fossil fuels, due to it having less carbon, sulphur and other contaminants that are typically seen in conventional residual or distillate fuels. However, the usage of pilot fuel may introduce some level of emissions and air pollution. The exact amount of pilot fuel will depend on the engine developments that are currently underway.

Using ammonia for an onboard fuel-cell system would reduce these emissions even more, as no combustion products are formed.

As indicated in Section 3, on the regulatory front, IMO and Member States could further develop the NOx technical code to introduce limits for ammonia and $N_2O$ emissions from Internal Combustion Engines and ensure a better coverage and framework for these engines. Table 8 below summarises the air pollutants and GHG emissions from ammonia as marine fuel in comparison to the usage of fossil marine fuels.

Finally, land-usage is a potential point of concern especially as production of renewable electricity would potentially rely on large area of land for solar and wind power generation. It is therefore advisable that focus should be given to non-agricultural lands or offshore development of wind energy.

Table 8. Air pollutant and GHG emissions from ammonia vs. fossil marine fuels*

| Pollutant | HFO, MGO | LNG | Ammonia (combusted in engines) |
|---|---|---|---|
| $SO_2$ and metals | Present | Not present | Not present |
| Carbon monoxide and hydrocarbons | Present | Present or increased | Not present |
| VOCs and PAHs | Present | Reduced | Not present |
| $NO_x$ ** | Needs SCR for Emission Control Area | Otto engines meet Emission Control Area without SCR | Needs SCR for Emission Control Area |
| Direct particulate matter | Present | Reduced | Reduced |
| Ammonia ($NH_3$) *** | Low | Not present | Unknown |
| $N_2O$ | Present | Present | Present or increased**** |
| $CH_4$ | Low | Present at Otto engines | Not present |
| $CO_2$***** | Present | Present | Not present |

Notes: HFO = heavy fuel oil; LNG = liquefied natural gas; MGO = marine gas oil; SCR = selective catalytic reduction.
*: Adapted from (Ash & Scarbrough, 2019). Pilot fuel is not considered in this table. Pilot fuel use may be larger for ammonia engines.
**: With exhaust gas recirculation (EGR), $NO_x$ emissions will go down. At the moment there are no engine makers considering using EGR for an ammonia fueled engine. However, the usage of EGR cannot be fully excluded as an option in the future.
***: A $NH_3$ slip catalyst could be used to reduce $NH_3$ emissions, but this may be too expensive. Alternative options are optimisation of the combustion process, adjusting the pilot fuel quantity, and using a bigger SCR unit. If the ammonia slip is less than what is required for the SCR to reduce NOx emissions, the former will be used as consumable for the catalyst. If the ammonia slip is higher than a second-stage ammonia catalyst may be needed. However, the level of $NH_3$ will depend on the further progress of the internal combustion engines as explained in section 2.4.3.
**** $N_2O$ is expected to be present, however at which level is yet unknown. For some engine cycles, the $N_2O$ levels may be higher.
***** Pilot fuel and upstream emissions.

## 2.3 Availability

To produce green ammonia on a large scale for maritime shipping, the production capacity of renewable electricity, green hydrogen and green ammonia would need to undergo a tremendous growth; the current global capacities of wind and solar farms - and especially electrolysers and green ammonia plants – are relatively low[3]. Also, demand for renewable electricity and green hydrogen is expected to rise in virtually all economic sectors (see subparagraph 2.3.3), so production capacity would need to increase far beyond the levels that could meet the anticipated demand of the maritime sector.

[3] The installed global renewable electricity capacity in 2020 was 2,800 GW (with more than 1,200 GW from hydropower), and the current installed global electrolyser capacity is about 200 MW (Aurora, 2021).

The need for electrolyser capacity relative to the wind and solar capacity will depend on the way the systems are configured. If an electrolyser is directly connected to a wind or solar farm, customising it to the maximum power output of the farm would result in the system having a low load factor and hydrogen output. A smaller electrolyser could curtail excess renewable electricity. This is illustrated in Figure 4.

There are several alternatives; storage of electricity is one option, and another is to connect the electrolyser to use power from the grid in areas where there is sufficient capacity available from the grid. This could increase the load factor from the production as in Figure 4 (thus, reducing the capacity required to obtain the same amount of hydrogen). The need for grid connectivity to achieve competitive price levels for e-fuels was demonstrated in a recent study (Nami, Butera, Campion, Frandsen, & Hendriksen, 2021) (Münster, Electro fuels for long-range maritime transport, 2021). However, this posed the need for reliable certification mechanisms to ensure the grid electricity is considered ‘green’ or at least to provide the information of the split between green and grey sources of energy. The advantage is that stable production of hydrogen at optimum capacity will optimise the Haber Bosch process for production of ammonia.

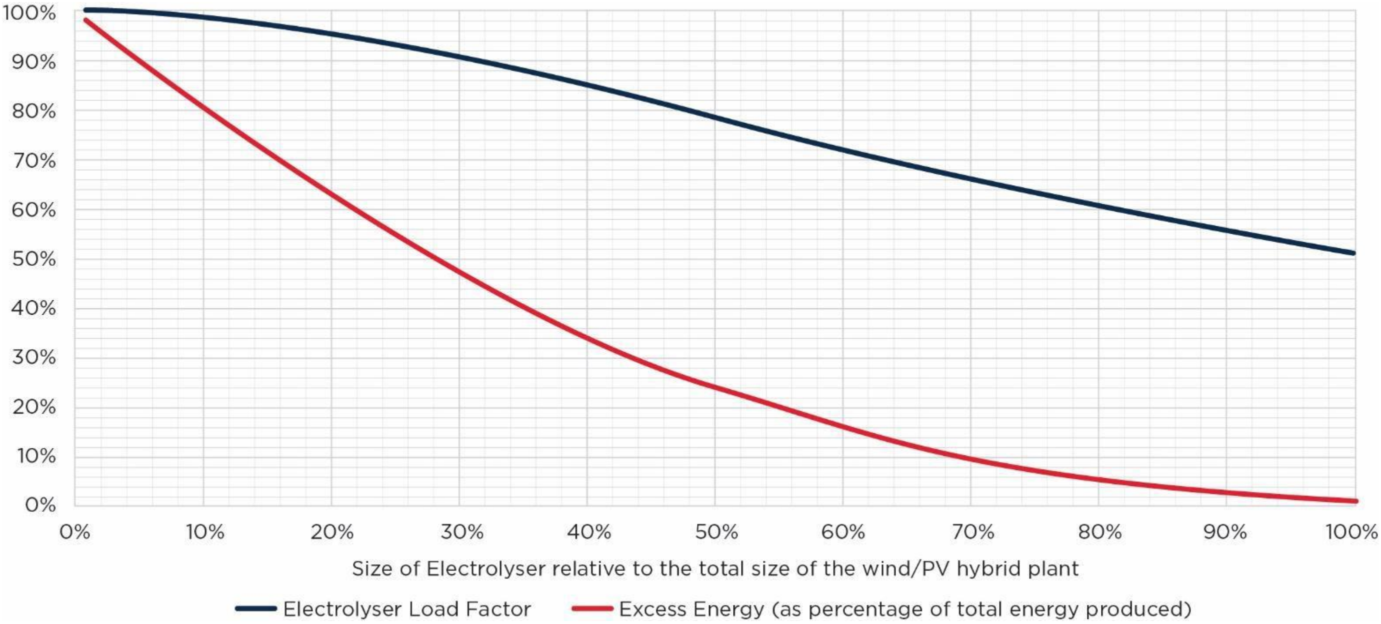


Figure 4. The relationship between the electrolyser’s load factor and excess renewable electricity, given the sizes of the system and wind/solar farms (IEA, 2017)

In summary (Nami, et al., 2021), the electrolyser and the Haber-Bosch process needs to be in operation at maximum capacity continuously. This leads to the need for some aspects to be considered in the design of the production facilities:

- For moments when the Ammonia production cannot be distributed efficiently, storage facilities for hydrogen and/or ammonia need to be in place to avoid the production to be stopped;
- Also, in case for any reason the Ammonia production needs to be stopped when energy is still available, either this energy is to be stored by means of battery system, or by means of hydrogen storage or even by selling the energy to the grid.

The renewable energy production is to be sized to the ammonia production capacity. In periods of low energy production, grid connectivity would ensure a constant supply to the ammonia synthesis and avoid low utilization electrolysers and ammonia production infrastructure.

Alternatively, the renewable power production can be oversized so that in a period of low wind or solar exposure, the risks of low utilization are reduced. In case of excess production, then this energy is sold to the grid.

### 2.3.1 European availability

It is theoretically possible to develop the capacity to produce green ammonia all over the world. Renewable electricity could be produced at most locations with favourable conditions for wind and solar irradiation. The inherent cost savings would easily outweigh the additional costs of intercontinental transport for renewable energy carriers. In this light, it is better to examine the potential worldwide capacity for green ammonia production than to look solely at availability in Europe.In 2019, Europe had 475 GW of production capacity for renewable electricity, with wind, solar and hydro each having a large share (Audrey Errard, 2021). Given the EC's proposal (in the 'Fit for 55' package) to raise the EU's renewable-energy target to 40% (from 32%) by 2030, the development of wind and solar power needs to be accelerated.

The EU also has ambition to develop 40 GW of electrolyser capacity by 2030; member states so far have pledged 34 GW by 2030 (Aurora, 2021).

The confirmed green-ammonia projects listed on Table 4 would appear to indicate that most of these will be located outside of Europe in countries that expect to generate renewable electricity in volumes that exceed national demand.

### 2.3.2 Worldwide availability

The amount of green ammonia that may become available for the global maritime shipping industry is difficult to estimate, because it is subject to market developments such as: industry investment plans; changes in demand for renewable energy and electricity; and technological advances in electrolysers and ammonia synthesis.

To gain a degree of insight, however, it is possible to calculate the global capacity that would be needed to supply enough green ammonia to meet the final energy demand of maritime shipping in 2040[4] and then compare that to projected developments in production capacity. This exercise is described below and summarised in Table 10.

The estimated final energy demand of global maritime shipping is projected to be 12.1 to 14.2 EJ in 2030 and 10.2 to 23.2 EJ in 2050 (IMO 2020 Fourth IMO GHG Study 2020) (CE Delft & RH DHV, 2020). Assuming linear demand growth, global ammonia demand from shipping is estimated at 600 to 1,000 Mt/year by 2040. This required production capacity is huge compared with current green development plans for green ammonia, which are a mere 5 Mt/year. As the production capacity for grey ammonia is currently about 235 Mt/year, ammonia production would need to increase by a factor of 3-4 just to satisfy shipping's fuel requirements alone.

Secondly, the required and projected production capacity for renewable electricity is examined. Assuming an electrolyser efficiency of 65% (lower heating value [LHV]) and electricity use from the ammonia synthesis process of 640 kWh per tonne of ammonia, 5,800 to 9,800 terawatt hours (TWh) of renewable electricity would be needed in 2040 to enable the complete switch of global maritime shipping to green ammonia.

This level of demand is in the same range as current global renewable electricity production. The worldwide renewable electricity production in 2018 was about 6,600 TWh, 63% of which was from hydropower, 19% from wind, 8% from bioenergy, 9% from solar, and 1% from geothermal (IRENA, 2020).

Some projections of global production capacity in 2030 and 2050 are listed in Table 9.

Summarising these volumes into a range and interpolating between the projected years, we arrive at a projected global renewable electricity production of 15,000-30,000 TWh in 2040[5], indicating that production is expected to increase by a factor of 2 to 5 between 2018 and 2040. These volumes would be sufficient to produce 600 to 1,000 Mt/year of green ammonia for the maritime sector, but a large share of the renewable electricity produced will feed into the power grids to supply worldwide demand for electricity.

Table 9. Projections of global renewable electricity production from various scenarios (TWh/year) (CE Delft & RH DHV, 2020)

| Scenario | 2030 | | 2050 | |
|---|---|---|---|---|
| | Min | Max | Min | Max |
| IEA, 2°C Scenario | 14,500 | | 28,700 | |
| IPCC RCP2.6 scenarios | 6,300 | 13,100 | 22,200 | 28,100 |
| IRENA REmap Case | 20,400 | | 47,400 | |
| IEA, Beyond 2°C Scenario | 14,500 | | 31,800 | |

[4] We focus on the year 2040, because electrolyser development plans take this as time horizon. Indeed, 2030 is too soon for large-scale expansion of production capacity. Furthermore, 2050 is the end year for full decarbonisation, whereas we are interested in gaining insight in the speed of capacity development.
[5] When assuming that the renewable electricity generation produces 40% of the time (which is representative for wind power), this translates to 4.3 to 8.6 TW of generation capacity.

| | | | | |
|---|---|---|---|---|
| IPCC RCP 1.9 scenarios | 8,100 | 14,700 | 31,200 | 49,100 |

To estimate the demand for electrolyser capacity, an energy efficiency of 65% (LHV) is again assumed, as is 4,000 full-load hours of the capacity, which could be realised by the direct use of electricity from wind and solar farms at an installed capacity similar to their sum.

It emerges that 1,400-2,300 GW of electrolyser capacity would be needed to produce enough green ammonia to supply the entire maritime sector in 2040. In contrast, the current capacity is only 0.2 GW.

The amount of announced electrolyser projects is impressive: at least 213.5 GW of related capacity is planned for delivery by 2040, 85% of which is located in Europe. However, the amount of electrolyser capacity worldwide would need to be 7 to 11 times higher than that just to supply global shipping with green ammonia in 2040.

Table 10. Availability of green ammonia production, renewable electricity production and electrolyser capacity for global maritime shipping in 2040

| Item/Aspect | Min | Max | Unit | Remarks |
|---|---|---|---|---|
| Required ammonia production in case of 100% green ammonia use in global maritime shipping in 2040 | 600 | 1,000 | Mt/ year | Calculated using projected global maritime fuel energy demand in 2030 and 2050 from Fourth IMO GHG Study (CE Delft & RH DHV, 2020). |
| Planned green ammonia capacity worldwide | 5 | ? | Mt/ year | Minimum value derived from current production capacity developments from Table 4. |
| Estimated global renewable electricity capacity required for green ammonia production for shipping alone in 2040 | 5,800 | 9,800 | TWh/ year | Sum of electricity used for elecrolyser (assuming electrolyser efficiency of 65% (LHV) of PEM in 2030 (CE Delft, 2018)) & ammonia synthesis plant (assuming an electricity use of 640 kWh/tonne (Morgan, 2013)). |
| Estimated global renewable electricity production in 2040 | 15,000 | 30,000 | TWh/ year | Low and high value of various global scenarios shown in Table 9 (interpolated from 2030 and 2050). |
| Required electrolyser capacity for green ammonia production to supply the entire global maritime shipping sector in 2040 | 1,400 | 2,300 | GW | 4,000 full-load hours of electrolyser assumed |
| Planned electrolyser capacity worldwide for delivery by 2040 | 213.5 | | GW | Pipeline of projects planned for delivery by 2040 globally. Of the 213.5 GW, 113 GW is at the development or operational stages (Aurora, 2021). |

Note: The global renewable electricity production in 2018 was about 6,600 TWh (IRENA, 2020).

### 2.3.3 Link with other sectors

Maritime shipping's share of total global energy consumption is limited (about 1.6% in 2019); its global energy demand was about 10 EJ/year (IRENA, 2021), whereas global primary energy consumption was 624 EJ/year (Roser, 2017).

If only global oil consumption is considered, the maritime sector has a higher share: in 2018, 6.8% of global final consumption was from navigation (IEA, 2020)

Industry (petrochemical, iron and steel, minerals, etc.), the residential sector, agriculture and fishing, the commercial and public services sectors and road transportation all have higher shares of global energy consumption than the maritime sector.

All sectors are faced with the challenging task of moving towards net zero GHG emissions by 2050. And for all sectors, renewable electricity from wind, as well as solar, hydro and geothermal energy are all attractive transitional alternatives to fossil fuels.

Renewable electricity could be used directly, for example by electric road vehicles or electric boilers and furnaces in the process industry, or indirectly, by producing e-fuels such as hydrogen, methane, methanol, diesel and kerosene. Therefore, it is almost assured that the shipping will compete with these other sectors for the use of renewable electricity and green hydrogen. The current ammonia production of 235 Mt which is in its majority used for agricultural purposes may grow in the future and, similarly to shipping, it would need to undergo a transition to green ammonia. Even though there should be enough renewable energy to cover for the forecast demand of green ammonia for shipping in 2040, if the current production of ammonia currently directed to agriculture is shifted towards green ammonia, this will increase the challenge to supply green ammonia to shipping. It is worth mentioning that there could also be a prioritization of resources between different sectors of the industry, i.e., agriculture, shipping, industry.

Theoretically, there are more than enough suitable locations to produce renewable electricity to meet global energy consumption. However, there is a limit to the speed at which economies can build solar and wind farms, conversion systems and transport and distribution infrastructure. Workforces, construction equipment, available capital and the minimum duration for permitting and project development processes are all constrained.

If the growth of renewable electricity production trails the demand for renewable electricity, scarcity will raise electricity prices, potentially making the production of green ammonia (or an alternative e-fuel) too expensive to be a viable alternative to fossil marine fuels, especially if other sectors are willing to pay more.

To secure the availability of renewable electricity, the maritime shipping sector could participate in the development of wind and solar projects, in return for a guaranteed share of renewable electricity. Some initiatives are being put forward in that direction (Seroff, 2020; Maersk, 2022), which demonstrates increased awareness of these issues in the shipping industry.

### 2.3.4 Availability Conclusions

To realise large-scale production of green ammonia for maritime shipping, the production capacity of renewable electricity, green hydrogen and green ammonia need to undergo tremendous growth; the current global capacity of wind and solar farms - and especially electrolysers and green ammonia plants - are relatively low.

Renewable electricity will be produced at locations around the globe that have favourable conditions of wind and solar irradiation. The potential cost savings from this are expected to easily outweigh the additional costs from the long-distance transport of renewable energy carriers.

The anticipated worldwide availability of renewable electricity in 2040 appears sufficiently large to produce green ammonia (using electrolysis and Haber-Bosch synthesis) for the entire global maritime fleet. However, the shipping sector will compete with all other sectors for renewable electricity and green hydrogen; likely the agricultural section will also come under pressure to decarbonise, adding additional demand for green ammonia.

In addition, there is a limit to the speed at which economies can build infrastructure, especially solar and wind farms, ammonia plants and transport and distribution infrastructure, which will restrict the availability of green ammonia, especially in the short to medium terms.

The pace at which the production of green hydrogen (and ammonia) will increase, and scale will be one of the driving forces to the uptake of ammonia as a fuel and its price. The scaling of the production passes through a decentralisation of production towards regions where there is availability of green energy sources (solar, wind and others). For international shipping this would require the development of new or adaptation of existing bunkering facilities to accommodate ammonia (further discussed in section 2.3.4). Scaling can also be improved by an increased reliability and efficiency of hydrogen and ammonia production reaching higher efficiency than the current ones (as discussed in section 2.1).

On top of it, the role of market forces and regulations to push the demand for green fuels is mandatory as further explained in section 2.5.

## 2.4 Suitability

Ammonia has the potential to be a fuel for the shipping sector in the longer term due to its zero-carbon content and its ability to be produced from renewable sources. It has a track record of being stored and distributed by land- and marine-based sectors, which use it as a commercial chemical product, fertiliser and refrigerant. These sectors have solutions for challenges with toxicity and material compatibility and their experience can be adapted to help use it as a marine fuel.

Recent regulatory developments for the use of low-flashpoint fuels and gases in the marine sector, together with experience from the use of cargoes such as LNG, ethane, LPG and methanol as fuel in the bulk transport sector, indicate the foundations for its use in the marine fleet are already in place.

This section will highlight some of the principal technologies and systems presently used to carry and combust ammonia in the marine sector, the technologies deployed for burning other low-flashpoint fuels and gases, and how these are enablers can be applied to support ammonia's use a marine fuel.

### 2.4.1 Storage, Distribution and Production

There is significant experience from the land-based sector with the production, storage and distribution of anhydrous ammonia. Ammonia is currently widely used in other industries and in the agricultural sector and therefore it has been handled in large quantities for the past decades. Consequently, there is a high level of maturity for the storage and distribution of ammonia in the industry. Currently, 25-30 million tonnes of ammonia are transported by road, trains, ship or by pipelines among which 18-20 million tonnes are carried by ship (IRENA, 2022) (40 LPG Carriers).

The most significant storage issue relates to stress corrosion cracking (SCC) in pressure vessels made of carbon steels. After the second world war, the U.S. agricultural industry used a method for injecting liquefied ammonia directly into the soil as a direct source for nitrogen fertilisation. This led to the development of the U.S. ammonia pipeline-distribution system and significant experience in storage of ammonia in pressure vessels in the agricultural sector. While liquefied ammonia had been used in the refrigeration and chemical sectors without significant difficulties, inexplicable ruptures of ammonia containers started to occur soon after introduction to the agricultural sector (Loginow, 1989).

In the 1950s, these failures were found to be caused by SCC and the U.S. National Association of Corrosion Engineers (NACE) recommended Department of Transportation (DOT) regulations to prevent such failures.

While failures are attributable to several factors linked to the grade or quality of the ammonia, material composition and production or repair practices, the recommendations still form the basis for the safe storage of anhydrous ammonia in carbon-steel pressure vessels.

These recommendations included the selection of lower strength steels, ensuring that pressure vessels were fully stress relieved, measures to eliminate air contamination and the retention of small quantities of water (0.1%-0.2%) within the ammonia to inhibit SCC and reduce the concentration of oxygen (United States, 2013; Liv Lunde, 1987). These principles are applied to the carriage of anhydrous ammonia in carbon manganese steels under the IMO IGC Code (*International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk*) – see section 3.2 of this report, issued in 1986.

The ability to store ammonia in a liquefied state at pressures of approximately 17 bar (or $-33^0$C) is a significant advantage compared with other gaseous fuels such as LNG – see Table 11. It enables storage in carbon manganese or low nickel steels, which are cheaper. The IGC Code requirements provide an established marine reference for ammonia storage in tanks manufactured from these steels.

The IGC Code requirement (under 17.12.6) specifically prohibits the use of nickel steels containing more than 5% nickel. For obvious commercial reasons, it is typical for designers and specifiers to select the cheapest materials suitable for the application. The Code applies the material storage requirements with respect to the specific conditions in which the product is stored, so it has more detailed requirements at cryogenic temperature thresholds from $-55^0$C to $-165^0$C for LNG.

It does not envisage the storage of ammonia in stainless-steel tanks, or it has differentiated specifically to restrict application of nickel steels; effectively the use of stainless steels containing chromium and nickel (such as 304 or 316 types) is unclear because of its high price and because there are ways to mitigate for SCC. The use of these stainless steels may be common in refrigerant piping and similar applications for ammonia, but data substantiating their use for bulk storage seems limited.

This requirement may only be an issue for designs that require these materials for other products at lower cryogenic temperatures, which intend to switch to ammonia at a later date. The British Stainless Steel Association notes that *"… It has been assumed that there is no corrosion risk to stainless steels that are normally considered for the storage and handling of bulk ammonia (i.e., 304 or 316 types), although there does not appear to be any published data to substantiate this. …"* (BSSA, 2022). Further, the Nickel Institute notes that the usage of steel types 304 and 316 are recommended in applications where freedom from corrosion products is essential and they have been in use in ammonia production plants (American Iron and Steel Insitute, 1978).

See section 3.2 of this report for more information on the approval of alternative materials under IMO's IGC and IGF Codes.

An additional advantage for ammonia is that the IGC Code requirements for storage allow ammonia to be carried in gas carriers designed for transport of LPG. There are currently about 2,228 gas carriers in service, 701 of which are LNG carriers, and there are 1,527 LPG carriers. Of those LPG carriers, 856 have capacities at or below 10,000m$^3$ – see Figure 5 – a size suitable for use as bunkering ships. Of those LPG carriers, about 167 are shown as capable of carrying anhydrous ammonia, making them suitable for an ammonia-bunkering fleet. Therefore, in case there is an uptake of Ammonia as a fuel for marine application, the existing infrastructure for LPG storage could be used for Ammonia and the vessels that are designed for the transport of LPG.

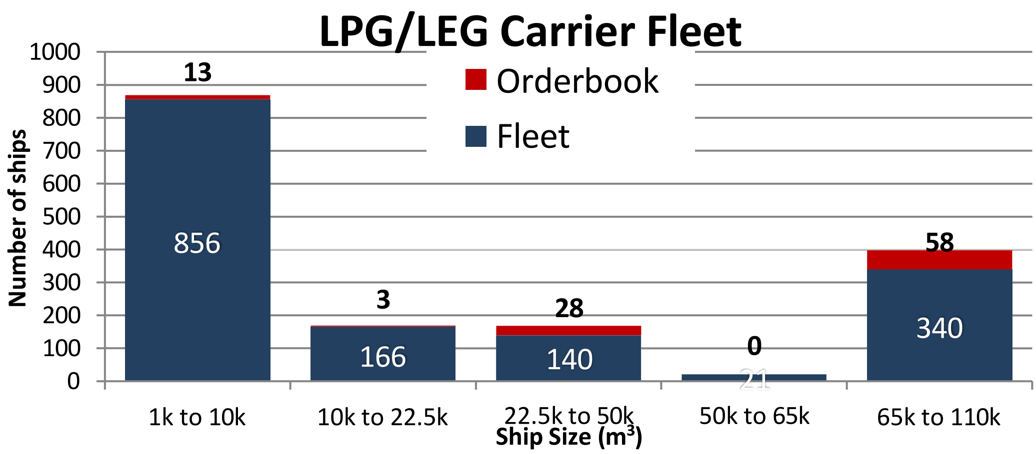

Figure 5. Current Global LPG/LEG Carrier fleet

Most of the production requirements are highlighted in section 2.3, where requirements for the location of the ammonia-production facilities are detailed. In addition to these, pertaining to the distribution, the proximity to ports or to a pipeline grid connection is also to be considered as important. This is to ensure feasible and rapid distribution of Ammonia at a lower cost (Nami, Butera, Campion, Frandsen, & Hendriksen, 2021) and lower the risk to stop the production of ammonia for lack of security in the distribution.

### 2.4.2 Onboard Fuel Supply

While no ammonia-fuelled marine engines or fuel supply systems are available, there are similarities with the fuel-supply systems that have entered the market for LNG, methanol, ethane and, particularly, LPG. These designs could form the starting point for ammonia systems.

Using low-flashpoint fuels and gases introduces complexity to the fuel supply and consumer systems, and there is a greater interdependence between their key systems than with conventional fuel systems. The purpose of the fuel gas supply system (FGSS), or fuel supply system (FSS), is to deliver fuel at the correct temperature and pressure to the engine or consumer.

For gaseous fuels using refrigeration or pressurised liquefied storage, such as LNG, ethane, LPG or ammonia, the fuel may be pumped or pressure fed directly in liquid form from the fuel-storage tank to the FSS.

For engines using gaseous fuels -- such as low-pressure Otto combustion process or high-pressure Diesel combustion process engines that burn methane -- the FSS may use pump and vapouriser systems to raise the pressure and temperature of the liquefied fuel to the required gaseous state, or the boil off gas vapour can be compressed to the same state. These systems can require significant energy input, either for running compressors or for the heat-exchange purposes.

Table 11. Key properties, required storage capacity and supply conditions of alternative fuels

| FUEL | Fuel Properties | | | | | | | Storage | FGSS/FSS |
|---|---|---|---|---|---|---|---|---|---|
| | Storage Conditions (liquid state) | | Specific Energy (MJ/kg) | Energy Density (MJ/L) | Carbon Content | $C_F$ (t-$CO_2$/t-Fuel) | kg $CO_2$/kWh | Fuel Tank Volume Compared to MGO (not including insulation and secondary barriers, as applicable) | Supply Pressure (bar) |
| | Temperature | Pressure | | | | | | | |
| **MGO** | atm | atm | 42.7 | 38.4 | 0.8744 | 3.206 | 0.2701 | 1 | 8 |
| **LNG** | -162C | atm (or pressurised ~5-10 bar) | 48 | 21.6 | 0.75 | 2.75 | 0.2061 | 1.8 | 300 (Diesel)<br>5 ~ 13(Otto) |
| **Ethane** | -89C | atm (or semi-ref ~ 5 bar) | 47.8 | 27.2 | 0.7989 | 2.927 | 0.2205 | 1.4 | 380 (Diesel) ~ 5 (Otto) |
| **Methanol** | atm | atm | 19.9 | 15.7 | 0.375 | 1.375 | 0.2486 | 2.4 | 10 |
| **LPG** | -48C (Propane) | atm (or fully pressurised up to 18 bar) | 46.3 (Propane)<br>45.7 (Butane) | 23.2<br>27.4 | 0.8182<br>0.8264 | 3.00<br>3.03 | 0.2331<br>0.2385 | 1.7<br>1.4 | 50 |
| **Ammonia** | -33C | atm ( or fully pressurised up to~ 18 bar) | 18.6 | 12.9 | N/A | N/A | N/A | 3.0 | 83 |

If the fuel is maintained in a liquid state, the systems required can be simpler than gaseous ones. The MAN Energy Solutions (MAN ES) 2-stroke DF range of engines uses the diesel-combustion process for oil, gas and alternative fuel modes. This range includes the 'ME-LGI' variant, which burns methanol and LPG -- the 'ME-LGIM' and 'ME-LGIP' engine types -- and uses a FSS similar to conventional fuel oil supply systems.

The fuel is supplied by a low-pressure system (10-50 bar) to the fuel injector, where the high pressures required for injection are generated by the engine pump injector, the fuel booster injector valve. For ammonia applications, the engine currently under development (ME-LGIA) is expected to require an FFS pressure of about 80 bar.

The FSS pressures for the MAN-ES range of DF engines, energy-related properties of the alternative fuels and corresponding sizes of the fuel tanks are shown in Table 11.

The key elements for the FSS are the fuel storage tank, FGSS and the safety-valve system, commonly known as gas valve unit (GVU), gas valve train (GVT), or for the liquid fuels fuel valve train (FVT).

A simplified arrangement for the MAN ES ME-LGIA engine showing a pressurised fuel tank with submerged supply pump, an FSS with high-pressure (80 bar) pump and the supply and return safety double block and bleed (DBB) valves is shown in Figure 6. For an Otto-cycle arrangement, Figure 7 shows low-pressure ammonia vapour (5-10 bar) being generated and injected in the combustion chamber.

Note that this system is similar to the one applied for LPG with the 'ME-LGIP' engine, but notably includes an additional 'ammonia recovery and catching' system designed to maintain a closed fuel system with no venting into the atmosphere due to ammonia's toxicity issues.

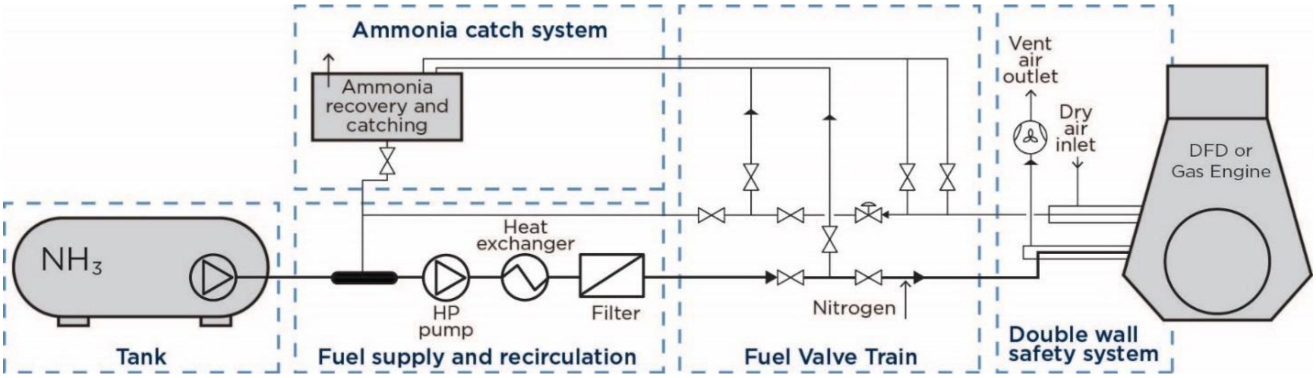


Figure 6. Schematic of the Fuel Supply System of a 2-stroke Diesel-cycle Ammonia Engine

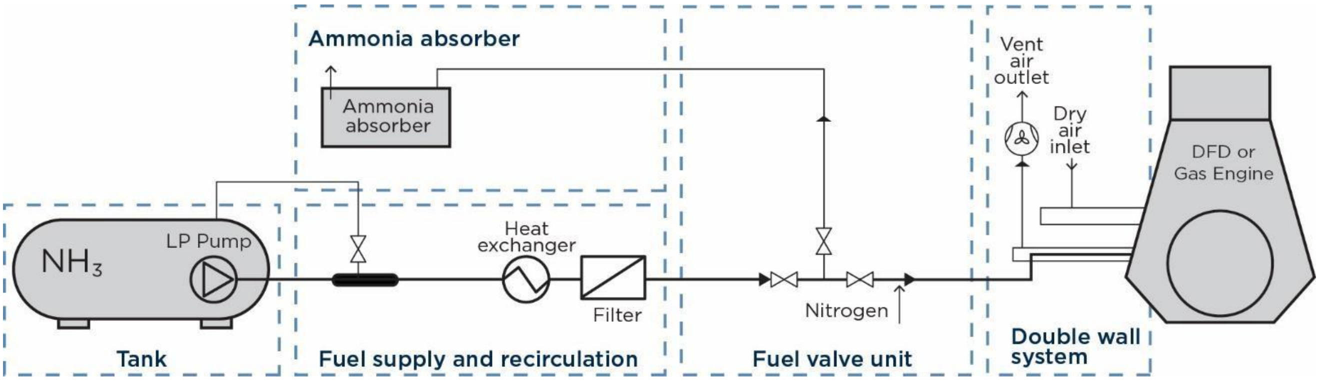


Figure 7. Schematic of the Fuel Supply System of a 2-stroke Otto-cycle Ammonia Engine

The basic arrangement for an ammonia FSS is similar to that used for LPG. The key changes are those to accommodate the additional capacity required for the lower energy content, possible material differences and the recovery and treatment system that is designed to prevent venting. In both engine types, an ammonia absorber or recovery and catch system (intrinsically the same technology) will be needed to limit the dispersion of ammonia vapour in and around the location where the vent mast is placed. This system is likely to be used for pipe purging during an emergency shut down. However, there will be occasions where the main engine will not be operating and excessive boil-off will need to be treated by either a Gas Combustion Unit (GCU)/boiler or a reliquification plant.

Questions remain for this aspect of the design, since it may require significant storage volumes or scrubbing systems. Ammonia is extremely harmful to aquatic life, so land-based regulations provide strict water-quality control criteria to limit the impact of ammonia releases – see subparagraph 3.4.1.

It is anticipated that holding tanks and reception facilities may be required for discharge ashore and regulatory limits for water (and air) discharges may be needed.

### 2.4.3 Internal Combustion Engines

Methane has been used as a fuel on LNG carriers for more than 60 years, originally in boilers for steam turbine propulsion. From around the year 2005, it was used in internal combustion (IC) engines in a dual-fuel diesel electric (DFDE) propulsion arrangement; also in 2015, the twin skeg, 2-stroke slow speed DF direct drive propulsion layout entered the market, and it is now the dominant propulsion choice, primarily due to the higher efficiencies it offers.

In 2000, the first gas (methane) only internal-combustion (IC) engine installations on ferries in northern Europe began replacing conventional fuel-oil burning engines to take advantage of the lower NOx emissions from the Otto-cycle engines. With approximately 220 LNG-fuelled ships (excluding gas carriers) now in operation, the adoption of this technology has not reached large numbers and its challenges with methane slip makes them an unlikely long-term solution.

However, at the time of publication, there were 136 LNG-fuelled ships on order[6] and the existing LNG-fuelled fleet had supported the development of DF engine technologies for other low-flashpoint fuels and gases and given rise to the regulatory framework for adopting the alternative fuels.

The first 2-stroke slow speed DF engines orders for the non-gas carrier fleet were the MAN ME-GI engines for the U.S. flagged *Isla Bella* for Tote Maritime, a 3,100 TEU containership that entered service in early 2016. This engine design utilises high-pressure gas injection of approximately 300 bar. It also uses the Diesel combustion cycle in gas mode, rather than the Otto cycle utilised on the 4-stroke engines, and the competitor 2-stroke engine from Winterthur Gas & Diesel (WinGD).

## Combustion Cycles

The choice of combustion cycle is significant for engine and FSS design, performance and emissions. The two different concepts are low-pressure (LP) gas engines using the Otto cycle and high-pressure (HP) gas engines using the diesel cycle.

The LP DF engines use the Otto process in gas mode and the conventional Diesel process when in oil mode. The HP DF engines use the Diesel combustion process for oil and gas modes. For both concepts, the gas is ignited by a pilot injection of liquid fuel from the conventional fuel-injection system, or a dedicated pilot system.

Table 12. Comparison between Low-Pressure and High-Pressure DF engines

| | **Low-Pressure (LP)** | | **High-Pressure (HP)** | |
|---|---|---|---|---|
| **Gas mode cycle type** | Otto | | Diesel | |
| **Gas injection / Combustion principles- methane and ammonia** | LP gas admission valves located on the cylinder for pre-mixed gas/air and in-cylinder compression (diesel pilot fuel required for start of combustion) | | HP gas injection valves located on the cylinder cover for direct gas injection into the cylinder for diffusion combustion (diesel pilot fuel required for start of combustion) | |
| **Fuel** | Methane gas | Ammonia (guid. values) | Methane | Ammonia (guid. values) |
| **Fuel supply pressure** | ~5 bar (4-stroke) <13-16 bar (2-stroke) | 5-16 bar | 300 bar | ~80 bar |
| **Injection pressure** | Same as supply pressure | Same as supply pressure | Same as supply pressure | 500-700 bar |
| **Liquid pilot % @MCR** | 0.5 – 1.0 | 15 - 30 | 0.5 – 1.5 | 5-10 |
| **BMEP [bar]** | 17.3 | 17 | 21.0 | 21.0 |
| **Min load for DF mode [%]** | ~5 | ~30 | ~5 | ~15 |
| **IMO NOx Compliance** | Tier II (oil mode) Tier III (gas mode) | Tier II (oil mode) Tier II (ammonia mode) | Tier II (oil mode) Tier II (gas mode) | Tier II (oil mode) Tier II (ammonia mode) |
| **Fuel Quality Sensitive** | Yes - Requirement for Methane Number | Yes | No | No |
| **Fuel Slip** | Yes | Yes | Insignificant | Insignificant |
| **Knock/Misfire Sensitive** | Yes | Yes | No | No |
| **Load response** | reduced | reduced | unchanged | unchanged |

The point during the combustion cycle where the gas is injected dictates the supply pressure that is required for the gas. The dual-fuel and single-fuel 4-stroke engines currently in operation use the Otto cycle with gas-supply

[6] ABS Zero Carbon Outlook, Setting the course to Low Carbon Shipping, 2022

pressures of approximately 5 bar. The 2-stroke DF high-pressure ME-GI engine delivers the gas by a direct-injection system at approximately 300 bar; for the low-pressure X-DF engine it is about 13 bar.

The different combustion concepts have distinct burning profiles. The Otto cycle engine burns the fuel in pre-mixed combustion, whereas the diesel cycle engine burns it in a diffusion-combustion process. The diffusion flame has the advantage of operating on a wide range of gaseous fuels; for this reason, it is predominately being used for large 2-stroke marine engines.

As indicated by the table above, the Otto combustion cycle has some limitations in terms of maximum Brake Mean Effective Pressure (BMEP) and is susceptible to gas quality, ie., the methane number (MN), which is an indicator of combustion derived from the composition of the natural gas. Furthermore, the Otto cycle process is subject to significant methane slip. While its combustion limitations are manageable for methane natural gas applications, they become more difficult to apply as a commercially competitive marine engine package for the other gaseous and low-flashpoint fuels under consideration.

This fact is acknowledged by Wärtsilä (Jay et al 2019), which states that: *"… Wärtsilä gas diesel history goes back to the 1990s, and it can be claimed this new development is an extension to LPG experiences within the company … The selection of the diesel engine rather than the Otto concept fits the need for fuel flexibility, avoidance of knock and common engine output rating whether using LFO [Light Fuel Oil] backup fuel, or low viscosity fuel."* It details Wärtsilä's laboratory experiences with the new W6L32LG engine design, using DF technologies and the diesel combustion cycle for all intended fuels.

**References**

For engines that are presently operating, both combustion concepts have been selected for methane. There are some examples of the Otto process being used to burn ethane or LPG, but with significant engine de-rates due to its combustion limitations with fuel slip, knock and misfire. The diesel cycle has been applied for burning methanol by MAN and Wärtsilä; MAN also has used the diesel cycle for ethane and LPG.

For fuels that can be maintained in a liquid state to the engine, MAN ES has developed the DF technology in order to move away from gaseous HP injection, with the engine designed to inject HP liquid fuels through a dedicated liquid fuel injector. This technology is applied for methanol, LPG, dimethyl ether (DME) and other similarly nominal liquid fuels at ambient or low-pressure conditions such as ammonia. The technology has been given the engine designation 'ME-LGI'. Figure 8 shows the main engine components for the MAN ES ME-LGIA ammonia engine design.

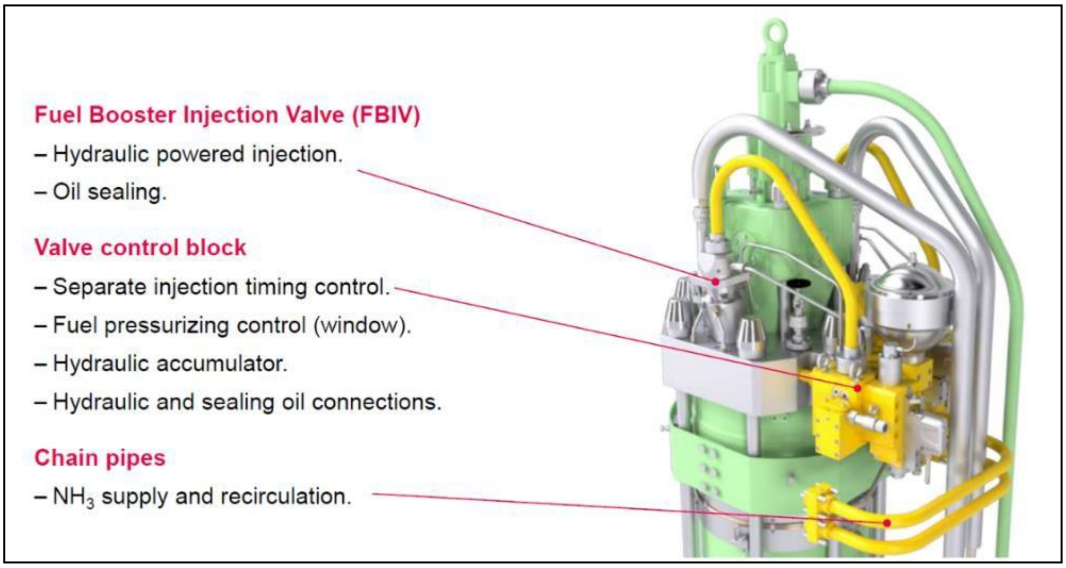


Figure 8. Main engine components of the MAN ES Ammonia 2-stroke engine (ME-LGIA)

Table 13 shows the main alternative fuel marine engine types and combustion cycles in service and under development, with the associated low-flashpoint fuels and gases they are designed to burn.

Table 13. Marine Engines in Service and under development, as per the different Alternative Fuels

| Engine Type | Layout | Alternative Fuel | Combustion Cycle | Year of first engine delivery (*expected) |
|---|---|---|---|---|
| MAN B&W ME-GI | 2-stroke, slow speed | Methane | Diesel | 2014 |
| WinGD X-DF | 2-stroke, slow speed | Methane | Otto | 2016 |
| Wärtsilä DF | 4-stroke, medium speed | Methane (Ethane, LPG) | Otto | 1995 (Methane) |
| MAN | 4-stroke, medium speed | Methane | Otto | 2016 |
| Wärtsilä GD (legacy engine) | 4-stroke, medium speed | Gas-Diesel | Diesel | 1987 |
| Wärtsilä SG and LG (land based only) | 4-stroke, medium speed | LPG | Otto (SG) Diesel (LG) | 1996 |
| MAN B&W ME-GIE | 2-stroke, slow speed | Ethane | Diesel | 2016 |
| MAN B&W ME-LGIM | 2-stroke, slow speed | Methanol | Diesel | 2015 |
| MAN B&W ME-LGIP | 2-stroke, slow speed | LPG | Diesel | 2020 |
| Wärtsilä (conversion) | 4-stroke, medium speed | Methanol | Diesel | 2015 |
| Himsen (under development) | 4-stroke, medium speed | Methanol | Diesel | 2023* |
| MAN B&W ME-LGIA (under development) | 2-stroke, slow speed | Ammonia | Diesel | 2024* |
| Wärtsilä DF (under development) | 4-stroke, medium speed | Ammonia | Otto | 2023* |
| Wärtsilä LG (under development) | 4-stroke medium speed | Ammonia | Diesel | 2025* |
| Himsen (under development) | 4-stroke, medium speed | Ammonia | Diesel | 2024* |
| MAN-ES | 4-stroke, medium speed | Ammonia | Diesel | 2026* |

**Research and Development**

Engine designers are currently investigating both combustion concepts but due to the fuel slip issues inherent with the Otto cycle process, difficulty in initiating the combustion of ammonia and its slow burn characteristics, the Diesel cycle is thought likely to be the most suitable combustion concept; in fact, it is in the process of being selected by MAN-ES for their ME-LGIA[7] engine.

Its selection builds directly on the experience with the LPG-fueled engine design, but also the DF experience gained with methane, ethane and methanol. MAN-ES is also investigating burning ammonia in its 4-stroke engine designs[8].

Wärtsilä is investigating both combustion concepts[9], including blending ammonia with methane in the Otto (or Diesel) cycles to reduce $CO_2$ emissions.

Hyundai, from Korea, is developing its Himsen engine in several sizes to use ammonia in the diesel cycle for their 4-stroke engine.

[7] MAN-ES Presentation "Propulsion of ships towards 2050 – Decarbonisation / Ammonia as a fuel", Michael Jeppesen, Atena, Genova Webinar, 2020.
[8] AmmoniaMot project as per MAN-ES press release in April 2021
[9] Wartsila Presentation "Multi-Fuel Engines for Future Propulsion", Frank Harteveld Motorship, Propulsion and Future Fuels Conference, Copenhagen , 2021

**Conclusions**

No showstoppers are anticipated in the use of ammonia as a combustion fuel in IC engines, but the amount of pilot fuel, and levels of NOx, $NH_3$ slip and $N_2O$ emissions have yet to be quantified. Marine engine makers generally agree that initially the Diesel cycle is found to be best suited for combustion of ammonia, but research is ongoing for both combustion concepts. Optimising the emissions is foreseen as being a challenge, and control of $N_2O$ and ammonia slip requires high temperature combustion, however high temperature combustion also generates high NOx levels.

Pilot fuel is necessary to ignite ammonia but also needed to keep combustion stable. Although, it is a common challenge for all the engine makers, they expect that IMO Tier II level may be met without any abatement system. For the smaller engines 10% pilot fuel is expected after engine optimisation and after longer service experience, for the bigger 2-stroke engines, then just 5% pilot fuel is targeted.

The actual amount of $NH_3$ and $N_2O$ emissions is therefore still to be seen, however the emissions are expected to be low, particularly for the Diesel combustion cycle. Even so, with $N_2O$ having a 20-year global warming potential (GWP) of 264 and a 100-year GWP of 298, the emitted levels may negate much of the $CO_2$ benefit of using ammonia as a fuel; this remains a potential barrier to adoption.

IC engines that burn ammonia are therefore expected to require existing aftertreatment technologies, such as SCR (Selective Catalytic Reduction) to control $NH_3$ slip and possible additional catalysis to control $N_2O$, both of which are available technologies.

To provide clarity for engine developers and support the adoption of ammonia as a fuel, regulators should consider either adding to their regulatory frameworks for air pollution or developing new ones that will limit the $NH_3$ and $N_2O$ emissions from IC engines that burn ammonia. While this is most easily implemented at international level through the IMO, the introduction of regional (or local) limits through the European Parliament may be quicker and stimulate the process at the IMO.

The limits already in place in land-based emission control regimes to control $NH_3$ slip from IC engines fitted with SCR systems; i.e., the 10ppm limit applicable to heavy duty diesel engines in the Euro VI limits, would provide a control level that may be appropriate for the control of marine IC engines.

### 2.4.4 Machinery Spaces

No showstoppers are anticipated for the machinery spaces around the application of ammonia as fuel, provided the established double-barrier principles for fuel-supply piping are applied. The conventional ‘gas-safe’ or non-hazardous machinery spaces, which are currently applied for all the other low-flashpoint fuels and gases, are expected to be suitable for ammonia with minor changes, including providing the appropriate PPE and operational procedures.

The fire and explosion risks are still to be considered for ammonia, but the toxicity risk will dictate the selection of the type of gas detector and the subsequent alarm levels. Typically, machinery space releases from the double-barrier fuel piping are identified during HAZID risk studies, for example, for dropped object or fatigue failures. But they are thought to be at an acceptable risk level since they are low probability, high consequence events that are brought in line with ALARP levels by the requirements of safety and design regimes.

Provisions for the location of PPE, such as placing emergency escape breathing devices (EEBD) in the machinery spaces may be a typical HAZID recommendation for ammonia as fuel.

In spaces where leak sources potentially exist, such as in fuel-preparation rooms containing pumps, compressors, valves, single-wall piping, etc., the likelihood of release is higher and will require additional safety features and operational safeguards.

For many years there have been rules from Classification Societies in place for the spaces where ammonia releases may occur from refrigeration equipment, such as on reefer ships or fishing vessels. These additional requirements, such as increased ventilation or water-deluge systems, may be appropriate for such ammonia FSS spaces; emerging guidelines and rules from Classification Societies for ammonia are already starting to provide prescriptive requirements for these spaces. See also subparagraph 3.2.6 of this report for more information on IACS’ requirements.

See section 4 for more information on the risks of using ammonia as a fuel and a summary of the risk-assessment case studies undertaken for this study.

### 2.4.5 Fuel Cells

A fuel cell is a device that converts chemical energy from a fuel into electricity through an electrochemical reaction of the fuel with oxygen or another oxidising agent. Fuel cells differ from batteries in that they require a continuous source of fuel and oxygen (usually from air) to sustain the chemical reaction; a battery's chemical energy is fixed by the amount of chemicals in the battery.

Fuel cells can produce electricity continuously if fuel and oxygen are supplied. There are many types of designs for fuel cells. Most consist of an anode, cathode and an electrolyte that allows positively charged hydrogen ions to move from the anode to the cathode side of the fuel cell. Their main benefits are increased energy efficiency, low to zero emissions and lower noise levels.

Fuel cells are generally classified by the type of electrolyte used in the electrochemical process. The main fuel cells available today include PEM, Alkaline Fuel Cells (AFC), Phosphoric Acid Fuel Cells (PAFC), Molten Carbonate Fuel Cells (MCFC) and Solid Oxide Fuel Cells (SOFC). See Table 14 for the operating temperatures and typical applications for these fuel cells. Refer to the EMSA '*Study on the Use of Fuel Cells in Shipping'* (Tomas Tronstad, 2017)for more information on marine fuel cells.

Table 14. Types of Fuel Cells and their Applications

| Type | Operating Temperature | Applications |
|---|---|---|
| Proton Exchange Membrane (PEM) | 30-120C | Vehicles and mobile applications and lower power Combined Heat and Power (CHP) systems |
| Alkaline Fuel Cell (AFC) | 100-250C | Used in space vehicles |
| Phosphoric Acid Fuel Cell (PAFC) | 150-220C | Large numbers of 200kW CHP systems in use |
| Molten Carbonate Fuel Cell (MCFC) | 600-700C | Suitable for medium to large scale systems |
| Solid Oxide Fuel Cell (SOFC) | 650-1000C | Suitable for all sizes of systems |

The fuel cell uses hydrogen as the mobile ion, which is typically produced on a continuous basis by converting a hydrocarbon fuel, such as methane or methanol, in a close coupled fuel reformer to produce a hydrogen, or hydrogen-rich, fuel source. They offer minimal hydrogen storage, for process purposes only. While offering lower efficiencies, this limitation avoids the complication of hydrogen storage and distribution systems.

With ammonia being a more volumetric (and cost) efficient means of transporting the hydrogen molecule, or energy vector, there are potential benefits from using ammonia as the fuel source for fuel cells. While the use of low-temperature Direct Ammonia Fuel Cells (DAFC) dates from the 1960s, ongoing research (Abbasi, et al., 2020) and the availability of direct or indirect ammonia fuel cells suggest it holds great promise as an alternative source of marine power generation, one that creates zero emissions. See Figure 9 for the electrochemical process for a DAFC.

As with all fuel cell and reformer applications, the specific technology will require monitoring for leakage of unreacted gases from the fuel-reforming or electrochemical processes. This may require further processing or catalysis control for safety reasons, or to meet (yet to be developed) regulatory limits. For a DAFC system, the concern about unreacted gases relates to $H_2$ and $NH_3$.

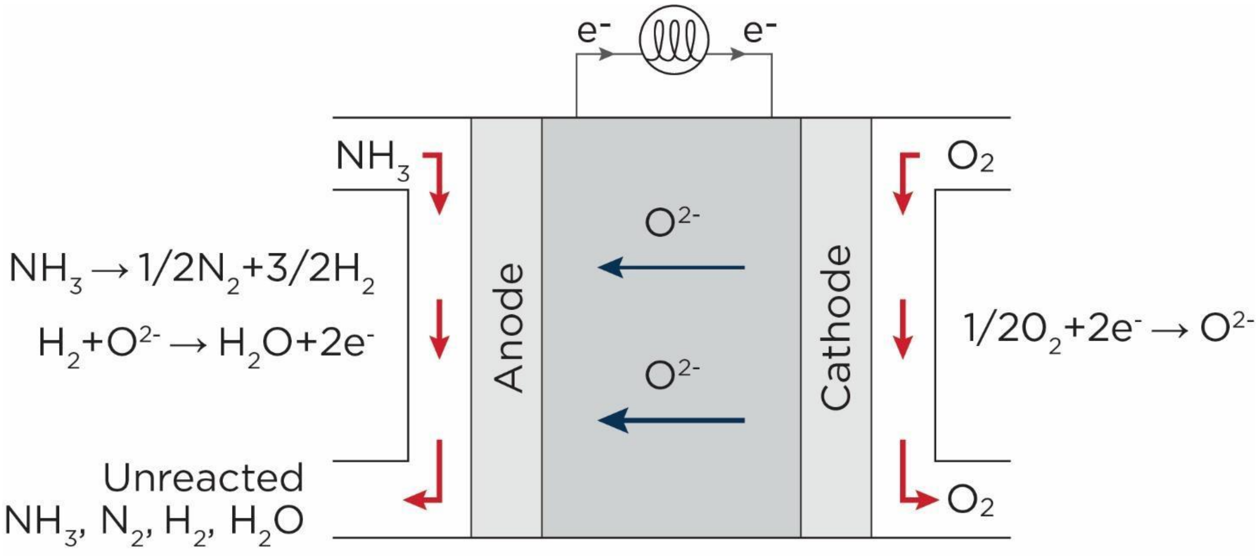


Figure 9. The electrochemical process for a DAFC (Jeerh et al 2021)

### 2.4.6 Emissions and Air Pollution

See subparagraph 3.2.2.2 for the international regulations for air pollution under MARPOL Annex VI. As highlighted in subparagraphs 2.2.1 and 3.2.2.2, burning ammonia in IC engines offers some significant benefits for reducing SOx, HC, PM, CO and $CO_2$.

However, questions remain about the impact on these emissions from factors such as the amount of pilot fuel required, the type of combustion cycle and the engine's design features. The control of NOx emissions from international shipping is regulated through Annex VI regulation 13, but $NH_3$ slip can be anticipated and would need to be controlled in the same way as $NH_3$ slip from IC engines fitted with SCR aftertreatment systems.

The potentially showstopping $N_2O$ emissions from IC engines will require careful monitoring during the engine-development stages and may require aftertreatment catalysis to control. It also will need the regulators to define limits if ambitions for reducing overall gaseous pollutants and GHG emissions are to be achieved.

IC engines are suited to burning ammonia but their unavailability at present introduces 'unknowns' in terms of performance and emissions, so some significant challenges remain. While IC engines will offer a significant reduction for some pollutants, they will not offer a complete reduction of emissions to air.

The greatest potential for reduction of all these emissions to air could come from using fuel cells. They offer the potential to eliminate emissions of all the gaseous, PM and GHG emissions from power generation, especially the direct $NH_3$ fuel cell conversion; the main emissions from the electrochemical process are $N_2$, $H_2O$ and $O_2$. However, at this point it is unknown whether NOx and $N_2O$ will form in the electrochemical reaction in a fuel cell. It has been found that in some types of fuel-cell technologies the appearance of NOx can be observed (Georgina Jeerh, 2021). As their development progresses, however, these aspects are expected to be mitigated.

### 2.4.7 Suitability Conclusions

While ammonia is not currently used as a fuel by oceangoing ships, it is widely regarded as a fuel of the future. Reviews of storage and distribution on land, onboard storage, conversion in either an IC engine or fuel cell have not revealed insurmountable barriers to its use as a fuel.

While ammonia is toxic and can harm the environment, the associated health, safety and environmental risks can be managed. The ongoing design developments and risk studies indicate a tendency towards solutions which fully contain ammonia in the case of a failure.

Several research-and-development projects are ongoing which will further the technology understanding and support the development of standards and guidelines for its use as a fuel. When those instruments have been developed, and the technologies reach the required TRL level, the conditions will be set for ammonia's use as a marine fuel.

In principle, ammonia is considered suitable as a marine fuel.

## 2.5 Cost developments and Techno-Economic Analysis

This section describes the cost developments for ammonia-powered ships in analyses that consider 'green' and 'blue' ammonias. Green ammonia is produced with renewable electricity, which also uses hydrogen that is generated with renewable electricity. Blue ammonia is produced with hydrogen from steam-reformed natural gas, and the $CO_2$ emissions from the process are captured and permanently stored geologically.

The total cost of ownership (TCO) is highlighted for the years 2030 and 2050. The TCO is a sum of the annuities of capital expenditures (CAPEX), fuel cost and annual operational expenditures (OPEX) and is calculated for the ship types and size categories defined in the Fourth IMO Greenhouse Gas Study 2020 [25]. The specifications of these cost elements are outlined in the forthcoming section.

The assumptions and input for the TCO model calculations are outlined in Appendix V - Input figures of TCO modelling and longlist of TCO for ammonia powered ships. Calculations for retrofitting ships to use ammonia as a fuel are based on actual retrofit cases[10] and expert cost estimations. These figures also serve as an indication of retrofit costs.

The following two sections (2.5.1 and 2.5.2) offer the methods and definitions for the capital and operational costs, which serve as input for the TCO model calculation for newbuild ammonia-powered ships. After the outline of all cost aspects, the method of the TCO calculation is presented (section 2.5.3). Section 2.5.4 provides examples of retrofit scenarios and section 2.5.5 newbuild estimations of ammonia-powered vessels from different production locations and compares them with the TCO for ships sailing on conventional fuels. The cost figures are presented in EUR using the year average exchange rate of 2020 (1 EUR = 1.1422 USD) based on Eurostat (Eurostat, 2020).

### 2.5.1 CAPEX

Capital expenditures are fixed costs borne from a newbuild vessel, including the cost of the engine, after-treatment, storage (tanks) and the FSS. These costs do not depend on the frequency and intensity of the use of the vessel.

**Engine cost**

The engine is a major cost in owning a vessel. The cost of the engine system depends on the ship's required power capacity (kW). The engine CAPEX is assumed as a yearly cost over a lifetime of 25 years with a weighted average cost of capital (WACC) of 7%. This is a representative value taken from figures used by shipping companies in several segments of shipping[11].

Table 15. Engine cost input for engine cost

| Ship category | Fuel type | Ship size | Average installed power (kW) | Engine Cost per kW (USD) | Engine cost per kW (EUR) |
|---|---|---|---|---|---|
| Small vessels | VLSFO | All vessel types* with size up to 15,000 dwt | 2,400 | 285 USD | 250 EUR |
| Large vessels | VLSFO | All vessel types* with size above 15,000 dwt | 11,000 | 230 USD | 200 EUR |
| Containerships | VLSFO | All sizes containerships | - | 215 USD | 190 EUR |
| Short-sea vessels | Ammonia | All vessel type with size up to 15,500 dwt | 2,400 | 377 USD | 330 EUR |
| Deep-sea vessels | Ammonia | All vessel types with size above 15,500 dwt | 11,000 | 320 USD | 280 EUR |

* Excluding containerships

[10] The retrofit of a VLGC from fuel oil to LPG as an indication of the workload and cost investment of such vessel modification
[11] The reported ranges of the WACC by several maritime freight operators (Hapag-Lloyd 7.7%-10.1%; Yang Ming Marine Transport 6.4%- 8.3%; Moller-Maersk 7.8%, Scorpio Tankers 5.2%, Western Bulk Chartering 7.2%, Eagle Bulk Shipping 7.4%).

For ammonia, a 2-stroke low-speed diesel IC engine is considered. Cost per kW is assessed to be comparable to IC engines for bio-methanol; no improvement in IC engine technology is assumed.

There are additional costs for an ammonia fuelled engine (e.g., injection system, safety system), and in the TCO they are included in the engine costs. This cost is proportional to the vessels' power capacity. Engine costs range from 200-440 USD/kW for conventional fuel IC engines (Horvath, 2017) (VLSFO vessels) to approx. 320-380 USD/kW for ammonia-eligible engines (based on industry experts assessment). The ammonia ICE cost is calculated depending on the tonnage of the vessels. Vessels up to 15k DWT are assigned the higher engine cost of 380 USD/kW, while for vessels over 15k DWT (and all sizes container ships) the engine cost input is 320 USD/kW. See Table 15 for an overview of the input engine cost for the calculation.

**After treatment system cost**

After-treatment costs are those borne by the system and the treatment of harmful substances or elements that cannot be released into the environment due to regulation. A commonly used technique is a selective catalytic reduction system (SCR) to treat the exhaust after the fuels are combusted in the engine to bring NOx emissions in line with the regulatory limits. According to Hansson, et al. (Hansson, Brynolf, Fridell, & Lehtveer, 2020), the cost for a SCR is proportional to the installed main engine power of the vessel. The SCR cost is 133 USD per kW for all vessel types and sizes, and no change in cost is assumed for the time periods under consideration. Based on budget cost proposals from Asian shipyards, the SCR for an ammonia-burning (assuming similar NOx values as for VLSFO) vessel values at 50 USD/kW of installed power for 2-stroke diesel-cycle ammonia engines.

**Onboard storage, fuel tank and piping**

For the supply and storage of the fuels, dedicated onboard tanks and piping systems are necessary. The cost for these materials is assumed to be proportional to the power of vessel's engine. The costs for pressurised storage tanks and FSS are additional to the engine cost. These costs are as stated in Hansson, et al. (Hansson, Brynolf, Fridell, & Lehtveer, 2020) and presented in Table 16. They are scaled to the per kW cost by calculating the total storage and FSS cost per vessel category and dividing them by the installed power of the ship.

Table 16 – Overview storage tank and FSS cost

| Ship category | Ship size | Average size storage tank (GJ) | Average installed power (kW) | Storage and FSS Cost per GJ (USD) | Storage and FSS Cost per GJ (EUR) |
|---|---|---|---|---|---|
| Short-sea vessels | All vessel types* with size up to 2500 dwt | 3,500 | 2,400 | 55 USD | 50 EUR |
| Deep-sea vessels | All vessel types* with size above 2500 dwt | 71,300 | 11,000 | 35 USD | 30 EUR |
| Containerships | All containerships | 74,600 | 23,000 | 35 USD | 30 EUR |

* Excluding containerships

The total CAPEX for ammonia-powered vessels includes the cost for the IC engine, pressurised storage tanks, the fuel supply system and the SCR. Together with the ship size and power figures, an approximation for the CAPEX can be reached.

## 2.5.2 OPEX

Operational expenditures (OPEX) are variable costs, depending on the use of the vessel and comprise the costs of carbon, fuel, bunkering, maintenance and repair, and crew training.

**Carbon cost**

The maritime shipping sector will be included into the European Emissions Trading System (EU ETS). This means that, from 2024 on, shipping companies will be obliged to surrender allowances for the $CO_2$ emissions that their ships emit on voyages to and from EEA ports as well as in EEA ports. Thus, next to the fuel costs, also carbon costs will accrue if, within the geographical scope of the EU ETS, fossil fuels are combusted on board ships (for more details see Section 3.3).

For the calculation of the carbon costs, as part of the TCO analysis, an ETS price of 46 EUR per tonne $CO_2$ in 2030 and of 150 EUR per tonne $CO_2$ in 2050 (EC, 2021) are considered. In addition, it is assumed that carbon costs accrue for each tonne of $CO_2$ emitted. For the $CO_2$ emitted on voyages between EEA and non-EEA ports, however, only for 50% of the emissions allowances will have to be submitted, leading to lower carbon costs on these voyages. And if vessels do not call at EEA ports at all, the baseline carbon costs for VLSFO will also be lower than assumed here, at least provided that no other policy measures, implementing a carbon price, were adopted at international level/in other regions.

Carbon costs are only considered for VLSFO, since blue and green ammonia is not associated with tank to wake $CO_2$ emissions and since, if ammonia is used with a pilot fuel, we assume this pilot fuel to be biofuel with the tank to wake $CO_2$ emissions of this biofuel being zero-rated.

Figure 10 illustrates the 2030 and 2050 carbon costs per tonne of VLSFO for the above mentioned ETS prices. For green and blue ammonia no carbon costs will accrue.

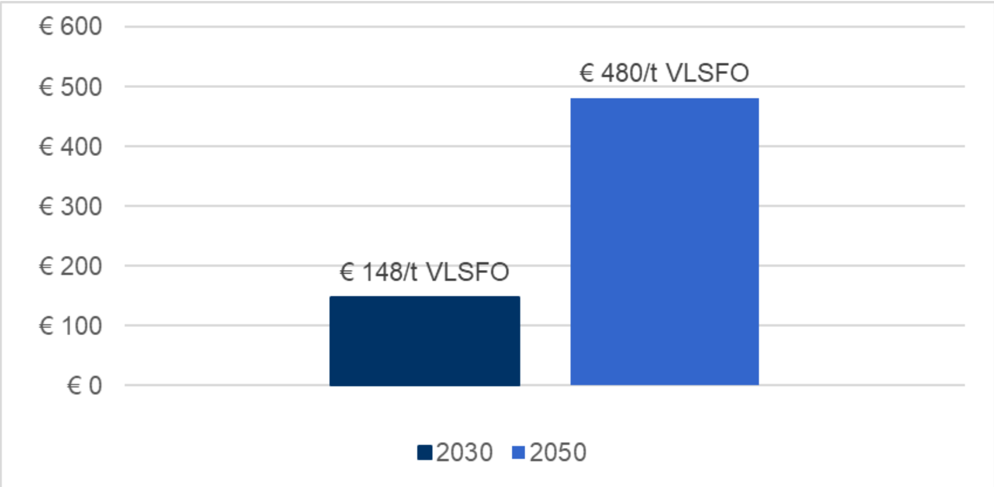


Figure 10. Carbon cost per tonne of VLSFO

**Fuel cost**

Fuel costs are another major cost item from owning a vessel. They are projected here for the years 2020, and 2030 and 2050. These costs include the production costs for the fuels, multiplied by the amount of fuel consumed, on average, by each of the 70 ship categories. Therefore, the fuel cost should be perceived as a minimum level of cost, as fuel producers and merchants may charge more.

Fuel costs per GJ include fuel oil (VLSFO) (IMO, 2020) and ammonia-production cost figures gathered from the Hy-Chain model (ISPT, 2019)[12]. An overview of exact fuel costs is available in Appendix V - Input figures of TCO modelling and longlist of TCO for ammonia powered ships.

The production cost of ammonia depends heavily on the price of the input energy and the cost of fuel transport. The price for the energy used to produce ammonia differs widely, depending on the location of the energy production.

Green-ammonia prices are considered from four production locations, Spain, Morocco, Chile and Australia. For comparison, 'blue' ammonia, produced from blue hydrogen, is also considered. This hydrogen is considered 'blue' because it was generated from natural gas and the carbon emissions were captured, suggesting, in practice, there were no carbon emissions from the production process. It was produced in the EU from natural gas.

Prices are offered in minimum and maximum cases, a range that reflects the cost in situations where renewable electricity (and natural gas) prices are stated as low and high. This is reflected in the shaded parts of the bars in Figure 11. The investment costs of ammonia synthesis are taken from and scaled according to Morgan (2013) (Morgan, 2013), Kalavasta (2019) (Kalavasta, 2019) and Sørensen and Laursen (2021) (Sørensen & Laursen, 2021). For this analysis, it has been assumed that the price of fuel oil and natural gas will go up towards 2050.

In Figure 11, the purple parts of the bars for VLSFO give the carbon costs that are assumed to accrue in 2030 and 2050 (see section 'Carbon cost' above).

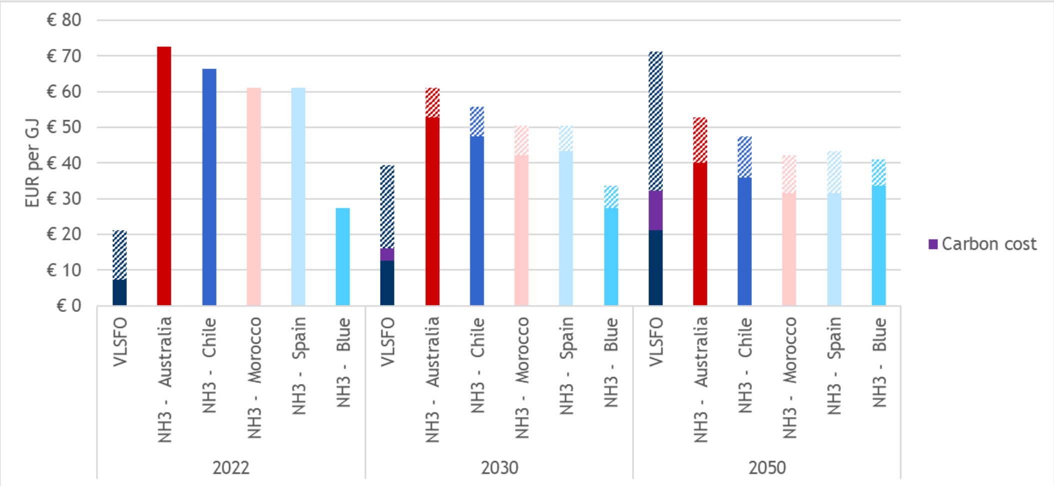


Figure 11. Fuel cost

The cost for green ammonia is currently more than 7 times higher than for VLSFO, and about 1-2 times higher for blue ammonia compared to VLSFO. However, in coming decades, the production cost for (green and blue) ammonia may decrease, and if so, result in a lower market price compared to VLSFO. Still, the cost for (liquefied) ammonia may not reach cost parity to conventional marine fuels such as VLSFO without introducing other measures such as carbon pricing. For fuel used within the scope of upcoming EU legislation, carbon allowances under the ETS would be needed for the $CO_2$ emitted by the combustion of fossil fuels (VLSFO). Initially, in the years 2030s, carbon pricing of fossil fuels may narrow the fuel cost gap compared to using ammonia only slightly. However, by 2050s the situation may change depending on the measures introduced and market dynamics.
A 20% improvement in energy efficiency for each ship is included in the estimates for 2030, which is in line with the regulations for the Carbon Intensity Indication adopted by the IMO. It is an estimation of the efficiency gains made from several energy-saving technologies and operational measures in this decade, partly stimulated by the regulation from the energy efficiency index. No other energy-efficiency improvements are assumed after 2030, so 2050 also has 20% efficiency improvement (compared to 2020).

[12] Figures for blue ammonia are from own calculations for this project, using the natural gas and synloop cost in HyChain model.

**Bunkering cost**

Bunkering costs are the costs of storing the fuels in a port and delivering it to a ship. They vary for each type of fuel. The costs are estimated proportional to the yearly energy consumption. They are derived from the Dutch technical research institute TNO (TNO, 2020a) (TNO, 2020b).

Bunkering costs are from bunker fuel's supply process – i.e., the cost of the port services supplying the fuel, including the logistics of loading and its storage. The bunker costs do not include the cost of the fuel.

Ammonia has a significantly lower volumetric density compared with fuel oil, meaning a vessel on ammonia should have to increase bunkering frequency to maintain similar transport performance as sailing on fuel oil. This leads to an increase of the bunkering cost by the factor in volumetric energy density. The increased bunkering factor is about 3.27 for ammonia compared to fuel oil (MJ/litre). This means, when maintaining equal size of on-board fuel storage, an ammonia powered vessel needs to refuel ammonia 3 times on the route to be able to sail the total distance a VLSFO vessel can sail on one full fuel storage tank. This fact may be an obstacle in practice when operating an ammonia powered vessel.

**Maintenance and repair**

Maintenance and repair (M&R) costs occur yearly for every ship. A factor of the ships' CAPEX is considered for the M&R cost. For VLSFO and ammonia, the M&R costs are 1.5% of the CAPEX; they are assumed to be proportionally equal to fuel oil (Kim, et al., 2020). However, because ammonia-powered vessels have a higher CAPEX, the M&R cost will be higher.

**Training cost**

The use of alternative fuels involves different risks associated with fuel handling. Ammonia is a corrosive and toxic substance. As such, it requires specialised handling during bunkering, system maintenance and use as a fuel. Specialised training is required for new and existing crews to ensure safe fuel handling. However, this cost is part of the staff (hiring) costs that exist for all ship operators, so it is not considered in this analysis.

### 2.5.3 Method

Using all cost components as outlined earlier in this section, it was possible to calculate indicative TCO figures for vessels powered by ammonia. First the fuel costs per year were calculated for all different fuel types[13] using total yearly fuel consumption (main engine, auxiliary and boiler engines) for each ship type and size class.

The engine costs are estimated by multiplying the average installed power (kW) of the main engine of a vessel type with the engine cost per kW as specified in Table 15. The total CAPEX is calculated to yearly cost using an annuity of 25 years lifetime for the engines and the WACC.

To calculate the bunkering cost, the yearly average fuel consumption in GJ is used. The fuel consumption is multiplied with the bunkering cost per GJ to obtain the yearly bunkering cost. Because ammonia has a lower volumetric density, the bunkering frequency has to increase to maintain the same yearly energy consumption and transport work. To account for the difference in volumetric density of ammonia, compared to VLSFO, we use the ratio in difference of energy density[14] per litre of VLSFO and ammonia. We multiply the yearly bunkering cost with this ratio to obtain the actual bunkering cost, corrected for the increase bunkering frequency. The energy consumption is assumed to remain at the same level when using an ammonia fuelled ship, however due to the difference in energy density, a higher amount (3.27 times more) fuel has to be supplied and consumed. This is incorporated in the calculations.

To obtain the yearly maintenance and repair cost, we multiply the total CAPEX with the M&R factor. The total yearly TCO is the sum of the yearly fuel cost, bunkering cost, yearly CAPEX and M&R cost. The TCO for ammonia-powered vessels is also calculated as a percentage of the TCO for a VLSFO-powered ship of the same type and size class.

### 2.5.4 TCO retrofit estimation

Retrofitting vessels is the process of replacing engine systems with adapted models that can combust alternative fuels, such as ammonia. This process generates the cost from the engine conversion, shipyard work, supplier work, new fuel-gas supply systems and tanks. These costs are all CAPEX-related; OPEX costs are considered to be consistent with those itemized in Section 2.5.2.

The engine has flexible fuel injection and combustion concepts, which adapt to the fuel type and quality. Out-of-service times are usually short because most retrofits can be completed in three weeks, but there are revenue losses related to transport being missed.

Depending on contracts, additional costs also may arise from retaining the crew while the vessel is idle, and extra fuel from rerouting to and from the shipyard. In Table 17, an indication of retrofit costs is presented for an engine suitable for the combustion of ammonia.

Table 17. Overview engine retrofit cost for ammonia ICE

| Type of vessel | Engine type | Indicative Engine conversion price* (USD) | Indicative Engine conversion price* (EUR) |
|---|---|---|---|
| 14.000 TEU Containership | 12RT-flex96C | 4.6 mln USD | 4.0 mln EUR |
| 310.000 DWT VLCC | W7X82 | 3.3 mln USD | 2.9 mln EUR |
| 210.000 DWT Cargo carrier | W6X72 | 3.1 mln USD | 2.7 mln EUR |

* Excluding engineering, shipyard work, fuel supply system and tanks. Source: Wärtsilä (Wärtsilä, 2022)

To give a more complete estimation for the entire cost of retrofitting, other costs from the process are presented in Table 18. These costs are from a retrofit of a VLGC[15] for conversion to LPG and are from older dates and have increased recently. They are unrelated to the type of engine, except for those associated with fuel-gas supply system and tanks. Of note, the MAN report estimates that the total emissions from production and conversion for retrofitting a vessel is about 3% of the total emissions from building a new ship designed to burn alternative fuel.

[13] VLSFO and ammonia. For ammonia we make the distinction between production locations which we define as a 'type' of fuel.
[14] VLSFO 36 MJ per litre, ammonia has 11 MJ per litre, from DNV GL (DNV GL, 2019), figure 6-1.
[15] Very large gas carrier, ~50.000 DWT (BW LPG, 2020).

Table 18 – Indicative non-engine retrofit cost, for LPG and Ammonia eligible ICE

| Cost aspect | Indicative cost LPG (USD) | Indicative cost LPG (EUR) | Indicative cost Ammonia* (USD) | Indicative cost Ammonia* (EUR) |
|---|---|---|---|---|
| Shipyard work | 2.0 mln USD | 1.8 mln EUR | 2.0 mln USD | 1.75 mln EUR |
| Owner supply work | 0.9 mln USD | 0.8 mln EUR | 0.9 mln USD | 0.8 mln EUR |
| Fuel gas supply system and tanks | 4.5 mln USD | 3.9 mln EUR | 5.4 mln USD | 4.7 mln EUR |
| Total non-engine retrofit cost* | 7.2 mln USD | 6.5 mln EUR | 8.3 mln USD | 7.3 mln EUR |
| Main engine conversion costs | 3.6 mln USD | 3.2 mln EUR | 3.6 mln USD | 3.2 mln EUR |

*The conversion cost of ammonia is based on the assumption that the scope is the same as for converting a VLGC to LPG. The cost of the FGSS and tanks are 20% higher than for LPG as the tanks are 2.4 times bigger. The cost of an ammonia catch system to remove the vapour and an eventually upgrade to Tier III equipment is not considered. Source: MAN-ES presentation at Motorship in Copenhagen 2021 (Wärtsilä, 2022; MAN Energy Solutions, 2021)

Finally, collating all of this information makes it possible to arrive at a rough estimation for an ammonia-suitable retrofit.

The main engine retrofit cost is around 4m USD, directly from the LPG retrofit case. The scope and equipment cost for retrofitting the engine on the ammonia ship will be very similar to LPG.

The LPG fuel gas supply system also is similar to the one required for ammonia, and the tanks will be the same type, except 2.4 times larger.

All told, the total cost for retrofitting to an ammonia-fueled ship, equipped with a 10-16 MW 2 stroke engine will be USD 10m-13m, depending on the type and size of the vessel, original engine and especially the number of retrofits being undertaken.

### 2.5.5 TCO newbuild estimation

Here, a detailed TCO comparison is made for two common ship types: bulkers and containerships. (For the indicative TCO of all ship types and sizes listed in the IMO Fourth GHG study (IMO, 2020) see appendix V). For the purposes of this exercise, ammonia is acquired at the lowest possible production cost price at the locations stated above. The figures for the TCO using both the lower and upper range of fuel costs are available in Appendix V - Input figures of TCO modelling and longlist of TCO for ammonia powered ships. In the following analysis, only the minimum fuel price cases are detailed.

The TCO for ammonia-fueled vessels is expressed as a percentage of additional yearly costs compared to those of the same vessel on fuel oil (VLSFO). Note: the price for fuel oil is increasing over time. This factor may in practice deviate from the (increasing) price trend which may produce a business case that deviates from the result found in this analysis.

The OPEX costs include those for fuels, bunkering and maintenance and repair. In the graphs that follow, the fuel costs representing the highest contribution to the OPEX are presented separately from the non-fuel OPEX. Ammonia has a lower volumetric density than fuel oil, so it has a lower energy content (MJ per litre of fuel). In order to fulfil the annual transport activities (which are kept constant and equal for all ships in the TCO analysis), a higher frequency of bunkering will be necessary. The cost for higher frequency of bunkering is included in the OPEX analysis.

**Containerships**

The yearly additional TCO for ammonia-fueled containerships in the 14,500-20,000 TEU range is indicated in Figure 12 compared to the TCO of a containership powered by VLSFO. There are significant differences in the cost of ammonia depending on where production takes place. The CAPEX and non-fuel OPEX are equal for all ammonia variants, only the production cost of ammonia (depending on the production location) is the varying factor for the differences in total TCO. The following production locations are indicated from left to the right: Australia (Aus), Chile (Cl), Morocco (Mor), Spain (Es), and 'blue' ammonia in the EU produced using natural gas.

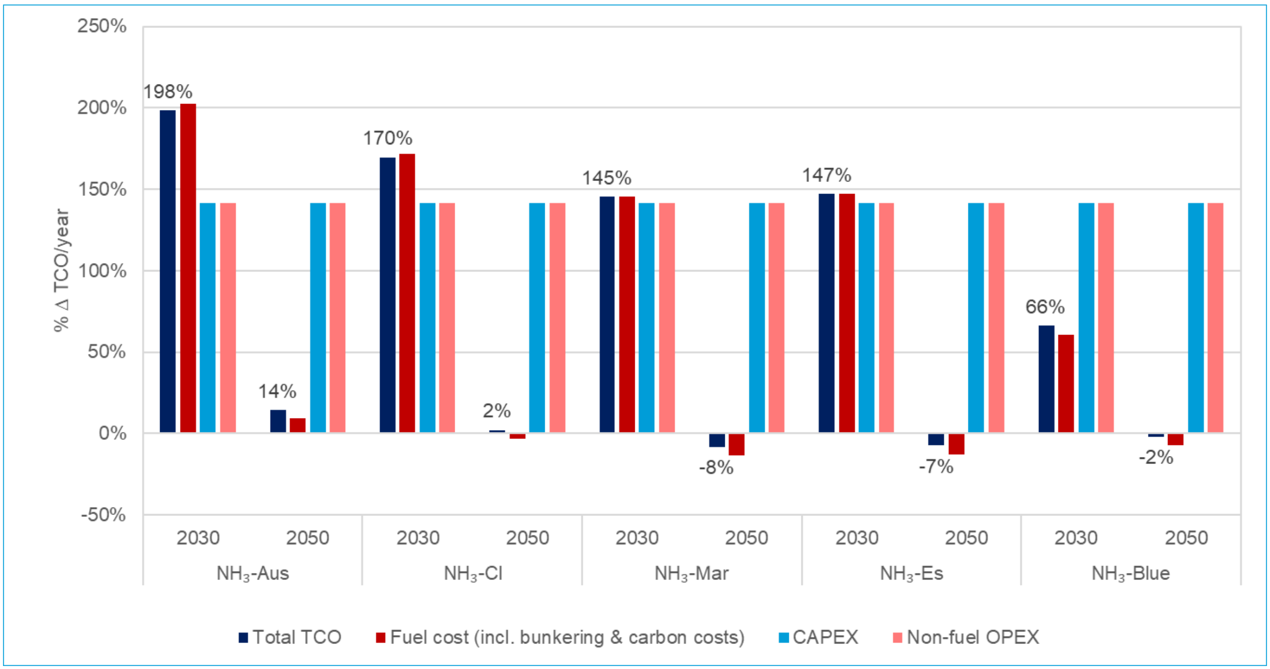


Figure 12. Additional cost (TCO per year) for ammonia powered containerships (14,500-20,000 TEU)

The figures above illustrate significant TCO increase in 2030 for a containership powered by green ammonia from four production countries (including the cost transporting the fuel to the EU), as well as the TCO for locally produced blue ammonia. Noting that the figures are for the low-fuel price scenario.

The highest cost component in the TCO of all ammonia 'variants' is the fuel. The fuel cost of green ammonia (including the cost transporting the fuel to the EU) differs depending on the country of production. Clearly, the least expensive green ammonia is produced in countries with a higher number and intensity of sun hours. In 2030, fuel cost of green ammonia is in general higher than fuel cost of locally produced blue hydrogen. This results in approximately 150% to 200% higher TCO for the containership fuelled by green ammonia and approximately 65% higher TCO for the containership fuelled by blue ammonia.

A decrease of the fuel cost for green ammonia and an increase of the fuel carbon cost for VLSFO, contribute to a decrease of the cost gap between the reference fossil fuel and ammonia, particularly towards 2050. The 2050, TCO for an ammonia powered containership may be break-even or even slightly lower than the TCO for the reference containership powered by VLSFO.

The difference in TCO between the fuel oil reference and ammonia powered vessels may differ in 2030 and 2050, depending on the developments of the production of green ammonia, the world's bunker price for fuel oil and the carbon costs.

The price for national gas, which is the energy input source for the production of blue ammonia may fluctuate highly and result in different TCO cases.

For the high fuel price ranges, as further detailed in Appendix V - Input figures of TCO modelling and longlist of TCO for ammonia powered ships, the increase of TCO for a blue and green ammonia fuelled container vessel ranges from 2.5 million USD to 45 million USD respectively in 2030, and from 6.5 million USD to 17 million USD in 2050.

To compare this model estimation with figures from the literature we found the following. The research from the MarE-Fuel project estimates the annual cost for a 15,000-TEU containership at about USD80m in 2030 (Sørensen & Laursen, 2021), which is comparable to the upper limit of the TCO estimation range for the same ship type and size from our calculation.

**Bulkers**

The yearly additional TCO for bulkers in the 35,000-59,999-DWT range is indicated in Figure 13 (below) for the low green and blue fuel price scenario compared to the TCO of an equally sized bulker running on VLSFO. Equal conditions are valid in the figure below for the production location and their implications for the fuel cost. Also, the CAPEX and OPEX are equal for all ammonia 'variants', which are about 400,000 USD and 300,000 USD per year higher respectively than those cost elements in a VLSFO case.

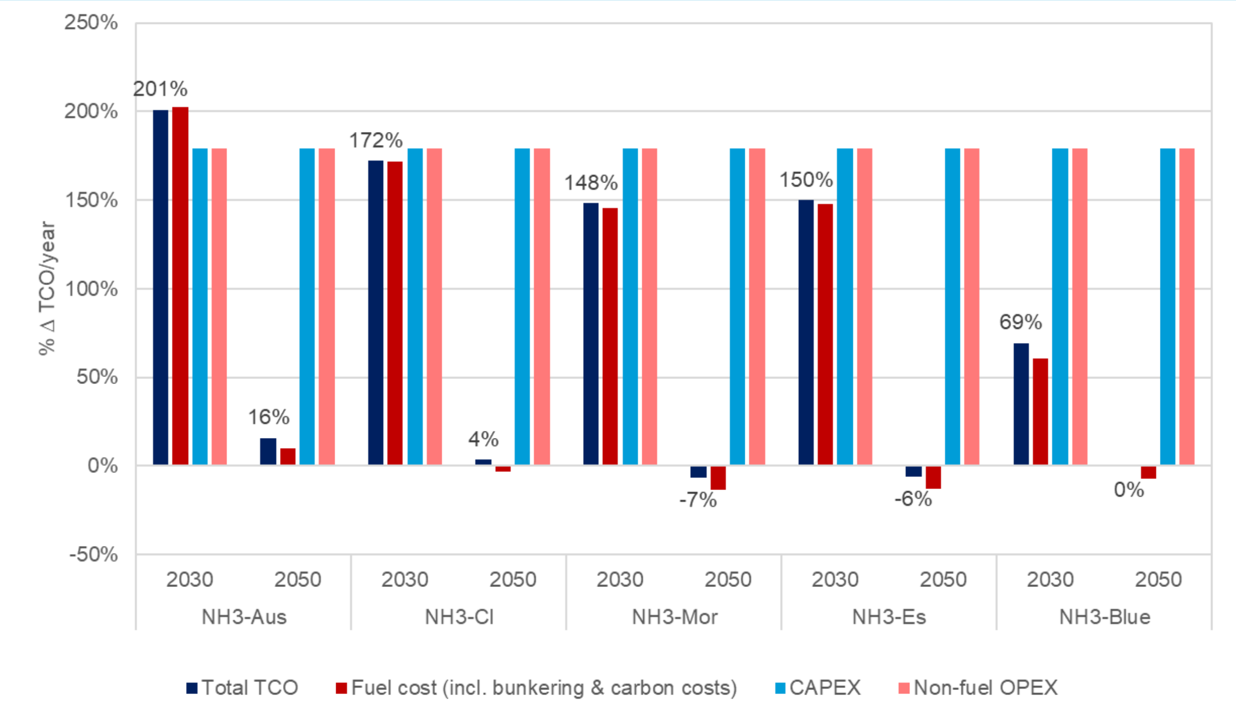


Figure 13. Additional cost (TCO per year) for ammonia powered bulkers (35,000-59,999 dwt)

For this ship type, the biggest single contributor to the TCO for an ammonia-fuelled bulker is also the fuel cost. The analysis indicates that the TCO of a bulk ship sailing on ammonia, regardless of the production location, will remain higher for the next decade (up to 2030) compared to a same-sized vessel burning fuel oil, even if considering carbon costs for the fossil fuel reference. In 2050, however, the TCO of an ammonia fuelled bulker may have reached cost parity to its fossil counterpart.

For the high fuel price ranges, as further detailed in Appendix V - Input figures of TCO modelling and longlist of TCO for ammonia powered ships, the increase in the TCO for a blue and green ammonia-fueled bulk carrier ranges from 1.8 million USD (blue NH3) to 5 million USD (green NH3) in 2030, and from equal TCO to 0.7 million USD in 2050. The smaller cost gap in 2050 in the high fuel price scenario is due to the fact the VLSFO price is more than 2 times higher compared to the VLSFO price in the low fuel price scenario and because of the ETS.

### 2.5.6 Techno Economic Conclusions

In 2030, the total cost of ownership of ammonia-fuelled vessels running on blue or green ammonia appears to be higher than the TCO of ships running on conventional fuel oils. The example cases of containerships and bulkers present additional TCO in that is about 2.5 to 3 times higher for green ammonia and 1.5 times higher for blue ammonia compared to conventional fuels, if carbon pricing is considered. The cost gap between ammonia powered vessels and conventional fossil fuelled vessels may, however, be closed by 2050, due to reduced ammonia production costs, a lower CAPEX for ammonia installations and higher carbon prices for fossil fuels. This however also depends on the development of the global fuel oil price.

Retrofit cost may be more expensive than a newbuild due to the additional pipework, cabling, structural adaptation and sometimes tailor-made modifications; all this adds more cost when compared to newbuilds. Still, this requires significant investment compared to operating business-as-usual. Also, there are possible other cost and practical barriers when switching to ammonia-fueled vessels, such as retraining personnel and the limited availability of ammonia fuel in destination ports.

# 3. Safety and environmental regulations, standards and guidelines

This section describes the environmental regulations, standards, and guidelines available and under development relating to the usage of ammonia.

## 3.1 Bunkering, on-board storage, handling and use of ammonia - Introduction

While the use of ammonia as an energy carrier and potential engine fuel has long been recognised (Cornelius, et al., 1965), it has yet to be utilised beyond research studies and some post-war necessities (Kroch, 1945) driven by the shortage of traditional hydrocarbon fuels. Consequently, there is a lack of regulation for its use as a fuel at national, regional and international levels.

However, interest in ammonia as a fuel has grown in the past few years, particularly in the maritime sector, where it is seen as a zero-carbon fuel that is more efficient on a volumetric basis than liquefied hydrogen; it is currently seen as a potential long-term solution for marine fuels, particularly for deep-sea applications.

This section starts with the regulations applicable to the storage, transport and use of anhydrous ammonia. It also provides a general overview of the policies driving the demand for renewable ammonia in shipping.

## 3.2 International

The following subsections identify current global regulations, standards and guidelines related to the application of ammonia as fuel in the maritime sector.

### 3.2.1 International Organization for Standardization (ISO)

***ISO 8217:2017 –*** *Petroleum products – Fuels (class F) – Specifications of marine fuels*

The most widely used fuel standard in the marine industry, which covers conventional residual or distillate fuel grades, is ISO 8217; the latest edition was issued in 2017. The ISO 8217:2017 standard Petroleum products – Fuels (class F) – Specifications of marine fuels offers the requirements for fuel oils for use in marine diesel engines and boilers prior to conventional onboard treatment. It specifies seven categories of distillate fuels and six categories of residual fuels.

The ISO standard defines fuel as hydrocarbons from petroleum crude oil, oil sands and shale, hydrocarbons from synthetic or renewable sources that are similar in composition to petroleum distillate fuels. It includes blends of these products with a fatty acid methyl ester (FAME) component, when permitted by the standard. The ISO 8217 standard provides detailed specifications for distillate (DM) grades, distillate FAME (DF) grades and residual (RM) grades of marine fuel oils.

*ISO Marine Fuel Standard for Ammonia?*

In response to growing industry interest and applications for LNG as a marine fuel and demand for an internationally recognised marine fuel standard, the ISO developed the ISO 23306:2020 standard '*Specification of liquefied natural gas as a fuel for marine applications'*, published in October 2020.

As this report went to press, the ISO methanol fuel standard was at the preparatory stage as ISO/AWI 6583 '*Specification of methanol as a fuel for marine application*'.

From these precedents, it can be concluded that an ISO marine fuel standard covering the specification for anhydrous ammonia will be developed. However, this would either require the IMO to make this request of the ISO, or for an ISO member to initiate a new work item through their national administration. So, it would be useful for an EU member state to officially request this of the IMO, to support early initiation.

For some of these emerging fuels, industrial specifications are sufficient; the products are not subject to the same variations in fuel property as conventional residual fuel oils. However, the lack of a marine fuel standard is often cited as a barrier to adoption.

Experience with the contamination of LNG and ethane also suggests a marine fuel specification will be required to document critical fuel properties and limits. These include properties such as ammonia, water, oxygen, debris, etc., which may be relevant to the tank material and the ability to document the sulphur content and the fuel-property test standards for each fuel parameter.

*Other ISO Standards for Anhydrous Ammonia*

The ISO already has many standards for the industrial or land-based sectors that may be suitable for marine application, a sample of which are referenced below.

**ISO 5771:2008 – Rubber hoses and hose assemblies for transferring anhydrous ammonia**. This international standard specifies the minimum requirements for rubber hoses used to transfer ammonia in liquid or in gaseous forms at ambient temperatures from -40 °C to +55 °C. It is limited to the performance of the hoses and hose assemblies, so it does not include specifications for end fittings, and is currently under development as ISO/CD 5771.

**ISO 7103:1982** – **Liquefied anhydrous ammonia for industrial use – Sampling – Taking a laboratory sample**. This international standard was last reviewed and confirmed in 2019, so it is current. It specifies the apparatus and the procedure for taking a representative laboratory sample of liquefied anhydrous ammonia from a container (barrel, cylinder, tank, etc.) for industrial use.

**ISO 7105:1985** – **Liquefied anhydrous ammonia for industrial use – Determination of water content – Karl Fischer method**. This standard was last reviewed and confirmed in 2019, therefore remains current. This International Standard specifies the Karl Fischer direct electrometric method for the determination of the water content of liquefied anhydrous ammonia for industrial use. The method is applicable to products having water contents equal to or greater than 50 mg/kg. For water contents greater than 1 000 mg/kg, it is preferable to dilute the evaporation residue with anhydrous methanol in accordance with ISO 4276 and titrate an aliquot portion of the diluted solution.

**ISO 7106:1985 – Liquefied anhydrous ammonia for industrial use – Determination of oil content – Gravimetric and infra-red spectrometric methods**. This international standard was last reviewed and confirmed in 2019, therefore it remains current. It specifies two methods for the determination of the oil content non-volatile components at about 105 °C, of liquefied anhydrous ammonia for industrial use: a gravimetric method and an infra-red spectrometric method. The gravimetric method is applicable to products having an oil content equal to or greater than 10 mg/kg. The infra-red spectrometric method, being more sensitive, is applicable to products having an oil content greater than 1 mg/kg.

**ISO 6957:1988 – Copper alloys – Ammonia test for stress corrosion resistance.** This standard was last reviewed and confirmed in 2019, therefore remains current. This International Standard specifies a test, using an ammoniacal atmosphere, for the detection of applied or residual stresses in copper alloy products which can cause failure of the material in service or storage through stress corrosion cracking. The method can also be used for testing assemblies and partial assemblies (of limited size).

**ISO 17179:2016 – Stationary source emissions – Determination of the mass concentration of ammonia in flue gas – Performance characteristics of automated measuring systems.** This International Standard specifies the fundamental structure and the most important performance characteristics of automated measuring systems for ammonia ($NH_3$) to be used on stationary source emissions, for example, combustion plants where SNCR/SCR NOx control systems ('deNOx systems') are applied. The procedures to determine the performance characteristics are also specified. Furthermore, it describes methods and equipment to determine $NH_3$ in flue gases including the sampling system and sample gas conditioning system.

**ISO 21877:2019 - Stationary source emissions – Determination of the mass concentration of ammonia – Manual method.** This document specifies a manual method of measurement, including sampling and different analytical methods for the determination of the mass concentration of ammonia in the waste gas of industrial plants; for example, combustion plants or agricultural plants. All compounds which are volatile at the sampling temperature and produce ammonium ions upon dissociation during sampling in the absorption solution are measured by this method, which gives the volatile ammonia content of the waste gas.

In addition to the required ISO marine fuel standard identified in the subsection above, other gaps exist in the available ISO standards for application of ammonia as a marine fuel. In this context, the standards developed for the adoption of LNG as a marine fuel can be taken as a precedent; they are detailed below for reference.

**ISO 21593:2019 – Ships and marine technology – Technical requirements for dry-disconnect/connect couplings for bunkering liquefied natural gas.** This document specifies the design, minimum safety, functional and marking requirements, as well as the interface types and dimensions and testing procedures for dry-disconnect/connect couplings for LNG hose bunkering systems intended for use on LNG bunkering ships, tank trucks and shore-based facilities and other bunkering infrastructures. It is not applicable to hydraulically operated quick connect/disconnect couplers (QCDC) used for hard loading arms, which is covered in ISO 16904.

**ISO 20159:2021 – Ships and marine technology – Specification for bunkering of liquefied natural gas fuelled vessels.** This document specifies requirements for LNG bunkering transfer systems and the equipment used to bunker LNG-fuelled vessels, which are not covered by the IGC Code. The document is applicable to vessels involved in international and domestic service regardless of size, and addresses the following five elements:

- hardware: liquid and vapour-transfer systems;
- operational procedures;
- requirement for the LNG provider to provide an LNG bunker delivery note;
- training and qualifications of personnel;
- requirements for LNG facilities to meet applicable ISO standards and local codes.

**ISO/TS 18683:2021 – Guidelines for safety and risk assessment of LNG fuel bunkering operations.** This document gives guidance on the risk-based approach to follow for the design and operation of the LNG bunker transfer system, including the interface between the LNG bunkering supply facilities and receiving LNG-fuelled vessels. The document provides requirements and recommendations for the development of a bunkering site and facility and the LNG bunker transfer system, providing the minimum functional requirements qualified by a structured risk assessment approach taking into consideration LNG properties and behaviour, simultaneous operations and all parties involved in the operation. It is applicable to bunkering of both seagoing and inland-trading vessels and covers LNG bunkering from shore or ship, mobile-to-ship and ship-to-ship LNG supply scenarios.

These published standards indicate that equivalent ammonia standards for dry-disconnect/connect couplings, bunkering specifications and guidelines for risk assessment of bunkering operations remain to be developed and therefore are a barrier to take up.

The latter is of particular relevance to port authorities that wish to assess the ammonia-bunkering interface (tank to ship, truck to ship or ship to ship) for establishing and permitting purposes. Toxicity adds an additional element to consider, but the cryogenic risks and the high expansion ratios are applicable to both LNG and liquefied anhydrous ammonia releases, drive the consideration of SIMOPS and the hazardous areas, safety zones and security zones that will be required to undertake safe bunkering of anhydrous ammonia in port areas.

### 3.2.2 International Maritime Organization (IMO) Requirements

#### 3.2.2.1 SOLAS

The IMO's safety-related regulations for international shipping are regulated through the *International Convention for the Safety of Life at Sea* (SOLAS, 1974, as amended) convention. SOLAS has historically prohibited the use of conventional fuel oils with less than a 60˚C flashpoint, except for emergency generator use (where the flashpoint limit is 43˚C) and subject to additional requirements detailed under SOLAS Chapter II-2 Regulation 4.2.1. To accommodate the interest in using gaseous and liquid fuels with a flashpoint of less than 60˚C, the IMO adopted the *International Code of Safety for Ships using Gases or Other Low-Flashpoint Fuels* (IGF Code) by including a new Part G to SOLAS II-1 in 2015.

The IGF Code is largely (prescriptively) based on the IMO's *International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk* (IGC Code), itself developed from the experience with carrying LNG in bulk on gas carriers over the past 60 years or so. The original IGC Code only permitted the burning of natural gas (methane) cargoes as fuel to control the pressure and temperature of LNG cargo by consuming the boil-off gas from LNG stored in low pressure (atmospheric) bulk storage tanks.

The traditional propulsion configuration was steam turbines. Dual-fuel 4-stroke diesel engines arranged with electric drive emerged as the preferred arrangement from around 2005, while 2-stroke direct engines (in a twin skeg arrangement) emerged from around 2015.

During the finalisation of the IGF Code and the revised IGC Code, it was recognised that applying the IGF code to gas carriers may create challenges. The codes were similar, but not the same, and differed in some fundamental areas. Consequently, the IMO Maritime Safety Committee acknowledged that a policy decision was required.

This is detailed in paragraph 3.17 of MSC 95/22, indicating that IMO "… *agreed that the IGF Code should not apply to ships subject to the IGC Code, even in the case of IGC Code ships using low-flashpoint fuels that are not cargo* …", effectively applying a 'one ship – one code' policy with respect to the application of the IGF and IGC Codes.

This policy decision was captured by implementing amendments to SOLAS to make the IGF Code mandatory. These amendments were adopted by IMO resolution MSC.392(95) in June 2015, which introduced a new Part G to SOLAS II-1 and with the 'one ship – one code' policy captured by the amendments to SOLAS II-1/56.4:

> "This part shall not apply to gas carriers, as defined in regulation VII/11.2:
>
> .1 using their cargoes as fuel and complying with the requirements of the IGC Code, as defined in regulation VII/11.1; or
>
> .2 using other low-flashpoint gaseous fuels provided that the fuel storage and distribution systems design and arrangements for such gaseous fuels comply with the requirements of the IGC Code for gas as a cargo.

**<u>IGC Code</u>**

The original, IGC Code (1993) only permitted the burning of natural gas as a fuel by application of its Chapter 16. However, the adoption of the revised IGC Code by IMO Resolution MSC.370(93) in May 2014, which became effective 1 July 2016, introduced the option to burn other alternative cargoes under a new section 'Alternative fuels and technologies'. Notably this new provision excluded burning toxic cargoes.

The IGC Code does include dedicated requirements for the carriage of anhydrous ammonia. Note, the IBC Code (*International Code for the Construction and Equipment of Ships Carrying Dangerous Chemicals in Bulk*) contains only the requirements for carriage of aqueous ammonia up to 28% in water.

*Stress Corrosion*

The main IGC Code requirements for carrying ammonia are detailed under Chapter 17 'Special Requirements', which focus on the problems with stress corrosion cracking of anhydrous ammonia in carbon manganese or nickel steels. These requirements are applicable to cargo tanks, pressure vessels and cargo piping systems and include these constructional or operational measures to limit stress corrosion in carbon manganese steels:

To be fine grained steel with a specified minimum yield strength of 355 $N/mm^2$ and with maximum yield strength not exceeding 440 $N/mm^2$. In addition, one of the following constructional or operational measures are also to be taken:

- Lower strength material with specified minimum tensile strength not exceeding 410 $N/mm^2$; or
- Post weld stress relieving; or
- Carriage temperature to be maintained close to the boiling point of -33˚ C, but in no case at a temperature above -20˚C; or
- The ammonia shall contain not less than 0.1% w/w water, and as documented.

Nickel steels containing more than 5% nickel are not to be used, which means the typical nickel steel materials used for storage of LNG containing 9% nickel are not suitable for storage of anhydrous ammonia.

Nickel steels containing not more than 5% nickel may be used, provided the ammonia is carried below -20˚C.

The IGC Code requirements also recommend keeping the dissolved oxygen content below 2.5 ppm w/w, driving operational measures to reduce tank oxygen content before loading ammonia.

There are other IGC Code requirements driven by the toxic and corrosive nature of the carriage of ammonia including:

- Gas and vapour detection to be suitable for toxicity
- Cargo tank gauging instrumentation to be of indirect or closed type
- Materials to be resistant to the corrosive nature of ammonia
- Mercury, copper, copper bearing alloys and zinc materials not to be used for cargo tanks, piping, valves, fittings, etc. that are normally in direct contact with the ammonia liquid or vapour
- In addition to the standard personnel protective equipment for gas carriers, including aprons, eye protection, first-aid equipment and full protective safety outfits and air sets, the carriage of ammonia also requires respiratory and eye protection for the emergency escape of every person onboard.

*IMO Tank Types*

The IGC Code includes detailed material and design requirements for the containment of liquefied gases covering the basic tank types found on gas carriers, namely independent types A, B, C and dependent membrane types.

Table 19. Main characteristics and attributes of IMO fuel containment systems

| | Type A | Type B | Type C | Membrane |
|---|---|---|---|---|
| **Tank Design** | Independent Prismatic Structure calculated on classical ship structure design rules | **Independent Prismatic or Spherical (Moss) Structure calculated on fatigue analysis and model tests – "leak before failure" concept** | Independent Cylindrical or Bi-Lobe or Tri-Lobe Pressure vessel design based on modified pressure vessel codes | Integrated Non self-supporting, thin membrane supported through insulation by adjacent hull |
| **Volume efficiency** | Medium, inspection space | Medium, inspection space | Lowest (better with bi-lobe and tri-lobe) | Maximum |
| **Max. Design Pressure** | 0.7 bar | 0.7 bar (prismatic tanks) | >2 bar | 0.7 bar |
| **Secondary barrier** | Full | Partial | None | Full |
| **Inerting requirements** | Inert inter-barrier (pressure & makeup) | Hold filled with dry air (standby inert capability) | Hold filled with inert gas or dry air | Inert inter-barrier (pressure & makeup) |
| **Volume/weight ratio** | Medium | Medium | Low | High |
| **Theoretical BOR** | Medium | Medium | High | Low |
| **Sloshing effects** | N/A | N/A | N/A | Reinforcements required |
| **Inspection** | Easy access, special test for secondary barrier | Easy access on both sides for inspection | Easy access (remote access on smaller tanks) | Special testing and inspection procedures |

A comparison of the main characteristics and attributes for IMO fuel containment are shown in Table 19. Types A, B and membrane tanks are low pressure, nominally 'atmospheric' tanks, and Type C are designed using pressure vessel codes. The predominant technology used for LNGC fuel containment in the past 20 years have been the membrane and Type B Moss systems.

Type A, B and membrane tanks require a secondary barrier to protect in case of leak from the primary barrier. Type A and membrane systems require a full secondary barrier. Type B tanks require a partial secondary barrier since they are designed using advanced fatigue analysis tools and a 'leak-before-failure' concept, for which small leaks can be managed with partial cryogenic barrier protection and inert gas management of the inter-barrier space.

Type C tanks are designed using code criteria for pressure vessels and conservative stress limits so they do not require a secondary barrier. They are also relatively cheap to fabricate but are not the most space-efficient designs.

Historically, ammonia has been carried in IMO Type A or C tanks on gas carriers that may have been designed predominantly for carrying LPG, with the Type C tanks enabling carriage at fully pressurised conditions (at the standard IMO upper ambient reference conditions of 45°C air and 32°C sea water) or semi-refrigerated or semi-pressurised conditions.

Since ammonia can be liquified relatively easily at -33°C (or 17-18 bar) it offers a range of design solutions and, using the stress corrosion design and operational measures indicated above, enables the use of cheaper materials than those required for other liquefied gases such as LNG.

Figure 14 shows the saturated-vapour pressure curves for the main liquefied gases carried under the IGC Code and the potential for fully refrigerated, semi-refrigerated and fully pressurised storage.

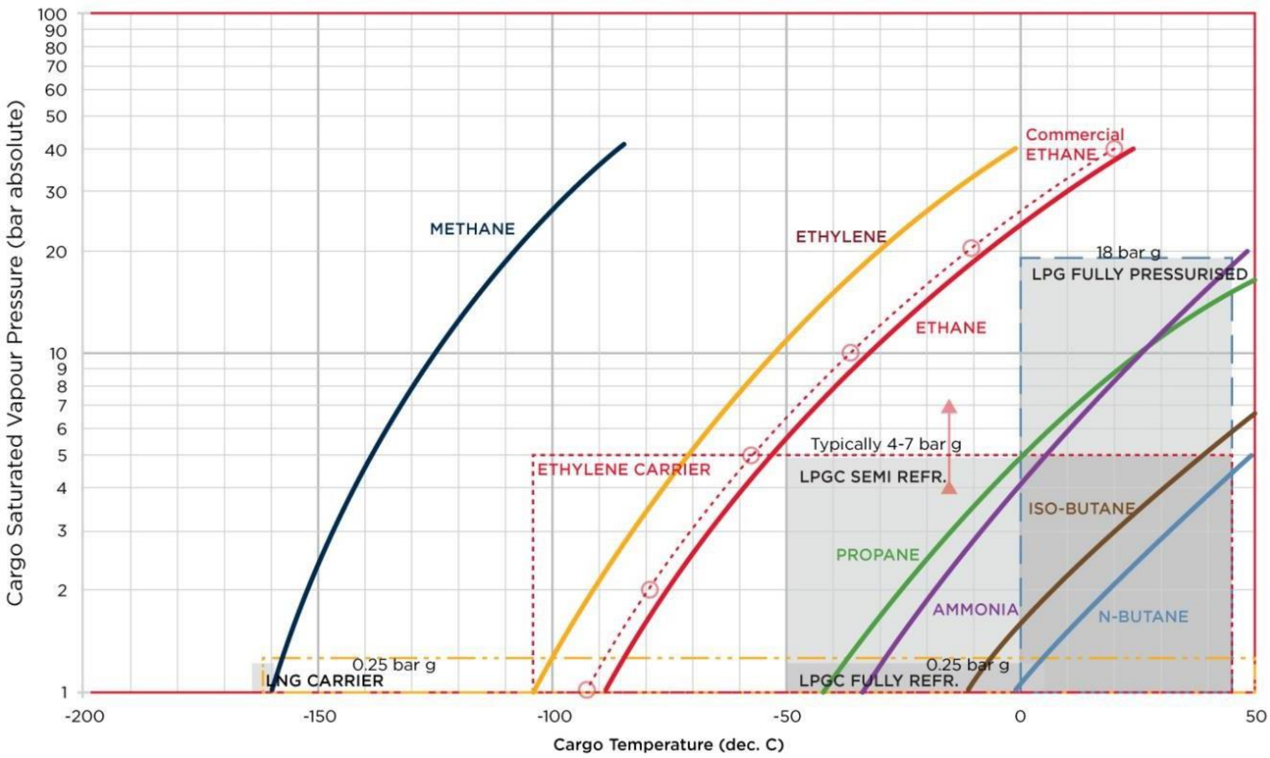


Figure 14. Typical operating range for Liquefied Gas Carriers

*Tank Materials*

The requirements for material specifications are included within the IGC Code (and the IGF Code), detailing chemical composition, mechanical properties, heat treatment, test requirements and the application of material with respect to minimum design temperatures of the product to be carried, see Table 20.

Table 20. Requirements for fuel tank material specifications

| Minimum Design temperature (°C) | Chemical composition | Impact test temperature (°C) |
|---|---|---|
| -60 | 1.5% nickel steel – normalised or normalised and tempered or quenched and tempered or TMCP | -65 |
| -65 | 2.25% nickel steel – normalised or normalised and tempered or quenched and tempered or TMCP | -70 |
| -90 | 3.5% nickel steel – normalised or normalised and tempered or quenched and tempered or TMCP | -95 |
| -105 | 5% nickel steel – normalised or normalised and tempered or quenched and tempered | -110 |
| -165 | 9% nickel steel – double normalised and tempered or quenched and tempered | -196 |
| -165 | Austenitic steels, such as types 304, 304L, 316, 316L, 321 and 347-solution treated | -196 |
| -165 | Aluminium alloys, such as type 5083 annealed | Not required |
| -165 | Austenitic Fe-Ni alloy (36% nickel). Heat treatment as agreed | Not required |

LNG is meant to be carried in carbon steels with a 9% nickel content, austenitic steels, aluminium, or a specific Fe-Ni (Invar) alloy. Nickel steels containing more than 5% nickel are explicitly prohibited by the IGC Code.

The general application of many of the IGC Code material requirements are applicable from -55°C to -165°C, so materials for the carrying liquefied ammonia at -33°C do not fall into this category. The use of anhydrous ammonia provides the opportunity to utilise cheaper tank materials than other liquefied fuels, such as LNG and hydrogen, that are being used and considered for marine applications.

To increase technological innovation in material development and recognising that the experience usually required by the IMO before it adopts alternative materials in the IGC Code may not be available, for the past few years the Organisation has been developing more guidelines under a CCC working group.

This work item was triggered by the introduction of High Manganese Austenitic Steels for cryogenic service on the bulk carrier *Ilshin Green Iris*[16].

The output from this working group has included MSC.1/Circ.1599, the *Interim Guidelines on the Application of High Manganese Austenitic Steel for Cryogenic Service* (MCS.1/Circ.1599, 2019) and MSC.1/Circ.1622, *Guidelines for the Acceptance of Alternative Metallic Materials for Cryogenic Service in Ships Carrying Liquefied Gases in Bulk and Ships Using Gases or Other Low-Flashpoint Fuels* (MSC.1/Circ.1622, 2020).

While both guidelines are currently undergoing updates and revisions, they indicate that tools are in place for the approval of alternative types of tank material under the IGC and IGF Codes.

With ammonia typically carried in tanks certified for LPG cargoes, the obvious transition fuel to ammonia (with the least impact on ship design) is LPG, albeit the differences in energy density mean that a reduced range would be applicable with application of ammonia, unless additional tanks were installed or oversized at the original installation.

However, the application of materials suitable for other fuels, such as stainless steel, to ammonia is possible and the IMO guidelines have opened the door for the application of emerging materials.

*Alternative Fuels and Technologies*

The provision to burn cargoes other than methane added in the 2016 IGC Code requires demonstrating the "same level of safety as natural gas". However, to burn these fuels in gas carriers, there are different requirements from the flag Administrations on how to demonstrate that equivalency.

The provisions for 'equivalents' provided by 1.3 of the IGC Code allows for approval of equivalent arrangements (excluding operational methods) and requires approvals from flag Administrations to be communicated to IMO.

[16] For more information on the service experience on this ship see CCC 7/4/1 and CCC 7/INF.7 from the Republic of Korea.

Those communications are available to all Administrations and other stakeholders through the IMO Global Integrated Shipping Information System (GISIS) database.

The approval under 'equivalents' paved a route to approval and recognition within the IGC Code, typically by applying a risk-based approval process incorporating HAZID, HAZOP, etc. techniques to demonstrate that the "*same level of safety as natural gas*" has been achieved.

This process was undertaken for the emerging fleet of dedicated ethane and LPG gas carriers, such as the conversion of the *Navigator Aurora* to burn ethane, the BW LPG carrier conversion of the *BW Gemini* to burn LPG and the *Seri Everest* as one of the latest Very Large Ethane Carriers (VLEC) built to carry ethane cargoes from the U.S. and burn ethane as fuel.

*Review of the IGC Code – Burning of Toxic Cargoes?*

Since the implementation of the revised IGC Code, a number of problems with its interpretation and application have been identified. These issues have driven many Unified Interpretations, but also papers to the IMO proposing a new output to review the revised IGC Code.

The IMO MSC subsequently agreed to review the IGC Code, and this has been added to the CCC 8 Sub-Committee meeting agenda for September 2022. Of note, among the submitted papers on this topic, is the proposal that the burning of toxic cargoes should be permitted and aligned with the IGF Code.

It is therefore possible that 16.9 of the IGC Code will be amended in due course to allow toxic cargoes to be used as fuel, or at least anhydrous ammonia. However, if the amendments are developed at the IMO and adopted before 1 July 2026, they will not enter into force until 1 January 2028, in accordance with the four-year cycle of the SOLAS amendment process.

**<u>IGF Code</u>**

*General*

In June 2015, the IMO adopted the IGF Code with Resolution MSC.391(95) and adopted amendments to SOLAS to make the IGF Code mandatory, including a new Part G to SOLAS II-1, by IMO Resolution MSC.392(95).

Prior to this, the only guidance from the IMO for using natural gas as fuel was detailed in IMO Resolution MSC.285(86), the '*Interim Guidelines on Safety for Natural Gas-fuelled Engine Installations in Ships'*, which was adopted on 1 June 2009.

The adoption of the IGF Code introduced a framework and requirements under SOLAS for burning gases or other low-flashpoint fuels with a flashpoint less than 60˚C.

### *Entry into force*

The IGF Code entered into force 1 January 2017 and was applicable to all ships, and ship conversions, over 500GT for which the building contract was placed on or after the same date. In the absence of a building contract, the IGF Code was made applicable to those ships with a keel laid on or after 1 July 2017, or which were delivered on or after 1 January 2021.

### *Structure*

The IGF Code is structured into Parts A, A-1, B-1, C-1 and D. Parts A and D are applicable to all gases and other low-flashpoint fuels, with the detailed prescriptive requirements for natural gas (methane) included under parts A-1, B-1 and C-1. In the longer term, it is understood that the IMO's intent is to amend the IGF Code to include detailed prescriptive requirements for all the gases and low-flashpoint fuels used by the marine industry. While experience develops with these fuels, interim guidelines such as MSC.1/Circ.1621 (2020) *Interim Guidelines for the Safety of Ships Using Methyl/Ethyl Alcohol as Fuel* (2020), are expected to be developed.

Prior to the availability of these guidelines for other fuels, such as LPG, ammonia and hydrogen, the IGF Code can still be applied. This is outlined by the preamble to the IGF Code which states:

> *"This Code addresses all areas that need special consideration for the usage of the low-flashpoint fuel. The basic philosophy of the IGF Code considers the goal-based approach (MSC.1/Circ.1394). Therefore, goals and functional requirements were specified for each section forming the basis for the design, construction and operation. The current version of this Code includes regulations to meet the functional requirements for natural gas fuel. Regulations for other low-flashpoint fuels will be added to this Code as, and when, they are developed by the Organization. In the meantime, for other low-flashpoint fuels, compliance with the functional requirements of this Code must be demonstrated through alternative design."*

*Alternative Design*

Applications for gases or low-flashpoint fuels other than methane need to apply the provisions from Part A, 2.3 of the IGF Code for 'Alternative Design' (see Table 21).

SOLAS regulation II-1/55 requires an engineering analysis to be submitted to the flag Administration, in accordance with the footnote to MSC.1/Circ.1212, *Guidelines on Alternative Design and Arrangements for SOLAS Chapters II-1 and III* (2006).

Once approved, the flag Administration will need to communicate this to the IMO's GISIS database. This process follows a risk-based approach for approval of the design to ensure the goals and functional requirements of the IGF Code have been met.

The IMO's MSC.1/Circ.1455, *Guidelines for the Approval of Alternatives and Equivalents as Provided in Various IMO Instruments* (2013), could offer a more appropriate framework for approval, subject to agreement by the flag Administration.

Table 21. Excerpts from IGF Code, Adoption of the International Code of Safety for Ships using Gases or Other Low-Flashpoint Fuels (MSC.391(95))

| **2.3 Alternative Design** | |
|---|---|
| ***2.3.1*** | *This Code contains functional requirements for all appliances and arrangements related to the usage of low-flashpoint fuels.* |
| ***2.3.2*** | *Fuels, appliances and arrangements of low-flashpoint fuel systems may either:*<br>*.1 deviate from those set out in this Code, or*<br>*.2 be designed to use fuel not specifically addressed in this Code.*<br>*Such fuels, appliances and arrangements can be used provided they meet the intent of the related goals and functional requirements and provide an equivalent level of safety of the relevant chapters.* |
| ***2.3.3*** | *The equivalence of the alternative design shall be demonstrated as specified in SOLAS regulation II-1/55 and approved by the Administration. However, the Administration shall not allow the application of operational methods or procedures as an alternative to a particular fitting, material, appliance, apparatus, item of equipment, or type thereof which is prescribed by this Code.* |
| **4.2 Risk assessment** | |
| ***4.2.1*** | *A risk assessment shall be conducted to ensure that risks are addressed related to the use of low-flashpoint fuels that affect persons onboard, the environment, the structural strength or the integrity of the ship. Consideration shall be given to the hazards associated with physical layout, operation and maintenance, following any reasonably foreseeable failure.* |
| ***4.2.3*** | *The risks shall be analysed using acceptable and recognised risk-analysis techniques, and loss of function, component damage, fire, explosion and electric shock shall as a minimum be considered. The analysis shall ensure that risks are eliminated wherever possible. Risks which cannot be eliminated shall be mitigated as necessary. Details of risks, and the means by which they are mitigated, shall be documented to the satisfaction of the Administration.* |

Using ammonia as a fuel brings some particular challenges because, unlike LNG, there is no gas carrier experience and no engines available for burning ammonia. The first step would be to undertake a preliminary risk assessment – see Section 4 of this report for further information and case studies on related risk assessments. The IGF Code details the high-level objectives for risk assessments of gases or low-flashpoint fuels other than methane in sections 4.2.1 and 4.2.3 (see Table 21).

Further guidance on risk assessments under the IGF Code is provided in IACS Recommendation No.146 - *Risk Assessment as Required by the IGF Code* (see also subparagraph 3.2.6 for more information on IACS's efforts to support the application of the IGF Code).

*IMO IGF Code Workplan*

Since the IGF Code was adopted, the IMO has continued to support work on fuel cell requirements and other low-flashpoint fuels, such as methanol and LPG. The CCC sub-committee has a permanent agenda item to cover this: '*Amendments to the IGF Code and development of guidelines for low-flashpoint fuels*'.

This agenda already has produced amendments to the IGF Code to clarify and develop further the requirements for methane as fuel: e.g., MSC.422(98) adopted 15 June 2017; MSC.458(101) adopted 14 June 2019; and MSC.475(102) adopted 11 November 2020. It has also produced many 'unified interpretations', which were predominantly raised by IACS.

The IMO's interim guidelines for methyl/ethyl alcohol fuels (MSC.1/Circ.1621 *Interim Guidelines for the Safety of Ships Using Methyl/Ethyl Alcohol as Fuel*) also were developed under this agenda item and, most recently, the CCC 7 meeting in September 2021 completed the draft *'Interim Guidelines for the Safety of Ships using Fuel Cell Power Installations*'.

The workload for the associated working group and correspondence group is high and will continue to be so for many years as more and more gases and low-flashpoint fuels enter the marine market. However, the work on considering how to develop IMO's requirements for ammonia as fuel has started.

### *Anhydrous Ammonia Under the IGF Code?*

IMO paper CCC 7/3/9 proposed that requirements for hydrogen and ammonia were needed urgently, that the fuels were separate contenders for zero- and low-carbon future fuels and that the requirements could be developed in parallel. The paper suggests separate guidelines for hydrogen and ammonia could be added to the terms of reference for the IGF Code work and correspondence group.

With reference to subparagraph 3.2.6 below, a number of classification societies have introduced guidelines or tentative rules for ammonia as fuel, many of which have adopted the format and structure of the IGF Code.

The goal and functional requirement-based structure of the IGF Code, together with a clear path to approving fuels not directly covered by the prescribed requirements using the 'alternative-design' process, illustrates that the Code has the right framework to approve all gases and low-flashpoint fuels.

Furthermore, the prescribed requirements developed for methane as a gas or stored as LNG, which are largely based on IGC Code requirements and experience, provide an easily adaptable set of design and safety concepts that are well suited to adoption by other gases or low-flashpoint fuels, once the specific fuel characteristics are accounted for.

The criteria for protective tank locations, cryogenic and pressurised fuel-containment and distribution requirements, the double-barrier concept for fuel-supply piping, the use of ventilation and gas-detection methods to detect leaks and mitigate them increasing to LEL (lower explosive limit) and the classification of hazardous areas, together with the requirements for training, PPE and operational measures, offer a strong set of safety concepts that are very transferrable to other gases.

For ammonia, this suite of requirements can reduce the likelihood of and mitigate accidental releases based on toxicity levels (i.e., ppm levels) rather than the historical percent levels required to prevent fire and explosion from methane.

As given by Table 1, ammonia can be said to have a relatively high flash point of approximately 132°C. However, many property-data tables do not quote flashpoints for gases because the flashpoint testing is applicable to closed-cup liquid hydrocarbon testing; the flammability range, autoignition temperature and ignition-energy levels are more relevant to determining the fire and explosion risk of a particular gas, and hence determine the appropriate safety mitigation.

However, this flashpoint characteristic of ammonia has been recently raised by paper MSC 104/15/9, which questions whether this emerging fuel falls under the scope of the IGF Code. The paper invites the IMO Maritime Safety Committee to add the development of non-mandatory guidelines for ships using ammonia as fuel to the CCC agenda to commence at CCC 8.

The applicability of the IGF Code for ammonia remains uncertain and may trigger an IMO policy decision or further amendments to SOLAS.

**Training - STCW**

Part D of the IGF Code, which covers all gases and low-flashpoint fuel applications for IGF Code ships under SOLAS, requires companies to ensure that the seafarers onboard these ships have completed the training that will give them the ability to fulfil their designated duties and responsibilities. This is applied through the IMO International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW).

When the SOLAS amendments were adopted for the IGF Code, the STCW Convention and Code was also amended (by MSC.396(95) and MSC.397(95)) to add specific training requirements and certification for IGF-Code seafarers.

Tables A-V/3-1 and A-V/3-2 of the STCW describe the requirements for competence, knowledge, understanding and proficiencies for basic and advanced training. The 'basic training' is for seafarers with "… *designated safety duties associated with the care, use or in emergency response to the fuel* …". 'Advanced training' is for "… *Masters, engineer officers and all personnel with immediate responsibility for the care and use of fuels and fuel systems on ships subject to the IGF Code* …".

To support application of ammonia as fuel, member states should develop national training and certification suitable for certification to the STCW Convention.

**ISM Code**

The IMO *International Safety Management Code* (ISM Code) provides an international standard for the safe management and operation of ships and to prevent pollution. Intended to have widespread application, based on general principles and objectives, this Code requires operators to assess all risks to a specific company's ships, personnel, and the environment, and to establish appropriate safeguards.

Notwithstanding the final decision on the application of ammonia as fuel under the IGF Code, there is a connection, or applicable analogy, to the operational requirements in place under the IGF Code Part C-1 for methane.

Under section 17, it is required that drills and emergency exercises be conducted onboard at regular intervals. Section 18 includes operational requirements, including the requirement for a fuel-handling manual and the provision of emergency procedures. The fuel-handling manual must cover the overall operation of the ship from dry-dock to dry-dock, including firefighting and emergency procedures, specific fuel properties and the equipment needed to safely handle specific fuel, etc.

The responsibility producing these manuals initially falls to the shipyard, or designer, and equipment suppliers. But it also makes some functions mandatory for the operators.

These IGF Code requirements provide the supporting documents and basis for operators to undertake their ISM Code obligations. It is recommended that, regardless of the IMO's final decisions on the appropriate instrument for ammonia as a marine fuel, applicable regulations, guidelines or amendments to the IGF Code, or newly developed instruments, adopt the same framework of operational requirements as those for methane by Part C-1 of the IGF Code. This will facilitate application under the ISM Code.

#### 3.2.2.2 MARPOL

The IMO's International Convention for the Prevention of Pollution from Ships (MARPOL) sets out the international requirements for preventing pollution from ships travelling internationally or between two member states. The Convention is divided into annexes covering specific pollution controls:

- Annex I – Regulations for the prevention of pollution by oil
- Annex II – Regulations for the control of noxious liquid substances in bulk
- Annex III – Regulations for prevention of pollution by harmful substances carried by sea in packaged form
- Annex IV – Regulations for the prevention of pollution by sewage from ships
- Annex V – Regulations for the prevention of pollution by garbage from ships

The last annex to be added to the Convention, Annex VI – Regulations for the prevention of air pollution from ships – was adopted by the Protocol of 1997 to MARPOL. It introduced the IMO's regulatory framework for air pollution and key air-pollutant controls for shipping, including for ozone-depleting substances, NOx, SOx, Volatile Organic Compounds (VOCs), shipboard incineration and the availability and quality of fuel oils. By later amendment, the IMO introduced regulations covering energy efficiency.

Four key regulations in MARPOL Annex VI are important when considering ammonia as a marine fuel.

**Air Pollution Annex VI, Regulation 13 – Nitrogen Oxides**

To reduce the harmful effects of NOx emissions on human health and the environment, Regulation 13 sets out the limits for their emissions from ship's diesel engines. It mandates that all marine diesel engines greater than 130 kW installed on vessels subject to MARPOL Annex VI are to comply with the applicable emission limit, except engines that are only used for emergency applications.

Marine diesel engines are defined by the IMO as any reciprocating internal combustion engine operating on liquid, gaseous or dual fuels, including those operating on the Diesel or Otto combustion cycles.

This regulation's NOx limits are based on engine-rated speed (see Figure 15), with the lowest limits applicable to medium and high-speed engines. The application date of Regulation 13's NOx limits is tied to the ship's construction date.

The Tier I NOx limit was retrospectively applicable to engines fitted to ships with keels laid on or after 1 January 2000, when Annex VI entered into force on 19 May 2005. Additional NOx limits were introduced by amendments to 2008 Annex VI and the NOx Technical Code (NTC), including the global Tier II limit from 1 January 2011.

They also introduced the Tier III limit, which is only applicable in Emission Control Areas (ECA), which effectively represented a NOx reduction of about 80% from the previous Tier I limit.

The Tier III limits are applicable to NOx ECAs once these areas are officially recognised by the IMO. Currently, the only NOx ECAs in force are the North American and United States Caribbean Sea areas, which entered into force on 1 January 2016, and the Baltic and North Sea ECAs (originally designated as SOx ECAs only), which became NOx ECAs from 1 January 2021.

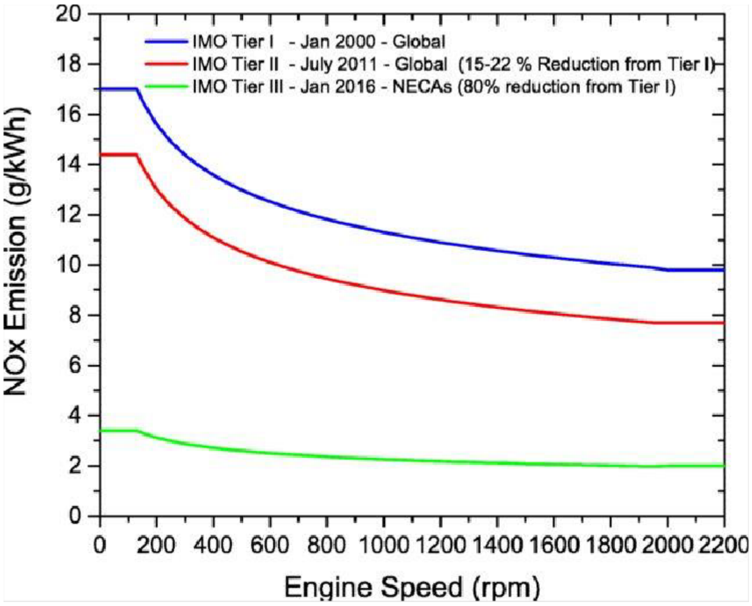


Figure 15. MARPOL 73/78 Annex VI Reg 13 – NOx emission limits with respect to engine speed

The key instrument supporting the Regulation 13's regulations is the NTC, which is in large part based on the ISO 8178 series of standards *"Reciprocating internal combustion engines – exhaust emission measurement*", in particular the following parts (showing current revision dates):

- ISO 8178-1:2020 Part 1: Test-bed measurement systems of gaseous and particulate emissions
- ISO 8178-4:2020 Part 4: Steady state and transient test cycles for different engine applications
- ISO 8178-5:2021 Part 5: Test fuels
- ISO 8178-6:2018 Part 6: Report of measuring results and test
- ISO 8178-7:2015 Part 7: Engine family determination
- ISO 8178-8:2015 Part 8: Engine group determination

As required by Annex VI, the NTC is to be applied for the reference testing and certification of all marine diesel engines subject to the requirements of Regulation 13. The NTC sets the application-specific test cycles from which the cycle-weighted NOx emission value for that particular group or family of engines as represented by the parent engine testing is determined, in accordance with the provisions of the NTC's chapter 5.

As part of those provisions, the NTC requires that the parent-engine test is undertaken on a DM grade (distillate) marine fuel in accordance with ISO 8217:2005, if a suitable reference fuel is not available.

Furthermore, if a DM grade is not available, the emissions testing for the parent engine is to be undertaken on a RM grade (residual) fuel oil. In all cases, the fuel oil used during the test is sampled and analysed for use in the calculation of the NOx emissions. The vast majority of certifications for marine NOx emissions has been undertaken on a DM grade fuel oil.

Marine engines, particularly the larger medium- and slow-speed engines, can operate on a wide range of ISO 8217 distillate and residual fuel oils and have adjustable features to compensate for variations in fuel quality and ignition properties. This is the basis of engine group (rather than engine family) certification, and these ranges of operation are covered in the technical files of engine group and individual engine certifications.

While the range of marine fuel oils varies significantly, including fuel-bound nitrogen and oxygen content, the IMO's NOx-certification regime is based on defined test-bed testing using DM- or RM-grade fuels and it accepts that NOx emissions in operation will vary from the certified values, depending on the fuel oil.

This recognition is confirmed by the allowance of 10% NOx emissions for onboard tests using RM grade fuel oils (refer to 6.3.11.2 of the NTC). This foundation is applied from a knowledge base of RM and DM grade fuel oils and blends derived from petroleum refining.

For the testing and certification of DF engines, Annex VI and the NTC has been consistently updated to add fuel-specific emissions factors and other items missing from the original 1997 documents and 2008 amendments, which covered marine fuels used and anticipate at the time. The latest amendments are detailed in MEPC.251(66) (2014), MEPC.258(67) (2014) and MEPC.272(69) (2016), adding to the requirements for petroleum-derived conventional fuel oils and to include more information on using the following fuels:

- Rapeseed Methyl Ester
- Methanol
- Ethanol
- Natural Gas
- Propane
- Butane

Amendments to update the NOx certification requirements under Annex VI and the NTC to include requirements for testing ammonia (and hydrogen) are outstanding and a hurdle to implementation. The vast majority of NOx certification is based on determining the flow of exhaust masses by applying the carbon-balance method to the fuel characteristics.

Currently, ammonia is considered to fall under the Annex VI definition of “fuel oil”, which includes “… *any fuel delivered to and intended for combustion purposes for propulsion or operation on board a ship, including gas, distillate and residual fuels*”. This needs to be considered during the development of the IMO instruments for application of ammonia as a marine fuel.

**Air Pollution Annex VI, Regulation 14 – Sulphur Oxides (SOx) and Particulate Matter**

By limiting the sulphur content of marine fuels, MARPOL Annex VI Regulation 14 restricts the volume of SOx, and therefore also the sulphate-based particulate matter (PM), emitted to the atmosphere from fuel oil-consuming equipment onboard ships.

Similar to the Regulation 13 limits for NOx, the IMO adopted sulphur content limits for fuels that were later updated with the 2008 revisions to Annex VI and allowed different limits for sulphur content to be applied globally and locally within ECAs.

Starting initially with limits of 4.5% sulphur globally and 1.5% in ECAs, the limits have been progressively reduced, with the ECA limit reduced to 0.1% from 1 January 2015 and the global limit reduced to 0.5 from 1 January 2020 – see Figure 16.

At present, there are no IMO initiatives to further reduce these limits to align them with those imposed on the use of diesel on roads, which are significantly below the IMO global limits of 5,000 ppm and 1,000 ppm in ECAs.

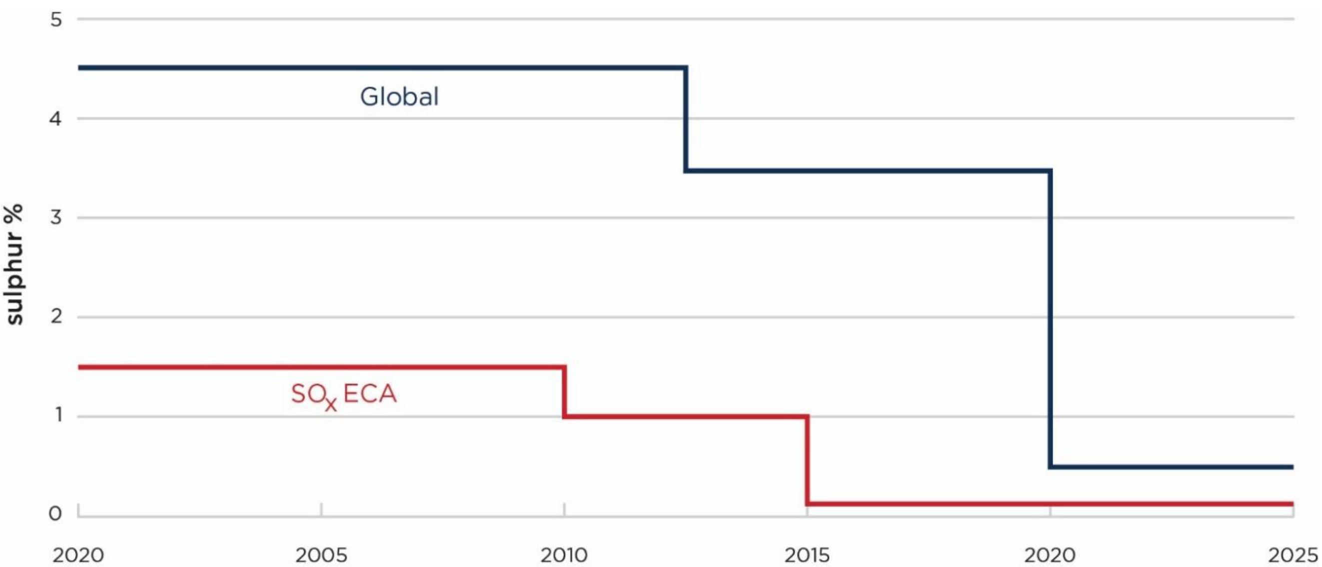


Figure 16. MARPOL 73/78 Annex VI Reg 14 – SOx emission limits

Ammonia is sulphur free and therefore provides a way to comply with, and go well beyond, the requirements of Regulation 14. It is expected that the DF ammonia engines will use sulphur-compliant pilot fuel and, depending on the engine technology, this may represent a significant proportion of the fuel consumed (possibly as much as 15-20%, but this is still under development).

It is perhaps unlikely, but applying 'equivalents' found in Regulation 4, may be a route to considering the use of high-sulphur pilot fuels for DF ammonia engines. Some precedents exist for this on LNG carriers burning high-sulphur pilot fuels with LNG boil-off gas; these have been recognised for application to the EU Sulphur Directive 1999/32/EC, as amended, and codified by EU Directive 2016/802, and by EU Regulation 2010/769/EU of 13 December 2010.

**Air Pollution, Annex VI Regulation 18 – Fuel Oil Availability and Quality**

Regulation 18 to MARPOL Annex VI details the requirements for Administrations, fuel suppliers and owner/operators regarding the availability and quality of fuel oil. As defined by Annex VI, fuel oil means 'any fuel delivered to and intended for combustion purposes for propulsion or operation onboard a ship, including gas, distillate and residual fuels'.

These requirements oblige the fuel supplier to document the fuel-sulphur content (and other parameters) within the Bunker Delivery Note (BDN), and also for the BDN to be accompanied with a sealed sample of the fuel, known as the MARPOL sample.

However, Regulation 18.4 clarifies that the BDN and fuel sample requirements do not apply to gaseous fuels such as LNG, CNG or LPG. Similar exemptions may also be considered applicable to ammonia; albeit they have not considered implications of the added toxicity levels. This is another area of amendment to Annex VI and the NTC that needs to be captured during the development of the IMO instruments for using ammonia as a marine fuel.

Regulation 18.3 explains the general fuel properties required for hydrocarbon fuel oils derived largely from petroleum refining and fuel oil for combustion purposes derived by methods other than petroleum refining. Ammonia will fall into the latter category, however many of the high-level fuel requirements are applicable to fuels derived from both methods. These requirements state that the fuels should not:

- Contain inorganic acid
- Jeopardise the safety of ships or adversely affect the performance of machinery
- Harm or be harmful to personnel
- Contribute overall to additional air pollution

The requirement under Regulation 18.3.2.2 requires that fuels derived by methods other than petroleum refining should not cause an engine to exceed the applicable NOx emission limit. This requirement is particularly challenging to deal with since Regulation 18 largely tackles obligations on fuel suppliers, who have no means of verifying it without the support of the owner/operators and engine designers.

However, in the case of ammonia and subject to the amendments that may be required, all engines will need to be Nox certified for using all of their fuels, including ammonia.

With regard to the legal obligations on documenting the fuel sulphur content and the BDN, for safety and toxicity reasons it is recommended that the process for sampling, testing and verifying the ammonia fuel characteristics is agreed with the fuel supplier and flag Administration prior to bunkering of any ammonia as fuel.

Documenting fuel properties, commercial aspects and verifying statutory sulphur compliance would need to be agreed with the fuel supplier.

**Air Pollution Annex VI, – required EEDI, EEXI and CII**

The Energy Efficiency Design Index (EEDI) was made mandatory for new ships at MEPC 62 (July 2011) with the adoption of amendments to MARPOL Annex VI (resolution MEPC.203(62)), by parties to MARPOL Annex VI. The EEDI baselines were constructed using ships built between 1999 and 2008, assuming the use of HFO and a tank-to-wake carbon factor of 3.114.

Accompanying guidelines for the calculation of the attained EEDI were developed and periodically updated. These calculation guidelines are listed in Table 22, which contains tank-to-wake carbon factors for different types of fuels.

Table 22. Tank-to-Wake Carbon Factors for different types of fuels (MEPC.308(73))

| Type of Fuel | Reference | Lower Calorific Value (LCV) | Carbon Content | Cf (t-CO2/t-Fuel) |
|---|---|---|---|---|
| MDO/MGO | ISO 8217 Grades DMX through DMB | 42,700 | 0.8744 | 3.206 |
| LFO | ISO 8217 Grades RMA through RMD | 41,200 | 0.8594 | 3.151 |
| HFO | ISO 8217 Grades RME through RMK | 40,200 | 0.8493 | 3.114 |
| LPG | Propane | 46,300 | 0.8182 | 3.000 |
| | Butane | 45,700 | 0.8264 | 3.030 |
| LNG | - | 48,000 | 0.7500 | 2.750 |
| Methanol | - | 19,900 | 0.3750 | 1.375 |
| Ethanol | - | 26,800 | 0.5217 | 1.913 |

As can be seen above, there is no provision for ammonia, which could be assigned a tank-to-wake carbon factor ($C_F$) of 0. A ship capable of operating primarily on ammonia (allowing for pilot fuel) could be assigned such a low attained EEDI as to render it effectively exempt from the regulation; this may call into question the necessity of adding ammonia to the table, even if the required levels of pilot fuel remain to be demonstrated.

There have been some initial calls for the EEDI framework to be converted into a pure energy-efficiency metric without the influence of carbon factors. This action would eliminate the need for more additions to this table.

However, there are other IMO regulations that refer back to this table in the EEDI Calculation Guidelines. The first is the EEXI framework for existing ships that was agreed at MEPC 76, which broadly applies the EEDI concept to existing rather than new ships; there are, however, some adaptations to the framework that recognise the difficulty in obtaining documentation, and the potential for existing ships to meet similar standards designed for new ships.

Since it is unlikely to be possible to retrofit ammonia engines and fuel-handling systems by the deadline for EEXI compliance, the absence of ammonia from the table is not likely to have any bearing on initial EEXI compliance.

The IMO Fuel Oil Consumption Database also refers to the carbon factors provided in the EEDI Calculation Guidelines and, to ensure consistent reporting, a table entry for the carbon factor of ammonia may be needed.

Additionally, the regulations from the IMO's Carbon Intensity Indicator (CII), which will enter into force in 2023, are built from the organisation's Fuel Oil Consumption Database and, by extension, this table of carbon factors will be used to calculate the attained CII.

The lifecycle GHG and Carbon Intensity Guidelines for Maritime Fuels (LCA Guidelines) are also being developed and will be used to derive well-to-wake carbon factors for fuels. Ammonia may be assigned a range of different carbon factors, depending on the production pathway.

Using well-to-wake carbon factors in EEDI, EEXI and CII has been discussed, but their inclusion remains uncertain at this point. This does, however, highlight the need to have the carbon factors of fuel defined separately from the EEDI calculation guidelines.

Another aspect that needs to be considered with a tank-to-wake carbon factor is GHG slip, whether methane or $N_2O$. There have been some proposals to include methane slip in the EEDI calculation; of course, this calculation would need to be extended to $N_2O$. Slip will however be addressed in the calculation methodology of the LCA Guidelines.

### 3.2.3 International Bunker Industry Association

The International Bunker Industry Association (IBIA) is based in the United Kingdom, with branches in Africa and Asia, representing industry stakeholders. Its membership is broad and includes participants from sectors such as: owner/operators, bunker suppliers, traders, brokers and port authorities. IBIA has consultative status at the IMO as a non-governmental organisation and is an important and active player in providing technical information to the IMO on marine fuel specifications, fuel sampling, etc.

IBIA develops positions on IMO regulations and industry guidance or best practice publications, both directly and as contributors. The joint industry guidance document '*The supply and use of 0.50% sulphur marine fuel*' is an example (OCIMF, 2019).

To support industry adoption of alternative marine bunker fuels, IBIA has created the Future Fuels Working Group, which has been assessing the associated technologies and fuels, including ammonia.

As soon as the results of this ongoing assessment are finalised, they will be available to IBIA members[17].

### 3.2.4 The Society of International Tanker and Terminal Owners (SIGTTO)

The Society of International Tanker and Terminal Owners (SIGTTO) is an international body established for the exchange of technical information and experience between members. SIGTTO has been instrumental in the development of the IGC Code and offers the most relevant marine experience for the carriage of anhydrous ammonia in bulk. With a membership encompassing ship owners/operators and terminal operators, it also provides the most competent source of experience on cargo loading and unloading, and the ship-to-ship transfers of liquefied gases.

SIGTTO produces publications covering position papers, standards, guidelines and recommendations applicable to gas carriers, solely and in association with other industry stakeholders such as OCIMF on common subjects. As with LNG bunkering ships, the IGC Code would be applicable to anhydrous ammonia bunkering ships which are subject to the SOLAS convention, and also to the ships typically required by flag Administrations for bunkering vessels or barges operating solely in their sovereign waters.

Some of the most relevant publications are detailed below for reference. At present it is understood that SIGTTO is not developing specific publications for anhydrous ammonia, but it may consider this if necessary. As can be seen from the existing IGC Code requirements and the additional publications in this space such as those identified below, everything for carriage of anhydrous ammonia in bulk, cargo loading/unloading, ship-to-ship transfers, etc., is already covered. It is more likely that the Society for Gas as a Marine Fuel – see section 3.2.5 below – and ISO will develop standards and industry guidance to support the bunkering of anhydrous ammonia.

**ESD Systems – Recommendations for Emergency Shutdown and Related Safety Systems.** Second Edition published 2021. This document provides recommendations for ESD and related safety systems, including overflow control, ship shore link and emergency release systems. Guidance for testing these systems is provided and 'bowties' are used to help explain the IGC Code requirements. In addition to discussing the requirements of the IGC Code, this document recommends additional measures for linked ESD systems for LPG. An overview of the types of ship-to-shore systems that are typically used in the industry is provided in the annexes, including guidance for cyber security issues associated with linked ESD systems.

**Recommendations for Relief Valves on Gas Carriers.** Third edition was published 2020. Relief valves perform a safety critical function, so proper design and robust maintenance procedures are essential to ensure that this equipment will function as required. The purpose of this document is to provide information to support this goal.

**Ship/Shore Interface for LPG/Chemical Gas Carriers and Terminals.** First edition published 2018. This publication identifies potential hazards at the LPG/chemical ship/shore interface. Referencing industry regulations and guidance, it suggests best working practices for the terminal and the ship to minimise the risk of incident and to help raise overall safety awareness. This publication describes risk assessment and hazard identification techniques that can be applied by LPG/chemical gas shipping staff and terminal operators. It identifies the

[17] https://ibia.net/2022/03/04/ibias-future-fuels-working-group-assessment/

principal risks at the ship/shore interface, including vessel arrival and departure, loading and discharge operations, as detection and exposure to hazardous products. Diagrams support the text and effectively illustrate how to mitigate 'top event' hazards to cargo containment.

**Guidelines for the Alleviation of Excessive Surge Pressures on ESD for Liquified Gas Transfer Systems.** Second edition published 2018. This publication explains the concept of surge pressure and provides practical advice on its associated hazards and risk management. It outlines the principal design and operational recommendations for cargo transfer systems and will benefit managers, designers and operators of liquefied gas carriers.

**Recommendations for Liquefied Gas Carrier Manifolds.** Second edition published 2018. This publication provides recommendations on the layout, strength and fittings for gas carrier manifolds and is applicable to LPG and LNG carriers. The aim of this publication is to improve standardisation of LPG and LNG carrier manifolds to assist in the safe connection of cargo transfer equipment at every facility. Guidance is also provided on cargo spill containment, including deck protection, coaming, drip trays, gratings, drainage and water curtains.

**Liquefied Gas Handling Principles on Ships and in Terminals, (LGHP4).** Fourth edition published 2016. This publication covers every aspect of the safe handling of bulk liquid gases (LNG, LPG and chemical gases) on board ships and at the ship/shore interface. Liquefied Gas Handling Principles on Ships and in Terminals emphasises the importance of understanding the physical properties of gases in relation to the practical operation of gas handling equipment on ships and at terminals.

**Ship to Ship Transfer Guide for Petroleum, Chemicals and Liquefied Gases.** CDI, ICS, OCIMF and SIGTTO. First Edition published 2013. This cross-industry publication provides guidance on planning and execution of STS operations. It is applicable to all ships involved in transfer activities and to all types of bulk liquid cargoes, whether transferred at sea or in port. It will benefit Masters, Marine Superintendents and others, such as STS service providers and transfer organisers, involved in STS operations.

**Liquefied Petroleum Gas Sampling Procedures**. First Edition published 2010. This publication is a comprehensive guide to sampling liquefied petroleum gas. It covers the whole process from beginning to end and looks at the basic reasons for taking cargo samples, sampling connections, e.g., open- and closed-loop systems, the types of sample containers, recommended standard sample connections and safe procedures for taking samples.

### 3.2.5 Society for Gas as a Marine Fuel (SGMF)

The Society for Gas as a Marine Fuel was established in 2013 from a SIGTTO-driven initiative. It is a non-governmental organisation established to promote safety and industry best practice for using gas as a marine fuel. It obtained NGO status at the IMO in 2019.

Most of the SGMF's activities, focus and publications have been on LNG as the marine 'gas' fuel. However, it is understood that the scope of its activities will expand to include other gases being considered for marine fuels, notably hydrogen and ammonia.

The SGMF has developed a tool called 'BASiL' (Bunkering Area Safety information LNG) to support processes related to bunkering interfaces, port permitting and establishing the safety and zones referenced in the ISO standard subsection of this report. Expanding this tool, or developing new ones, to support other fuels of interest is a work in progress and would support the adoption of ammonia as a marine fuel.

The list of publications for LNG from SGMF are for reference below; they are helpful documents, which also illustrate the current gaps in industry guidance and best-practice for using ammonia as a marine fuel, and industry would therefore benefit from these publications being updated to cover a wider range of liquefied gases or developing ammonia specific guidance.

**FP00-01-06 Ver4.0 LNG as a marine fuel: An Introductory Guide; June 2021.** This high-level publication sets out the key facts about LNG: what it is, how it is used, its environmental and safety profile, which countries have invested in it, ship design and systems, bunkering facilities and process, how it is purchased, and how the personnel involved in handling LNG should be trained and familiarised.

**FP02-01 Ver1.0 Gas as a marine fuel: Recommendation of Controlled Zones during LNG bunkering; May 2018.** This publication details how to effectively determine the location and size of ‘controlled zones’ around bunkering equipment.

**FP05-01 Ver1.0 Gas as a marine fuel: contractual guidelines; September 2015.** This publication provides an overview of the process of custody transfer for LNG to marine vessels. It describes the variables to be measured for the main marine engine types, and its latter sections describe proven techniques for measuring LNG quantity and quality. The guide describes several methods, all of which provide accuracy and auditability to support the custody-transfer process.

**FP07-01 Ver3.0 LNG as a marine fuel: Safety and Operational Guidelines - Bunkering; December 2021. This** covers recommendations from design stage of vessel and bunkering facility, via the planning and preparation stages of the bunkering location and vessel operations for all stakeholders in the bunkering process.

**FP08-01 Ver1.0 Gas as a marine fuel: Simultaneous Operations during LNG bunkering; May 2018.** This publication looks at undertaking typical ship operations in port while simultaneously transferring fuel (SIMOPS). It is imperative not to compromise safety when using LNG, but it is also important to support other operations that promote, and in some cases improve, operational efficiencies while at ports. This publication looks at the issues and clearly describes the process of managing the associated risks.

**FP10-01 Ver1.0 Gas as a marine fuel: Work practices for maintenance, repair and dry-dock operations; May 2020.** This document provides new guidance on the work practices for maintenance, repair and dry-dock operations for ships that use gas/LNG as fuel. It seeks to ensure safe maintenance of gas-fuelled ships.

**FP14-01 Ver1.0 Gas as a marine fuel: Operations of ships with Liquefied Natural Gas (LNG) competency and assessment guidelines; May 2021.** This document focuses on all activities related to the preparation, storage, handling and use of gas as a fuel -- from the storage tank through to delivery to the consumer. It also highlights the competencies required for the personnel who perform related tasks.

**TGN06-04 Ver1.0 Gas as a marine fuel: manifold arrangements for gas-fuelled vessels; May 2019.** This document is intended to focus discussion and industry alignment on the manifold arrangements fitted onboard gas-fuelled vessels.

**TGN06-05 Ver1.0 Gas as a marine fuel: recommendations for linked emergency-shutdown arrangements for LNG Bunkering; May 2019.** This technical guidance note (TGN) provides recommendations for the emergency-shutdown (ESD) arrangements, integration, data and voice communication and their interfaces for LNG bunkering of gas-fuelled ships. It specifically addresses the functional safety principles of the linked ESD system to ensure a controlled shutdown of the bunkering operation in the case of an emergency.

**TGN06-06 Ver1.0 Gas as a marine fuel: LNG bunkering with hose bunker systems: considerations and recommendations; February 2020.** This TGN provides recommendations for the safe handling and operation of bunker systems using cryogenic flexible hoses as the main means to transfer LNG. It specifically addresses the selection of the hoses, their handling and functional safety principles.

**TGN06-07 Ver1.0 Gas as a marine fuel: Bunker Station Location: Considerations and Recommendations; January 2021.** This TGN addresses the industry requirement for guidelines for locating the bunkering manifolds and/or bunker stations installed on gas-fuelled vessels subject to the IGF Code.

The EMSA study “*Guidance on LNG Bunkering to Port Authorities and Administrations*”, published in January 2018, is another guidance document that could be updated to include ammonia.

### 3.2.6 International Association of Classification Societies (IACS)

Classification societies play an active maritime role in assuring the safety of life, property and the environment. The members of IACS collectively make a unique contribution to maritime safety and regulation by providing technical support, compliance verification (of statutory instruments in their role as Recognised Organizations) and research and development. The collaborative effort of the multiple class societies in IACS leads to the implementation of common rules, unified requirements (UR) for typical Class Rules, unified interpretations (UI) of statutory instruments and other recommendations that are applied consistently by IACS members.

**Recommendation No.33**. With respect to ammonia, in 1992 IACS published Recommendation 33, Guidelines for the Construction of Pressure Vessel Type Tanks Intended for the Transportation of Anhydrous Ammonia at Ambient Temperatures. This recommendation provided guidance on the construction of ammonia tanks built from carbon-manganese steels that are meant to carry ammonia at temperatures at or above 0ºC. The recommendation at one time provided the requirements for materials, welding, stress-relieving and non-destructive testing, largely to address stress corrosion issues with ammonia. However, these were deleted in March 2021 once they were captured in the revised 2016 IGC Code.

**Unified Requirement M57**. To address the safety risks from using ammonia as a refrigerant, IACS introduced Unified Requirement UR M57 in 1993, the Use of ammonia as a refrigerant. As a UR, this must be uniformly implemented by IACS members and would have been captured in their respective Rules. This UR establishes safety principles to mitigate the release of ammonia in enclosed spaces and protect seafarers from the toxicity. These include:

- gastight compartments
- two access doors
- ventilation at 30 air changes per hour
- ammonia gas detection
- water screens over doorways
- independent bilge system
- PPE
- breathing apparatus

This publication has not been revised since its release in 1993 and would benefit from an update.

As indicated above, the IGF Code is the most appropriate IMO instrument to deal with ammonia as a fuel until the organisation develops non-mandatory guidelines or amends SOLAS instruments to cover its application. The goal and functional requirement-based structure of the IGF Code, together with the clear path to approval of fuels not directly covered by the requirements through the 'alternative-design' process, means the IGF Code has the right framework for approving all gases and low-flashpoint fuels.

Furthermore, IACS has been active in developing URs, UIs and recommendations to support application of the IGF Code, many of which are transferrable to ammonia, or other gases or low-flashpoint fuels. It would benefit the marine adoption of ammonia and other fuels if IACS updated these documents to cover a broader range of fuels than just LNG. Until then, applying the intent and principles of these documents will be necessary. The documents include:

- IACS Unified Requirement M78 – *Safety of Internal Combustion Engines Supplied with Low-Pressure Gas*
- IACS "GF" Unified Interpretations of the IGF Code – *GF1 through GF 18*
- IACS Recommendation No. 142 – *LNG Bunkering Guidelines*
- IACS Recommendation No. 146 – *Risk assessment as required by the IGF Code*
- IACS recommendation No. 148 – Survey of liquefied gas fuel containment systems

All IACS publications are publicly available on their website: https://www.iacs.org.uk/publications/.

Recognising the increased interest in ammonia as a fuel, some class societies have recently published several rules, guides and supporting documents:

- Guidelines:
  - **American Bureau of Shipping (ABS)**. ABS Guide for Ammonia Fuelled Vessels. Published September 2021.
  - **Bureau Veritas (BV)**. Ammonia-fuelled Ships – Tentative Rules. Rule Note NR 671 DT R00 E. Published July 2021.
  - **Det Norske Veritas (DNV)**. Rules for Ammonia in Part 6 Chapter 2 Section 14. Published July 2021.
  - **Korean Register (KR)**. Guidelines for Ships Using Ammonia as Fuels. Published July 2021.

- **NKK (Nippon Kaiji Kyokai – ClassNK)**. Guidelines for Ships Using Alternative Fuels (Edition 1.1) (Methyl / Ethyl Alcohol / LPG / Ammonia). published September 2021.

- Supporting Documents:
  - ABS Sustainability Whitepaper on Ammonia as Marine Fuel. Published October 2020.
  - DNV Ammonia as a marine fuel white paper.
  - DNV (on behalf of the Green Shipping Programme and with input from the Norwegian Maritime Authority and other partners) Ammonia as a Marine Fuel Safety Handbook.
  - KR Whitepaper on Forecasting the Alternative Marine Fuel: Ammonia. Published January 2020.
  - Lloyd's Register. Ammonia Detection Limits Discussion Paper. Published January 2021.

Ammonia's properties have a significant impact on the development of rules for its use as a marine fuel. Risk-mitigation strategies may include robust design, early leak detection, water dousing and PPE. Effectively, the safety concepts introduced by UR M57 are the starting point for guidelines and tentative rules, many of which also follow the structure and content of the IGF Code.

To further support its adoption as a marine fuel and understanding of the risks associated with its use, class societies offer advisory or consultancy services, including risk assessments, a review of statutory rules or international standards, workshops, and recommendations for approving alternative designs.

Furthermore, many class societies have introduced 'ready' rules or guides. These were introduced to respond to demand for flexibility and capability in vessel designs that would support future conversions to alternative fuels such as LNG, methanol or ammonia.

The scope of such 'ready' preparations or modifications can differ significantly from ship to ship, so they need to be agreed between the shipowner and the shipbuilder on a case-by-case basis.

It is important to recognise that these 'ready' assessments only should be reviewed in association with the Rules or regulations in place at the time of construction; they also do not guarantee compliance with the Rules or regulations in place at the time of conversion.

There is a broad scope of application for these 'ready' assessments, ranging from high-level concepts with little detail and no installed systems or components, to more mature designs with some components or systems installed at new construction, or which are suitable for easier conversion at a later date; in some cases, they are designed to be suitable for switching to other fuels.

However, the wide variability of items such as fuel properties, energy density, storage conditions, material properties and density make the options for transitioning from one (gaseous or liquefied gaseous fuel) to another limited without oversizing or over-specifying at the initial design stage; this is particularly so for high-cost items such as fuel containment systems and IC engines. In many cases, it may not be cost effective to convert equipment later.

**<u>For Onboard Power Production</u>**

All internationally trading ships subject to SOLAS need to comply with its requirements for machinery arrangements. Chapter II-1 of SOLAS (Construction – structure, stability, installations) includes requirements for machinery installations under Part C, specifically for machinery including IC engines under regulation 27.

Part D includes the requirements for electrical installations; Part F holds the IMO criteria for alternative design and arrangements.

Chapter II-2 of SOLAS (Construction – Fire protection, fire detection and fire extinction) has additional requirements for machinery spaces.

These high-level mandatory safety requirements, together with the SOLAS-driven requirements of the IGF Code, comprise the primary regulatory safety rules for onboard propulsion and power generation for ships using gases or other low-flashpoint fuels.

For fuel-cell applications, IMO's draft *'Interim Guidelines for the Safety of Ships using Fuel Cell Power Installations*', which are expected to be approved at MSC 105, are applicable, subject to agreement from the flag Administration.

Supporting the IMO requirements are extensive IC engine and machinery requirements from the classification societies. Many IACS URs are applicable and class societies have incorporated them into their respective rules and collectively applied them in a harmonised manner. The most relevant URs and recommendations are shown below in Table 23 and Table 24

Table 23. IACS URs

| UR No. | Description | Revision |
|---|---|---|
| M | Machinery Installations | |
| M2 | Alarm devices of internal combustion engines | Rev. 0 1971 |
| M3 | Speed governor and overspeed protective device | Rev.6 Nov 2018 |
| M9 | Crankcase explosion relief valves for internal combustion engines | Rev.3 Jan 2005 Corr.1 Nov 2005 Corr.2 Sep 2007 |
| M10 | Protection of IC engines against crankcase explosions | Rev.4 July 2013 |
| M11 | Protective devices for starting air mains | Rev.0 1972 |
| M12 | Fire extinguishing systems for scavenge manifolds | Rev.0 1972 |
| M25 | Astern power for main propulsion | Rev.4 June 2017 |
| M27 | Bilge-level alarms for unattended machinery spaces | Rev.0 1976 |
| M28 | Ambient reference conditions | Rev.0 1978 |
| M29 | Alarm systems for vessels with periodically unattended machinery spaces | Rev.3 1997 |
| M30 | Safety systems for vessels with periodically unattended machinery spaces | Rev.1 1997 |
| M31 | Continuity of electrical power supply for vessels with periodically unattended machinery spaces | Rev.0 1978 |
| M35 | Alarms, remote indications and safeguards for main reciprocating IC engines installed in unattended machinery spaces | Rev.8 Jan 2019 |
| M36 | Alarms and safeguards for auxiliary reciprocating IC engines driving generators in unattended machinery spaces | Rev.6 Dec 2018 |
| M40 | Ambient conditions – Temperatures | Rev.0 1981 |
| M43 | Bridge control of propulsion machinery for unattended machinery spaces | Rev.0 1982 |
| M44 | Documents for the approval of diesel engines | Rev.10 Feb 2021 Corr.1 Feb 2022 |
| M45 | Ventilation of machinery spaces | Rev.2 Feb 2011 |
| M46 | Ambient conditions - Inclinations | Rev.2 Dec 2018 |
| M47 | Bridge control of propulsion machinery for attended machinery spaces | Rev.0 1983 |
| M51 | Factory Acceptance Test and Shipboard Trials of IC Engines | Rev.4 Feb 2015 Corr.1 Oct 2018 |
| M53 | Calculations for IC engine crankshafts | Rev.4 Aug 2019 |
| M57 | Use of ammonia as a refrigerant | Rev.0 1993 |
| M60 | Control and Safety of Gas turbines for Marine Propulsion Use | Rev.1 Nov 2021 |
| M61 | Starting Arrangements of IC Engines | Rev.1 Feb 2022 |
| M63 | Alarms and safeguards for emergency diesel engines | Rev.0 Jan 2005 |
| M66 | Type Testing Procedure for Crankcase Explosion Relief Valves | Rev.4 Feb 2021 Corr.1 Oct 2021 |
| M67 | Type Testing Procedure for Crankcase Oil Mist Detection and Alarm Equipment | Rev.2 Feb 2015 |
| M71 | Type Testing of IC Engines | Rev.0 Feb 2015 Corr.1 June 2016 |
| M72 | Certification of Engine Components | Rev.2 Jan 2019 |
| M73 | Turbochargers | Rev.0 Feb 2015 Corr.1 June 2016 |
| M75 | Ventilation of emergency generator rooms | Rev.1 Jan 2021 |
| M76 | Location of fuel tanks in cargo area on oil and chemical tankers | Rev.1 June 2018 |
| M77 | Storage and use of SCR reductants | Rev.3 Sep 2021 |

| | | |
|---|---|---|
| M78 | Safety of IC Engines Supplied with Low Pressure Gas | Rev.1 Feb 2021 |
| M80 | Requirements for AC generating sets | Rev.0 May 2019 |
| M81 | Safety measures against chemical treatment fluids used for exhaust gas cleaning systems and the residues which have hazardous properties | Rev.0 Jan 2021 |
| E | Electrical and Electronic Installations | |
| E5 | Voltage and frequency variations | Rev.1 Sep 2015 |
| E7 | Cables | Rev.5 Feb 2021 |
| E9 | Earthing and bonding of cargo tanks/process plant/piping systems for the control of static electricity | Rev.1 Oct 2012 |
| E10 | Test Specification for Type Approval | Rev.8 Feb 2021 Corr.1 Jan 2022 |
| E13 | Test requirements for Rotating Machines | Rev.3 Dec 2020 |
| E15 | Electrical Services Required to be Operable Under Fire Conditions and Fire-Resistant Cables | Rev.4 Dec 2020 |
| E19 | Ambient Temperatures for Electrical Equipment installed in environmentally controlled spaces | Rev.1 Sep 2005 |
| E20 | Installation of electrical and electronic equipment in engine rooms protected by fixed water-based local application fire-fighting systems | Rev.1 June 2009 |
| E22 | On Board Use and Application of Computer-based systems | Rev.2 June 2016 |
| F | Fire protection | |
| F20 | Inert Gas Systems | Rev.7 May 2015 |
| F26 | Safety aspects of double bottoms and duct keels under cargo oil tanks | Rev.3 May 2004 |
| F29 | Non-sparking fans | Rev.6 June 2005 |
| F32 | Fire detecting system for unattended machinery spaces | Rev.0 1976 |
| F33 | Prohibition of carriage in fore peak tanks of oil or other liquid substances which are flammable | Rev.0 1981 |
| F35 | Fire Protection of Machinery Spaces | Rev.8 June 2005 |
| F42 | Fire testing of flexible pipes | Rev.0 1995 |
| F43 | Installation requirements for analysing units for continuous monitoring of flammable vapours | Rev.2 June 2002 |
| G | Gas Tankers | |
| G1 | Vessels with cargo containment system for liquefied gas | Rev.3 June 2016 Corr.1 may 2018 Corr.2 Oct 2021 |
| G2 | Liquefied gas cargo tanks and process pressure vessels | Rev.2 Dec 2018 |
| G3 | Liquefied gas cargo and process piping | Rev.7 Dec 2019 |
| P | Pipes and Pressure Vessels | |
| P1 | Rules for pipes | Rev.5 Nov 2001 |
| P2 | Rules for piping design, construction and testing | Rev.2 Nov 2001 |
| W | Materials and Welding | |
| W1 | Material and welding for ships carrying liquefied gases in bulk and ships using gases or other low-flashpoint fuels | Rev.4 Apr 2021 |
| Z | Survey and Certification | |
| Z16 | Periodical surveys of cargo installations on ships carrying liquefied gases in bulk | Rev.4 Oct 2013 |
| Z18 | Survey of Machinery | Rev.9 Apr 2020 |
| Z25 | Periodic Survey of Fuel Installations on Ships other than Liquefied Gas Carriers utilising gas or other low-flash point fuels | Rev.1 Sep 2017 |
| Z26 | Alternative Certification Scheme | Rev.0 Feb 2015 |

Table 24. IACS Recommendations

| Rec No. | Description | Revision |
|---|---|---|
| 26 | List of minimum recommended spare parts for main IC engines of ships for unrestricted service | Rev. 1 Nov 2006 |
| 27 | List of minimum recommended spare parts for each type of auxiliary IC engine driving electric generators for essential services on board ships for unrestricted service | Rev.1 Nov 2006 |
| 30 | List of minimum recommended spare parts for essential auxiliary machinery of ships for unrestricted service | Rev.1 Jan 2006 |
| 35 | Inspection and Maintenance of Electrical Equipment Installed in Hazardous Areas for Ships other than Tankers | Rev.2 Feb 2021 |
| 41 | Guidance for Auditors to the ISM Code | Rev.5 Oct 2019 |
| 57 | Maintenance and inspection of electrical equipment on the ship | Rev.1 Mar 2016 |
| 58 | Fire Protection of Machinery Spaces | Rev.2 Feb 2021 |
| 74 | A guide to managing maintenance in accordance with the requirements of the ISM Code | Rev.2 Aug 2018 |
| 114 | Recommendation for operational testing, inspection and documentation of emergency shutdown valves for liquefied gas carriers | Rev.1 Dec 2018 |
| 123 | Recommendation based on IMO instruments -MSC.1/Circ.1370 “Guidelines for the design, construction and testing of fixed hydrocarbon gas detection systems” and Resolution MSC.292 (87) “Amendments to the FSS Code Chapter 16 Fixed Hydrocarbon Gas Detection Systems” | Rev.0 May 2012 |
| 138 | Recommendation for the FMEA process for diesel engine control systems | Rev.0 Dec 2104 |
| 142 | LNG bunkering guidelines | Rev.0 June 2016 |
| 146 | Risk assessment as required by the IGF Code | Rev.0 Aug 2016 |
| 147 | Type Approval Certificate of IC Engine | Rev.0 Oct 2016 |
| 148 | Survey of liquefied gas fuel containment systems | Rev.1 Mar 2020 |
| 169 | Guidelines on Approval of High Manganese Austenitic Steel for Cryogenic Service | Rev.0 Sep 2021 |

The majority of these requirements are applicable to engines and machinery installations for all types of fuels, including those using gases or low-flashpoint fuels, without the need for revision or change of scope. However, there are some significant gaps that require new or revised publications to be developed by IACS. Experience from similar processes with LNG would dictate that additional updates to IACS’ recommendations will be required to promote adoption. These new or revised IACS publications may require action:

- IACS UR M78. Safety of Internal Combustion Engines Supplied with Low Pressure Gas. This UR is currently under revision; as published, it only covers low-pressure trunk piston engines using gas (methane) as fuel. IACS UR M59, which covered high-pressure applications has been withdrawn, so the association’s guidance has gaps for high-pressure and cross-head (2-stroke slow speed) engines burning methane. It also has gaps on equivalent requirements for all other low-flashpoint fuels. It may be possible to update UR M78 to cover all engine types and fuels in a more general way, but industry awaits IACS’ efforts on this.
- Recommendation No. 142. LNG bunkering guidelines. Updating this document to cover bunkering of all liquefied gases would be a way to address the gap; alternatively. A new IACS publication should be encouraged.
- Recommendation No. 146. Risk assessment as required by the IGF Code. This publication needs revising to provide specific guidance for undertaking risk assessments for ammonia.
- Recommendations 26, 27 and 30. Investigation is needed to determine whether recommendations for spare parts need to be updated to fully cover modern electronic engines, including DF components.
- Recommendation 138. Consider updating the engine FMEA recommendation to fully cover modern electronic engines including, DF components and systems.

## 3.3 Regulations for EU member states

On 14 July 2021, the European Commission presented 'Fit-for-55' (Figure 17 and Figure 18), a package of measures that seeks to align EU policies on climate, energy, land use, transport and taxation in such a way that the net GHG emissions can be reduced at least 55% by 2030, compared to 1990. It contains proposals for revising regulations and directives and some new policy initiatives.


Figure 17. The European Commission 'Fit-for-55' package.

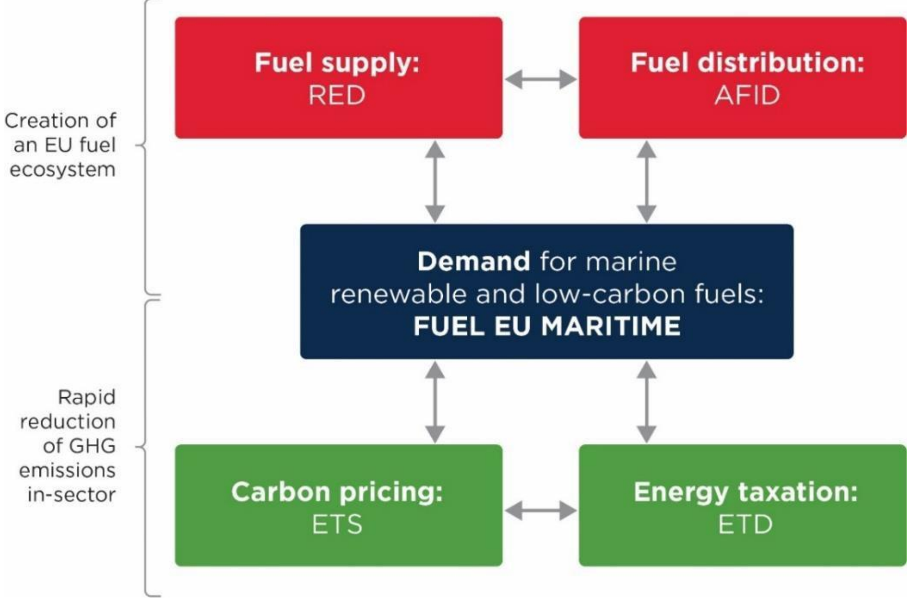


Figure 18. EU policies related to maritime transport

**FuelEU Maritime**

As part of the 'Fit for 55' package, the EC launched the FuelEU Maritime Initiative to increase demand for renewable and low-carbon fuels (RLF) for ships sailing to and from EU ports. It also sought to reduce the emissions from navigation and at berth, and support EU and international climate objectives.

FuelEU Maritime sets a harmonised regulatory framework in the EU and aims to increase the share of renewable and low-carbon fuels (RLF) used in the fuel mix of international maritime transport, including: liquid biofuels, e-liquids, decarbonised gas (including bio-LNG and e-gas), decarbonised hydrogen and its derived fuels (including methanol and ammonia) and electricity.

The initiative will contribute to wider goals by pursuing specific objectives to:

1. Enhance predictability by setting a clear regulatory environment for the use of RLF in maritime transport
2. Stimulate technology development
3. Stimulate production on a larger scale of RLF with high technology readiness levels (TRLs) and reduce the price gap with current fuels and technologies
4. Create demand from ship operators to bunker RLF or connect to electric grid while at berth
5. Avoid carbon leakage

The current proposal focuses on demand policy that sets requirements for ships' fuel consumption and complements the EU regulatory framework related to supply and infrastructure (EC, 2020).

FuelEU maritime, if adopted as proposed, would require ships to use fuels with a 2% lower GHG intensity (measured in $gCO_2e/MJ$) than the average 2020 value, moving to 6% lower by 2030 and up to 75% lower by 2050. Renewable ammonia, which has a lower GHG intensity than fossil fuels on a well-to-wake basis, is likely to be used to comply with 'Fit for 55' requirements.

**<u>EU ETS</u>**

Another important part of the 'Fit-for-55' package is the proposal to gradually add shipping to the European Union Emission Trading system (EU ETS) from 2023. Under this system, shipowners would have to buy permits based on the amount of $CO_2$ emitted in the area where the system is in force. The EU ETS aims to contribute to the wider EU goal to eliminate at least 55% of the continent's net GHG emissions by 2030, compared to 1990.

Since shipowners will pay for the $CO_2$ they emit, this system can stimulate lower output; it will be up to them to determine the method by which that is achieved. Although renewable fuels, such as renewable ammonia, can reduce GHG emissions, it would not be directly stimulated by the shipping industry implementing EU ETS. (EC, 2021)

**<u>RED II</u>**

The second phase of the Renewable Energy Directive (RED II) is an EU instrument that aims to promote the use of energy from renewable sources. The RED II sets a target for all modes of transport to use at least 32% renewable energy by 2030. It includes a specific 'RES-T' target of at least 14% renewable energy in the final energy consumption (level of energy consumed after losses) from transport by 2030.

The renewable energies in transport could consist of biofuels, renewable fuels of non-biological origin (RFNBO, such as hydrogen and ammonia) and could include recycled carbon fuels. At all times, the sustainability requirements should be met. With respect to renewable fuels in maritime shipping, the RED II allows member states to apply those fuels towards their RES-T target.

The RED II's impact assessment identified an additional challenge specific to the maritime sector: the juxtaposition of the shipowners' and operators' incentives does not work to stimulate the deployment of renewable fuels.

In response, and to introduce incentives for the maritime and aviation sectors, fuels supplied to either are measured at 1.2 times their energy content (except for fuels produced from food and feed crops) when demonstrating compliance with the renewable-energy target. This provision is meant to boost the uptake of renewable energy in these transport modes.

The 20% extra counting has implications for fuel volumes. As lower fuel volumes will be required to meet the target, the amount by which GHG emissions are reduced may be adversely impacted.

*Type of renewable fuels within the RED II*

The original RED required member states to oblige fuel suppliers within their jurisdiction to supply a minimum share of renewable energy to the transport sector and design their supply policies accordingly.

Although the RED only plays a limited role in increasing the share of renewable fuels in shipping, it remains relevant to the maritime sector, given its mature sustainability framework; lessons learned in the past from using biofuels (both liquid and gaseous) in the road-transport sector can help to shape a sustainability framework for use in shipping.

For sustainability reasons, the growth in the RED should come from advanced biofuels and RFNBOs. A dedicated act, which was expected to be published by the end of 2021, should have further specified the calculation methodology for RFNBO and will determine how and under which conditions renewable ammonia can count towards the targets.

***Revision of the REDII: the REDIII***

Because of the higher ambitions of the European Green Deal for reducing net GHG emissions by at least 55% by 2030, the RED II is already being revised before many member states have transposed it into national legislation. The ‘Fit for 55’ package contains a proposal for the revised directive, referred to as the Renewable Energy Directive III.

To achieve the 2030 target, the proposal suggests increasing the overall binding target for renewables in the EU energy mix to 40% from the current 32%. This will be complemented by indicative national targets that show what each member state should contribute to secure the collective target.

The directive aims for large-scale renewables-based electrification. In transport and industry, with market segments that are harder to electrify, renewable fuels such as clean hydrogen should also play a major role.

The transport target, which aims for a specific share of renewables in final consumption, will be replaced by a GHG-intensity target: the GHG intensity of fuels (in $gCO_2/MJ$) is to be reduced by at least 13% by 2030 compared to the baseline. This will replace the average reduction target for GHG intensity found in the Fuel Quality Directive.

In addition to the sub-target for the share of advanced biofuels and biogas (based on feedstocks from Part A of Annex IX), the RED also introduces a 2.6% sub-target for the share of RFNBOs by 2030, which is applicable to renewable ammonia. The RED contains various multiplication factors that made some of the targets purely administrative. By abolishing these multiplication factors, the proposal for revision makes the targets more ambitious. (Van Grinsven et al., to be published).

**Energy Taxation Directive (ETD)**

Taxation initiatives at the EU and member-state level help industries to reach the climate-policy goals by encouraging a switch to cleaner energy. The EU’s ETD entered into force in 2003, offering structural rules and minimum rates for excise duties to tax the energy products that are used as motor and heating fuels and for electricity.

Individual member states are free to set their own rates provided the directive’s minimum rates are respected.

Some sectors, such as aviation and maritime transport, are currently fully exempt from energy taxation in the EU. A revision of the ETD was proposed in the EU’s ‘Fit-for-55’ package; it introduces a new structure of tax rates based on the energy content and the environmental performance of fuels and electricity. This will help the system to ensure the most polluting fuels are taxed the highest.

The revision also broadens the taxable base by including more products into the scope and removing some of the current exemptions and reductions (EC, 2020).

## 3.4 Other relevant regulations from other Nations

In this section, other relevant regulations from other than European nations are listed. This covers land based and onboard ships.

### 3.4.1 Land Based

Individual sovereign governments have developed their own national regulations related to the production, transport, storage, and application of anhydrous ammonia, such as the requirements for ammonia refrigeration equipment. An in-depth analysis of all global regulation is beyond the scope of this study. However, brief reference and summary information is included in this subsection. Of particular interest to the application of anhydrous ammonia as a marine fuel, and ongoing studies to determine acceptable circumstances for overboard discharge (such as emergency venting or jettison) and the implications of that for the marine environment remain incomplete.

**U.S. 40 CFR Ch. I Subchapter J Part 372 – Toxic Chemical Release Reporting: Community Right-To-Know**. This part of the United States EPA CFRs details information relating to the release of toxic chemicals, with the intention of informing the general public and communities surrounding any covered facilities about releases of toxic chemicals. 40 CFR 372.65 details the list of chemicals to which that part applies and includes anhydrous ammonia and aqueous ammonia from water, dissociable ammonium salts and other sources with 10% of total aqueous ammonia as reportable.

**U.S. 33 U.S.C §1251 – Clean Water Act**. The U.S. Clean Water Act (CWA) regulates discharges of pollutants into the waters of the United States and regulates water quality standards, including setting wastewater standards for industry.

**U.S. EPA 822-R-18-002 – Aquatic Life Ambient Water Quality Criteria for Ammonia – Freshwater 2013**. This is the EPA water quality criteria for ambient concentrations of ammonia to protect freshwater aquatic life. It is published as scientific recommendations to the U.S. states and (indigenous) tribes authorised to establish water-quality standards under the CWA. It is not in itself a regulation, but is issued to advise, and is updated based on developments in scientific knowledge, to protect endangered marine species, including salmonid fish species and sensitive freshwater mussel species. As an example, at a pH of 7 and temperature of 20˚C, the 2013 acute criterion magnitude is 17 mg TAN/L and the chronic criterion magnitude is 1.9 mg TAN/L.

**ANSI K61.1-1999 / CGA G-2.1 – American National Standard Safety Requirements for the Storage and Handling of Anhydrous Ammonia**. This covers the topic of design, construction, locations and operation of anhydrous ammonia systems, specifically for the purpose of transportation, e.g., on tank motor vehicles and tank railcars (not applicable to ammonia-manufacturing plants or refrigerating or air conditioning systems.)

**ANSI/CGA G-2.1-2014** – Requirements for the design, construction, repair, arrangement, and operation of storage and handling systems for anhydrous ammonia, including refrigerated ammonia storage systems. This national American standard is not necessarily applicable to ammonia storage on ships.

**ASME B31.3-2020 Process Piping.** This ASME Code covers requirements for industrial pipelines in general for all fluids, covering materials and components, design, fabrication, assembly, erection, examination, inspection and pipe testing.

**U.S. e-CFR 29 1910.111 Occupational Safety and Health Standards: Storage and handling of anhydrous ammonia.** While this is a standard regarding the safe operation for the protection of health, it covers basic design, construction, location, installation and operation of anhydrous-ammonia systems, including refrigerated ammonia-storage systems.

### 3.4.2 Onboard ship

**U.S. e-CFR 46 98.25 Shipping: Anhydrous Ammonia in Bulk**. This Code applies to self-propelled vessels carrying anhydrous ammonia onboard as a cargo, cargo residue, or vapor that is not regulated under Title 46 Part 154 (Certain Bulk Dangerous Cargos).

**U.S. e-CFR 46 151.50-32 Shipping – Barges Carrying Bulk Liquid Hazardous Material Cargoes: Ammonia, Anhydrous**. This Code covers requirements for specific cargoes, including the location of anhydrous ammonia tanks, and related materials, designs, valves, flanges and pipe fittings.

**U.S. CFR § 130.230 – Protection from Refrigerants**. This USCG regulation requires the provision of a self-contained breathing apparatus to be stowed outside OSV spaces containing refrigeration equipment that exceeds $0.6m^3$ of ammonia.

## 3.5 Gap Analysis

The regulatory framework for rules, standards, guidelines, recommendations, and best practices, etc., for ammonia is tabulated in detail as Appendix XVI – Detailed Regulatory Gap Analysis to this report. This highlights where the existing publications contribute to, or restrain, the adoption of ammonia as a marine fuel.

As referenced throughout this section of the report, there are 'gaps' that will restrain adoption. Notably, these gaps are within the IMO's safety and environmental regulations, together with the international ISO standards that are referenced by the IMO mandatory requirements.

The precedent set by regulatory and industry publications for LNG provides a roadmap for filling some of the gaps that are anticipated; in many cases, this includes publications that are relatively easy to update to include a wider scope of liquefied gases.

The detailed Gap Analysis is shown in Appendix XVI – Detailed Regulatory Gap Analysis, and a synopsis of the findings is presented in Table 25 and Table 26.

Table 25. Gap Analysis Legend

| |
|---|
| No Gap or Changes needed to address ammonia |
| Small Gap or Minor Change to address ammonia |
| Medium Gap or Some Challenging Change to address ammonia |
| Large Gap or Many Challenging Changes to address ammonia |

Table 26. Synopsis on Regulatory Gap Analysis for Ammonia

| Subject | Rule/Guidance | Comment on Code/Standard - Gaps |
|---|---|---|
| Sustainability and Emissions Regulations | EU 'Fit-for-55' Fuel EU Maritime | - Focus is only on decarbonised (green) ammonia produced from hydrogen<br>- Focus is on well-to-wake emissions |
| | EU Emissions Trading System (ETS) | - Not directly applicable to shipping industry (until 2023 adoption of the 'Fit-for-55' package)<br>- Only focused on tank-to-wake emissions, does not incorporate emissions from consumption |
| | EU Energy Taxation Directive | - Maritime sector fully exempt<br>- Member states independently implement national policy |
| | EU RED III | - Divided incentives for shipowners and operators do not stimulate the deployment of renewable fuels<br>- Member states independently implement national policy |
| | MARPOL Annex VI EEDI, EEXI, CII & DCS | - No explicit provision in the IMO regulations and guidelines for the direct use of an ammonia carbon factor in EEDI, EEXI, CII and DCS<br>- Provision for well-to-wake emissions considerations should be considered in these instruments |
| | MARPOL Annex VI and NOx Technical Code (NTC | - Requires NTC amendment to include $NH_3$ analysers, measurement and calculation provisions for ammonia as fuel to enable NOx certification to regulation 13<br>- Air emissions limits for $NH_3$ and $N_2O$ from marine engines, and associated measurement and calculation procedures, are missing from Annex VI and the NTC<br>- Regulation 18 of Annex VI would benefit from clarification on BDN and fuel sampling obligations for ammonia as fuel<br>- Application of ammonia as fuel (particularly for retrofits) would benefit from clarification on application of regulation 18.3.2.2 for NOx implications where ammonia is derived from methods other than petroleum refining<br>- No limits or guidelines exist for environmental impacts of potential $NH_3$ emissions to water in normal or emergency operations from exhaust |

| Subject | Rule/Guidance | Comment on Code/Standard - Gaps |
|---|---|---|
| | | cleaning or fuel-system cleaning systems. Precedent exists for water quality limits for SOx EGCS under Annex VI but unclear which |
| | ISO 17179:2016 - Stationary source emissions - Determination of the mass concentration of ammonia in flue gas - Performance characteristics of automated measuring systems | - May be considered or referenced in development of IMO marine standards |
| | ISO 21877:2019 - Stationary source emissions - Determination of the mass concentration of ammonia - Manual method | |
| Storage – Land | ANSI K61.1-1999 / CGA G-2.1 Requirements for the Storage and Handling of Anhydrous Ammonia | - Not applicable to ammonia storage on ships |
| | U.S. 33 U.S.C. §1251 – Clean Water Act | - No significant gaps for supporting the application of ammonia |
| | U.S. EPA 822-R-18-002 - Aquatic Life Ambient Water Quality Criteria for Ammonia - Freshwater 2013 | |
| | U.S. 40 CFR Ch. I Subchapter J Part 372 - Toxic Chemical Release Reporting: Community Right-To-Know | |
| Storage – Onboard | IMO IGF Code | - IGF Code Part A-1 prescriptive provisions are specifically for natural gas (methane). Alternative Design process enables approval of other gases and low-flashpoint fuels, but could be revised to include specific provisions for ammonia in the longer term. Development of interim guidelines for ammonia is now added to the CCC workplan, commencing CCC 8 in September 2022. |
| | IMO IGC Code | - Provisions could be added to allow toxic anhydrous ammonia to be used as fuel. Review of IGC Code is now added to the CCC workplan, commencing CCC 8 in September 2022. |
| | U.S. CFR 46 98.25 Shipping: Anhydrous Ammonia in Bulk | - No details of anhydrous ammonia as marine fuel<br>- National regulation not applicable to international vessels |
| | U.S. CFR 46 151.50-32 Shipping: Barges Carrying Bulk Liquid Hazardous Material Cargoes: Ammonia, Anhydrous | - No details of anhydrous ammonia as marine fuel<br>- National regulation not applicable to international vessels |
| Quality | International Bunker Industry Association | - No specific guidance for ammonia. Missing ISO fuel quality standard together with missing BDN and sampling requirements under Annex VI Regulation 18 hinders consistent implementation |
| | ISO 8217:2017 Petroleum Products - Fuels (class F) - Specifications of Marine Fuels | - Not applicable to and does not discuss ammonia marine fuel<br>- Additional provisions for ammonia as marine fuel could be developed as a new standard |

| Subject | Rule/Guidance | Comment on Code/Standard - Gaps |
|---|---|---|
| | ISO 7103:1982 - Liquefied anhydrous ammonia for industrial use - Sampling - Taking a laboratory sample | - May be referenced in marine standards |
| | ISO 7106:1985 - Liquefied anhydrous ammonia for industrial use - Determination of oil content - Gravimetric and infra-red spectrometric methods | - May be referenced in marine standards |
| | ISO 7105:1985 - Liquefied anhydrous ammonia for industrial use - Determination of water content - Karl Fischer method | - May be referenced in marine standards |
| | IMO MARPOL Annex VI | - Regulation 18 for fuel oil availability and quality requires onboard fuel to be tested for sulphur content and seal-fuel samples for the record. While regulation 18.4 exempts gas fuels from BDN and fuel sample requirements, regulation 18 would benefit from explicit clarification on BDN and fuel-sampling obligations for ammonia as fuel |
| Transportation & Handling | ASME B31.3-2020 Process Piping | - Not specific to marine, may be referenced in marine standards |
| | ISO 6957:1988 - Copper alloys - Ammonia test for stress corrosion resistance | - May be referenced in marine standards |
| | ISO 5771:2008 - Rubber hoses and hose assemblies for transferring anhydrous ammonia | - Subject limited to hose performance and hose assemblies, may be referenced in marine standards |
| | SIGTTO Liquefied Gas Sampling Procedures | - Not applicable to ammonia. SIGTTO could produce similar recommendations for ammonia gas cargo or fuel |
| | U.S. CFR § 130.230 – Protection from Refrigerants | - National regulation not applicable to international vessels<br>- Not specific or considering marine applications |
| | U.S. CFR 29 1910.111 Occupational Safety and Health Standards: Storage and Handling of anhydrous ammonia | - Not specific to marine, may be referenced in marine standards |
| Bunkering | ISO 20159:2021 - Ships and Marine Technology - Specification for bunkering of liquefied natural gas fueled vessels | - Not applicable to liquefied anhydrous ammonia. Could be modified or used to develop liquefied ammonia bunkering guidelines |
| | ISO/TS 18683:2021 - Guidelines for safety and risk assessment of LNG fuel bunkering operations | |
| | ISO 21593:2019 - Ships and Marine Technology - Technical requirements for dry-disconnect/connect couplings for bunkering liquefied natural gas | - Not applicable to liquefied anhydrous ammonia. Could be modified or used to develop liquefied ammonia bunkering coupling standard |
| | IBIA Future Fuels Working Group | - Currently undertaking the assessment of ammonia fuel and associated technologies; results to be released |
| | SIGTTO Ship/Shore Interface for LPG/Chemical Gas Carriers and Terminals | - SIGTTO publications address liquefied gases including anhydrous ammonia, so no big gaps, but it could provide specific guidance for ammonia gas cargo or fuel |
| | SIGTTO Recommendations for Liquefied Gas Carrier Manifolds | |
| | SIGTTO Liquefied Gas Handling Principles on Ships and Terminals (LGHP4) | |

| Subject | Rule/Guidance | Comment on Code/Standard - Gaps |
|---|---|---|
| | SIGTTO, CDI, ICS, OCIMF: Ship to Ship Transfer Guide for Petroleum, Chemicals and Liquefied Gases | - Could be modified or used to develop recommendations for ammonia bunkering |
| | SGMF Bunkering Area Safety information LNG | - Not applicable to ammonia. SGMF could expand these tools and guidelines, or develop new ones, to cover ammonia as fuel |
| | SGMF FP05-01 Ver1.0 Gas as a marine fuel: Recommendation of Controlled Zones during LNG bunkering; May 2018 | |
| | SGMF FP07-01 Ver3.0 LNG as a marine fuel: Safety and Operational Guidelines - Bunkering; December 2021 | |
| | SGMF FP-08-01 Ver1.0 Gas as a marine fuel: Simultaneous Operations (SIMOPs) during LNG bunkering; May 2018 | |
| | SGMF FP05-01 Ver1.0 Gas a marine fuel: Contractual guidelines; September 2015 | |
| | SGMF TGN06-04 Ver1.0 Gas as a marine fuel: manifold arrangements for gas-fueled vessels; May 2019 | |
| | SGMF TGN06-06 Ver1.0 Gas as a marine fuel: LNG bunkering with hose bunker systems: considerations and recommendations; February 2020 | |
| | SGMF TGN06-07 Ver1.0 Gas as a marine fuel: Bunker station location: Considerations and Recommendations: January 2021 | |
| | EMSA *Guidance on LNG Bunkering to Port Authorities and Administrations*; January 2018 | - Not applicable to ammonia. EMSA could expand or use this tool to develop ammonia guidance |
| Use & Consumption | IMO IGF Code | - IGF Code Part A-1 prescriptive provisions are specifically for natural gas (methane). Alternative Design process enables approval of other gases and low-flashpoint fuels, but it could be revised to include specific provisions for ammonia in the longer term. Development of interim guidelines is now added to the CCC workplan, commencing CCC 8 in September 2022. |
| | IMO MARPOL Annex VI and NOx Technical Code | - Could include specific provisions for using and consuming anhydrous ammonia onboard ships<br>- Air emissions limits for $NH_3$ and $N_2O$ from marine engines, and associated measurement and calculation procedures, are missing from Annex VI and the NTC. To consider in service monitoring of $NH_3$ emissions.<br>- Regulation 18 of Annex VI would benefit from clarification on BDN and fuel-sampling obligations for ammonia as fuel<br>- No limits or guidelines exist for environmental impacts of potential $NH_3$ emissions to water in normal or emergency operations from exhaust-cleaning or fuel-system cleaning systems. Precedent exists for water quality limits for SOx EGCS under Annex VI but unclear which is appropriate instrument to regulate $NH_3$ discharges to water |

| Subject | Rule/Guidance | Comment on Code/Standard - Gaps |
|---|---|---|
| | ISM Code | - Development of operational requirements under IGF Code, or Interim Guidelines, would facilitate operators undertaking obligations under ISM Code. |
| | IMO STCW Convention | - Regulation for training of crew for IGF Code ships exists under STCW Convention. Question mark remains on application of ammonia under IGF Code, but development of training courses by flag Administrations is still required to enable crew certification for ammonia as fuel under STCW. |
| | SIGTTO ESD Systems - Recommendations for Emergency Shutdown and Related Safety Systems | - SIGTTO publications cover gas carriers and carriage of anhydrous ammonia but would benefit from specific consideration for ammonia gas cargo or fuel |
| | SIGTTO Recommendations for Relief Valves on Gas Carriers | |
| | SIGTTO Guidelines for the Alleviation of Excessive Surge Pressures on ESD for Liquified Gas Transfer Systems | |
| | SGMF FP00-01-06 Ver4.0 LNG as a marine fuel: An Introductory Guide; June 2021 | - Not applicable to ammonia. SGMF could expand, or develop new, publications for ammonia as fuel |
| | SGMF FP10-01 Ver1.0 Gas as a marine fuel: Work practices for maintenance, repair and dry-dock operations; May 2020 | |
| | SGMF FP14-01 Ver1.0 Gas as a marine fuel: Operations of ships with Liquefied Natural Gas (LNG) competency and assessment guidelines; May 2021 | |
| | SGMF TGN06-05 Ver1.0 Gas as a marine fuel: recommendations for linked emergency shutdown (ESD) arrangements for LNG bunkering; May 2019 | |
| | IACS Unified Requirement M57 *Use of ammonia as a refrigerant*; 1993 | - No significant gaps for supporting the application of ammonia as a refrigerant, however this publication has not been updated since original publication in 1993 and would benefit from updating |
| | IMO draft *Interim Guidelines for the Safety of Ships using Fuel Cell Power Installations* | - No significant gaps for supporting the application of marine fuel cells, however these guidelines do not cover fuel storage and distribution and therefore application is limited by lack of those IMO requirements |
| | IACS UR M78 *Safety of Internal Combustion Engines Supplied with Low Pressure Gas* | - Does not cover high pressure and cross-head (2-stroke slow speed) engines burning methane.<br>- Does not cover other low-flashpoint fuels.<br>- Could be updated to include all engine types and fuels in a more general way |
| | IACS Recommendation No.146 *Risk assessment as required by the IGF Code*. | - Could be updated to include specific requirements for ammonia |
| | IACS Recommendation No. 142 *LNG bunkering guidelines* | - Could be updated to cover bunkering guidelines for all liquefied gases or new publication could be developed |
| | IACS Recommendation Nos.26, 27 and 30; recommended spare parts for IC main and auxiliary engines and essential auxiliary machinery | - Could be updated to cover spare parts for DF engines and fuel supply systems |

| Subject | Rule/Guidance | Comment on Code/Standard - Gaps |
| --- | --- | --- |
| | IACS Recommendation No.138 Recommendation for the FMEA process for diesel engine control systems | - Could be updated to cover DF engines and fuel supply systems |
| | IACS Classification Societies Rules | - Harmonisation of class society rules or guidelines, through the development of URs, would facilitate harmonised application of ammonia as fuel |

## 3.6 Marine regulation conclusions

There is a lack of regulation for the use of ammonia as a fuel at the national, regional and international levels. This imposes a direct barrier to adoption. However, there are established methods for approving ship designs using the risk-based 'alternative design' approval process. Furthermore, classification societies have introduced tentative rules and guidelines to facilitate the adoption of ammonia-fuelled ships.

Marine and land-based regulations for the storage, transport and use of anhydrous ammonia provide significant regulatory references to facilitate its application as a marine fuel.

The basket of measures introduced by the European Commission under the ‘Fit-for-55’ initiative, which includes revising regulations, directives and new policy initiatives, signals a strong commitment from the EU to a decarbonised and sustainable future for shipping.

To move further down this pathway at international level, the EU could encourage submissions from member states to IMO MEPC and MSC (including associated sub-committees) and drive regulatory change on the safety and environmental fronts.

The EU also could support and encourage the development of the industry requirements, guidance, recommendations and best-practice publications that will enable the application of ammonia as a marine fuel. The precedents set by the application of LNG as a marine fuel provide a template for this.

Specifically, these are the actions and regulatory gaps that need to be addressed in the near term:

- Support the development under the IMO CCC sub-committee of interim guidelines for ammonia as a marine fuel
- Investigate appropriate situations for discharge of ammonia to air and water and acceptable limits for same in normal and emergency scenarios
- Support the IGC Code review for greater harmonisation with the IGF Code and consider amendments that would enable the combustion of ammonia cargoes
- Encourage member states to develop national training and certification programmes under the STCW Convention and Code
- Develop guidance to help operators implement their obligations to the ISM Code
- Prepare the amendments to Annex VI and the NOx Technical Code that would enable approval and certification to the EEDI, EEXI and NOx regulations, together with developing amendments to regulations 14 and 18 of Annex VI
- Consider more amendments to Annex VI and the NOx Technical Code to introduce IC engine limits for $NH_3$ and $N_2O$
- Request the IMO to task the ISO with developing a marine-fuel standard and relevant standards for couplings and bunkering
- Encourage IACS to develop Unified Requirements for machinery and equipment and Recommendations for risk-assessment guidance under the IGF Code and ammonia bunkering to reduce industry uncertainty and support harmonized application of requirements for ammonia as fuel
- Encourage SGMF, IBIA and other industry stakeholders to develop their respective guidance and best practice publications to support application of ammonia as fuel

# 4. Risk assessment of using Ammonia as Marine Fuel in Merchant ships

The safety regulations for the use of ammonia as marine fuel are still under development, as described in Section 3. As part of this study, a HAZID assessment was carried out for generic ship types to contribute to discussions regarding the safety and risk management for ammonia-fuelled ships. This part of the report provides an analysis of key aspects of ammonia safety for its use as marine fuel in various types of marine vessels. Three types of marine vessels were considered to develop this report:

- Very Large Crude Oil Carrier (VLCC)
- Bulk Carrier
- Ro-Pax Vessel

The purpose of this study is to identify the potential major hazards relative to the operational configuration of a proposed ammonia-fuelled vessel at an early stage of concept development, review the effectiveness of selected safety measures and, where required, expand the safety measures to achieve tolerable levels of residual risk.

Early identification and assessment of hazards provides essential input to decisions for concept development at a time when a change in the design has a minimal cost penalty. Typically, the potential problems are highlighted for action outside the actual workshop. In the context of this study, the outcomes will support the European Maritime Safety Agency (EMSA) in drafting recommendations to develop and adapt (existing) procedures and regulations. It will also provide further awareness to the hazards that can be found in connection to the usage of ammonia as a marine fuel.

In that context, HAZID workshops were undertaken to evaluate and summarise key aspects of safety as it pertained to installation onboard a vessel. These HAZIDs included participation from an ABS multi-disciplinary team, as well as shipowners, a shipyard, an engine manufacturer and a port.

## 4.1 Ammonia Safety

Ammonia is a colourless, acrid-smelling and highly water-soluble gas at room temperature, also referred to as anhydrous (without water) ammonia. It is a clear, colourless liquid under pressure. To understand risk of ammonia for use in marine environment it is necessary to understand the associated risks in detail. The following is provided for understanding:

- The physical properties of ammonia in Section 2.1.1,
- Ammonia Acute Exposure Limits in Appendix II– Acute Ammonia Exposure Limits,
- Ammonia Classification per Globally Harmonised System (GHS) of Classification and Labelling of Chemicals Appendix VI: NH3 Classification per GHS

The sections that follow apply to all three HAZIDs, whereas the specific assumptions made and HAZID results for each vessel type are reported in Section 4.3.

A detailed list of $NH_3$ hazards is listed in Section 4.2.6.

## 4.2 HAZID Objectives, Process, Scope and Assumption

This section explains the common objectives, scope, methodology, etc., for all vessel types in the study.

### 4.2.1 Objectives

The preliminary objectives of the HAZID study are to identify the risks of using ammonia as a marine fuel for bulk carriers, VLCCs and Ro-Pax, and to verify that its prospective use at the conceptual stage of design development will satisfy the goals and functional requirements identified in the IMO IGF code. The objectives were to:

- identify potential and new hazards introduced by ammonia that require mitigation
- determine the potential consequences of the hazards

- identify safeguards for hazard prevention, control, or mitigation (including safeguards for each stage of the project)
- propose recommendations to eliminate, prevent, control, or mitigate hazards
- provide early safety and risk considerations for design and safety-management requirements
- provide a clear framework for future safety-assessment studies that will help to anticipate major accidents
- compare this safety performance with the current practice under the IGF code

The outcome of the exercise is a hazard register for owners of each vessel type to consider. It will include:

- Potential hazardous scenarios, including causes, consequences and existing safeguards
- The risks inherent in each developed scenario, evaluated according to the severity and likelihood of the consequence
- Opportunities to improve design or risk-mitigation measures to reduce the estimated safety risks

### 4.2.2 Common Scope

It is assumed that all vessel types are in full compliance with regulatory and classification requirements, including with the requirements of the IGF code, except for provisions related to $NH_3$, which will require further risk assessment, as those have yet to be fully developed by the IMO and other administrative bodies.

The scope of this assessment looks at almost all aspects of the vessels, with specific focus on the interaction between vessel systems based on the information available for each type. It will include:

- Ammonia storage and vapour-/pressure-management system
- Venting and ventilation arrangements
- Engine room and machinery spaces
- Ammonia-consumption equipment
- Ammonia fuel supply and return system

The HAZID study covers the following areas (as applicable):

- General arrangement of vessels
- $NH_3$ fuel-storage arrangement and details
- $NH_3$ fuel supply and vapour-handling system, from fuel storage to machinery spaces
- $NH_3$ fuel arrangement in fuel handling room and engine room
- General arrangement of the fuel-handling and engine rooms, including their ventilation
- Main engine safety concepts and vessel integration
- Hazardous area classification plans
- Ventilation and vents for stored $NH_3$ fuel, fuel-supply system, machinery space and consumer
- $NH_3$ fuel-bunkering arrangement
- Safety systems
- Gas detection and firefighting arrangement
- Arrangements to purge or make $NH_3$ inert
- Cargo storage and its impact
- Bunkering
- Emergency Escape and Rescue

### 4.2.3 HAZID Workshop Methodology

A HAZID analysis is an extremely useful tool for performing high-level risk assessments of specific systems. ABS has used this approach in numerous risk-assessment projects, as a standalone analysis, and to compare similar situations.

A HAZID workshop was held via video-conference. After the workshop, a brief review was conducted with the participants. A flow diagram for the overall HAZID process is shown in Figure 19 below.

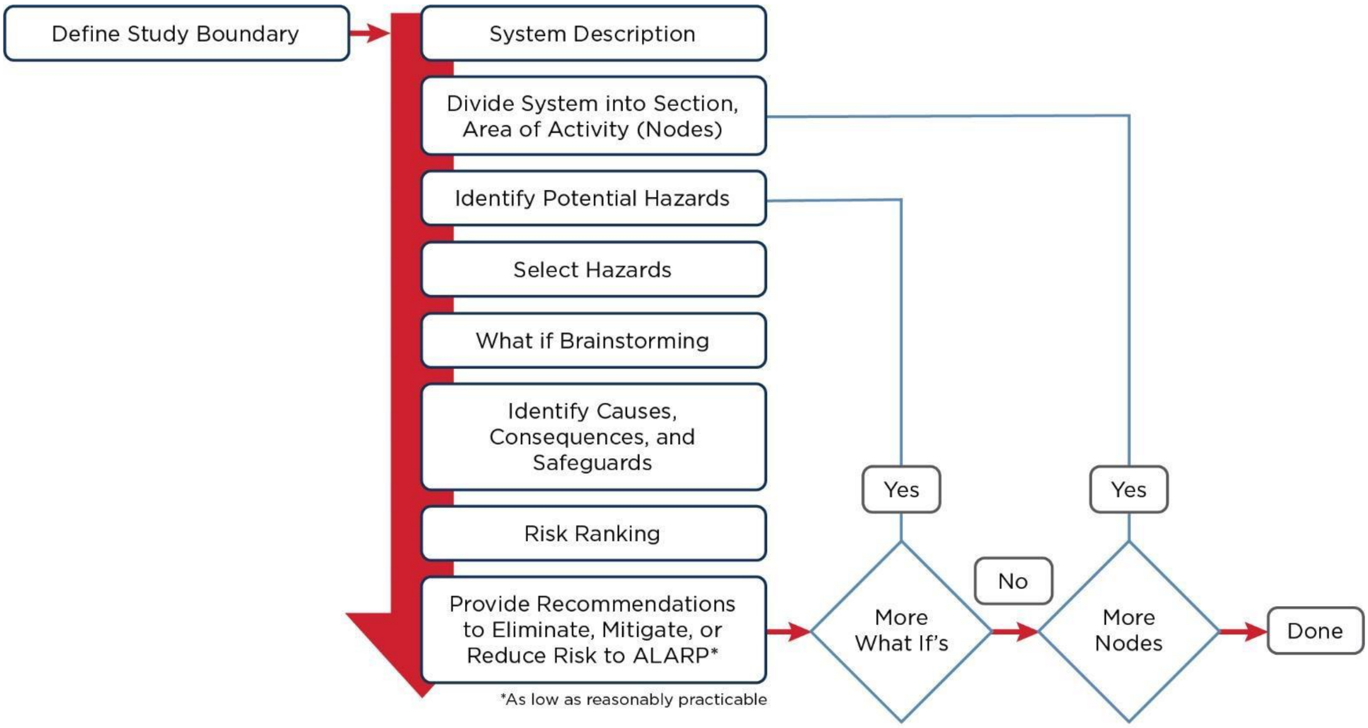


Figure 19: HAZID Process

During the workshop, a facilitator guided the subject-matter experts through a structured discussion to identify and risk-rank the hazards. Participants were asked to provide input on preloaded scenarios (e.g., modifying, adding, or removing risk scenarios) within the hazard register, as well as to discuss the location of the scenario on a risk matrix. These discussions guided the focus areas, nodes and hazards to be considered before the study could be considered complete.

HAZID team members used a workshop environment to identify and analyse the boundaries of the study and to brainstorm potential ‘what if’ scenarios in a node. For clarity, a ‘node’ is a clearly defined, manageable section or system to be discussed in the brainstorming activity. ‘Guidewords’ are a set of conditions, such as “high pressure” or “vessel collision”, that help streamline to brainstorming activity and identify potential hazards. Guidewords and sub-categorisations were used to identify the potential threats and the existing controls that could be used to limit or prevent their impact. Where required, recommendations were generated.

The HAZID analysis was conducted in sessions, which individually addressed each arrangement, process and operation on the ships.

### 4.2.4 Limitations

The risk assessment was limited to a “simplified HAZID” analysis following the methodology described in this section. In most cases, the use of ammonia as fuel is at the concept-development stage, making HAZID the most appropriate way to identify the risks.

This high-level concept provides a baseline to identify $NH_3$ hazards and risks, and to develop recommendations. Design variations such as the location of fuel tanks, venting and relief arrangements were considered for the baselines, but an evaluation of how those variations increased or lowered the general risk environment relative to the base case was not undertaken.

The workshop team identified several significant hazards related to the nodes for the systems analysed in this study. There may be other hazards that are not included, so further safety assessments should be conducted for each vessel due to toxicity risks, which are greatly impacted by general arrangement and type of each asset.

**Limitations of the VLCC concept**

For VLCC concept, the installation case considered where the fuel tanks were installed above the cargo tank on deck, as this provides a higher risk. It leads to a risk of cargo tank fire/explosion and may consequently lead to $NH_3$ leak/releases issues; in contrast, other options such as Type A tanks located inside the cargo block can provide better protection for the fuel tank.

However, alternate Type A or independent tanks were not considered at this stage; they may offer a safer approach at the expense of an unknown volume of cargo spaceand such projects had not arisen in the market.

**Limitations of the Bulk Carrier Concept**,

For the bulk-carrier concept, this study considers two general arrangements for Type A tanks. There are currently several proposals for using Type C tanks in the market, which were not considered here. Type C tanks are generally considered much safer arrangements.

**Limitations of the Ro-Pax concept**

The specific exercise was meant to produce a viable concept and provide a baseline for the discussion. The main weakness of the concept is the installation area: Storing ammonia requires significantly more installation area and separation space than conventional liquid marine fuels. Even with the current state-of-the-art technologies, this means less cabin and/or vehicle space will be available, a limitation that needs to be considered when building and for retrofit projects.

Also, due to the toxicity-related threats from ammonia, each arrangement would have its own unique risks. The Ro-Pax model used in this study will be examined for the major risks identified at this stage, but not all.

### 4.2.5 Risk Ranking

A risk matrix, found in Appendix VII, was used for a high-level evaluation of the risks from each hazardous scenario and its impact on personnel injury and disease, asset, environment and reputation. In selected cases where a scenario has multiple impacts, such as “environmental” and “personnel injury”, the study will document “overall” impact. The process used to rank the risks included a:

- **Consequence review**: To identify the most credible worst outcome for each scenario, the team determined the outcome’s location on the consequence axis.
- **Likelihood review**: The team determined the location of the undesired outcome along the frequency axis, considering the probability of failure for the preventive, detection and recovery safeguards designed to ensure that does not take place.
- **Risk**: The intersection of the likelihood and consequence ratings produces the risk level for that specific hazard scenario.
- **Action**: The risk ranking was used to help assess whether the current controls and safeguards are adequate; if not, then additional safeguards/controls were identified to potentially reduce the risk (or identify areas where further review or analysis would be required to better understand the risk and potential mitigating measures) and recorded as ‘actions’ to be taken.

#### 4.2.5.1 Grouping Systems/Areas for HAZID

Drawings for each vessel HAZID were reviewed, while recognising that the design was at the preliminary stage and not all information was currently available. To derive maximum benefit, it was determined that focus should be on general arrangement (GA) related issues and operational aspects. In terms of systems and areas, the following were considered (where applicable):

- General arrangement
- $NH_3$ fuel storage/tank
- Bunkering arrangement
- $NH_3$ fuel system/preparation room/arrangement
- Hazardous area plan
- $NH_3$ supply system/vapour handling
- Engine room arrangement, safety concept

- Ventilation and venting system
- Safety system: fire and gas detection, fire-fighting, PPE

#### 4.2.5.2 Modes of Operation

For this report, each mode of operation will be considered for the entire lifecycle of vessel. The modes included (but were not limited to): bunkering, port departure, port entry, cargo loading/unloading in port, voyage (ballasted/loaded), standing by, maintenance, overhaul, emergency/upset situations, simultaneous operations, passenger loading/unloading in port and passenger volumes.

### 4.2.6 Hazards

The hazard scenarios used throughout the study to help the team identify potential loss scenarios were categorised into primary groups: ammonia-related general hazards, system-related hazards, external hazards and ship-related hazards, as described in the following sub-sections.

#### 4.2.6.1 General NH3 Related Hazards

The key hazards considered in this study are further elaborated below. These were an important part of the HAZID's scope of work, as they form the basis for design development and provide the understanding that formed the ALARP criteria.

Table 27 contains a list of hazards related to ammonia that were considered in the HAZID workshop to develop proper risk identification.

Table 27. Ammonia-related Hazards

| Ammonia Related Hazard | Description |
|---|---|
| Toxic for humans | At high dosages, gaseous ammonia can be lethal if inhaled and lead to adverse health impacts, including severe skin burn, eye damage and damage to the respiratory system. Prolonged and repeated exposure to the skin can lead to dermatitis. Long-term exposure can lead to potential lung injuries.<br>In liquid form, ammonia can also cause frostbite. |
| Toxic to aquatic life | Ammonia is toxic to aquatic life with potentially long-lasting effects |
| Low temperature embrittlement | The low temperatures of ammonia can lead to embrittlement, which can cause material loss of elasticity. |
| Flammability | Ammonia gas is flammable with a lower flammability limit is 15% by volume; its upper flammable limit is 28% by volume in air. It can be ignited and poses an explosion hazard. |
| Pool Fire | Spillage can create a liquid ammonia pool which can lead to a pool fire where a layer of flammable and volatile liquid fuel evaporates and burns. |
| Flash fire | Ammonia can lead to flash fire, intense and sudden, but typically of a short duration. |
| Boiling Liquid Expanding Vapour Explosion (BLEVE) | A BLEVE is typically caused by an external fire engulfing and heating a vessel containing liquified gas, causing an increase in internal pressure due to the vapourisation and expansion of liquid. This can lead to the rupture of the vessel, an explosion and fireball. |
| Affinity to water | Ammonia gas is hygroscopic (readily absorbs moisture) and forms a dense, visible white cloud of ammonium hydroxide. |
| Material reactivity | Ammonia reacts violently with certain materials upon exposure – e.g., chlorine, acids, brass, copper, silver and zinc |
| Material incompatibility | Ammonia is incompatible with some materials which leads to increased risk of fire and explosion, especially if it is in contact with: oxidising agents (e.g., peroxides), strong acids (e.g., hydrochloric acid) and halogens (e.g., chlorine). |
| High temperature degradation | At high temperatures, ammonia can disintegrate into flammable gas, hydrogen and toxic nitrogen dioxide. |
| Alkaline/Corrosive | The corrosiveness of ammonia can lead to material degradation and equipment damage under extended exposure. |

#### 4.2.6.2 System Hazards

Pertaining to the systems used to handle ammonia, the following hazards are considered in the analysis:

- **Process Hazards:** such as those related to $NH_3$/boil-off gas and other flammable/toxic fluids, e.g., the release of flammable inventory (for each area of the system), ruptures and start-up/shutdown issues.
- **Utility Hazards:** such as those related to fire and water systems, fuel oil, heating/cooling mediums, power supply, drains/sumps, air, nitrogen, chemical injections, etc.
- **Venting**: Normal and abnormal
- **Maintenance Hazards:** such as those related to maintenance culture and provisions for safe maintenance, etc.
- **SIMOPS:** such as those related to cargo operations loading/unloading, bunkering, supply, etc.
- **Interface Issues:** such as those related to process, instrumentation, utilities or structural elements, etc.
- **Emergency Response:** such as those related to access/egress areas, communication (alarms [audible/visual], call-points, CCTV, radio) and fixed/portable firefighting equipment
- Any other hazards: such as those related to lifting operations, structural failure, rotating machinery, cold/hot surfaces, etc.
- Any other issues or items of concern that were raised during the workshops.

#### 4.2.6.3 External Hazards

Consideration of other external hazards included:

- Cargo
- Dropped objects
- External fires
- Water ingress
- Physical damage
- Smoke
- Temperature
- Lightning
- Humidity
- Collison
- Grounding
- Mooring hazards
- Weather
- Storm
- Wind
- Wave
- Current

#### 4.2.6.4 Ship-Applicable Hazards

Other ship-applicable hazards were also considered under the definition of Global Hazards:

- **Natural and Environmental Hazards:** climatic extremes, lightning, seismic events, erosion, subsidence, etc.
- **Movement/Floatation Hazards:** grounding, collision, etc.
- **Effect of Facility on Surroundings:** proximity to adjacent installations, proximity to transport, proximity to population, etc.
- **Effect of Man-Made Hazards:** - security hazards, social/political unrest, etc.
- **Infrastructure:** communication, supply support, mutual aid, emergency services, etc.
- **Environmental Damage:** discharges to air/water, emergency discharges, water disposal, etc.
- **Product Hazards:** oil
- **Health Hazards:** disease, carcinogens, toxic effects, occupational hazards, etc.

### 4.2.7 General Assumptions – Applicable to all HAZID studies

There were a number of critical assumptions made for the workshops. They are based on current documentation, and some were deemed of such importance to be considered ‘assumptions’ rather than ‘recommendations’. Most were considered to be safeguards in the workshop records. The most common critical assumptions are listed below.

Any assumption specifically applicable to a particular vessel type was listed within its HAZID section.

- The vessel will be designed and built-in compliance with class and statutory regulations
- Fuel storage, preparation, supply and venting will comply with the requirements of IMO IGF code, except those directly related to $NH_3$ (for reasons previously mentioned)
- The $NH_3$ fuel system will be designed to not release ammonia into the atmosphere during normal operational conditions. Ammonia may be released during emergency conditions.
- The capacity of any relief valves will be in line with requirements from the IGF Code and ABS Rules.
- All releases through the relief valves will release to a single-vent mast.
- $NH_3$ bunkering will be undertaken at anchorage or port, using an ammonia bunker barge or vessel in a side-by-side configuration by transfer hoses.
- Bunkering vessels will have fenders and hoses, so the vessels themselves will not carry this equipment.
- Cargo operations and bunkering will not occur simultaneously.
- A catch system for ammonia will be provided to capture and treat the chemical during normal operations to facilitate shutdowns, purging etc. of the fuel-preparation systems, consumer supplies and return lines.
- During gas shutdowns, nitrogen will purge the fuel lines.
- Heating and cooling systems have an intermediate circuit to avoid any contamination of the ship’s cooling water.
- The intermediate heating/cooling circuit will use a water/glycol medium.
- The bunker system will have a liquid-supply and vapour-return line, in most cases.

## 4.3 HAZID Results – Findings and Recommendations

All high-level risks were considered, and the safeguards required by codes/standards/regulation were identified; the risk rankings were developed and listed in the risk register’s appendix for the three vessel types. Due to ammonia’s toxicity-related risks to human and aquatic life forms, many risks and safeguards were identified, and a significant proportion were additional to those normally required by the IGF Code. Because no codes were available, many of the study’s recommendations called for further analysis and research.

However, they were all listed for consideration and may help to inform future prescriptive requirements and develop safer designs and arrangements. The recommendations are listed for each vessel in the appendix:

- Appendix VIII – List of Recommendations – VLCC
- Appendix X – List of Recommendations BC Proposal I
- Appendix XII – List of Recommendations BC Proposal II
- Appendix XIV – List of Recommendations RO-Pax

A high-level summary of important recommendations which require further study and research is listed below.

1. Ammonia is considered flammable within a very narrow range that requires high energy to ignite. But it is still hazardous, so rules for hazard areas and security zones need to be developed.
2. It is extremely important to develop guidelines for ‘toxic zones’ based on dispersion analysis and including measures that will help to avoid contact or inhalation by personnel.
3. CAT A machinery spaces and other safe areas must be outside the toxic zones.
4. A detailed dispersion assessment to establish hazardous and toxic zones for $NH_3$-release scenarios is required.
5. Due to the dispersion characteristics of ammonia, a review of distances for vent-mast outlets around hazardous areas and toxic zones is needed. Particular attention needs to be paid to the attraction of ammonia to the water/moisture found in air during the analysis.
6. Hazardous areas, toxic, safety and security zones need to be established and aligned with the unique behaviours, dispersion and ignition characteristics of ammonia.

7. Due to its threat to humans and aquatic life, a system is needed that will prevent the release of ammonia during normal and emergency situations. During emergencies, the release of ammonia into the atmosphere should be considered.
8. Any water contaminated with ammonia is to be treated before release into the sea.
9. An ammonia-burning engine on a commercial ship potentially increases the scope of a cargo fire. An installation-specific fire study should be conducted to address the risk and consequences of exposing an $NH_3$ tank to high heat loads and fire.
10. The storage of ammonia in Type A or Type C tanks next to accommodation should be evaluated further
11. The location of ammonia tanks on any commercial vessel should be evaluated with respect to collisions and groundings, which current data suggest occur relatively frequently. Damage to $NH_3$ tanks potentially would have a larger impact on human safety and the environment, and the data indicates that the majority of these events happen near harbours or close to shorelines. Emergency procedures need to be developed to address the risk of releasing ammonia and to establish transfer procedures, if the tank is not damaged.
12. Emergency procedures need to be developed that address emergency fuel transfers, such when leaks occur after collisions and groundings, etc.
13. For pressurised storage, additional safety measures need to be introduced to prevent the uncontrolled release of ammonia from storage tanks.
14. All piping should be designed to 'leak-before-breaking' criteria to minimise the potential for larger leaks.
15. Firefighting requirements for ammonia should be developed that take into consideration its properties, such as its high absorbency in water, toxicity, liquid-to-vapour expansion ratios, etc.
16. Additional instruments and measures will be needed to detect ammonia leaks, such as those that monitor toxicity levels (ppm) and warn of fire and explosion risks.
17. In case of large leaks, additional safety measures will be needed to prevent loss of life.
18. Eye wash and shower facilities should be provided close to all ammonia spaces where the potential for exposure exists on ships.
19. Proper PPE should be provided for all crew who need to respond to an emergency, perform maintenance, firefighting, etc.
20. Enclosed lifeboats should be considered to prevent/minimise exposure to ammonia in an emergency.
21. Proper training needs to be developed to handle ammonia risks and related emergencies.
22. Ammonia-burning engines are in development, so their related hazards need to be identified by engine manufacturers and detailed FMECA (failure mode effects and criticality analyses) should be performed
23. A detailed HAZOP study is recommended for the entire fuel system, supporting systems, interfaces, etc. to identify additional hazards. Ammonia systems will need to be designed to minimise the possibility of fuel leaks.
24. An operational bunkering-safety study will need to be conducted and new designs should help to mitigate any risks that may impact on the vessel and its fuel system.
25. A minimum hourly air-change rate of 30 for ventilation is required in any space containing ammonia, with the potential to raise those rates to 45 in emergencies.
26. It is recommended that all inlet and outlet spaces containing ammonia equipment be provided with an ammonia detector.
27. Entrances to spaces containing ammonia should be provided with water curtains.

### 4.3.1 Cargo ship 1: VLCC with a 2-stroke DF main engine and 4-stroke gensets

The concept VLCC that burns ammonia as its main marine fuel uses a dual-fuel slow-speed main propulsion engine designed by a recognised engine manufacturer. A side view of the proposed VLCC is shown in Figure 20 (below). The concept has two semi-refrigerated Type C ammonia tanks for fuel storage on the weather deck on both port and starboard sides over the cargo tank area. Two bunker manifolds (port and starboard) will be installed between the oil-cargo manifold and the ammonia tank.

Figure 20: VLCC Side View

Installation of a fuel preparation room (FPR) between the ammonia tanks was proposed. The project will use the MAN dual-fuel $NH_3$ engine currently in development and anticipated for market by 2024.

The general arrangement of the proposed ammonia system is shown in Figure 21. The key elements of this design are listed below:

- The vent mast is located at the top of the FPR
- FPR is between the two Type C fuel tanks
- All piping from the FPR to the engine room will be double walled and include a 30 air-change rate
- There is double-walled exhaust via the vent mast
- A three-meter gap between the deck and the bottom of the FPR
- The bunkering manifold is located forward of fuel-storage tank (port and starboard)
- There is an A-60 class wall for the forward section of deckhouse with no entrance
- There is a redundant re-liquefaction plant to manage fuel-tank pressures and temperatures

Figure 21 shows the general arrangement of the vessel where the different items of interest are highlighted.

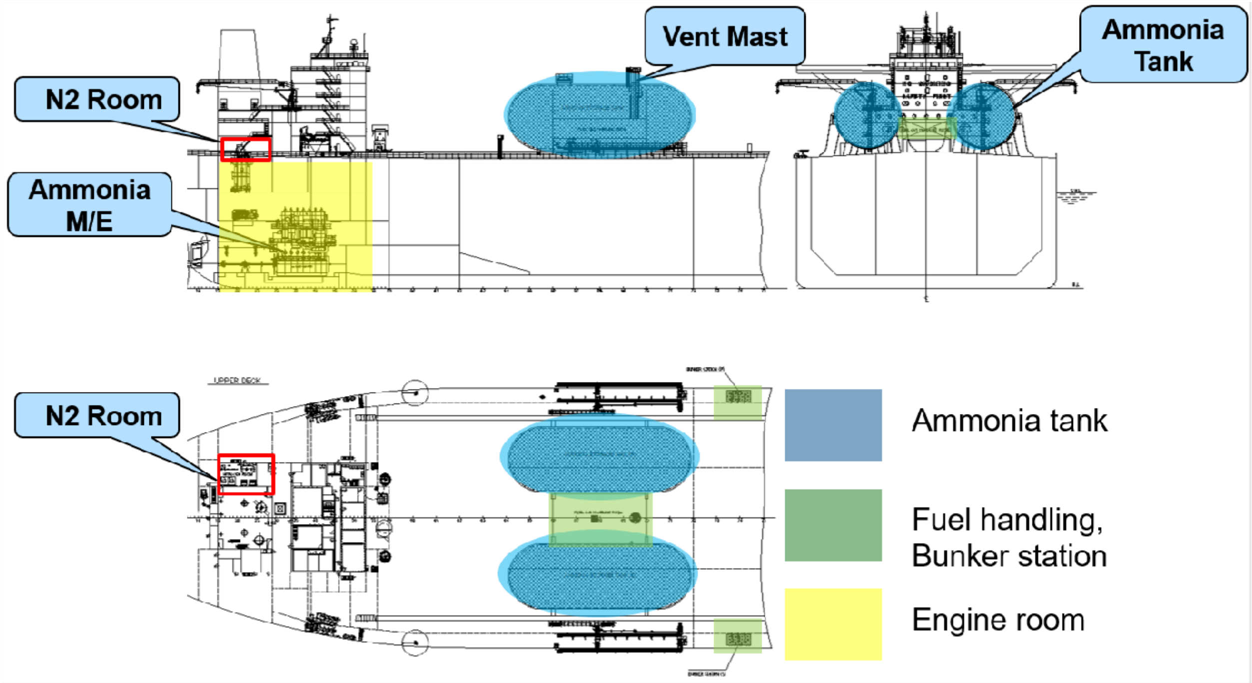


Figure 21: General Arrangement

The proposed bunker, fuel supply and reliquefication system are shown in Figure 22. One notable exception to the proposed system (as shown in Figure 22) is that ammonia released during normal operations will be captured in a catchment system. Any release from the fuel tank and bunker manifold will be routed to a vent mast.

The cooling and heating circuit for this arrangement uses a glycol-water mixture. An expansion tank will be located inside the fuel-handling room (FHR). Fuel piping between the FHR and engine will be double walled, with extraction fans for the double-wall annulus located with the vent mast at the top of the FHR.

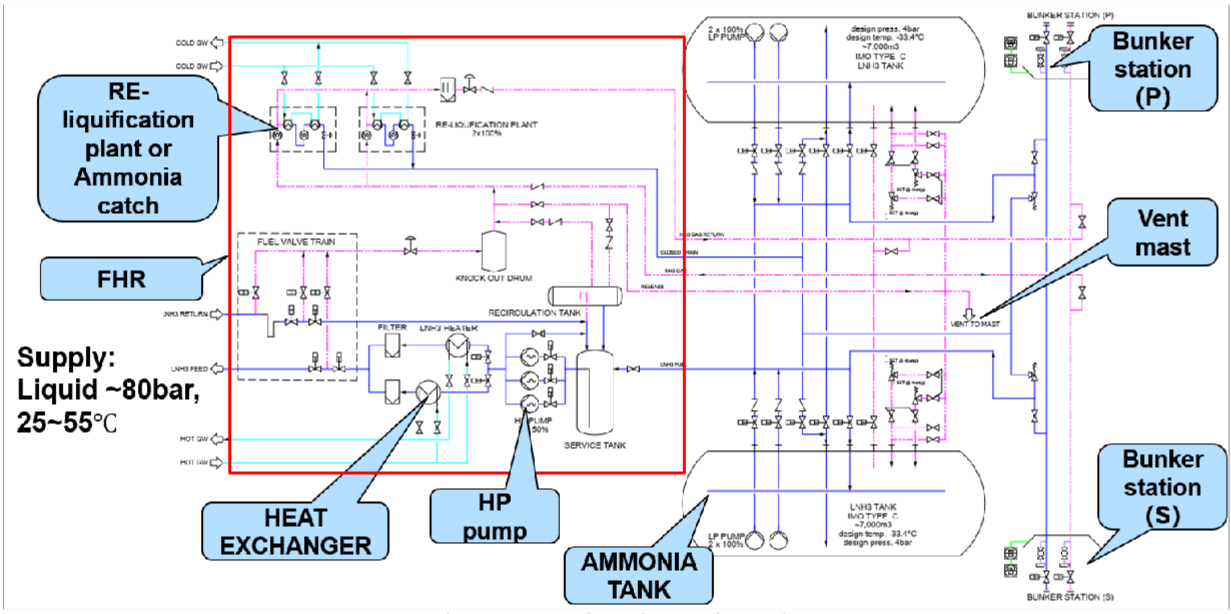


Figure 22: Fuel Bunker and Supply

#### 4.3.1.1 Assumptions – VLCC

In addition to the assumptions listed in Section 4.2.7, other assumptions from the workshop are listed below:

- All release-through relief valves will release ammonia into a single-vent mast located at the top of the fuel preparation room.
- Ammonia bunkering will be done at anchorage using an ammonia bunkering vessel in a side-by-side configuration using transfer hoses.
- The FHR is approximately three metres above the weather deck.
- All cargo and other piping near the fuel-preparation room will be under the FHR.
- The service tank is pressurised to ~20 bar to avoid cavitation and to support the operation of the high-pressure pump.
- The glycol heat-exchanger system is located in the FHR. It is heated by seawater or steam from the engine room.
- An A-60 class wall with no entrance is used for the forward section of the deckhouse.
- The cargo-tank vents should be relocated to outside of the FHR area.
- The fuel system is still being developed, so the proposed system is only for the basic information required to identify high-level risks.
- If bunker vessels lack the capacity to receive all vapour returns, then the ammonia in gaseous form will go through re-liquification.

#### 4.3.1.2 Conclusions and Recommendations

The project is at the concept stage and, for the workshop's recommendations to be feasible, certain conditions were assumed and listed in the assumption section. For some nodes, not enough information was available. This precluded a risk ranking being attributed to some hazards. But the activities associated with those scenarios were discussed and, where feasible, recommendations were made.

The results of the HAZID workshop are to be analysed and incorporated into future developments of the concept. A complete list of recommendations and the HAZID register are in Appendix VIII – List of Recommendations – VLCC & Appendix IX – HAZID Register - VLCC. System and operational level nodes, along with the scenarios associated with each node, were discussed. Where the risk was deemed to be high, recommendations were developed from the scenarios identified during the workshop.

The HAZID register identifies the hazards and documents the recommendations from the workshop's discussions. Fifteen (15) 'extreme' and 22 'high' risk scenarios were identified that will require mitigation as the design progresses. Each of those have recommendations listed in the HAZID register. See the summary in Table 28 below.

Table 28. VLCC HAZID Risk Ranking Summary

| Key system level HAZID nodes | Risk Ranking of Hazards Identified | | | |
|---|---|---|---|---|
| | Low | Moderate | High | Extreme |
| Node 1: General Arrangement: Bunkering | 1 | 4 | 4 | 0 |
| Node 2: General Arrangement: Fuel Storage | 0 | 4 | 6 | 5 |
| Node 3: General Arrangement: Fuel Handling Room | 0 | 0 | 4 | 5 |
| Node 4: General Arrangement: Fuel Handling Room, Fuel transfer, Fuel preparation, Reliquification, pumps and piping | 0 | 0 | 1 | 2 |
| Node 5: GA Machinery space (ER)/Use of Fuel/ Engine Maintenance Activity/Engine | 3 | 1 | 1 | 0 |
| Node 6: Vent / Vent Liner / Vent Mast | 0 | 3 | 6 | 4 |
| Node 7: Safety System/Emergency - Not enough Information | 0 | 0 | 0 | 0 |
| Node 8: Ship's Operation /Simultaneous Operation | 0 | 2 | 1 | 0 |

There were no unresolvable risks identified during the preliminary HAZID that would prevent further development of the VLCC with an emission-control system. Appendix VIII – List of Recommendations – VLCC provides a summary of the recommendations from the HAZID register with applicable nodes for the HAZID scenarios.

The key findings and recommendations from the HAZID study and the additional risks that would need to be addressed are summarised below:

- The fire risk to the VLCC's cargo and impact to the ammonia storage tanks on the weather deck pose significant risks and need to be studied further.
- The explosion and fire risks associated with the VLCC's cargo tank and the impact on the integrity of the ammonia tank need further investigation. Specific studies on conditions such as fire and explosion risks, fire loads and BLEVE potential need to be conducted and their results implemented in the final design.
- The potential for an explosion inside the FPR could impact the integrity of the ammonia and VLCC cargo tanks, so analyses of fire and explosion risks and separation measures need to be undertaken.
- It is recommended that ammonia piping on the open deck should be of a double-walled construction and protected against damage and the hazards associated with dropped objects.
- Any ammonia-related installations on deck need to be undertaken with consideration for the VLCC-deck opening; installing a tank or FPR room above deck openings should be avoided.
- The VLCC's deck, FPR and cargo tanks should be installed at heights that provide enough neutral ventilation to avoid the formation of vapours in enclosed or semi-enclosed spaces and minimise the risk of explosion.
- Operators should avoid any lifting above the fuel tank, FRP room and deck piping to minimise the risks associated with dropped objects.
- An ammonia-dispersion analysis should be performed to establish hazardous areas and toxic zones
- Creating an opening in front of the accommodation wall and between FHR (e.g., pump room inlet outlet), should be specifically considered as, in an emergency, these areas can be exposed to high concentrations of ammonia. A dispersion analysis needs to consider worst-case discharges such as tank damage, a fire on the VLCC, etc.

### 4.3.2 Cargo ship 2: Ammonia-Fueled Bulk carrier

This design uses ammonia as the main marine fuel and a dual-fuel slow-speed main propulsion engine designed by MAN Energy Solutions SE. The two options for general arrangement are shown in Figure 23 and Figure 25 (below). The first option (Figure 23) features two fully refrigerated Type A ammonia tanks for fuel storage installed on the port and starboard sides of the accommodation area. The tank bottom is inside engine room with the appropriate boundary. The accommodation is narrow and longer compared to traditional designs to accommodate the ammonia-storage tank.

Two bunker manifolds (port and starboard) are installed between cargo holds 7 and 8. The FPR is aft of the accommodation between the two fuel tanks. The ship uses the MAN dual-fuel ammonia engine that is currently under development and expected to be ready for the market by 2024. The top view is shown in Figure 24.

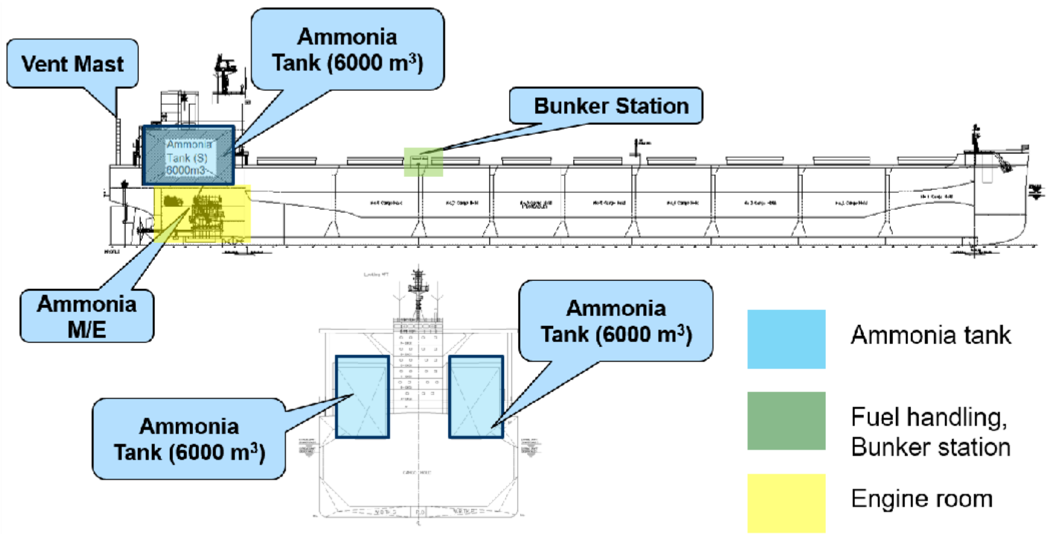


Figure 23. Proposal I: General Arrangement – Fuel Storage and Bunkering

The general arrangement of the fuel tank, FSS room, vent mast, bunker station and bunker manifold are shown in Figure 24. The ammonia piping from the bunker station to the Type A tank dome is on the weather deck. The tank dome is located at the top of the fuel tank. Any release from the fuel tank and bunker manifold will be routed to a vent mast.

The cooling and heating circuit for this arrangement uses a glycol-water mixture. An expansion tank will be located inside the FHR. Fuel piping between the FHR and engine is double walled, with extraction fans for the double-wall annulus located with the vent mast at the top of the FHR.

Any release of ammonia during normal operations will be captured in an ammonia-catchment system.

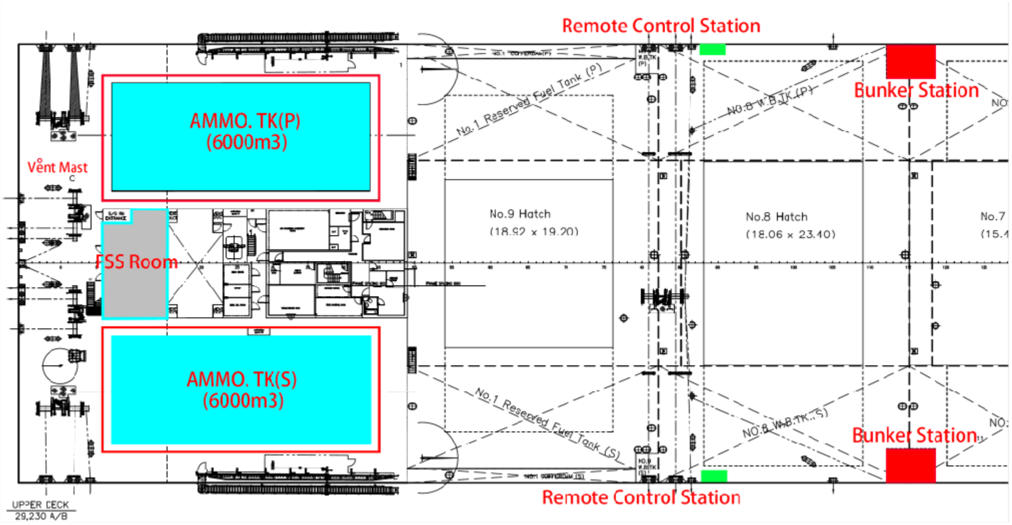


Figure 24. Proposal I Top View – Fuel Storage and Bunkering

The second general-arrangement option for the bulk carrier proposed is shown in Figure 25 . It features a fully refrigerated Type A ammonia tank for fuel storage installed between cargo hold tanks 3 and 4.

Two bunker manifolds (port and starboard) are also installed between cargo holds 3 and 4. The FPR is located on top of the aft fuel tank. Fuel supply lines run along the deck from the FPR to the engine room.

This vessel also will use the MAN dual-fuel ammonia engine that is currently under development. Its general arrangement is shown in Figure 25.

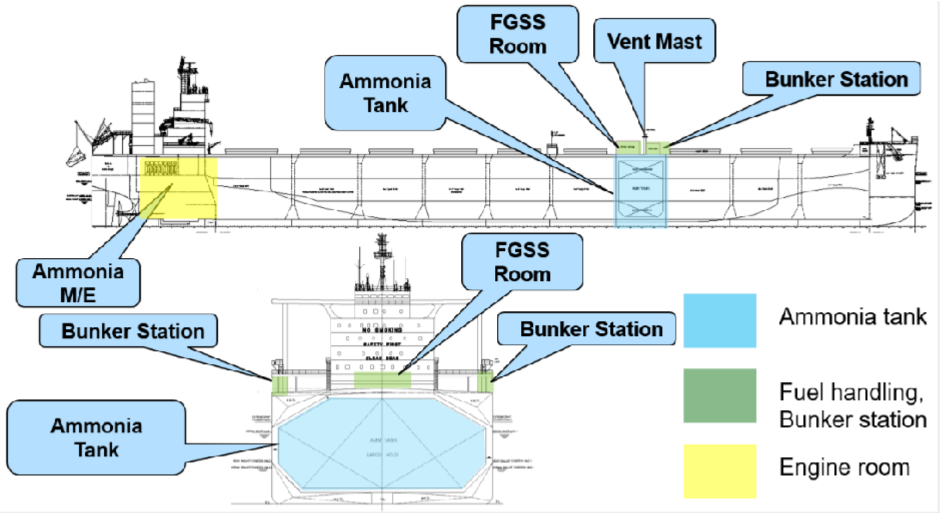


Figure 25. Proposal II: General Arrangement – Ammonia Tank in Cargo Hold Area

The general arrangement for the fuel tank, FSS room, vent mast, bunker station and bunker manifold is shown in Figure 26. Figure 26 and Figure 27 show the bunkering, fuel storage and FSS room location from the side and top views. The FSS room is located on the top of the fuel tank and the tank connection space is located inside the FSS room. The tank dome is located at the top of the fuel tank.

Any ammonia released from the fuel tank and bunker manifold will be routed to a vent mast, which is located on the top of the fuel tank aft of the FSS room. The fuel pipe is installed on the weather deck with mechanical protection.

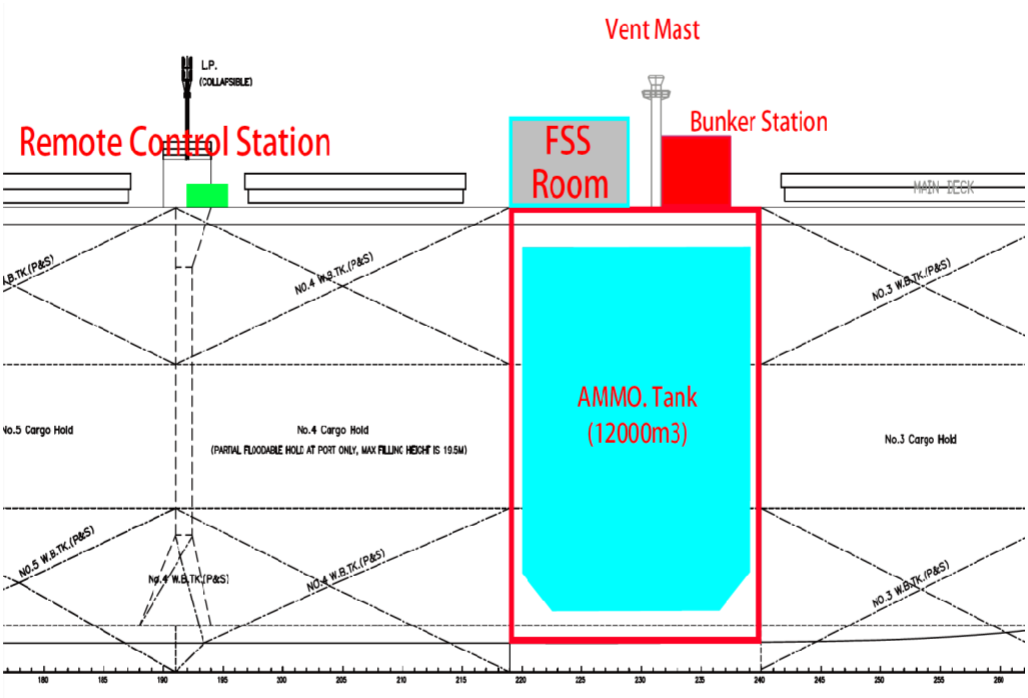


Figure 26. Proposal II: Fuel Storage and Bunkering.

The key safety features for both options are to assure that any ammonia released from the FPS during normal operations will be captured in an ammonia-catchment system. Any relief-valve release from the fuel tank and bunker manifold will be routed to a vent mast. The cooling and heating circuit for this arrangement uses a glycol-water mixture. An expansion tank will be located inside FHR and fuel piping between the FHR and the engine will be double walled.

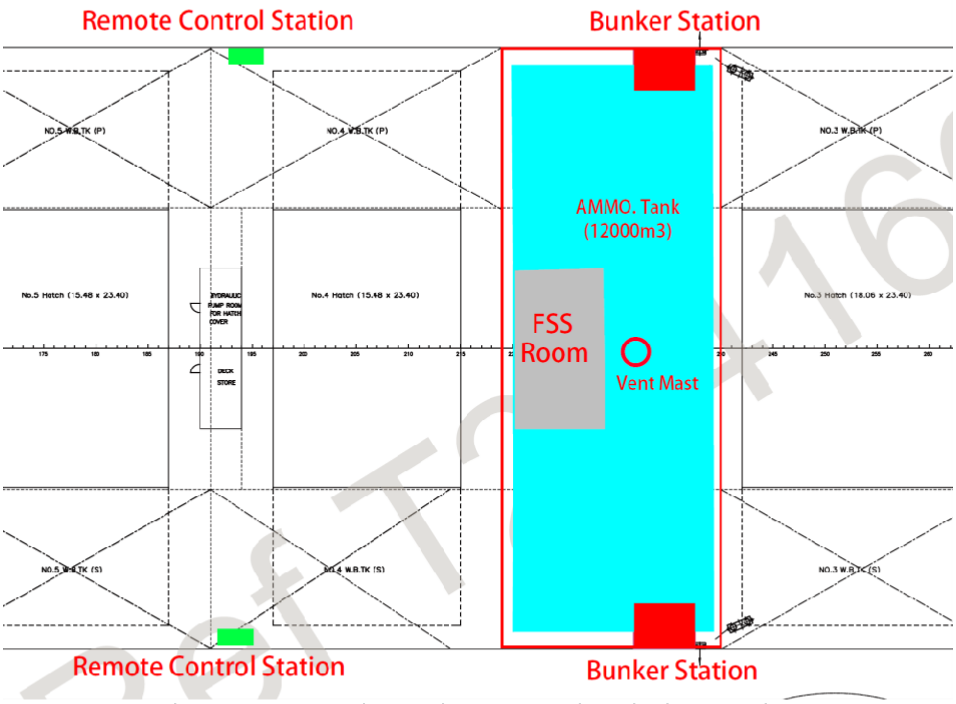


Figure 27. Proposal II: Fuel Storage and Bunkering Top view

#### 4.3.2.1 Assumptions – Bulk Carrier

In addition to those listed in Section 4.2.7, other assumptions from the HAZID workshop are listed below:

- The ammonia-fuel system is designed to prevent any releases of ammonia into the atmosphere during normal operating conditions. Ammonia may be released during emergency conditions via the vent mast.
- Ammonia bunkering is only performed at anchorage with an ammonia-bunkering vessel in a side-by-side configuration using transfer hoses.
- Bunkering vessels will have fenders and hoses; the vessel being serviced will not carry a fender or hoses.
- Cargo operations and bunkering will not occur simultaneously.
- During an engine shutdown or similar situations, nitrogen will purge the fuel lines into the knockout drum or service tank.
- The service tank is pressurised to ~20 bar to avoid cavitation and facilitate operation of high-pressure pumps.
- The glycol heat exchanger system is located in the FSS. The glycol is heated by seawater or steam, supplied from the engine room.
- All ammonia piping will be run on the main deck and protected against mechanical damage.
- For Proposal 1, the piping from the tank to the FPR – and from the bunker station to the tank -- are installed between the Type A tank and the side wall of the accommodation room. It is single-wall piping.
- Piping from the FPR to the engine room is double-walled for Proposal 1.

#### 4.3.2.2 Results and Recommendations

The project is at the preliminary-concept stage and, for the workshop to be feasible, some conditions were assumed (they are listed in the assumption section). For some nodes, there was a lack of information available, so no hazard-risk ranking was offered. But the activities associated with those scenarios were discussed and, where feasible, recommendations were made.

The results of the HAZID workshop are to be analysed and incorporated into future development of the concept. A complete list of recommendations and the HAZID register are in Appendix X – List of Recommendations BC Proposal I, Appendix XI – Hazard Register BC Proposal I – Fuel Storage tank port/starboard of Accommodation and penetrating Engine Room, Appendix XII – List of Recommendations BC Proposal II and Appendix XIII – Hazard Register BC Proposal II – Fuel Storage Tank in Cargo Area.

The system and operational level nodes, along with some scenarios for each node were discussed in the HAZID workshops. Where the risks were deemed high, recommendations were developed based on the scenarios from the HAZID workshop.

There were no unresolvable risks identified during the preliminary HAZID study that would prevent further development of the bunker barge with an emission-control system.

The recommendations from the HAZID study for the major nodes at system and operational levels are listed in the register (Appendix XI – Hazard Register BC Proposal I – Fuel Storage tank port/starboard of Accommodation and penetrating Engine Room and Appendix XIII – Hazard Register BC Proposal II – Fuel Storage Tank in Cargo Area).

One hundred and six (106) recommendations were documented for Proposal I in Appendix XI – Hazard Register BC Proposal I – Fuel Storage tank port/starboard of Accommodation and penetrating Engine Room and 113 recommendations were documented for proposal II in Appendix XIII – Hazard Register BC Proposal II – Fuel Storage Tank in Cargo Area. These recommendations are based on the discussions between the participants of the preliminary HAZID study.

Table 29. Bulk Carrier Proposal I HAZID Risk- Ranking Summary

| Bulk Carrier Vessel (Proposal I) Risk Profile | | | | |
|---|---|---|---|---|
| Key system level HAZID nodes | Risk Ranking of Hazards Identified | | | |
| | Low | Moderate | High | Extreme |
| Node 1: General Arrangement: Bunkering | 2 | 3 | 6 | 3 |
| Node 2: General Arrangement: Fuel Storage | 0 | 1 | 7 | 4 |
| Node 3: General Arrangement: Fuel Handling Room | 0 | 0 | 4 | 2 |
| Node 4: General Arrangement: Fuel Handling Room, Fuel transfer, Fuel preparation, Reliquification, pumps and piping | 0 | 3 | 2 | 1 |
| Node 5: GA Machinery space (ER)/ Use of Fuel/ Engine Maintenance Activity/Engine | 0 | 3 | 1 | 1 |
| Node 6: Vent /Vent Liner/Vent Mast (Not risk ranked, recommendations provided to improve design) | 0 | 0 | 0 | 0 |
| Node 7: Safety System / Emergency | 0 | 0 | 0 | 1 |
| Node 8: Ship's Operation /Simultaneous Operation | 0 | 0 | 2 | 0 |

Table 30. Bulk Carrier Proposal II HAZID Risk Ranking Summary

| Bulk Carrier Vessel (Proposal II) Risk Profile | | | | |
|---|---|---|---|---|
| Key system level HAZID nodes | Risk Ranking of Hazards Identified | | | |
| | Low | Medium | High | Extreme |
| Node 1: General Arrangement: Bunkering | 2 | 4 | 8 | 2 |
| Node 2: General Arrangement: Fuel Storage | 0 | 4 | 6 | 3 |
| Node 3: General Arrangement: Fuel Handling Room | 0 | 1 | 4 | 0 |
| Node 4: General Arrangement: Fuel Handling Room, Fuel transfer, Fuel preparation, Reliquification, pumps and piping | 0 | 3 | 2 | 3 |
| Node 5: GA Machinery space (ER)/Use of Fuel/ Engine Maintenance Activity/Engine | 0 | 4 | 1 | 1 |
| Node 6: Vent / Vent Liner/Vent Mast (Not risk ranked, recommendations provided to improve design) | 0 | 0 | 0 | 0 |
| Node 7: Safety System/Emergency (Not risk ranked, recommendations provided to improve design) | 0 | 0 | 0 | 0 |
| Node 8: Ship's Operation /Simultaneous Operation | 0 | 0 | 0 | 1 |

The key findings and recommendations from the HAZID study and the additional risks that would need to be addressed for the bulk carriers are summarised below. As there were two proposals for general arrangement, these are divided into General Findings and Specific Findings:

**General Findings**

- Because many bulk carriers feature cargo-handling operations that create a higher risk of dropped objects, designers need to evaluate the associated risks and provide robust mitigation.
- Due to the long length of ammonia piping on deck and at different elevations, the ability to purge the ammonia piping could be challenging. A special study will need to be conducted to determine the best way to purge on-deck piping and how long that process will take. It has an impact on safety for both vessel options.
- Trapped fluids were a key concern for both proposed arrangements; further investigation is required to avoid that possibility, as trapped fluids can warm, expand and create very high stresses on equipment.
- Purging is done with $N_2$ and will be introduced into the ammonia tank. This needs to be considered during system design, equipment selection, etc.

**Specific findings for Proposal I - fuel tank next to accommodation port/starboard**

- The workshop found the risks associated with this general arrangement to be very high due to the proximity of the ammonia-storage/system to the accommodation. This will require further improvements to the overall design.
- Given the proximity of the accommodation to the fuel tank, further study is needed to develop requirements for structural fire protection and fire-fighting.
- The greater elevation of the tank dome raises questions about the ability to purge ammonia in all operational and emergency situations. This is a significant concern. A further study needs to be conducted to verify that purging can be done for all piping in this condition (e.g., bunker, FPR to engine, between FPR and tank, etc.).
- Any emergency can expose the life-saving appliances (LSA), which are installed aft. This is also a significant concern. Gas dispersion and fire analyses are needed and should consider worst-case discharges to verify that the safe evacuation of onboard personnel is possible; alternatively, design improvements or other mitigation strategies should be provided.
- The systems that ventilate and discharge ammonia are too close to accommodation and Cat A machinery spaces. A detailed dispersion analysis needs to be conducted to develop safer arrangements.

**Specific findings for Proposal II – fuel tank, FPR and vent mast in Cargo area**

- It is recommended that cargo tanks be separated by a cofferdam from other cargo holds and the FPR room, etc.
- Fuel pipes running on the weather deck need to be protected from dropped objects and mechanical damage. Further study needs to be conducted to examine the associated risks.

### 4.3.3 Ro-Pax ship: Diesel Mechanical, Fuelled by Ammonia

The first GA option calls for the ammonia storage tank to be located inside the hull and next to the engine room. The lower hold is converted to install two ammonia tanks. They are Type C insulated tanks with the capacity to store 576m3 of ammonia in each. Figure 28 shows this GA.

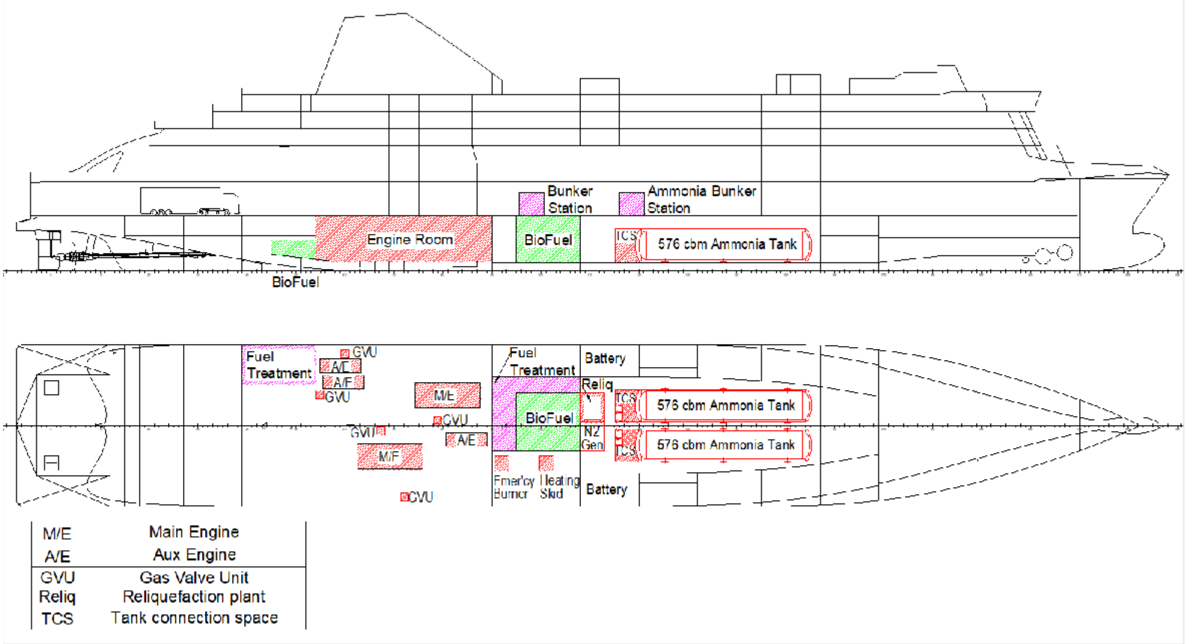


Figure 28. GA – NH3 tank inside Hull

Some key elements of the GA are described below:

- The tank connection space (TCS) is next to the tank, features gas/liquid-tight construction and is classified as a Zone 1 space.
- The TCS space is connected to the tank, which has instrumentation to notify of any leaks. It is designed to contain ammonia and is vented independently to the vent mast.
- The tank bottom is connected to the fuel supply; its location complies with the requirements of the IGF Code.
- There is energy storage (battery: Li-ION) with 2x5 MWh capacity.
- The ammonia tank's first stop valve is welded to a connection on tank. Piping between the first stop valve and tank is a double-walled welded construction (the connection between the tank and first valve is double-valved).
- All TCS piping is designed for -33°C
- All piping for the TCS space is stainless steel and designed to the 'leak-before-fail' principle
- The IGF/IGC-compliant Tank C has an additional safety margin compared with standard pressure vessels
- Two types of tanks are considered: a single-wall tank with insulation and a double-wall tank with vacuum insulation
- The ship is designed for MGO, so there is no heating circuit
- Current technology suggests a high proportion of MGO will be used as pilot fuel, so significant biofuel storage is still required
- Ammonia will not be used in port and the changeover strategy will need to be established
- Each consumer has its own gas valve unit, as per IGF Code requirements
- The engine for this arrangement will be supplied by Wartsila, and can use gaseous fuels

The second general arrangement option considered in the workshop features ammonia tanks on the open deck aft. The capacity of the tanks had to be reduced to 350m$^3$ each and the ammonia bunker stations relocated accordingly. The re-liquefaction plant is also relocated. All piping from the TCS to the boundary of the engine room are in a ducted tunnel and gas tight. The piping inside the engine room is double walled. The bunker station has been moved aft close to ammonia tank. Figure 29 shows this GA.

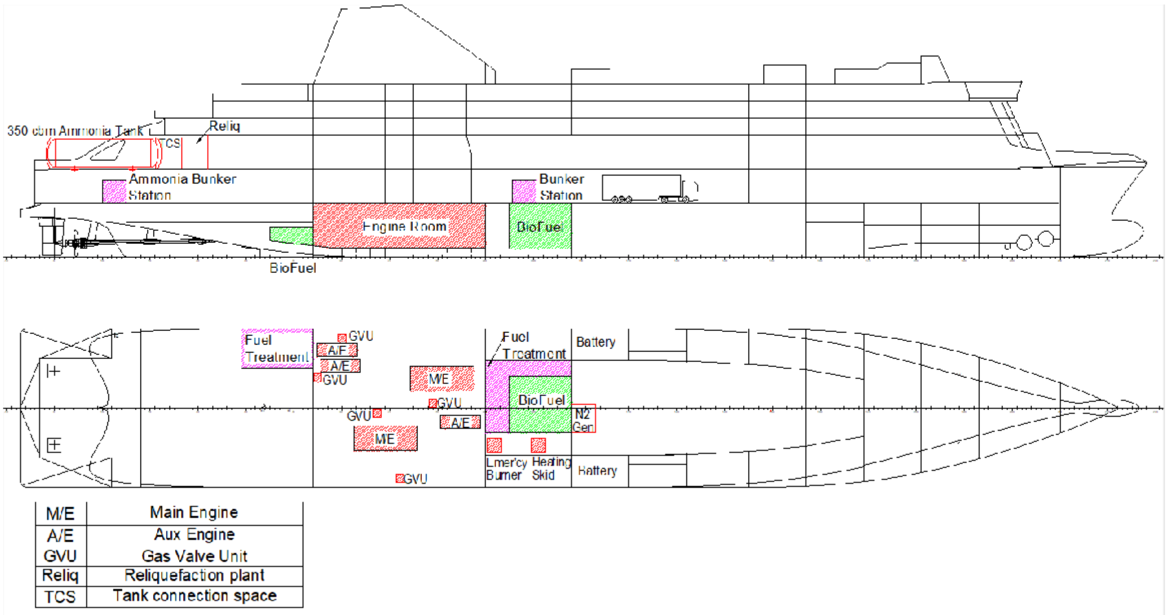


Figure 29. GA – NH3 tank on aft Deck of RO-Pax

#### 4.3.3.1 Results and Recommendations

During the HAZID workshop, all high-level risks were considered, and the safeguards required by codes/standards/regulation were identified. Risk rankings were developed and are listed in Appendix XV – Ro-Pax HAZID Register.

Due to ammonia's toxicity and the associated hazards to humans and aquatic lifeforms, many risks and safeguards were identified; a significant proportion of these were additional to those required by IGF Code.

With few codes available, many recommendations were for further analysis and research. However, they are all listed for consideration and may help to inform/form prescriptive requirements and safer designs and arrangements. The recommendations developed by the team are listed in Appendix XIV – List of Recommendations RO-Pax.

The recommendations from the HAZID study are listed in the HAZID register (Appendix XIV – List of Recommendations RO-Pax) for all major nodes at the systems at the operational levels. Seventy-eight (78) recommendations were documented in Appendix XIV – List of Recommendations RO-Pax. These recommendations are based on discussions with the participants in the preliminary HAZID study.

Table 31. Ro-Pax Vessel HAZID Risk Ranking Summary

| Ro-Pax Vessel HAZID Risk Profile | | | | |
|---|---|---|---|---|
| Key system level HAZID nodes | Risk Ranking of Hazards Identified | | | |
| | Low | Moderate | High | Extreme |
| Node 1: General Arrangement Ro-Pax (No new risk identified) | 0 | 0 | 0 | 0 |
| Node 2: $NH_3$ fuel storage tank A (engine room) | 1 | 34 | 72 | 7 |
| Node 3: $NH_3$ fuel storage tank B (on open deck) | 0 | 5 | 8 | 2 |
| Node 4: Bunkering Arrangement (tank in hold) | 2 | 16 | 11 | 12 |
| Node 5: Bunkering arrangement (on deck) | 0 | 0 | 1 | 0 |
| Node 6: Fuel preparation room | 0 | 0 | 0 | 0 |
| Node 7: Machinery space (ER) | 3 | 17 | 8 | 2 |
| Node 8: Ventilation (not risk ranked, recommendations provided to improve design) | 0 | 0 | 0 | 0 |
| Node 9: Safety Systems (not risk ranked, recommendations provided to improve design) | 0 | 0 | 0 | 0 |
| Node 10: Ship's Operation (not risk ranked, recommendations provided to improve design) | 0 | 0 | 0 | 0 |
| Node 11: Biofuels (no new risk identified) | 0 | 0 | 0 | 0 |
| Node 12: Engines (no new risk identified) | 0 | 0 | 0 | 0 |

The key findings and recommendations from the HAZID study and the additional risks that would need to be addressed for the Ro-Pax are summarised below:

- Passengers on Ro-Pax vessels can smell very low levels of ammonia (about 5 ppm) if venting is not correct. This creates comfort issues for them and can have an impact on a company's reputation. It is important to absorb all ammonia from any source to eliminate release into the atmosphere.
- Bunkering operations will pose significant risks to passengers. Additional risk studies, such as bunkering operation HAZID/HAZOP and dispersion analysis, must be conducted and additional measures put in place to minimise these risks.
- Dropped-object risks are significant when an ammonia tank is placed on deck. No overhead lifting should be allowed above the area of this tank.
- Collision/grounding can pose significant risks to the integrity of the ammonia tanks. While the arrangement of the fuel tanks complies with the IGF Code, it needs to be re-evaluated to consider the risk to passengers.
- No open ammonia piping should be allowed in any area where there is passenger traffic. Most piping should be run in ducted or double-wall configurations and the annulus should be vented at a safe location.
- An emergency evacuation and rescue study should be performed to consider worst-case scenarios.

## 4.4 Overall conclusion on ammonia HAZIDs

The HAZID studies demonstrated that the major concerns related to ammonia as marine fuel are related to ammonia toxicity and ammonia gas dispersion issues. These issues require further studies to understand the risks and additional safeguards that will need to be implemented to prevent or mitigate the major hazards.

Ammonia is a toxic, corrosive, flammable gas with a strong characteristic odor. The odor threshold for ammonia is between 5-50 parts per million (ppm) of air. Although repeated exposure to ammonia produces no chronic effects to the human body, exposure to small concentrations of ammonia in the air can be extremely irritating to the eyes, throat and breathing pathways.

The HAZID studies identified preventive and mitigative safeguards and recommendations for various ship types. While some safeguards stemmed from the IGF Code for methane as marine fuel, a large number of safeguards identified in the studies are considered additional safeguards due to the inherent risks of ammonia. They are not found in the IGF Code.

It is important to note that not all safeguards and recommendations listed in HAZID registers will be applicable to all ship types. Some are obviously practical and of benefit, but others may require further investigation of their merit. However, they are all listed for consideration and may help to inform prescriptive requirements and develop inherently safer designs and arrangements. Importantly, the additional safeguards and recommendations will contribute to further risk reduction.

It is also important to consider that ammonia is not new to shipping: it is commonly transported as cargo, and it is common practice to use ammonia onboard as refrigerant. All the necessary practices for the safe handling of ammonia onboard -- including operational and safety procedures -- are well known in marine liquified gas industries and accepted by crew and operators.

However, because most of this experience is concentrated in one segment of the maritime industry, opening the use of ammonia as a fuel to the wider industry will add risks. This is an important factor to be considered. Very detailed training requirements will need to be in place for safe operation by an expanded class of mariners, and specific regulations will need to be developed.

**Toxicity and dispersion characteristics**

The prevention of ammonia gas release and dispersion will be an important safety precaution during the ships' operations. Regulations to monitor and limit concentrations and identify likely 'toxicity zones' will be required. Gas-detection equipment capable of monitoring the full ammonia concentration range (from low ppm/toxicity to flammability) will need to be provided and connected to automated safety-protection responses for all vessel types.

Regulations for personnel protection will need to be developed for all commercial vessel installations. Respiratory and eye protection devices for emergency escape purposes should be provided for every person onboard (filter-type, self-contained breathing apparatus, with durations based on risk studies). Gas-tight protective clothing and clearly marked decontamination showers should be available on deck near potential exposure areas and be able to operate under all ambient conditions.

Ammonia gas is considerably lighter than air and will rise in dry air. Another characteristic of ammonia is that it has tremendous affinity for water; it reacts immediately with the humidity in the air and becomes heavier than air, so it may remain close to the ground and limit dispersion efforts. Detailed dispersion studies will be needed to protect the ship, its personnel and the environment.

**Environmental Impact**

While ammonia is not a greenhouse gas, it is very toxic to marine life. Fuel slip and other gaseous ammonia emissions that might occur during normal operation and emergency scenarios will need to be kept under control. It is recommended to build a closed system, where any release of ammonia will be absorbed using water absorption or an absorber. Any contaminated water with ammonia will need to be collected and processed for safe discharge.

**Corrosivity and material selection**

Anhydrous ammonia is an alkali and can combine with water to form ammonium hydroxide. Ammonia, especially in the presence of moisture, reacts with and corrodes copper, zinc and many other alloys. Only select rubbers and polymers are suitable for liquid anhydrous ammonia, limiting the material selection for gaskets and sealing. The IGC Code and other industrial codes used in the refrigeration industry have detailed material requirements that need to be followed.

Oxygen levels of more than a few ppm in liquid ammonia can promote stress-corrosion cracking in steels, which spread very rapidly at elevated temperatures. Therefore, it is important during operations to have proper purge procedures and to keep oxygen away. The purity of purging mediums such as nitrogen is especially important to avoid oxygen contamination.

**Bunkering**

Because ammonia fuel could be used by a wide variety of ships that travel to and from disparate port environments, there will be additional risks for bunkering. Bunkering is expected to take place at or near a port, locations that are usually close to cities and other vulnerable areas. Accounting for the potential environmental impact from any release of ammonia during bunkering will be a primary concern for responsible ship-owners. As designs and the adoption of ammonia as a fuel expand throughout the maritime industry, it is expected that additional studies will be conducted in co-operation with local governments and port authorities.

The following studies should be considered at the development stages for ammonia-as-fuel projects.

- Bunkering operation procedural HAZID/HAZOP
- Development of an emergency plan with local port authorities and regulatory bodies to consider the ammonia hazards to local human and aqua life.
- Mooring analysis for each type and size of vessel with its supporting bunker vessel.
- Plans to monitor mooring-line tension, vessel separation and weather at all times while bunkering
- Dedicated safety plans for high-pressure bunkering where ammonia is being transferred to Type C containment systems under pressure.

**Engine**

Many engine-makers are developing ammonia-fuelled engines; some have entered prototype testing, but there are not fully approved/type-tested engines on the market. It is expected that in the coming years, as testing progresses, more information is expected to be made available, allowing safety issues be addressed. These are some of the present concerns that need to be resolved:

- Ammonia slippage's impact on environment
- The impact of $NO_x$, $SO_x$ and $N_2O$ (particularly, $N_2O$ which is harmful to humans).

- The development of ammonia-absorption systems to eliminate all ammonia discharges into the atmosphere during normal or emergency operations; these systems will be new to shipping and will require further study and development
- Methods to contain, pre-treat and discharge ammonia-contaminated water from absorption systems, firefighting and leakage etc., before being sent to shore for further treatment.
- A reassessment of engine-room safety systems from the toxicity perspective, which may include design improvements and new procedural measures to address ammonia leaks.

**Exhaust treatment**

Ammonia engines are expected to need pilot fuels to improve combustion efficiency. This may generate some carbon emissions, but the main focus will be on NOx and particularly $N_2O$, which has a significant global warming potential. In addition, some ammonia slips are likely to be encountered from incomplete fuel combustion. As tests are ongoing, it is hard to quantify those emissions or the environmental impact.

It is expected that some form of exhaust treatment will be needed, so the regulator will need to develop and enforce related emission limits.

**Fuel System**

Ammonia fuel systems, which will feed the potential new fuel to the engine, will be new to the marine industry. There are basically two concepts for these fuel systems: high and low pressure. Each system has its own set of risks that need to be considered. Many of these have been defined in this study, and the primary concerns and recommendations are summarised below:

- Engine manufacturers and shipyards/designers will need to work together to design the entire ammonia system anew. Currently, engine manufacturers are designing proprietary closed systems; it will require all parties to work together to design a fully integrated system.
- The industry's firefighting strategy will need to be further developed and unified, as various strategies currently exist, each with its own strengths and weaknesses.
- Fuel system rooms will need to be equipped with increased ventilation systems
- Depending on the type of vessel, the location of the fuel-treatment room will present its own unique risks; those will need to be addressed with actions supported by additional studies.
- Ventilation from the fuel-preparation room will need to be independently studied for each project and type of vessel.
- Due to the risks that dropped objects from cargo handling pose for each ship type, the entire handling operation will need to be independently reassessed to identify the potential threats to the fuel-preparation room and fuel tanks.
- Recommendations for structural fire protection will need to be followed
- Additional studies on fire and explosion risks from external and internal factors will need to be conducted.
- Depending on the general arrangement, the fuel piping on the weather deck will need to be adequately protected against dropped objects or other physical damage; double-walled piping with protection should be considered.

**Accommodation**

From a risk perspective, the general arrangements for accommodation should be a primary concern. Each arrangement should be studied separately when fuel storage is located close to mariner accommodations. The safest location will always be away from the accommodation in the cargo hold or on the weather deck. Additional safety measures to be considered are:

- Placing toxicity detectors at all air inlets for the accommodation spaces
- Ammonia vents should be located in areas that do not bring accommodation into the toxicity zone
- Air locks should be considered for all entrances
- LSA should be located as far away as practicable from the toxicity zones and account for worst-case discharges
- The side of the accommodation closest to any potential ammonia release or fire should have adequate structural protection
- Water curtains and water mists to dilute ammonia clouds should be considered to enable a safe escape.

### Fuel Storage

Fuel storage will need to be in compliance with IGF/IGC code requirements. The tank designs themselves may be to code, but ammonia's toxicity and potential environmental hazards may bring additional internal/external risks that need to be evaluated and addressed. These items may require additional attention:

- Data suggests most groundings and collisions happen near ports or populated areas. Such events can cause damage to tanks located in the cargo holds and release ammonia into the atmosphere and surrounding waters. The potential impact on the population and surrounding areas will need to be evaluated and safety responses put in place.
- A related safety plan to protect the mariners from such an event will also need to be put in place.
- For container carriers, depending on the location of the tanks, there can be additional risks from container fires and dropped object. The potential impact of these will need to be studied.
- For other product carriers, depending on the location of the fuel tanks, the cargo risks to those fuel tanks will need to be studied and defensive strategies put in place.
- For on deck fuel-storage systems, depending on the type of vessel and cargo operation, there may be increased risks from dropped objects or other cargoes. The related risks will need to be evaluated.

### Ventilation

Most ammonia systems are likely to be located in closed spaces, either near accommodation or in the cargo block. The starting point for ventilation will be to comply with the IGF Code. Due to ammonia's toxicity, ventilation studies will need to be conducted, with an eye to increasing the rate of air flow during emergencies after detection. All ventilation inlets and outlets will need to have enough separation to avoid mixing and interfering with other ventilation openings.

### Vents

The location and height of vents will require special consideration. The separation between openings/inlets and vents should be greater than IGF/IGC code requirements. For safety, a gas-dispersion analysis for multiple release scenarios will be needed to establish hazardous and toxicity zones. It is also advised that as many ammonia vents as possible are discharged at one location.

### Safety System

Gas-detection detection equipment should trigger alarms and shutdowns based on toxicity levels and activate the appropriate responses at 'lower-explosive' and 'upper-flammable' limits. The selection of efficient ammonia detectors is critical to these safety systems.

Ammonia can be easily absorbed in water, so water spray and fog, etc. systems will be needed to absorb any ammonia clouds from large leaks.

### Emergency

An effective emergency study will need to be conducted and associated plans put in place with controls and adequate training. There are two primary considerations in an ammonia-related emergency: the first is the risk and impact to the mariner. To address their safety, a full 'escape, evacuation and rescue' study will need to be conducted. The second concerns the impact on the surrounding areas, which can be addressed by designing an emergency plan in consultation with the local authorities.

### Personal Protective Equipment (PPE)

Suitable PPE for use with ammonia gases will need to be provided onboard for each mariner. Eye wash and shower facilities should be located at all locations where the possibility of ammonia exposure exists. Anyone working on or passing by an ammonia system should wear professional PPE at all times.

Certified lifesaving appliances will need to be provided to ensure survival and escape from released ammonia atmosphere and it is advised that suitable study to be conducted.

### Firefighting Systems

Suitable firefighting mediums to extinguish ammonia fire are water spray, alcohol-resistant foam, dry chemicals, or carbon dioxide. When ammonia is released into the atmosphere in a vapour form, it is best to spray water to limit the spread of the vapours, since ammonia easily dissolves in water. However, water should not be sprayed directly on a large pool of liquid ammonia, as it can cause the ammonia to boil and rapidly evaporate, with volatile consequences.

**Summary of major hazards and causes:**

Table 32 below summarises the hazards and causes for each system-level node in the HAZID studies.

Table 32. Summary of hazards and causes from HAZID studies

| System/Area | Hazards | Causes |
|---|---|---|
| **Bunkering** | Ammonia vapor leak | • Material degradation<br>• Connection leak<br>• Joint leak<br>• Operator error |
| | Liquid ammonia leak – hose failure/ loading arm | • Vessel movement<br>• Mooring line failure<br>• Extreme weather<br>• A passing vessel generating a huge wave |
| **Global Risk** | Vessel collision leading to $NH_3$ leak and fuel tank damage | • Pilot/human error<br>• Port congestion/traffic density<br>• Low Visibility<br>• Adverse Weather |
| | Grounding leading to NH3 leak and fuel tank damage | • Pilot/human error<br>• Adverse Weather<br>• Low Visibility<br>• Miscommunication / Lack of information<br>• Port congestion/traffic density |
| **Fuel Storage** | Ammonia vapour leak | • Manufacturing related defects on fuel storage piping and equipment<br>• Over-pressurisation of fuel storage tank<br>• Dropped object impacting fuel storage area |
| | Liquid ammonia leak | • Grounding<br>• Vessel Collision<br>• Fatigue crack in piping and equipment<br>• Dome connection/valve leak<br>• Dropped object impacting fuel storage area |
| **Fuel preparation/handling system** | Ammonia vapour leak | • Connection leak<br>• Flange/joint leak<br>• Seal failure<br>• Dropped object impacting fuel preparation/handling area<br>• Improper or lack of maintenance<br>• Human error |
| | Liquid ammonia leak | • Dropped object impacting fuel preparation/handling area<br>• Pipe/joint/connection failure<br>• Seal failure<br>• Human error<br>• Improper or lack of maintenance<br>• Over-pressurisation of fuel handling piping and equipment<br>• Blocked flow in system |

| System/Area | Hazards | Causes |
|---|---|---|
| | Structure damage | • Over-pressurisation of fuel preparation room<br>• Pressure vacuum in the fuel preparation room |
| **Fuel Management system** | Over-pressurisation of tank | • Human error<br>• Improper training and/or procedures<br>• Control instrument failure<br>• Blocked flow in system |
| | Overfilling of tank | • Human error<br>• Control instrument failure |
| **Engine room** | Ammonia leak | • Piston cover failure<br>• Connection failure<br>• Crank case failure<br>• Dropped object leading to double wall pipe rupture in the engine room<br>• Improper or lack of maintenance<br>• Improper training and/or procedures<br>• Human error |
| | Exhaust explosion | • Unburned ammonia in exhaust |
| | Ammonia vapour release in secondary systems | • $NH_3$ migration into lube oil, cooling water circuit |
| **Accommodation** | Internal fire | • Gally fire<br>• Electrical fire |
| | External fire | • Cargo fire<br>• Ammonia-related fire |
| | Ammonia leakage in accommodation | • Ammonia tank leakage<br>• Fuel handling room leakage<br>• Tank damage due to vessel collision or grounding<br>• Cargo fire<br>• Relief valve discharge to vent mast |
| **External risk** | Grounding | • Human/pilot error<br>• Low visibility<br>• Adverse weather<br>• Lack of information |
| | Collision | • Traffic density in area<br>• Human/pilot error<br>• Visibility<br>• Weather<br>• Miscommunication / Lack of information |
| | Dropped object | • Cargo mishandling<br>• Simultaneous operation |
| | Cargo fire | • Cargo container with petroleum product and other transported cargo |

# 5. Overall conclusions of Ammonia study

Ammonia is currently seen as one of the fuels that could greatly support the decarbonisation of shipping and it has multiple advantages that will encourage wider adoption. As highlighted in this study, the production process of ammonia is based on known and well-established technologies. Ammonia is a chemical compound already well known to the maritime industry, as it is widely transported in gas carriers; this practice had led to the establishment of industry-tested technical rules and safety regulations.

However, using ammonia to decarbonise shipping should rely on two elements: (1) using 'green' ammonia, a requirement that will pose challenges in terms of production, sustainability, scalability and economic viability; and (2) using ammonia as a fuel for shipping will intrinsically lead to a requirement for specific regulations, safety precautions and personnel training.

In relation to other fuels, ammonia does provide some advantages. It can be stored in liquified condition at atmospheric pressure, or fully pressurised at 18 bar. It does not require the cryogenic temperatures demanded for LNG and hydrogen, nor does it take as much volume to store as hydrogen. This makes it an easier gas to transport and a strong candidate for use as a marine fuel.

Indeed, ammonia is a product that is already commonly available in many industrial sectors such as agriculture. Knowledge and technology are available on how to produce, distribute and keep ammonia under safe conditions. However, the wider adoption and use of ammonia in combustion engines poses some challenges.

In addition, although the combustion of ammonia is free of $CO_2$, the current production of ammonia is $CO_2$ intensive as it is made predominantly from natural gas or coal. For ammonia to become a carbon-free fuel alternative, it must be sourced using green energy.

**Production**

From the production side, this study has identified five production pathways for green ammonia. The first three make use of Haber-Bosch synthesis process in which the natural gas sourcing of hydrogen is replaced by either an electrolysis process (1), direct solar energy (2) or biogenic hydrogen production (3). An alternative pathway relies on an innovative synthesis process called non-thermal plasma synthesis (4). Finally, the last process is electrochemical ammonia synthesis, which would not require a separate hydrogen production step.

Currently, there is a large technology-readiness gap between the established processes based on Haber-Bosch principles and the others, suggesting that the Haber-Bosch process will dominate at least the short-term future for the production of green ammonia. Enhancements in production efficiency and cost will probably be made, but they may mainly come from improvements in the electrolysis for hydrogen production.

**Sustainability**

The green production of ammonia -- relying on green energy or carbon-free feedstocks for natural gas -- could reduce GHG emissions by as much as 91% on a well-to-wake basis, since the main contribution to the emissions comes from production (well-to-tank). When compared to traditional marine fuels such as VLSFO and MGO, the total GHG emissions would be reduced by about 85% if green ammonia is used. Other emissions such as sulphur dioxide, carbon monoxide, heavy metals, particulate matter and polycyclic aromatic hydrocarbons (PAH) are also reduced substantially (in some cases to virtually zero).

However, particular attention needs to be paid to potential presence of ammonia slip, $N_2O$ or NOx emissions, due to the imperfect combustion of ammonia and the use of pilot fuels. These emissions will need to be kept as low as possible and any progress regarding this will only be confirmed after further development of internal combustion engines capable of consuming this fuel.

Ammonia may also be used as a fuel for an onboard fuel-cell system; in such case, the resulting emissions would be even lower when compared to using ammonia in internal combustion engines, as no combustion byproducts would be formed. Solid oxide fuel cells using ammonia are unfortunately still some years away from becoming viable, due to their comparatively high costs and unreliability. IC engines, especially 2-strokes, will most likely continue to dominate shipping, even as the industry transitions to other fuels, because it is a known technology, efficiency and reliability are proven and CAPEX and OPEX are competitive.

**Availability**

The decarbonisation of the maritime sector would require large amounts of green fuels, ammonia being one of them, which in turn would require tremendous growth in green energy production (ie., wind, solar) and, in particular, the electrolysers which are a fundamental part of green ammonia production plants.

The current capacity for green-ammonia production is relatively low. However, the anticipated availability of green energy sources by 2040 should be sufficient to produce enough green ammonia for the global shipping fleet, if it were the sole demand market.

On the other hand,, demand for green energy will also come from other industries (automotive, aviation fuel, construction, heating, etc.), so shipping will face strong competition.

Ammonia, however, has advantages that do not depend on the availability of carbon; for example, biomass or carbon capture. In the long run, this potentially gives ammonia an edge against other alternative fuels. As shipping is international, green energy will need to be available worldwide, so some coordination between states will be needed to ensure the transition.

**Suitability**

Aside from the challenges related to production, sustainability and availability, the suitability of ammonia for use in the current known fuel-cells and internal-combustion processes needs to be considered. There are no insurmountable barriers to prevent the use of ammonia in the marine context. Some technological development will be necessary to optimise its combustion and to meet safety requirements, but the risks have been shown to be manageable. Technologies such as smaller-sized reliquefication, ammonia absorbers or ammonia combustion units exist for other land-based applications, however they will need to be optimised for marine use. These safety risks are further detailed in the risk assessments that were carried out in this study.

**Techno-Economic Aspects**

With all of green ammonia's production and utilisation challenges, it is important to consider total cost of ownership for a green ammonia-fuelled ship. In this study, different ship types have been evaluated. Indeed, with a time horizon of 2030 and 2050. In 2030, blue or green ammonia-fuelled vessels are expected to still have a high total cost of ownership (considering carbon pricing, for green ammonia 2.5 to 3 times higher and for blue ammonia 1.5 times higher than that of conventional fueled ships). The cost gap between ammonia powered vessels and conventional fossil fuelled vessels may, however, be closed by 2050, due to reduced ammonia production costs, lower ammonia system CAPEX and higher carbon prices for fossil fuels. This, however, also depends on the development of the global fuel oil price.

This shows that there is a need for international or regional policy to bridge the gap between blue or green ammonia and other conventional fuels. The market can also play a role in replacement of or complementing policies, e.g., by increasing demand for low- or zero-carbon freight.

**Regulations**

Even though policies for net zero or reduced GHG emissions from shipping are in place, regulations need to follow. Currently, the IMO is discussing market-based measures. The process at the IMO may take some years to be developed; meanwhile, at regional level such as in the EU, the 'Fit-for-55' initiative is taking shape. This mechanism signals a strong commitment from the EU to a decarbonised, sustainable future for shipping.

Beyond the environmental front, there is also a need to further develop safety and technical regulations. Currently, there is a lack of regulation related to the use of ammonia as a fuel at national, regional and international levels, and this might impose a direct barrier to the wider adoption of ammonia.

In the interim, risk-based 'alternative-design' procedures can be followed during the approval process for ammonia-fuelled vessels; classification societies have recently introduced and updated tentative rules and guidelines to support the adoption of ammonia as a marine fuel.

Some important remarks on work to fill regulatory gaps are summarised below:

- Review the IGC Code to produce greater harmonisation with the IGF Code and consider amendments to enable the combustion of toxic ammonia cargoes.
- Support the development of interim guidelines for the use ammonia as a marine fuel.
- Amendments Annex VI and the NOx Technical Code to enable approval and certification to the EEDI, EEXI and NOx regulations, together with developing amendments to regulations 14 and 18 of Annex VI.
- Consider further amendments to Annex VI and the NOx Technical Code to introduce limits for $NH_3$ and $N_2O$ from internal-combustion engines.
- Task the ISO to develop an ammonia marine-fuel standard and other relevant standards for couplings and bunkering.
- Further develop Unified Requirements by IACS for machinery and equipment, recommendations for risk-assessment guidance under IGF Code and ammonia bunkering; these measures would reduce industry uncertainty and support the harmonised application of requirements for ammonia as a marine fuel.
- Establish international-certification mechanisms to ensure that the production of green ammonia is in fact 'green'; these are needed to encourage the adoption of green fuels. This also requires the introduction of standards and guidelines for the calculation, reporting and verification of emission factors for different fuels.

Other relevant elements are highlighted in this study in Section 3.

**Risk Aspects**

Under this study, several risk assessments for several ammonia-fuelled ship concepts have been performed, by means of a HAZID workshop conducted together with cross-sector industry experts. It included a RO-PAX vessel, a VLCC and a bulk carrier. These assessments confirmed that the main concerns related to using ammonia as a marine fuel are safety and toxicity related.

On general safety and risk aspects, the use of ammonia benefits from shipping's existing experience with its carriage as a cargo; as a matter of fact, very few ammonia-related incidents have been reported in the past 50 years.

Consequently, many practices for the safe onboard handling of ammonia are known and regularly put in practice by crew and operators. That said, when used as a fuel, the frequency that ammonia will be handled onboard can be expected to rise exponentially, depending also on the number of ships, bunker events (which will be greater than the present number of cargo-loading and discharge events) and the need for maintenance. Therefore, a very detailed training requirement covering the proposed safeguards and recommendations would need to be in place to ensure safe operation; regulations will also need to be developed for training.

More precisely, on ammonia **toxicity and gas dispersion characteristics**, the study highlighted that the appropriate handling of ammonia release and dispersion is a key precaution.

Regulations would need to be developed to further define items such as: toxicity-zone requirements, gas-detection equipment, respiratory and eye protection for personnel (filter-type self-contained breathing apparatus with minimum durations), and the placement of decontamination showers on deck or near exposure areas.

Ammonia is lighter than air but also has tremendous affinity to water, so it reacts immediately with the humidity in the air to become heavier than air. As a consequence, its releases may remain close to the ground, accentuating the need for dedicated dispersion analyses to be carried out.

**Environmental aspects** (other than the ones related to GHG emissions) are of concern as ammonia is toxic to marine life; closed systems will need to be put in place to prevent any release of ammonia or water contaminated by ammonia into the ocean.

**Material selection** for equipment handling must consider that anhydrous ammonia is highly corrosive. However, knowledge from other industries and the IGC Code have established requirements for safely handling ammonia to avoid issues such as stress corrosion cracking. Safeguards, such as for the allowable level of water in ammonia to avoid the effect of impurities such as oxygen, are common practice in the industry.

As highlighted, the use of ammonia as a fuel will increase the number of interactions with it, especially **bunkering**. The new ship design incorporating ammonia with its lower LHV can lead to reduced sailing range increasing the number of port calls and number of interactions or alternative the ships will be larger, taking more berth space. This could lead to increased port congestion.

In addition, considering the toxicity, and the potential environmental impacts of ammonia, at design stages, additional studies and close collaboration with port authorities will be needed. Some of these studies are further detailed in Section 4.4. Dual-fuel **engines** using ammonia are in development and being tested as this report is being written. These units have yet to be fully approved or type tested. As development progresses, it is expected that safety issues will be identified and addressed prior to their commercialisation.

The study highlighted a few items to be considered during the related technology development, such as: ammonia slip; NOx and SOx (from pilot fuel usage) and $N_2O$ emissions; achieving zero ammonia discharges into the atmosphere during normal operations; any contaminated water (after purging, venting, accidental releases, etc.) to be treated and discharged offshore after treatment; and a re-assessment of the engine-room safety for toxicity and exposure to ammonia and other potential releases. The final development of the engine may rely on after-treatment solutions to further reduce emissions in the exhaust gases.

In addition to the engine, the **fuel gas supply system** is another technology under development. There are basically two types of systems under consideration: high pressure and low pressure, each with specific risk considerations. All parties involved in the design of ammonia-fuelled engines (the engine manufacturer, fuel gas-supply system designer, shipyard, etc.) will need to work together to integrate the engine, supply system and cargo tanks into a seamless system.

A list of items to consider is provided in Section 4.4 and it highlights the need to fully understand risks associated with dropped objects, ventilation systems, and the eventual demands for double-wall piping on different parts of the ship, etc.

This study examined the risks associated with ammonia storage being close to the **accommodation area**. In that event, vessel-specific studies will need to investigate the associated risks and the safety considerations of each design.

With regard to the toxicity challenges associated with ammonia, some items will need to be considered: gas detectors at the inlet of ventilation systems, placing the ammonia vent a sufficient distance from the accommodation, the placement of structural and fire protection in regions closest to fire risk, etc. These are further detailed in Section 4.4.

The fuel-**storage system** is expected to be compliant with the requirements in the IGC and IGF codes, but some additional external and internal risks may require specific studies. The report highlights the need for specific analysis related to dropped objects, vessel impact and grounding which may lead to release of ammonia into the surroundings, considerations specific to ship types (i.e., the risk of container fires and the system's proximity to other products being carried in a product chemical tanker, for example), etc.

As the ammonia systems are expected to be located in closed spaces either near the accommodation or cargo blocks, compliance with the IGF code is expected. In addition, it is expected that due to ammonia's toxicity, increased **ventilation** rates will be in place, in particular to accommodate emergency situations such as when ammonia is detected.

Further, the location of the **vent** mast will need to be carefully assessed, specifically in relation to its location and height. The separations between inlets and outlets will need to be greater than those currently specified in the IGC/IGF codes. In addition, gas dispersion analyses will need to be conducted to properly evaluate the location of the vent masts.

All these points lead to the need for specific **safety systems** to be in place. These include gas-detection systems that trigger alarms based on the level of ammonia emissions. Critical to the effectiveness of that system will be the selection of detectors with the capacity to detect low concentrations of ammonia at different locations and under different ambient conditions. As ammonia can be easily absorbed in water, 'fog' systems to absorb any release will be needed.

**Emergency** studies will need to be conducted and emergency plans put in place to identify effective controls and training. These will handle the situations where the mariner onboard is at risk and/or the surroundings are impacted by the release of ammonia. For these purposes, specific studies are recommended.

Proper **PPE** selection is to be conducted and equipment provided to all personnel onboard the ship. It is advised that anyone working close to or on an ammonia system – or passing by an ammonia system – should always wear the appropriate PPE. Also, it is important to put in place both eye and body wash facilities at locations releases may occur.

***Summarizing****, green ammonia is a promising candidate as a maritime fuel to decarbonise the shipping industry and there are many arguments playing in its favour. Being naturally carbon-free, it has the potential to reduce drastically the emissions both from GHG and from air emissions perspectives. There is also existing knowledge in the shipping industry on ammonia as a cargo, providing a sound basis to develop upon. Knowledge from other industries (fertilizers) is also available, from which the entire supply chain can benefit from: ammonia has and is being used and transported onshore for decades and this lead to relevant understanding on how to transport and handle ammonia safely. Ammonia production technologies are mature enough to support the uptake of its synthesis, however there is a need of further development and scaling on the production of green hydrogen, the backbone of green ammonia production. The prospect is however looking good for production of green ammonia, at the time of writing there has been announced more than 130 Mt per year of green and blue ammonia production facilities. And judging by the number of announced JDP about ammonia fueled ship including announce about ammonia engine development, ammonia as marine fuel will take up in the coming years.*

*There are, however, still many barriers and challenges to overcome. The first barrier is still on the production of green ammonia, much of the new announcement of green ammonia production is likely go to the fertiliser industry, so there is a need for considerable scaling up of renewable energy capacity to support its uptake for ammonia as a marine fuel. As all segments will be increasingly demanding for green energy, its availability is seen as a major barrier for the proper uptake of green ammonia production. Even if ammonia is made available at large scale, shipping will be competing with other industry segments, either those currently already using widely ammonia (e.g., fertiliser industry) or those that see it as a hydrogen carrier. Notwithstanding the above, the concern of the issue of ammonia production costs remains as based on current estimates, ammonia as a fuel should yield considerably higher TCO values than VLSFO.*

*The introduction of regional market-based measures (Fit for 55) provides a good starting point to promote ammonia as a fuel and to improve its TCO performance. However, being shipping an international industry, international decarbonisation policies are needed, otherwise there may be an uneven focus and distribution of investments which may hinder the uptake of ammonia as a fuel.*

*Another barrier lies on the lack of existing regulations on ammonia as a fuel. Although the existence of a relevant basis, being ammonia a corrosive and toxic gas, when considered as a fuel, the safety and reliability concerns need the accounted for more carefully in the regulations when. Contrary to other alternative fuels under consideration by the industry, current regulations cannot be easily transferable to ammonia as a fuel.*

*For these regulations to be developed, it is relevant that further analysis, investigations, and developments to be made to better understand and tackle the safety concerns relating to usage of ammonia as a fuel. The knowledge needs to increase and to be shared with all stakeholders: legislators, class societies, owners, engine makers, equipment providers, operators, port authorities, etc.*

*The study thus highlights that ammonia as a marine fuel is possible, but to unblock the barriers as identified above, there is a need for coordination among industry and government to:*

- *Manage and expand the use of renewable energy*
- *Promote the development of decarbonisation policies*
- *Foster the development of new technologies to improve the production efficiency*
- *Develop an international regulation framework at IMO for using ammonia as a fuel*
- *Encourage collaboration between stakeholders to address technology and safety issues*
- *Carry out additional studies to develop a better understanding of the risks and safety challenges of using ammonia as a marine fuel and how to mitigate them.*

Table 33 (below) provides a summary of the observations detailed in this report, together with some proposed solutions and suggestions.

Table 33. Summary of the Observations

| Subject | Observation/Mitigations/Suggestions |
|---|---|
| **Production** | **Observation**<br>• Production of ammonia is currently at 235 mt worldwide;<br>• This production is based currently on the well-established Haber-Bosch Process using either coal or natural gas as a feedstock.<br>• The green pathway for production of ammonia is likely to use the HB process, using hydrogen produced from renewable energy via electrolysers.<br>• 3 options of electrolysers are available, alkaline, PEM and SOEC. Alkaline has been in use since the 1920s.<br>• Alternative pathways are available and under development that could improve production capacity. However, at this stage, the technological gap between the established processes and the new ones is wide<br>• By using the latest technology, there is a potential to increase efficiency of the production of ammonia and this is under investigation.<br>• Totally production volumes of more than 130 Mt has been announced for production of green and blue ammonia<br><br>**Mitigations and Suggestions:**<br>• In the short term, it is more feasible to rely on the currently known technologies and processes and replace the energy and/or hydrogen with renewable sources<br>• Further R&D should still focus on alternative production pathways to further increase production capacity |
| **Sustainability** | **Observation**<br>• Current production processes for ammonia mainly rely on natural gas, resulting in high well-to-tank emissions. Despite very low tank-to-wake emissions, overall well-to-wake emissions of grey ammonia are higher than conventional marine fuels;<br>• Green ammonia would allow a reduction of up to 91% of the emissions than for grey ammonia, and 85% lower than MGO and HFO;<br>• In the combustion of ammonia, $N_2O$ can be formed at a level that is as yet unknown. These emissions are expected to play a role in the further development of marine engines.<br>• Other emissions and air-pollutants such as sulfur dioxide, carbon monoxide, heavy metals, hydrocarbons, PAHs and PM are significantly reduced compared to traditional fuels<br>• The use of pilot fuel may induce some emissions and air pollution, but these can be mitigated.<br>• The potential of ammonia spills needs to be monitored as the uptake of the fuel increases, as this can lead to eutrophication of the receiving waters. Injection of ammonia into seawater and at the expense of brines can be detrimental to ocean life and biodiversity<br>• Production of hydrogen needed for ammonia synthesis requires pure and deionised water and this can increase water scarcity as the production of renewable ammonia increases.<br>• Desalination of water is an alternative possibility; it will only add a little cost (<5%) to the ammonia fuel cost.<br>• Land-usage due to the increased need for renewable electricity is to be closely monitored and attention will need to be given to non-agricultural land or offshore wind production<br><br>**Mitigation and suggestions**<br>• The IMO and members states could further develop international lifecycle-guideline standards to allow for a complete assessment of the GHG impacts of alternative fuels, including green ammonia. This is to allow a fair comparison between the different production pathways for the different types of fuels;<br>• Standards, reporting,<br>• The engine development is expected to take place in this decade, and this will shed light on the sustainability issues raised in the report;<br>• Particular attention is to be given to the usage of water to produce hydrogen and subsequently ammonia |
| **Availability** | **Observation**<br>• Availability of green ammonia will depend on renewable energy production<br>• The production capacity for renewable energy will need to undergo tremendous growth to fulfil the potential demand for green energy from maritime shipping. Notwithstanding the fact that the shipping industry will compete with other sectors currently demanding 235 Mt of ammonia such (i.e., agricultural) for the demand of green ammonia.<br>• For those purposes, the current level of production of green ammonia is at a very low level<br>• The anticipated availability of renewable electricity in 2040 appears to be sufficient to cover the demands to produce green ammonia<br>• There is a limit at which economies can grow the renewable energy-production capacity, especially in the short and medium terms.<br>• The scaling of production will need to be decentralised towards regions in which there is availability of green energy sources. |

| | |
|---|---|
| | **Mitigations and Suggestions:**<br>• To fulfill the need for cheap green ammonia, the production plants are to be operated at full capacity continuously:<br>  ○ Storage facilities for ammonia to be considered when the distribution cannot be ensured<br>  ○ When production is stopped, the excessive renewable energy produced can be stored or distributed to the grid<br>  ○ The energy source of renewable energy could be sized above the capacity of the ammonia production, ensuring a higher reliability of production. Excessive energy can be either stored to cover periods of low energy production or distributed to the grid<br>  ○ Grid connectivity can ensure a constant supply of energy although not necessarily 100% green before 2050.<br>• Decentralisation of the production to ensure availability of green ammonia for international shipping is required<br>• Production is to be kept close to bunkering or distribution facilities |
| **Suitability** | **Observation**<br>• Ammonia is a known product for international shipping as it is currently handled as a cargo onboard LPG carriers<br>• Current tank technologies are suitable for the storage of ammonia, and there are regulations (IGC Code) for these<br>• Engines and fuel gas supply systems designs exist today and are currently being tested. Both Diesel and Otto cycle engines are under development and currently no major showstoppers are identified<br>• Methane slip and usage of pilot fuel are to be further evaluated as the engine designs are further developed<br>• The most significant issues in relation to storage relate to the stress corrosion cracking, but investigations have discovered ways to prevent this by adding small quantities of water (0.1 to 0.2%) to eliminate impurities.<br>• Fuel cells technology does seem to be a promising alternative to Internal combustion engines; development of the former is underway<br>• On land, onboard storage and use of ammonia in internal combustion engines or fuel cells is possible<br>• Some challenges arise from safety considerations for handling ammonia, as it is a toxic gas<br>• Risk analyses have identified feasible solutions that could fully contain emissions and ammonia leaks<br>• The report did not show any insurmountable barriers to the suitability of ammonia as a fuel.<br><br>**Mitigations and Suggestions:**<br>• Observe and monitor the development of the internal combustion engines with regards to the use of pilot fuels, ammonia slip and appearance of $N_2O$<br>• Observe and monitor the development of fuel cells technologies<br>• Study the development of the first ammonia-fuelled vessels |
| **Techno-economical** | **Observation**<br>• By 2030, considering carbon pricing, the total cost of ownership for an ammonia-fuelled vessel is expected to be 2.5 to 3 times higher for green ammonia and around 1.5 times higher for blue ammonia compared to a similar vessel running on conventional fuels<br>• The cost gap between ammonia powered vessels and conventional fossil fuelled vessels may, however, be closed by 2050, due to expected reduced ammonia production costs, lower ammonia system CAPEX and higher carbon prices for fossil fuels.<br>• Without policy measures being put in place to bridge the gap between green fuels and traditional fuels, the transition is unlikely to take place in the next decade<br>• Other cost and practical barriers have been identified, such as retraining personnel and the availability of fuels in destination ports<br><br>**Mitigations and Suggestions:**<br>• To ensure the adoption of green ammonia, regulations will need to be put in place to bridge the price gap between it and conventional fuels<br>• Market pressure also may play an equivalent or support role in the transition towards green fuels<br>• Further policy incentives may also lower the prices of green-ammonia production |
| **Rules and Regulation** | **Observation**<br>• There are regulations currently in place covering the handling of ammonia for in-land transportation, agricultural usage, and for carriage onboard a ship as a cargo<br>• There is a lack of regulation for ammonia as a fuel at multiple levels: national, regional and international<br>• Established methods are nonetheless in place for approving ship designs using ammonia and these are based on risk-based 'alternative design' principles.<br>• Some class societies have introduced rules and guidelines, but these need further harmonisation<br>• Currently, GHG regulations are being put in place in Europe via the 'Fit-for-55' initiative and these should provide a regional framework that will incentivise the adoption of these fuels<br>• In existing IMO instruments, such as the EEDI/EEXI and CII, there are no provisions to account for ammonia. Ther same can be said for the NOx Technical Code in that there are no provisions for NOx or $N_2O$ emissions resulting from the ammonia-combustion process. |

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| | • The IMO is initiating the discussion on Lifecycle Guidelines for Maritime Fuels and Market-Based Measures and, in principle, this should provide further frameworks for ammonia and alternative fuels<br><br>**Mitigations and Suggestions:**<br>• Support the development under the IMO CCC sub-committee of interim guidelines for ammonia as a marine fuel<br>• Establish the appropriate situations for the discharge of ammonia to air and water, as well as acceptable limits for those in normal and emergency scenarios<br>• Support the IGC Code review for greater harmonisation with the IGF Code and consider amendments that would enable the combustion of ammonia cargoes<br>• Encourage member states to develop national training and certification programmes under the STCW Convention and Code<br>• Develop guidance to help operators implement their obligations to the ISM Code<br>• Prepare the amendments to Annex VI and the NOx Technical Code that would enable approval and certification to the EEDI, EEXI and NOx regulations, together with developing amendments to Regulations 14 and 18 of Annex VI<br>• Consider more amendments to Annex VI and the NOx Technical Code to introduce limits for $NH_3$ and $N_2O$ from internal-combustion engines<br>• Request the IMO to task the ISO with developing a marine-fuel standard and relevant standards for couplings and bunkering<br>• Encourage IACS to develop Unified Requirements for machinery and equipment and recommendations for risk-assessment guidance and ammonia bunkering under the IGF Code to reduce industry uncertainty and support the harmonised application of requirements for ammonia as fuel<br>• Encourage SGMF, IBIA and other industry stakeholders to develop their respective guidance and best practice publications to support the application of ammonia as fuel |
| **Risk & Safety** | **Observation:**<br>• The major safety concerns related to ammonia as marine fuel are due to its toxicity and gas dispersion issues<br>• Ammonia is toxic, corrosive, flammable gas with a strong characteristic odor. The odor threshold for ammonia is between 0-50ppm.<br>• Although repeated exposure to ammonia produces no chronic effects to the human body, exposure to small concentrations of ammonia in the air can be extremely irritating to the eyes, throat and breathing pathways<br>• Wider adoption of ammonia as a marine fuel will add risks<br>• Prevention of ammonia gas release and dispersion will be an important safety precaution<br>• Due to its affinity to water, when released to the air, ammonia will react immediately with the humidity in the air, becoming heavier than air, so it may remain close to the ground and limit dispersion efforts<br>• Additional risks are expected due to bunkering activities<br>• From a risk perspective, the general arrangements for accommodation should be a primary concern<br><br>**Mitigations and Suggestions:**<br><br>• Training requirements will need to be in place for safe operation by an expanded class of mariners, and specific regulations will need to be developed<br>• Gas-detection equipment capable of monitoring the full ammonia concentration range (from low ppm/toxicity to flammability) will need to be provided and connected to automated safety-protection responses for all vessel types<br>• Regulations for personnel protection will need to be developed for all commercial vessel installations<br>• Respiratory and eye protection devices for emergency escape purposes should be provided for every person onboard (filter-type, self-contained breathing apparatus, with durations based on risk studies).<br>• Gas-tight protective clothing and clearly marked decontamination showers should be available on deck near potential exposure areas and be able to operate under all ambient conditions.<br>• Fuel slip and other gaseous ammonia emissions that might occur during normal operation and emergency scenarios will need to be kept under control. It is recommended to build a closed system, where any release of ammonia will be absorbed using water absorption or an absorber.<br>• Any contaminated water with ammonia will need to be collected and processed for safe discharge.<br>• Due to its corrosion properties, it is important during operations to have proper purge procedures and to keep oxygen away<br>• As adoption of ammonia as a fuel expand throughout the maritime industry, it is expected that additional studies will be conducted in co-operation with local governments and port authorities in view of developing safe operations procedures, in particularly for bunkering operations in port and coastal areas<br>• Methods to contain, pre-treat and discharge ammonia-contaminated water from absorption systems, firefighting and leakage etc., before being sent to shore for further treatment will need to be further developed and assessed<br>• A reassessment of engine-room safety systems from the toxicity perspective, which may include design improvements and new procedural measures to address ammonia leaks.<br>• Engine manufacturers and shipyards/designers will need to work together to design the entire ammonia system anew |

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| | • The industry's firefighting strategy will need to be further developed and unified, as various strategies currently exist, each with its own strengths and weaknesses.<br>• Depending on the type of vessel, the location of the fuel-treatment room will present its own unique risks; those will need to be addressed with actions supported by additional studies.<br>• Ventilation from the fuel-preparation room will need to be independently studied for each project and type of vessel.<br>• Due to the risks that dropped objects from cargo handling pose for each ship type, the entire handling operation will need to be independently reassessed to identify the potential threats to the fuel-preparation room and fuel tanks<br>• Additional studies on fire and explosion risks from external and internal factors will need to be conducted.<br>• Depending on the general arrangement, the fuel piping on the weather deck will need to be adequately protected against dropped objects or other physical damage; double-walled piping with protection should be considered.<br>• Placing toxicity detectors at all air inlets for the accommodation spaces is recommended<br>• Ammonia vents should be located in areas that do not bring accommodation into the toxicity zone and air locks should be considered for all entrances<br>• LSA should be located as far away as practicable from the toxicity zones and account for worst-case discharges<br>• Water curtains and water mists to dilute ammonia clouds should be considered to enable a safe escape.<br>• Ventilation studies will need to be conducted, with an eye to increasing the rate of air flow during emergencies after detection. All ventilation inlets and outlets will need to have enough separation to avoid mixing and interfering with other ventilation openings.<br>• An effective emergency study will need to be conducted and associated plans put in place with controls and adequate training<br>• Design an emergency plan in consultation with the local authorities<br>• Suitable PPE for use with ammonia gases will need to be provided onboard for each mariner.<br>• Suitable firefighting mediums to extinguish ammonia fire are water spray, alcohol-resistant foam, dry chemicals, or carbon dioxide. However, water should not be sprayed directly. |

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# Appendix I – Symbols, Abbreviations and Acronyms

| | |
|---|---|
| **ABS** | American Bureau of Shipping |
| **AER** | Annual Efficiency Ratio (IMO) |
| **AFC** | Alkaline Fuel Cell |
| **AIP** | Approval In Principle |
| **ALARP** | As Low As Reasonably Practical |
| **ANSI** | American National Standards Institute |
| **API** | American Petroleum Institute |
| **ASME** | American Society of Mechanical Engineers |
| **ASTM** | American Society for Testing of Materials |
| **ATR** | AutoThermal Reforming |
| **BC** | Black Carbon |
| **BDN** | Bunker Delivery Note |
| **BLEVE** | Boiling Liquid Expanding Vapor Explosion |
| **BMEP** | Brake Mean Effective Pressure |
| **BOG** | Boil Off Gas |
| **nBOG** | Natural Boil Off Gas |
| **CAPEX** | Capital Expenditure |
| **CARB** | California Air Resources Board |
| **CCC** | Carriage of Cargoes and Containers Sub-Committee (IMO) |
| **CCR** | California Code of Regulation |
| **CCUS** | Carbon Capture Utilization Storage |
| $C_F$ | Fuel-Conversion Factor (IMO - EEDI) |
| **CFR** | Code of Federal Regulations |
| **CHP** | Combined Heat and Power |
| **CII** | Carbon Intensity Indicator (IMO) |
| **CIMAC** | International Council on Combustion Engines |
| **CNG** | Compressed Natural Gas |
| **CO** | Carbon Monoxide |
| $CO_2$ | Carbon Dioxide |
| $CO_2e$ | Carbon Dioxide Equivalent |
| **DBB** | Double Block Bleed |
| **DCS** | Data Collection System (IMO) |
| **DF** | Dual Fuel |
| **DFDE** | Dual Fuel Diesel Electric |
| **DOT** | Department of Transport |
| **DPF** | Diesel Particulate Filter |
| **DWT** | Deadweight Tonnage |
| **ECA** | Emission Control Area |
| **EEA** | Exhaust Emission Abatement |
| **EEBD** | Emergency Escape Breathing Devices |
| **EEDI** | Energy Efficiency Design Index (IMO) |
| **EEOI** | Energy Efficiency Operational Index (IMO) |
| **EEXI** | Energy Efficiency Existing Ship Index (IMO) |
| **EEZ** | Exclusive Economic Zone |
| **EGR** | Exhaust Gas Recirculation |
| **EIAPPC** | Engine International Air Pollution Prevention Certificate (IMO) |
| **EMSA** | European Maritime Safety Agency |
| **EN** | European Standards (European Norm) |
| **EPA** | Environmental Protection Agency |
| **ESD** | Emergency Shutdown |
| **EU** | European Union |
| **FAT** | Factory Acceptance Test |
| **FGSS** | Fuel Gas Supply System |
| **FMEA** | Failure Mode and Effects Analysis |
| **FOC** | Fuel Oil Consumption |
| **FSS** | Fuel Supply System |
| **FT** | Fischer-Tropsch |
| **GA** | General Arrangement |
| **GESAMP** | Group of Experts on the Scientific Aspect of Marine Environmental Protection |
| **GFS** | Gas-Fuelled Ship |
| **GHG** | Green House Gas |
| **GISIS** | Global Integrated Ship Information System (IMO) |
| **GNSS** | Global Navigational Satellite System |
| **GVT** | Gas Valve Train |
| **GVU** | Gas Valve Unit |
| **GWP** | Global Warming Potential |
| **HAZID** | Hazard Identification Studies |
| **HAZOP** | Hazard and Operability Study |
| **HB** | Haber-Bosch |
| **HC** | Hydrocarbon |
| **HFO** | Heavy Fuel Oil |
| **HP** | High Pressure |
| **IACS** | International Association of Classification Societies |
| **IAPPC** | International Air Pollution Prevention Certificate (IMO) |
| **IBIA** | International Bunker Industry Association |
| **IC** | Internal Combustion |
| **ICE** | Internal Combustion Engine |
| **IDLH** | Immediately Dangerous to Life or Health |
| **IEA** | International Energy Agency |
| **IEC** | International Electrotechnical Commission |
| **IEEC** | International Energy Efficiency Certificate |
| **IGC** | International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IMO) |

| | |
|---|---|
| **IGF** | International Code of Safety for Ships Using Gases or other Low-Flashpoint Fuels (IMO) |
| **IMO** | International Maritime Organization |
| **IPCC** | Intergovernmental Panel on Climate Change |
| **IRENA** | International Renewable Energy Agency |
| **ISO** | International Organization for Standardization |
| **ISSC** | International Sustainability and Carbon Certification |
| **LFO** | Light Fuel Oil |
| **LFL** | Lower Flammability Limit |
| **LHV** | Lower Heating Value |
| **LL** | Loading Limit |
| **LNG** | Liquified Natural Gas |
| **LNGC** | Liquified Natural Gas Carrier |
| **LP** | Low Pressure |
| **LPG** | Liquified Petroleum Gas |
| **MAN ES** | MAN Energy Solutions |
| **MARPOL** | Marine Pollution (IMO) |
| **MCFC** | Molten Carbonate Fuel Cell |
| **MCR** | Maximum Continuous Rating |
| **MDO** | Marine Diesel Oil |
| **MFV** | Master Fuel Valve |
| **ME-GI** | MAN engine identifier – M series Electronic Gas Injection |
| **ME-LGI** | MAN engine identifier – M series Electronic Liquid Gas Injection |
| **ME-LGIA** | MAN engine identifier – M series Electronic Liquid Gas Injection Ammonia |
| **ME-LGIM** | MAN engine identifier – M series Electronic Liquid Gas Injection Methanol |
| **ME-LGIP** | MAN engine identifier – M series Electronic Liquid Gas Injection LPG |
| **MEPC** | Marine Environment Protection Committee (IMO) |
| **MGO** | Marine Gas Oil |
| **MGV** | Master Gas Valve |
| **MRV** | Monitoring Reporting Verification (EU) |
| **MSC** | Maritime Safety Committee (IMO) |
| **MSDS** | Material Safety Data Sheet |
| **Mtoe** | Million Tonnes Oil Equivalent |
| **NACE** | National Association of Corrosion Engineers |
| **NGO** | Non-Governmental Organisation |
| **$NH_3$** | Ammonia |
| **NIOSH** | National Institute for Occupational Safety and Health (U.S.) |
| **NMHC** | Non-methane Hydrocarbon |
| **NOAA** | National Oceanic and Atmospheric Administration |
| **NOx** | Nitrogen Oxides |
| **NO** | Nitrogen Oxide |
| **$N_2O$** | Nitrous Oxide |
| **$NO_2$** | Nitrogen Dioxide |
| **NRMM** | Non-Road Mobile Machinery |
| **NTC** | NOx Technical Code |
| **NTE** | Not To Exceed |
| **OECD** | Organization for Economic Co-operation and Development |
| **OEM** | Original Equipment Manufacturer |
| **OPEX** | Operating Expenditure |
| **PAH** | Polycyclic Aromatic Hydrocarbons |
| **PAS** | Publicly Available Specification |
| **PEM** | Proton Exchange Membrane |
| **PEL** | Permitted Exposure Limit |
| **PAFC** | Phosphoric Acid Fuel Cell |
| **PM** | Particulate Matter |
| **PN** | Particle Number |
| **PPM** | Parts Per Million |
| **PPR** | Pollution Prevention and Response Sub-Committee (IMO) |
| **PRV** | Pressure Relief Valve |
| **PSC** | Port State Control |
| **PTO** | Power Take Off |
| **RA** | Risk Assessment |
| **RED** | Renewable Energy Directive (EU) |
| **REL** | Recommended Exposure Limit |
| **RO** | Recognised Organization |
| **SCC** | Stress Corrosion Cracking |
| **SCR** | Selective Catalytic Reduction |
| **SDS** | Safety Data Sheet |
| **SECA** | SOx Emission Control Area |
| **SFOC** | Specific Fuel Oil Consumption |
| **SGC** | Specific Gas Consumption |
| **SGMF** | Society for Gas as a Marine Fuel |
| **SIGTTO** | Society of International Tanker and Terminal Operators |
| **SIMOPS** | Simultaneous Operations |
| **SMR** | Steam Methane Reforming |
| **SOFC** | Solid Oxide Fuel Cell |
| **SOLAS** | International Convention for the Safety of Life at Sea, 1974, as amended (IMO) |
| **SOEC** | Solid Oxide Electrolyser Cell |
| **SOFC** | Solid Oxide Fuel Cell |
| **$SO_2$** | Sulphur Dioxide |
| **$SO_3$** | Sulphur Trioxide |
| **SOx** | Sulphur Oxides |

| | |
|---|---|
| **STCW** | Standards of Training, Certification and Watchkeeping for seafarers |
| **TAN** | Total Ammonia Nitrogen |
| **TCO** | Total Cost of Ownership |
| **TCS** | Tank Connection Space |
| **TEU** | Twenty Foot Equivalent (Container) |
| **THC** | Total Hydrocarbon |
| **ToR** | Terms of Reference |
| **TRL** | Technology Readiness Level |
| **TTW** | Tank To Wake |
| **UI** | Unified Interpretation |
| **UNECE** | United Nations Economic Commission for Europe |
| **UNFCCC** | United Nations Framework Convention on Climate Change |
| **UR** | Unified Requirement |
| **USCG** | United States Coast Guard |
| **VOC** | Volatile Organic Compound |
| **WinGD** | Winterthur Gas & Diesel |
| **WTT** | Well To Tank |
| **WTW** | Well To Wake |

# Appendix II– Acute Ammonia Exposure Limits

| Reference | 10 min | 30 min | 1 hour | 4 hour | 8 hour |
|---|---|---|---|---|---|
| AEGL-1[a,b] | 30 ppm | 30 ppm | 30 ppm | 30 ppm | 30 ppm |
| AEGL-2[c] | 220 ppm | 220 ppm | 160 ppm | 110 ppm | 110 ppm |
| AEGL-3[d] | 2,700 ppm | 1,600 ppm | 1,100 ppm | 550 ppm | 390 ppm |
| ERPG-1 (AIHA)[e] | | | 25 ppm | | |
| ERPG-2 (AIHA)[e] | | | 150 ppm | | |
| ERPG-3 (AIHA)[e] | | | 750 ppm | | |
| EEGL (NRC)[f] | | | 100 ppm | | 100 ppm (24 h) |
| PEL-TWA (OSHA)[g] | | | | | 50 ppm |
| IDLH (NIOSH)[h] | | 300 ppm | | | |
| REL-TWA (NIOSH)[i] | | | | | 25 ppm |
| REL-STEL (NIOSH)[j] | 35 ppm (15 min) | | | | |
| TLV-TWA (ACGIH)[k] | | | | | 25 ppm |
| TLV-STEL (ACGIH)[l] | 35 ppm (15 min) | | | | |
| MAK (Germany)[m,n] | | | | | 20 ppm |
| OELV (Sweden)[o] (Dutch) | 50 ppm (15 min) | | | | 25 ppm |
| SMAC[p] | | | 20 ppm | | 14 ppm (24 h) |
| OSHA[q] | | | | | 50 ppm |

Under the authority of the United States Federal Advisory Committee Act (P.L. 92-463) of 1972, the National Advisory Committee for Acute Exposure Guideline Levels (AEGL) for Hazardous Substances has been established to identify, review, and interpret relevant toxicological and other scientific data and develop acute exposure guideline levels (AEGLs) for high-priority, acutely toxic chemicals. AEGLs represent threshold exposure limits for the general public.
AEGL-1 is the airborne concentration (expressed as parts per million [ppm] or milligrams per cubic metre [mg/m$^3$]) of a substance above which it is predicted that the general population, including susceptible individuals, could experience notable discomfort, irritation, or certain asymptomatic non-sensory effects. However, the effects are not disabling and are transient and reversible upon cessation of exposure.
AEGL-2 is the airborne concentration (expressed as ppm or mg/m3) of a substance above which it is predicted that the general population, including susceptible individuals, could experience irreversible or other serious, long-lasting adverse health effects or an impaired ability to escape.
AEGL-3 is the airborne concentration (expressed as ppm or mg/m3) of a substance above which it is predicted that the general population, including susceptible individuals, could experience life-threatening health effects or death.
ERPG (emergency response planning guideline, American Industrial Hygiene Association) (AIHA 2000). The ERPG-1 is the maximum airborne concentration below which it is believed nearly all individuals could be exposed for up to 1 h without experiencing other than mild, transient adverse health effects or without perceiving a clearly defined objectionable odor. The ERPG-1 for ammonia is based on a concentration associated with a mild odor perception or mild irritation. The ERPG-2 is the maximum airborne concentration below which it is believed nearly all individuals could be exposed for up to 1 hour without experiencing or developing irreversible or other serious health effects or symptoms that could impair an individual's ability to take protective action. At the ERPG-2 level, ammonia will likely have a strong odor and cause some eye and upper respiratory irritation in susceptible populations, but serious effects are unlikely. The ERPG-3 is the maximum airborne concentration below which it is believed nearly all individuals could be exposed for up to 1 h without experiencing or developing life-threatening health effects. The ERPG-3 for ammonia is based on the median lethal

concentrations of 7,340-16,600 ppm for the rat and 4,230-4,840 ppm for the mouse. This concentration may cause respiratory distress and severe eye and nasal irritation.

EEGL (Emergency exposure guidance level, National Research Council) (NRC 1987). The EEGL is the concentration of contaminants that can cause discomfort or other evidence of irritation or intoxication in or around the workplace but avoids death, other severe acute effects, and long-term or chronic injury. The EEGL for ammonia is based on effects experienced by subjects exposed to it at 140 ppm for up to 2 h.

PEL-TWA (permissible exposure limit–time-weighted average, Occupational Health and Safety Administration) (OSHA 1999) is defined analogous to the ACGIH TLV-TWA but is for exposures of no more than 10 h/day, 40 h/week.

IDLH (immediately dangerous to life and health, National Institute of Occupational Safety and Health) (NIOSH 1997) represents the maximum concentration from which one could escape within 30 min without any escape-impairing symptoms or any irreversible health effects. The IDLH for ammonia is based on acute toxicity data in humans.

REL-TWA (recommended exposure limit–time-weighted average, National Institute of Occupational Safety and Health) (NIOSH 1997) is defined analogous to the ACGIH TLV-TWA. NIOSH recommendations are not enforceable.

REL-STEL (recommended exposure limit–short-term exposure limit) (NIOSH 1997) is defined analogous to the ACGIH TLV-STEL. NIOSH recommendations are not enforceable.

TLV-TWA (American Conference of Governmental Industrial Hygienists, Threshold Limit Value-time-weighted average) (ACGIH 2001) is the time-weighted average concentration for a normal 8-h workday and a 40-h workweek, to which nearly all workers may be repeatedly exposed, day after day, without adverse effect.

TLV-STEL (Threshold Limit Value–short-term exposure limit) (ACGIH 2001) is defined as a 15-min TWA exposure, which should not be exceeded at any time during the workday even if the 8-h TWA is within the TLV-TWA. Exposures above the TLV-TWA up to the STEL should not be longer than 15 min and should not occur more than four times per day. There should be at least 60 min between successive exposures in this range.

MAK (maximale arbeitsplatzkonzentration [maximum workplace concentration]) (Deutsche Forschungsgemeinschaft [German Research Association] 2000) is defined analogous to the ACGIH TLV-TWA.

MAC (maximaal aanvaarde concentratie [maximal accepted concentration]) (SDU Uitgevers [under the auspices of the Ministry of Social Affairs and Employment], The Hague, The Netherlands 2000) is defined analogous to the ACGIH TLV-TWA.

OELV (occupational exposure limit value) (Swedish National Board of Occupational Safety and Health 1996) is the maximum acceptable average concentration (time-weighted average) of an air contaminant in respiratory air. An occupational exposure limit value is either a level limit value (one working day) or a ceiling limit value (15 min or some other reference time period).

SMACs (spacecraft maximum allowable concentrations) (NRC 2000) provide guidance on chemical exposures during normal operations of spacecraft as well as emergency situations. Short-term (1-24 h) SMACs refer to concentrations of airborne substances (such as a gas, vapour, or aerosol) that will not compromise the performance of specific tasks by astronauts during emergency conditions or cause serious or permanent toxic effects. Such exposures may cause reversible effects such as mild skin or eye irritation but are not expected to impair judgment or interfere with proper responses to emergencies. The 1- and 24-h SMACs are based on concentrations that would cause only slight mucosal irritation (Wong 1995).

United States Occupational Safety and Health Administration. This is the standard that must be met in every workplace in the United States. The OSHA Permissible Exposure Limit (PEL) for Anhydrous Ammonia is based on a full shift, 8-hour time weighted average (TWA) exposure.

# Appendix III – Ammonia Safety Data Sheet (SDS)

Safety Data Sheet - Ammonia - Air Liquid

Safety Data Sheet - Ammonia - Air Liquid

# Appendix IV - Pilots with ammonia-powered ships

| Company / project | Engine | Ship | Type of pilot | Start year | Remarks |
|---|---|---|---|---|---|
| Wärtsilä , Knutsen, Repsol, Sustainable Energy Catapult Centre | Four-stroke combustion engine | Unknown | Test | 2021 | Source: (ABS, 2020). Long-term and full-scale testing. |
| Wärtsilä, Samsung Heavy Industries [18] | Four-stroke auxiliary engines | Newbuilds | Development programme | 2023 | Agreements signed in 2021. |
| MAN, Samsung Heavy Industries [19] | Two-stroke engine | Oil tanker | Demonstration project | 2024 | |
| Equinor, Eidesvik, Prototech [20] (ShipFC project) | Fuel cell system | Offshore supply vessel | Demonstration project | 2024 | The *Viking Energy*, use of both LNG and ammonia, 2 MW fuel cell. |
| ShipFC project | Solid oxide fuel cell system | Commercial ship | Test | unknown | Source: (ABS, 2020) |

General source: [21]

[18] https://www.wartsila.com/media/news/22-09-2021-wartsila-and-shi-agree-to-collaborate-on-ammonia-fuelled-engines-for-future-newbuilds-2978445
[19] https://www.ammoniaenergy.org/articles/the-maritime-sectors-ammonia-learning-curve-moving-from-scenario-analysis-to-product-development/
[20] https://www.bbc.com/news/business-54511743
[21] https://spectrum.ieee.org/why-the-shipping-industry-is-betting-big-on-ammonia

# Appendix V - Input figures of TCO modelling and longlist of TCO for ammonia powered ships

In this appendix, input figures and a long list of indicative TCO for vessels is presented. The minimum and maximum reflect the cost range of the fuel price. The other cost aspects are assumed to be more or less constant for all time periods.

Table 34 – Fuel cost input, in USD/GJ

| NH3 production type | Year | Min | Max | NH3 production type | Year | Min | Max |
|---|---|---|---|---|---|---|---|
| VLSFO | 2021 | $6.61 | $19.80 | NH3-Morocco | 2021 | $58.00 | $58.00 |
| | 2030 | $12.00 | $27.80 | | 2030 | $40.00 | $48.00 |
| | 2050 | $19.60 | $36.60 | | 2050 | $30.00 | $40.00 |
| NH3-Australia | 2021 | $69.00 | $69.00 | NH3-Spain | 2021 | $58.00 | $58.00 |
| | 2030 | $50.00 | $58.00 | | 2030 | $41.00 | $48.00 |
| | 2050 | $38.00 | $50.00 | | 2050 | $30.00 | $41.00 |
| NH3-Chile | 2021 | $63.00 | $63.00 | NH3-Blue | 2021 | $26.00 | $26.00 |
| | 2030 | $45.00 | $53.00 | | 2030 | $26.00 | $32.00 |
| | 2050 | $34.00 | $45.00 | | 2050 | $32.00 | $39.00 |

The cost input for VLSFO cost is based on the EU ETS proposal (EC, 2021) and spot market bunker prices (Shipandbunker, 2022). The cost input for ammonia is based on based on the Fourth IMO GHG study HyChain model (IMO, 2020; ISPT, 2019).

On the following pages, the tables present indicative TCO for a number of commercially used and ammonia-powered vessels. The cost depends on the production location of the ammonia and the cost scenario. The minimums and maximums reflect the cost range of the fuel price.

Table 35 – TCO (mln EUR) estimations of ammonia powered vessels, $NH_3$ produced in Australia

| Ship type | Size category | Unit | Yearly TCO 2023 | Yearly TCO 2030 Min | Yearly TCO 2030 Max | Yearly TCO 2050 Min | Yearly TCO 2050 Max |
|---|---|---|---|---|---|---|---|
| Bulk carrier | 0-9999 | dwt | € 3.6 | € 2.1 | € 2.9 | € 1.7 | € 2.1 |
| Bulk carrier | 10000-34999 | dwt | € 8.3 | € 5.0 | € 6.7 | € 3.9 | € 5.0 |
| Bulk carrier | 35000-59999 | dwt | € 11.1 | € 6.7 | € 9.0 | € 5.3 | € 6.7 |
| Bulk carrier | 60000-99999 | dwt | € 15.2 | € 9.1 | € 12.3 | € 7.1 | € 9.1 |
| Bulk carrier | 100000-199999 | dwt | € 26.1 | € 15.6 | € 21.1 | € 12.3 | € 15.6 |
| Bulk carrier | 200000-+ | dwt | € 34.9 | € 20.8 | € 28.3 | € 16.3 | € 20.8 |
| Chemical tanker | 0-4999 | dwt | € 5.0 | € 3.0 | € 4.0 | € 2.3 | € 3.0 |
| Chemical tanker | 5000-9999 | dwt | € 7.9 | € 4.6 | € 6.4 | € 3.6 | € 4.6 |
| Chemical tanker | 10000-19999 | dwt | € 11.5 | € 6.8 | € 9.3 | € 5.3 | € 6.8 |
| Chemical tanker | 20000-39999 | dwt | € 17.9 | € 10.6 | € 14.4 | € 8.2 | € 10.6 |
| Chemical tanker | 40000-+ | dwt | € 18.1 | € 10.8 | € 14.7 | € 8.4 | € 10.8 |
| Container | 0-9999 | teu | € 9.5 | € 5.6 | € 7.6 | € 4.4 | € 5.6 |
| Container | 1000-1999 | teu | € 17.9 | € 10.7 | € 14.5 | € 8.4 | € 10.7 |
| Container | 2000-2999 | teu | € 25.8 | € 15.5 | € 20.9 | € 12.1 | € 15.5 |
| Container | 3000-4999 | teu | € 40.4 | € 24.3 | € 32.7 | € 19.0 | € 24.3 |
| Container | 5000-7999 | teu | € 60.1 | € 36.1 | € 48.9 | € 28.4 | € 36.1 |
| Container | 8000-11999 | teu | € 76.8 | € 45.9 | € 62.2 | € 36.0 | € 46.0 |
| Container | 12000-14499 | teu | € 80.2 | € 48.0 | € 65.0 | € 37.6 | € 48.0 |
| Container | 14500-19999 | teu | € 79.9 | € 47.8 | € 64.8 | € 37.4 | € 47.8 |
| Container | 20000-+ | teu | € 66.2 | € 39.7 | € 53.8 | € 31.3 | € 39.7 |
| General cargo | 0-4999 | dwt | € 1.8 | € 1.1 | € 1.5 | € 0.9 | € 1.1 |

| Ship type | Size category | Unit | Yearly TCO 2021 | Yearly TCO 2030 Min | Yearly TCO 2030 Max | Yearly TCO 2050 Min | Yearly TCO 2050 Max |
|---|---|---|---|---|---|---|---|
| General cargo | 5000-9999 | dwt | € 4.9 | € 2.9 | € 3.9 | € 2.3 | € 2.9 |
| General cargo | 10000-19999 | dwt | € 9.7 | € 5.8 | € 7.9 | € 4.6 | € 5.8 |
| General cargo | 20000-+ | dwt | € 14.2 | € 8.5 | € 11.5 | € 6.7 | € 8.5 |
| Liquefied gas tanker | 0-49999 | cbm | € 9.8 | € 5.8 | € 7.9 | € 4.5 | € 5.8 |
| Liquefied gas tanker | 50000-99999 | cbm | € 32.3 | € 19.2 | € 26.1 | € 14.9 | € 19.2 |
| Liquefied gas tanker | 100000-199999 | cbm | € 70.4 | € 41.8 | € 56.9 | € 32.6 | € 41.8 |
| Liquefied gas tanker | 200000-+ | cbm | € 101.3 | € 60.0 | € 81.9 | € 46.6 | € 60.0 |
| Oil tanker | 0-4999 | dwt | € 4.0 | € 2.4 | € 3.2 | € 1.8 | € 2.4 |
| Oil tanker | 5000-9999 | dwt | € 6.1 | € 3.6 | € 4.9 | € 2.8 | € 3.6 |
| Oil tanker | 10000-19999 | dwt | € 9.5 | € 5.6 | € 7.6 | € 4.4 | € 5.6 |
| Oil tanker | 20000-59999 | dwt | € 18.4 | € 10.9 | € 14.9 | € 8.6 | € 10.9 |
| Oil tanker | 60000-79999 | dwt | € 23.0 | € 13.7 | € 18.6 | € 10.7 | € 13.7 |
| Oil tanker | 80000-119999 | dwt | € 24.9 | € 14.8 | € 20.1 | € 11.6 | € 14.8 |
| Oil tanker | 120000-199999 | dwt | € 34.1 | € 20.3 | € 27.6 | € 15.8 | € 20.3 |
| Oil tanker | 200000-+ | dwt | € 49.6 | € 29.5 | € 40.1 | € 23.1 | € 29.5 |
| Other liquids tankers | 0-999 | dwt | € 7.0 | € 4.1 | € 5.6 | € 3.2 | € 4.1 |
| Other liquids tankers | 1000-+ | dwt | € 17.2 | € 10.1 | € 13.9 | € 7.8 | € 10.1 |
| Ferry-pax only | 0-299 | gt | € 1.8 | € 1.1 | € 1.5 | € 0.9 | € 1.1 |
| Ferry-pax only | 300-999 | gt | € 2.6 | € 1.6 | € 2.2 | € 1.3 | € 1.6 |
| Ferry-pax only | 1000-1999 | gt | € 2.4 | € 1.4 | € 1.9 | € 1.1 | € 1.4 |
| Ferry-pax only | 2000-+ | gt | € 11.3 | € 6.7 | € 9.1 | € 5.3 | € 6.7 |
| Cruise | 0-1999 | gt | € 6.7 | € 3.9 | € 5.4 | € 3.1 | € 3.9 |
| Cruise | 2000-9999 | gt | € 7.9 | € 4.6 | € 6.4 | € 3.6 | € 4.6 |
| Cruise | 10000-59999 | gt | € 33.1 | € 19.8 | € 26.8 | € 15.5 | € 19.8 |
| Cruise | 60000-99999 | gt | € 97.9 | € 59.1 | € 79.6 | € 46.6 | € 59.1 |
| Cruise | 100000-149999 | gt | € 120.2 | € 73.2 | € 98.1 | € 58.0 | € 73.2 |
| Cruise | 150000-+ | gt | € 114.1 | € 68.3 | € 92.5 | € 53.5 | € 68.3 |
| Ferry-RoPax | 0-1999 | gt | € 3.3 | € 1.9 | € 2.6 | € 1.5 | € 1.9 |
| Ferry-RoPax | 2000-4999 | gt | € 7.3 | € 4.4 | € 5.9 | € 3.4 | € 4.4 |
| Ferry-RoPax | 5000-9999 | gt | € 12.8 | € 7.7 | € 10.4 | € 6.0 | € 7.7 |
| Ferry-RoPax | 10000-19999 | gt | € 26.8 | € 16.0 | € 21.7 | € 12.6 | € 16.0 |
| Ferry-RoPax | 20000-+ | gt | € 49.3 | € 29.6 | € 40.0 | € 23.3 | € 29.6 |
| Refrigerated bulk | 0-1999 | dwt | € 4.7 | € 2.8 | € 3.9 | € 2.2 | € 2.8 |
| Refrigerated bulk | 2000-5999 | dwt | € 9.6 | € 5.7 | € 7.8 | € 4.4 | € 5.7 |
| Refrigerated bulk | 6000-9999 | dwt | € 15.0 | € 8.8 | € 12.1 | € 6.9 | € 8.8 |
| Refrigerated bulk | 10000-+ | dwt | € 32.2 | € 19.1 | € 26.0 | € 14.8 | € 19.1 |
| Ro-Ro | 0-4999 | dwt | € 5.3 | € 3.2 | € 4.3 | € 2.5 | € 3.2 |
| Ro-Ro | 5000-9999 | dwt | € 20.2 | € 12.0 | € 16.4 | € 9.4 | € 12.0 |
| Ro-Ro | 10000-14999 | dwt | € 31.8 | € 18.9 | € 25.7 | € 14.7 | € 18.9 |
| Ro-Ro | 15000-+ | dwt | € 34.4 | € 20.6 | € 27.9 | € 16.0 | € 20.6 |
| Vehicle | 0-29999 | gt | € 15.1 | € 8.9 | € 12.2 | € 7.0 | € 8.9 |
| Vehicle | 30000-49999 | gt | € 21.5 | € 12.9 | € 17.4 | € 10.1 | € 12.9 |
| Vehicle | 50000-+ | gt | € 29.4 | € 17.5 | € 23.8 | € 13.7 | € 17.5 |
| Yacht | 0-+ | gt | € 1.1 | € 0.6 | € 0.9 | € 0.5 | € 0.6 |
| Service - tug | 0-+ | gt | € 1.3 | € 0.8 | € 1.1 | € 0.6 | € 0.8 |
| Miscellaneous - fishing | 0-+ | gt | € 1.6 | € 0.9 | € 1.2 | € 0.7 | € 0.9 |
| Offshore | 0-+ | gt | € 2.8 | € 1.7 | € 2.3 | € 1.3 | € 1.7 |
| Service - other | 0-+ | gt | € 2.5 | € 1.5 | € 2.1 | € 1.2 | € 1.5 |

Table 36 - TCO (mln EUR) estimations of ammonia-powered vessels, $NH_3$ produced in Chile

| Ship type | Size category | Unit | Yearly TCO 2023 | Yearly TCO 2030 Min | Yearly TCO 2030 Max | Yearly TCO 2050 Min | Yearly TCO 2050 Max |
|---|---|---|---|---|---|---|---|
| Bulk carrier | 0-9999 | dwt | € 3.2 | € 1.9 | € 2.6 | € 1.5 | € 1.9 |
| Bulk carrier | 10000-34999 | dwt | € 7.5 | € 4.5 | € 6.1 | € 3.5 | € 4.5 |
| Bulk carrier | 35000-59999 | dwt | € 10.2 | € 6.0 | € 8.2 | € 4.7 | € 6.0 |
| Bulk carrier | 60000-99999 | dwt | € 13.9 | € 8.2 | € 11.3 | € 6.4 | € 8.2 |
| Bulk carrier | 100000-199999 | dwt | € 23.7 | € 14.1 | € 19.3 | € 10.9 | € 14.1 |
| Bulk carrier | 200000-+ | dwt | € 31.9 | € 18.8 | € 25.8 | € 14.5 | € 18.8 |
| Chemical tanker | 0-4999 | dwt | € 4.6 | € 2.6 | € 3.7 | € 2.0 | € 2.6 |
| Chemical tanker | 5000-9999 | dwt | € 7.2 | € 4.2 | € 5.8 | € 3.2 | € 4.2 |
| Chemical tanker | 10000-19999 | dwt | € 10.4 | € 6.1 | € 8.5 | € 4.7 | € 6.1 |
| Chemical tanker | 20000-39999 | dwt | € 16.3 | € 9.5 | € 13.1 | € 7.4 | € 9.5 |
| Chemical tanker | 40000-+ | dwt | € 16.5 | € 9.7 | € 13.4 | € 7.5 | € 9.7 |
| Container | 0-9999 | teu | € 8.6 | € 5.1 | € 6.9 | € 3.9 | € 5.1 |
| Container | 1000-1999 | teu | € 16.4 | € 9.7 | € 13.3 | € 7.4 | € 9.7 |
| Container | 2000-2999 | teu | € 23.6 | € 14.0 | € 19.1 | € 10.9 | € 14.0 |
| Container | 3000-4999 | teu | € 36.9 | € 21.9 | € 29.9 | € 17.0 | € 22.0 |
| Container | 5000-7999 | teu | € 54.9 | € 32.7 | € 44.6 | € 25.4 | € 32.7 |
| Container | 8000-11999 | teu | € 70.0 | € 41.5 | € 56.8 | € 32.1 | € 41.5 |
| Container | 12000-14499 | teu | € 73.1 | € 43.3 | € 59.4 | € 33.6 | € 43.3 |
| Container | 14500-19999 | teu | € 72.8 | € 43.2 | € 59.1 | € 33.4 | € 43.2 |
| Container | 20000-+ | teu | € 60.4 | € 36.0 | € 49.1 | € 28.0 | € 36.1 |
| General cargo | 0-4999 | dwt | € 1.7 | € 1.0 | € 1.3 | € 0.8 | € 1.0 |
| General cargo | 5000-9999 | dwt | € 4.5 | € 2.6 | € 3.6 | € 2.0 | € 2.6 |
| General cargo | 10000-19999 | dwt | € 8.8 | € 5.3 | € 7.2 | € 4.0 | € 5.3 |
| General cargo | 20000-+ | dwt | € 13.0 | € 7.7 | € 10.5 | € 6.0 | € 7.7 |
| Liquefied gas tanker | 0-49999 | cbm | € 8.9 | € 5.2 | € 7.2 | € 3.9 | € 5.2 |
| Liquefied gas tanker | 50000-99999 | cbm | € 29.4 | € 17.2 | € 23.8 | € 13.3 | € 17.2 |
| Liquefied gas tanker | 100000-199999 | cbm | € 64.1 | € 37.7 | € 51.9 | € 29.1 | € 37.7 |
| Liquefied gas tanker | 200000-+ | cbm | € 92.3 | € 54.0 | € 74.6 | € 41.5 | € 54.1 |
| Oil tanker | 0-4999 | dwt | € 3.7 | € 2.1 | € 3.0 | € 1.7 | € 2.1 |
| Oil tanker | 5000-9999 | dwt | € 5.5 | € 3.2 | € 4.5 | € 2.5 | € 3.2 |
| Oil tanker | 10000-19999 | dwt | € 8.6 | € 5.1 | € 7.0 | € 3.9 | € 5.1 |
| Oil tanker | 20000-59999 | dwt | € 16.8 | € 9.9 | € 13.6 | € 7.6 | € 9.9 |
| Oil tanker | 60000-79999 | dwt | € 21.0 | € 12.4 | € 17.0 | € 9.5 | € 12.4 |
| Oil tanker | 80000-119999 | dwt | € 22.7 | € 13.4 | € 18.4 | € 10.3 | € 13.4 |
| Oil tanker | 120000-199999 | dwt | € 31.1 | € 18.3 | € 25.1 | € 14.1 | € 18.3 |
| Oil tanker | 200000-+ | dwt | € 45.2 | € 26.7 | € 36.6 | € 20.6 | € 26.7 |
| Other liquids tankers | 0-999 | dwt | € 6.4 | € 3.7 | € 5.1 | € 2.8 | € 3.7 |
| Other liquids tankers | 1000-+ | dwt | € 15.7 | € 9.1 | € 12.6 | € 6.9 | € 9.1 |
| Ferry-pax only | 0-299 | gt | € 1.7 | € 1.0 | € 1.3 | € 0.8 | € 1.0 |
| Ferry-pax only | 300-999 | gt | € 2.5 | € 1.5 | € 2.0 | € 1.1 | € 1.5 |
| Ferry-pax only | 1000-1999 | gt | € 2.2 | € 1.3 | € 1.8 | € 1.1 | € 1.3 |
| Ferry-pax only | 2000-+ | gt | € 10.2 | € 6.0 | € 8.3 | € 4.6 | € 6.0 |
| Cruise | 0-1999 | gt | € 6.1 | € 3.6 | € 5.0 | € 2.7 | € 3.6 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Cruise | 2000-9999 | gt | € 7.2 | € 4.2 | € 5.8 | € 3.2 | € 4.2 |
| Cruise | 10000-59999 | gt | € 30.2 | € 17.9 | € 24.5 | € 13.9 | € 17.9 |
| Cruise | 60000-99999 | gt | € 89.4 | € 53.6 | € 72.8 | € 41.8 | € 53.6 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Cruise | 100000-149999 | gt | € 109.9 | € 66.5 | € 89.8 | € 52.2 | € 66.5 |
| Cruise | 150000-+ | gt | € 104.0 | € 61.7 | € 84.5 | € 47.8 | € 61.7 |
| Ferry-RoPax | 0-1999 | gt | € 3.0 | € 1.8 | € 2.5 | € 1.3 | € 1.8 |
| Ferry-RoPax | 2000-4999 | gt | € 6.6 | € 3.9 | € 5.3 | € 3.1 | € 3.9 |
| Ferry-RoPax | 5000-9999 | gt | € 11.6 | € 7.0 | € 9.5 | € 5.4 | € 7.0 |
| Ferry-RoPax | 10000-19999 | gt | € 24.4 | € 14.5 | € 19.9 | € 11.2 | € 14.5 |
| Ferry-RoPax | 20000-+ | gt | € 45.0 | € 26.8 | € 36.6 | € 20.8 | € 26.8 |
| Refrigerated bulk | 0-1999 | dwt | € 4.3 | € 2.5 | € 3.5 | € 1.9 | € 2.5 |
| Refrigerated bulk | 2000-5999 | dwt | € 8.8 | € 5.1 | € 7.1 | € 3.9 | € 5.1 |
| Refrigerated bulk | 6000-9999 | dwt | € 13.7 | € 8.0 | € 11.0 | € 6.1 | € 8.1 |
| Refrigerated bulk | 10000-+ | dwt | € 29.3 | € 17.2 | € 23.7 | € 13.2 | € 17.2 |
| Ro-Ro | 0-4999 | dwt | € 4.8 | € 2.8 | € 3.9 | € 2.2 | € 2.8 |
| Ro-Ro | 5000-9999 | dwt | € 18.4 | € 10.9 | € 14.9 | € 8.3 | € 10.9 |
| Ro-Ro | 10000-14999 | dwt | € 28.9 | € 17.1 | € 23.5 | € 13.1 | € 17.1 |
| Ro-Ro | 15000-+ | dwt | € 31.3 | € 18.6 | € 25.5 | € 14.4 | € 18.6 |
| Vehicle | 0-29999 | gt | € 13.7 | € 8.1 | € 11.1 | € 6.2 | € 8.1 |
| Vehicle | 30000-49999 | gt | € 19.6 | € 11.6 | € 15.9 | € 8.9 | € 11.6 |
| Vehicle | 50000-+ | gt | € 26.8 | € 15.8 | € 21.7 | € 12.2 | € 15.8 |
| Yacht | 0-+ | gt | € 1.0 | € 0.6 | € 0.8 | € 0.4 | € 0.6 |
| Service - tug | 0-+ | gt | € 1.2 | € 0.7 | € 1.0 | € 0.5 | € 0.7 |
| Miscellaneous - fishing | 0-+ | gt | € 1.4 | € 0.8 | € 1.1 | € 0.6 | € 0.8 |
| Offshore | 0-+ | gt | € 2.5 | € 1.5 | € 2.1 | € 1.2 | € 1.5 |
| Service - other | 0-+ | gt | € 2.4 | € 1.4 | € 1.9 | € 1.1 | € 1.4 |
| Cruise | 100000-149999 | gt | € 109.9 | € 66.5 | € 89.8 | € 52.2 | € 66.5 |

Table 37 - TCO (mln EUR) estimations of ammonia-powered vessels, $NH_3$ produced in Morocco

| Ship type | Size category | Unit | Yearly TCO 2023 | Yearly TCO 2030 Min | Yearly TCO 2030 Max | Yearly TCO 2050 Min | Yearly TCO 2050 Max |
|---|---|---|---|---|---|---|---|
| Bulk carrier | 0-9999 | dwt | € 3.0 | € 1.8 | € 2.5 | € 1.3 | € 1.8 |
| Bulk carrier | 10000-34999 | dwt | € 6.9 | € 4.1 | € 5.7 | € 3.2 | € 4.1 |
| Bulk carrier | 35000-59999 | dwt | € 9.4 | € 5.5 | € 7.6 | € 4.3 | € 5.5 |
| Bulk carrier | 60000-99999 | dwt | € 12.8 | € 7.5 | € 10.3 | € 5.8 | € 7.5 |
| Bulk carrier | 100000-199999 | dwt | € 21.9 | € 12.9 | € 17.8 | € 9.8 | € 12.9 |
| Bulk carrier | 200000-+ | dwt | € 29.2 | € 17.2 | € 23.8 | € 13.1 | € 17.2 |
| Chemical tanker | 0-4999 | dwt | € 4.2 | € 2.4 | € 3.4 | € 1.8 | € 2.4 |
| Chemical tanker | 5000-9999 | dwt | € 6.6 | € 3.8 | € 5.3 | € 2.9 | € 3.8 |
| Chemical tanker | 10000-19999 | dwt | € 9.6 | € 5.6 | € 7.8 | € 4.3 | € 5.6 |
| Chemical tanker | 20000-39999 | dwt | € 15.0 | € 8.7 | € 12.1 | € 6.7 | € 8.7 |
| Chemical tanker | 40000-+ | dwt | € 15.2 | € 8.8 | € 12.3 | € 6.7 | € 8.8 |
| Container | 0-999 | teu | € 7.9 | € 4.6 | € 6.4 | € 3.5 | € 4.6 |
| Container | 1000-1999 | teu | € 15.1 | € 8.8 | € 12.2 | € 6.7 | € 8.8 |
| Container | 2000-2999 | teu | € 21.6 | € 12.7 | € 17.6 | € 9.7 | € 12.7 |
| Container | 3000-4999 | teu | € 33.9 | € 20.0 | € 27.6 | € 15.3 | € 20.0 |
| Container | 5000-7999 | teu | € 50.4 | € 29.8 | € 41.1 | € 22.9 | € 29.8 |
| Container | 8000-11999 | teu | € 64.3 | € 37.8 | € 52.3 | € 28.9 | € 37.8 |
| Container | 12000-14499 | teu | € 67.2 | € 39.5 | € 54.6 | € 30.2 | € 39.5 |
| Container | 14500-19999 | teu | € 67.0 | € 39.3 | € 54.4 | € 30.1 | € 39.3 |
| Container | 20000-+ | teu | € 55.6 | € 32.8 | € 45.3 | € 25.2 | € 32.8 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| General cargo | 0-4999 | dwt | € 1.5 | € 0.9 | € 1.2 | € 0.7 | € 0.9 |
| Ship type | Size category | Unit | Yearly TCO 2023 | Yearly TCO 2030 Min | Yearly TCO 2030 Max | Yearly TCO 2050 Min | Yearly TCO 2050 Max |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| General cargo | 5000-9999 | dwt | € 4.1 | € 2.4 | € 3.3 | € 1.8 | € 2.4 |
| General cargo | 10000-19999 | dwt | € 8.1 | € 4.8 | € 6.7 | € 3.7 | € 4.8 |
| General cargo | 20000-+ | dwt | € 11.9 | € 7.0 | € 9.6 | € 5.3 | € 7.0 |
| Liquefied gas tanker | 0-49999 | cbm | € 8.1 | € 4.7 | € 6.6 | € 3.5 | € 4.7 |
| Liquefied gas tanker | 50000-99999 | cbm | € 27.1 | € 15.7 | € 21.9 | € 11.9 | € 15.7 |
| Liquefied gas tanker | 100000-199999 | cbm | € 58.8 | € 34.2 | € 47.7 | € 26.1 | € 34.2 |
| Liquefied gas tanker | 200000-+ | cbm | € 84.7 | € 49.0 | € 68.5 | € 37.2 | € 49.0 |
| Oil tanker | 0-4999 | dwt | € 3.3 | € 1.9 | € 2.7 | € 1.5 | € 1.9 |
| Oil tanker | 5000-9999 | dwt | € 5.1 | € 3.0 | € 4.1 | € 2.3 | € 3.0 |
| Oil tanker | 10000-19999 | dwt | € 7.9 | € 4.6 | € 6.4 | € 3.5 | € 4.6 |
| Oil tanker | 20000-59999 | dwt | € 15.4 | € 9.0 | € 12.5 | € 6.8 | € 9.0 |
| Oil tanker | 60000-79999 | dwt | € 19.3 | € 11.3 | € 15.7 | € 8.6 | € 11.3 |
| Oil tanker | 80000-119999 | dwt | € 20.8 | € 12.2 | € 16.9 | € 9.3 | € 12.2 |
| Oil tanker | 120000-199999 | dwt | € 28.5 | € 16.6 | € 23.1 | € 12.7 | € 16.6 |
| Oil tanker | 200000-+ | dwt | € 41.5 | € 24.3 | € 33.6 | € 18.6 | € 24.3 |
| Other liquids tankers | 0-999 | dwt | € 5.9 | € 3.3 | € 4.7 | € 2.5 | € 3.3 |
| Other liquids tankers | 1000-+ | dwt | € 14.4 | € 8.2 | € 11.6 | € 6.2 | € 8.2 |
| Ferry-pax only | 0-299 | gt | € 1.5 | € 0.9 | € 1.2 | € 0.7 | € 0.9 |
| Ferry-pax only | 300-999 | gt | € 2.2 | € 1.3 | € 1.8 | € 1.1 | € 1.3 |
| Ferry-pax only | 1000-1999 | gt | € 2.0 | € 1.2 | € 1.7 | € 1.0 | € 1.2 |
| Ferry-pax only | 2000-+ | gt | € 9.5 | € 5.5 | € 7.6 | € 4.2 | € 5.5 |
| Cruise | 0-1999 | gt | € 5.6 | € 3.2 | € 4.6 | € 2.5 | € 3.2 |
| Cruise | 2000-9999 | gt | € 6.6 | € 3.8 | € 5.3 | € 2.9 | € 3.8 |
| Cruise | 10000-59999 | gt | € 27.8 | € 16.3 | € 22.6 | € 12.5 | € 16.3 |
| Cruise | 60000-99999 | gt | € 82.2 | € 48.9 | € 67.1 | € 37.7 | € 48.9 |
| Cruise | 100000-149999 | gt | € 101.3 | € 60.8 | € 82.9 | € 47.3 | € 60.8 |
| Cruise | 150000-+ | gt | € 95.6 | € 56.2 | € 77.7 | € 43.1 | € 56.2 |
| Ferry-RoPax | 0-1999 | gt | € 2.7 | € 1.6 | € 2.2 | € 1.2 | € 1.6 |
| Ferry-RoPax | 2000-4999 | gt | € 6.0 | € 3.6 | € 4.9 | € 2.7 | € 3.6 |
| Ferry-RoPax | 5000-9999 | gt | € 10.7 | € 6.4 | € 8.8 | € 4.9 | € 6.4 |
| Ferry-RoPax | 10000-19999 | gt | € 22.5 | € 13.2 | € 18.3 | € 10.2 | € 13.2 |
| Ferry-RoPax | 20000-+ | gt | € 41.4 | € 24.4 | € 33.7 | € 18.7 | € 24.4 |
| Refrigerated bulk | 0-1999 | dwt | € 3.9 | € 2.3 | € 3.2 | € 1.8 | € 2.3 |
| Refrigerated bulk | 2000-5999 | dwt | € 8.1 | € 4.6 | € 6.5 | € 3.5 | € 4.6 |
| Refrigerated bulk | 6000-9999 | dwt | € 12.5 | € 7.3 | € 10.2 | € 5.5 | € 7.3 |
| Refrigerated bulk | 10000-+ | dwt | € 27.0 | € 15.6 | € 21.8 | € 11.8 | € 15.6 |
| Ro-Ro | 0-4999 | dwt | € 4.5 | € 2.5 | € 3.6 | € 1.9 | € 2.5 |
| Ro-Ro | 5000-9999 | dwt | € 16.9 | € 9.9 | € 13.7 | € 7.5 | € 9.9 |
| Ro-Ro | 10000-14999 | dwt | € 26.5 | € 15.5 | € 21.5 | € 11.8 | € 15.5 |
| Ro-Ro | 15000-+ | dwt | € 28.8 | € 16.9 | € 23.4 | € 12.9 | € 16.9 |
| Vehicle | 0-29999 | gt | € 12.6 | € 7.4 | € 10.2 | € 5.6 | € 7.4 |
| Vehicle | 30000-49999 | gt | € 18.0 | € 10.6 | € 14.6 | € 8.1 | € 10.6 |
| Vehicle | 50000-+ | gt | € 24.6 | € 14.4 | € 20.0 | € 10.9 | € 14.4 |
| Yacht | 0-+ | gt | € 0.9 | € 0.5 | € 0.7 | € 0.4 | € 0.5 |
| Service - tug | 0-+ | gt | € 1.1 | € 0.6 | € 0.9 | € 0.5 | € 0.6 |
| Miscellaneous - fishing | 0-+ | gt | € 1.3 | € 0.8 | € 1.1 | € 0.6 | € 0.8 |
| Offshore | 0-+ | gt | € 2.4 | € 1.4 | € 1.9 | € 1.1 | € 1.4 |
| Service - other | 0-+ | gt | € 2.2 | € 1.2 | € 1.8 | € 1.0 | € 1.2 |

Table 38 – TCO (mln EUR) estimations of ammonia-powered vessels, $NH_3$ produced in Spain

| Ship type | Size category | Unit | Yearly TCO 2023 | Yearly TCO 2030 Min | Yearly TCO 2030 Max | Yearly TCO 2050 Min | Yearly TCO 2050 Max |
|---|---|---|---|---|---|---|---|
| Bulk carrier | 0-9999 | dwt | € 3.0 | € 1.8 | € 2.5 | € 1.3 | € 1.8 |
| Bulk carrier | 10000-34999 | dwt | € 7.0 | € 4.1 | € 5.7 | € 3.2 | € 4.1 |
| Bulk carrier | 35000-59999 | dwt | € 9.5 | € 5.6 | € 7.7 | € 4.3 | € 5.5 |
| Bulk carrier | 60000-99999 | dwt | € 12.9 | € 7.5 | € 10.4 | € 5.8 | € 7.5 |
| Bulk carrier | 100000-199999 | dwt | € 22.0 | € 13.0 | € 17.9 | € 9.9 | € 12.9 |
| Bulk carrier | 200000-+ | dwt | € 29.5 | € 17.2 | € 23.9 | € 13.2 | € 17.2 |
| Chemical tanker | 0-4999 | dwt | € 4.2 | € 2.5 | € 3.4 | € 1.8 | € 2.5 |
| Chemical tanker | 5000-9999 | dwt | € 6.7 | € 3.9 | € 5.3 | € 2.9 | € 3.9 |
| Chemical tanker | 10000-19999 | dwt | € 9.6 | € 5.6 | € 7.8 | € 4.3 | € 5.6 |
| Chemical tanker | 20000-39999 | dwt | € 15.1 | € 8.8 | € 12.2 | € 6.7 | € 8.8 |
| Chemical tanker | 40000-+ | dwt | € 15.3 | € 8.9 | € 12.4 | € 6.8 | € 8.9 |
| Container | 0-999 | teu | € 8.0 | € 4.6 | € 6.5 | € 3.5 | € 4.6 |
| Container | 1000-1999 | teu | € 15.1 | € 8.8 | € 12.3 | € 6.7 | € 8.8 |
| Container | 2000-2999 | teu | € 21.8 | € 12.8 | € 17.7 | € 9.8 | € 12.8 |
| Container | 3000-4999 | teu | € 34.1 | € 20.1 | € 27.8 | € 15.4 | € 20.0 |
| Container | 5000-7999 | teu | € 50.8 | € 29.9 | € 41.3 | € 23.0 | € 29.9 |
| Container | 8000-11999 | teu | € 64.8 | € 38.0 | € 52.6 | € 29.2 | € 38.0 |
| Container | 12000-14499 | teu | € 67.7 | € 39.7 | € 55.0 | € 30.5 | € 39.7 |
| Container | 14500-19999 | teu | € 67.4 | € 39.6 | € 54.7 | € 30.3 | € 39.5 |
| Container | 20000-+ | teu | € 55.9 | € 33.0 | € 45.5 | € 25.4 | € 33.0 |
| General cargo | 0-4999 | dwt | € 1.5 | € 0.9 | € 1.2 | € 0.7 | € 0.9 |
| General cargo | 5000-9999 | dwt | € 4.1 | € 2.5 | € 3.3 | € 1.8 | € 2.4 |
| General cargo | 10000-19999 | dwt | € 8.2 | € 4.8 | € 6.7 | € 3.7 | € 4.8 |
| General cargo | 20000-+ | dwt | € 12.0 | € 7.0 | € 9.7 | € 5.4 | € 7.0 |
| Liquefied gas tanker | 0-49999 | cbm | € 8.2 | € 4.7 | € 6.7 | € 3.6 | € 4.7 |
| Liquefied gas tanker | 50000-99999 | cbm | € 27.2 | € 15.8 | € 22.0 | € 12.0 | € 15.8 |
| Liquefied gas tanker | 100000-199999 | cbm | € 59.3 | € 34.5 | € 48.0 | € 26.3 | € 34.4 |
| Liquefied gas tanker | 200000-+ | cbm | € 85.2 | € 49.4 | € 68.9 | € 37.5 | € 49.4 |
| Oil tanker | 0-4999 | dwt | € 3.4 | € 1.9 | € 2.7 | € 1.5 | € 1.9 |
| Oil tanker | 5000-9999 | dwt | € 5.2 | € 3.0 | € 4.1 | € 2.3 | € 3.0 |
| Oil tanker | 10000-19999 | dwt | € 8.0 | € 4.6 | € 6.5 | € 3.5 | € 4.6 |
| Oil tanker | 20000-59999 | dwt | € 15.5 | € 9.0 | € 12.6 | € 6.9 | € 9.0 |
| Oil tanker | 60000-79999 | dwt | € 19.4 | € 11.4 | € 15.8 | € 8.7 | € 11.3 |
| Oil tanker | 80000-119999 | dwt | € 20.9 | € 12.3 | € 17.0 | € 9.4 | € 12.3 |
| Oil tanker | 120000-199999 | dwt | € 28.7 | € 16.7 | € 23.3 | € 12.8 | € 16.7 |
| Oil tanker | 200000-+ | dwt | € 41.8 | € 24.4 | € 33.9 | € 18.6 | € 24.4 |
| Other liquids tankers | 0-999 | dwt | € 5.9 | € 3.3 | € 4.7 | € 2.5 | € 3.3 |
| Other liquids tankers | 1000-+ | dwt | € 14.4 | € 8.3 | € 11.6 | € 6.2 | € 8.3 |
| Ferry-pax only | 0-299 | gt | € 1.5 | € 0.9 | € 1.2 | € 0.7 | € 0.9 |
| Ferry-pax only | 300-999 | gt | € 2.3 | € 1.3 | € 1.8 | € 1.1 | € 1.3 |
| Ferry-pax only | 1000-1999 | gt | € 2.0 | € 1.2 | € 1.7 | € 1.0 | € 1.2 |
| Ferry-pax only | 2000-+ | gt | € 9.5 | € 5.5 | € 7.7 | € 4.2 | € 5.5 |
| Cruise | 0-1999 | gt | € 5.7 | € 3.2 | € 4.6 | € 2.5 | € 3.2 |
| Cruise | 2000-9999 | gt | € 6.7 | € 3.9 | € 5.3 | € 2.9 | € 3.9 |
| Cruise | 10000-59999 | gt | € 27.9 | € 16.5 | € 22.7 | € 12.6 | € 16.4 |
| Cruise | 60000-99999 | gt | € 82.7 | € 49.2 | € 67.5 | € 38.0 | € 49.1 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Cruise | 100000-149999 | gt | € 101.9 | € 61.2 | € 83.4 | € 47.6 | € 61.1 |
| Cruise | 150000-+ | gt | € 96.2 | € 56.6 | € 78.2 | € 43.3 | € 56.5 |
| Ferry-RoPax | 0-1999 | gt | € 2.8 | € 1.6 | € 2.3 | € 1.2 | € 1.6 |
| Ferry-RoPax | 2000-4999 | gt | € 6.1 | € 3.6 | € 5.0 | € 2.8 | € 3.6 |
| Ferry-RoPax | 5000-9999 | gt | € 10.8 | € 6.4 | € 8.8 | € 4.9 | € 6.4 |
| Ferry-RoPax | 10000-19999 | gt | € 22.6 | € 13.3 | € 18.4 | € 10.2 | € 13.3 |
| Ferry-RoPax | 20000-+ | gt | € 41.7 | € 24.6 | € 33.9 | € 18.9 | € 24.5 |
| Refrigerated bulk | 0-1999 | dwt | € 4.0 | € 2.3 | € 3.2 | € 1.8 | € 2.3 |
| Refrigerated bulk | 2000-5999 | dwt | € 8.1 | € 4.6 | € 6.6 | € 3.5 | € 4.6 |
| Refrigerated bulk | 6000-9999 | dwt | € 12.6 | € 7.4 | € 10.2 | € 5.5 | € 7.4 |
| Refrigerated bulk | 10000-+ | dwt | € 27.1 | € 15.7 | € 22.0 | € 11.9 | € 15.7 |
| Ro-Ro | 0-4999 | dwt | € 4.5 | € 2.5 | € 3.6 | € 1.9 | € 2.5 |
| Ro-Ro | 5000-9999 | dwt | € 17.0 | € 9.9 | € 13.7 | € 7.5 | € 9.9 |
| Ro-Ro | 10000-14999 | dwt | € 26.7 | € 15.6 | € 21.7 | € 11.9 | € 15.6 |
| Ro-Ro | 15000-+ | dwt | € 29.1 | € 17.0 | € 23.6 | € 13.0 | € 17.0 |
| Vehicle | 0-29999 | gt | € 12.7 | € 7.4 | € 10.2 | € 5.6 | € 7.4 |
| Vehicle | 30000-49999 | gt | € 18.2 | € 10.6 | € 14.7 | € 8.1 | € 10.6 |
| Vehicle | 50000-+ | gt | € 24.8 | € 14.4 | € 20.1 | € 11.0 | € 14.4 |
| Yacht | 0-+ | gt | € 0.9 | € 0.5 | € 0.7 | € 0.4 | € 0.5 |
| Service - tug | 0-+ | gt | € 1.1 | € 0.6 | € 0.9 | € 0.5 | € 0.6 |
| Miscellaneous - fishing | 0-+ | gt | € 1.3 | € 0.8 | € 1.1 | € 0.6 | € 0.8 |
| Offshore | 0-+ | gt | € 2.4 | € 1.4 | € 1.9 | € 1.1 | € 1.4 |
| Service - other | 0-+ | gt | € 2.2 | € 1.2 | € 1.8 | € 1.0 | € 1.2 |

Table 39 - TCO (mln EUR) estimations of ammonia-powered vessels, 'Blue' $NH_3$; produced using European natural gas

| Ship type | Size category | Unit | Yearly TCO 2023 | Yearly TCO 2030 Min | Yearly TCO 2030 Max | Yearly TCO 2050 Min | Yearly TCO 2050 Max |
|---|---|---|---|---|---|---|---|
| Bulk carrier | 0-9999 | dwt | € 1.4 | € 1.1 | € 1.1 | € 1.4 | € 1.7 |
| Bulk carrier | 10000-34999 | dwt | € 3.4 | € 2.8 | € 2.8 | € 3.3 | € 3.9 |
| Bulk carrier | 35000-59999 | dwt | € 4.6 | € 3.8 | € 3.8 | € 4.6 | € 5.3 |
| Bulk carrier | 60000-99999 | dwt | € 6.1 | € 5.1 | € 5.1 | € 6.1 | € 7.2 |
| Bulk carrier | 100000-199999 | dwt | € 10.6 | € 8.8 | € 8.8 | € 10.5 | € 12.3 |
| Bulk carrier | 200000-+ | dwt | € 14.1 | € 11.6 | € 11.6 | € 14.0 | € 16.5 |
| Chemical tanker | 0-4999 | dwt | € 1.9 | € 1.6 | € 1.6 | € 1.9 | € 2.3 |
| Chemical tanker | 5000-9999 | dwt | € 3.1 | € 2.5 | € 2.5 | € 3.1 | € 3.7 |
| Chemical tanker | 10000-19999 | dwt | € 4.6 | € 3.8 | € 3.8 | € 4.6 | € 5.3 |
| Chemical tanker | 20000-39999 | dwt | € 7.1 | € 5.9 | € 5.9 | € 7.1 | € 8.4 |
| Chemical tanker | 40000-+ | dwt | € 7.3 | € 6.0 | € 6.0 | € 7.2 | € 8.5 |
| Container | 0-999 | teu | € 3.8 | € 3.1 | € 3.1 | € 3.8 | € 4.4 |
| Container | 1000-1999 | teu | € 7.2 | € 6.0 | € 6.0 | € 7.2 | € 8.5 |
| Container | 2000-2999 | teu | € 10.5 | € 8.7 | € 8.7 | € 10.4 | € 12.3 |
| Container | 3000-4999 | teu | € 16.5 | € 13.6 | € 13.7 | € 16.4 | € 19.3 |
| Container | 5000-7999 | teu | € 24.5 | € 20.3 | € 20.3 | € 24.3 | € 28.6 |
| Container | 8000-11999 | teu | € 31.1 | € 25.6 | € 25.7 | € 30.8 | € 36.4 |
| Container | 12000-14499 | teu | € 32.4 | € 26.8 | € 26.8 | € 32.2 | € 38.0 |
| Container | 14500-19999 | teu | € 32.3 | € 26.6 | € 26.7 | € 32.0 | € 37.8 |
| Container | 20000-+ | teu | € 27.1 | € 22.4 | € 22.4 | € 26.9 | € 31.6 |

| General cargo | 0-4999 | dwt | € 0.7 | € 0.6 | € 0.6 | € 0.7 | € 0.9 |
|---|---|---|---|---|---|---|---|
| General cargo | 5000-9999 | dwt | € 1.9 | € 1.6 | € 1.6 | € 1.9 | € 2.3 |
| General cargo | 10000-19999 | dwt | € 3.9 | € 3.2 | € 3.2 | € 3.9 | € 4.6 |
| General cargo | 20000-+ | dwt | € 5.8 | € 4.7 | € 4.7 | € 5.7 | € 6.7 |
| Liquefied gas tanker | 0-49999 | cbm | € 3.9 | € 3.2 | € 3.2 | € 3.8 | € 4.6 |
| Liquefied gas tanker | 50000-99999 | cbm | € 12.8 | € 10.5 | € 10.5 | € 12.7 | € 15.1 |
| Liquefied gas tanker | 100000-199999 | cbm | € 28.0 | € 22.9 | € 23.0 | € 27.8 | € 32.9 |
| Liquefied gas tanker | 200000-+ | cbm | € 40.0 | € 32.7 | € 32.8 | € 39.7 | € 47.2 |
| Oil tanker | 0-4999 | dwt | € 1.6 | € 1.3 | € 1.3 | € 1.6 | € 1.8 |
| Oil tanker | 5000-9999 | dwt | € 2.5 | € 2.0 | € 2.0 | € 2.4 | € 2.9 |
| Oil tanker | 10000-19999 | dwt | € 3.8 | € 3.1 | € 3.1 | € 3.8 | € 4.5 |
| Oil tanker | 20000-59999 | dwt | € 7.4 | € 6.0 | € 6.0 | € 7.3 | € 8.7 |
| Oil tanker | 60000-79999 | dwt | € 9.2 | € 7.6 | € 7.6 | € 9.2 | € 10.9 |
| Oil tanker | 80000-119999 | dwt | € 10.0 | € 8.2 | € 8.2 | € 9.9 | € 11.7 |
| Oil tanker | 120000-199999 | dwt | € 13.7 | € 11.2 | € 11.2 | € 13.6 | € 16.0 |
| Oil tanker | 200000-+ | dwt | € 19.9 | € 16.4 | € 16.4 | € 19.8 | € 23.4 |
| Other liquids tankers | 0-999 | dwt | € 2.7 | € 2.2 | € 2.2 | € 2.7 | € 3.2 |
| Other liquids tankers | 1000-+ | dwt | € 6.7 | € 5.4 | € 5.4 | € 6.7 | € 7.9 |
| Ferry-pax only | 0-299 | gt | € 0.7 | € 0.6 | € 0.6 | € 0.7 | € 0.9 |
| Ferry-pax only | 300-999 | gt | € 1.1 | € 1.0 | € 1.0 | € 1.1 | € 1.3 |
| Ferry-pax only | 1000-1999 | gt | € 1.0 | € 0.8 | € 0.8 | € 1.0 | € 1.1 |
| Ferry-pax only | 2000-+ | gt | € 4.5 | € 3.7 | € 3.7 | € 4.5 | € 5.3 |
| Cruise | 0-1999 | gt | € 2.6 | € 2.1 | € 2.1 | € 2.6 | € 3.1 |
| Cruise | 2000-9999 | gt | € 3.1 | € 2.5 | € 2.5 | € 3.1 | € 3.7 |
| Cruise | 10000-59999 | gt | € 13.4 | € 11.1 | € 11.1 | € 13.3 | € 15.8 |
| Cruise | 60000-99999 | gt | € 40.4 | € 33.6 | € 33.6 | € 40.2 | € 47.1 |
| Cruise | 100000-149999 | gt | € 50.5 | € 42.2 | € 42.3 | € 50.2 | € 58.7 |
| Cruise | 150000-+ | gt | € 46.2 | € 38.2 | € 38.2 | € 45.9 | € 54.1 |
| Ferry-RoPax | 0-1999 | gt | € 1.3 | € 1.1 | € 1.1 | € 1.3 | € 1.6 |
| Ferry-RoPax | 2000-4999 | gt | € 3.0 | € 2.5 | € 2.5 | € 2.9 | € 3.4 |
| Ferry-RoPax | 5000-9999 | gt | € 5.3 | € 4.4 | € 4.4 | € 5.3 | € 6.1 |
| Ferry-RoPax | 10000-19999 | gt | € 10.9 | € 8.9 | € 8.9 | € 10.8 | € 12.7 |
| Ferry-RoPax | 20000-+ | gt | € 20.1 | € 16.6 | € 16.6 | € 20.0 | € 23.6 |
| Refrigerated bulk | 0-1999 | dwt | € 1.8 | € 1.5 | € 1.5 | € 1.8 | € 2.2 |
| Refrigerated bulk | 2000-5999 | dwt | € 3.8 | € 3.1 | € 3.1 | € 3.8 | € 4.5 |
| Refrigerated bulk | 6000-9999 | dwt | € 6.0 | € 4.9 | € 4.9 | € 5.9 | € 7.0 |
| Refrigerated bulk | 10000-+ | dwt | € 12.7 | € 10.4 | € 10.4 | € 12.6 | € 15.0 |
| Ro-Ro | 0-4999 | dwt | € 2.1 | € 1.7 | € 1.7 | € 2.1 | € 2.5 |
| Ro-Ro | 5000-9999 | dwt | € 8.1 | € 6.7 | € 6.7 | € 8.1 | € 9.5 |
| Ro-Ro | 10000-14999 | dwt | € 12.7 | € 10.4 | € 10.4 | € 12.6 | € 14.9 |
| Ro-Ro | 15000-+ | dwt | € 13.8 | € 11.4 | € 11.4 | € 13.7 | € 16.3 |
| Vehicle | 0-29999 | gt | € 6.0 | € 4.9 | € 4.9 | € 6.0 | € 7.1 |
| Vehicle | 30000-49999 | gt | € 8.7 | € 7.1 | € 7.1 | € 8.6 | € 10.2 |
| Vehicle | 50000-+ | gt | € 11.7 | € 9.6 | € 9.7 | € 11.6 | € 13.8 |
| Yacht | 0-+ | gt | € 0.4 | € 0.4 | € 0.4 | € 0.4 | € 0.5 |
| Service - tug | 0-+ | gt | € 0.5 | € 0.4 | € 0.4 | € 0.5 | € 0.6 |
| Miscellaneous - fishing | 0-+ | gt | € 0.6 | € 0.5 | € 0.5 | € 0.6 | € 0.7 |
| Offshore | 0-+ | gt | € 1.1 | € 1.0 | € 1.0 | € 1.1 | € 1.3 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Service - other | 0-+ | gt | € 1.1 | € 0.9 | € 0.9 | € 1.1 | € 1.2 |

# Appendix VI: $NH_3$ Classification per GHS

- Link: Link for GHS Classification [GHS Classification (nih.gov)]

[Globally Harmonised System] **(GHS) of Classification and Labelling of Chemicals** for ammonia:

**Signal:** Danger

**GHS Hazard Statements**

H220: Extremely flammable gas [Danger Flammable gases]
H280: Contains gas under pressure; may explode if heated [Warning Gases under pressure]
H314: Causes severe skin burns and eye damage [Danger Skin corrosion/irritation]
H318: Causes serious eye damage [Danger Serious eye damage/eye irritation]
H332: Harmful if inhaled [Warning Acute toxicity, inhalation]
H334: May cause allergy or asthma symptoms or breathing difficulties if inhaled [Danger Sensitisation, respiratory]
H370: Causes damage to organs [Danger Specific target organ toxicity, single exposure]
H372: Causes damage to organs through prolonged or repeated exposure [Danger Specific target organ
H400: Very toxic to aquatic life [Warning Hazardous to the aquatic environment, acute hazard]
H410: Very toxic to aquatic life with long lasting effects [Warning Hazardous to the aquatic environment, long-term hazard, toxicity, repeated exposure]

**Precautionary Statement Codes**

P210, P260, P261, P264, P270, P271, P280, P285, P301+P330+P331, P303+P361+P353, P304+P312, P304+P340, P304+P341, P305+P351+P338, P307+P311, P310, P312, P314, P321, P342+P311, P363, P377, P381, P403, P405, P410+P403, and P501

(The corresponding statement to each P-code can be found at the GHS Classification page XX.)

# Appendix VII – HAZID Risk Matrix

| **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 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 spill causing impacts on shoreline. | Serious environmental effects with some impairment of ecosystem function e.g., displacement of species. Relatively widespread medium-long term 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 NGOs. Significant difficulties in gaining approvals. Environmental credentials 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 hospitalisation. | 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** | **Minor** | **Moderate** | **Major** | **Critical** |
| | | | **1** | **2** | **3** | **4** | **5** |
| **Likelihood** | **Almost Certain - Occurs 1 or more times a year** | **E** | **High** | **High** | **Extreme** | **Extreme** | **Extreme** |
| | **Likely - Occurs once every 1-10 years** | **D** | **Moderate** | **High** | **High** | **Extreme** | **Extreme** |
| | **Possible - Occurs once every 10-100 years** | **C** | **Low** | **Moderate** | **High** | **Extreme** | **Extreme** |
| | **Unlikely - Occurs once every 100-1,000 years** | **B** | **Low** | **Low** | **Moderate** | **High** | **Extreme** |
| | **Rare - Occurs once every 1,000-10,000 years** | **A** | **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 | | | | |

# Appendix VIII – List of Recommendations – VLCC

| Recommendation Type | VLCC HAZID References | Recommendations (R#) |
|---|---|---|
| Training and Procedures | General Recommendations | 1 Fuel-handling manual to be developed including fuel handling, bunkering, and supply per IGF code requirement. "IGF Code 18.2.3 requires: the ship shall be provided with operational procedures including a suitably detailed fuel-handling manual, such that trained personnel can safely operate the fuel bunkering, storage and transfer systems…" |
| Safety and General Arrangement | | 2 $NH_3$ storage tank, fuel preparation room, and bunker area are to be located such that it does not interfere with any vent opening, manhole or other cargo tank connection on weather deck and complies with HAZ area requirements.<br>Avoid any vent opening under fuel tank and FPR. |
| Training and Procedures | | 3 Bunker procedures and hose-handling procedures to be developed |
| **1. General Arrangement / Bunkering** | | |
| Monitoring/Procedure | **1.1** Loss of containment | 4 Consider continuous watch of bunkering area or an equivalent method |
| Design | | 5 Drip tray sizing to be based upon worst case discharge |
| Firefighting | | 6 Consider firefighting for $NH_3$ leak and fire in bunker area |
| Pollution and Environment | | 7 Local Regulations and IMO Regulations are to be studied for discharge into the sea |
| Personnel Safety | **1.2** Makeup and breakup of bunkering hose connection on VLCC | 8 Consider PPE and eyewash/shower near bunker station/manifold<br>See recommendation # 1 (fuel handling & bunkering) |
| Training and Procedure | **1.3** Vessel drift away | 9 Bunker transfer operation & philosophy to be developed. |
| Monitoring | | 10 Consider video camera for monitoring bunkering manifold area |
| Design/Safety | **1.4** Over-pressurisation of Storage Tanks | 11 Fuel tank filling/loading limit philosophy to be developed |
| Training and Procedure | **1.5** Pressure difference b/w ammonia storage & bunker vessel | 12 Fuel handling manual to be developed including fuel handling, bunkering, and supply per IGF Code requirement |
| Personnel Safety | | 13 Consider shower and eye wash station near bunker manifold and LFSS room to decontaminate crew from ammonia exposure |
| Training and Procedure | | 14 Detailed bunkering procedure to be developed per applicable codes and standards |
| Safety/ Additional Study | | 15 Detail HAZOP to be conducted for system design |

| Recommendation Type | VLCC HAZID References | Recommendations (R#) |
|---|---|---|
| Operational procedure | **1.7** Overfill of tank above allowed reference limit | 16 Client to develop cargo liquids management |
| Design | | 17 Develop liquid level measurement and control system |
| Personnel Safety | **1.8** Over-pressurisation of bunker manifold | 18 Pressure protection of Bunker manifold and pipes are to be provided against over pressurisation |
| Safety / Additional Study | | 19 Detail HAZOP study to be conducted |
| Personnel Safety / Emergency | **1.9** Emergency on bunker vessel | 20 Emergency procedures are to be developed considering emergency on other vessels |
| **2. General Arrangement / Fuel Storage** | | |
| Design | **General for Node** | 21 Consider drip tray and catch system around all connections/dome of the fuel tanks |
| Safety / Additional Study | | 22 Dispersion analysis considering various release scenarios including fire conducted |
| Operational Procedure / design | **2.1** Overfill of tank above allowed reference limit | 23 Client to develop cargo liquid management and liquid level measurement system<br><br>See recommendation #22 (dispersion analysis) |
| Additional Study | **2.2** Fire on VLCC cargo tank | 24 Calculations to be conducted on fire-loading conditions and for the ammonia tank protection |
| Fire-fighting/Safety | | 25 Consider open-deck piping b/w two tanks and loading manifold to be covered by water spray system |
| Firefighting | | 26 Study tank protections in worst case fire scenario EG water spray, pressure release requirement |
| Additional Study | | 27 In case of fire on VLCC, possibility of BLEVE (boiling liquid expanding vapour explosion) is to be studied<br>Consider water spray capacity requirement for VLCC type fire<br>Insulation of cargo tank to be determined.<br>Consider relief valve capacity calculation<br><br>See recommendation #22 (dispersion analysis) |
| Safety / General Arrangement | **2.3** Explosion on VLCC cargo tank | 28 Consider piping and fuel tank location should be such that it is away from the opening on the cargo tanks e.g., manhole, gauging locations, piping penetrations |
| Additional Study / Fire safety | | 29 Considering the fire scenario, study the valve ratings requirements "Capacity, fire rating, etc." |

| Recommendation Type | VLCC HAZID References | Recommendations (R#) |
|---|---|---|
| Additional Study | | 30 Consider the tank isolation and blow down philosophy for the fire scenario |
| Additional Study / Fire safety | | 31 Fire and explosion study to be conducted to ensure the fuel tank is not damaged in the case of explosion under FHR<br><br>See recommendation #22 (dispersion analysis) |
| Personnel Safety / Emergency | **2.4** Collision | 32 Emergency evacuation plan to be in place. |
| Procedure | **2.5** Over-pressurisation of Storage Tanks | 33 Fuel tank management, considering fuel consumption to be developed |
| Safety / Design | | 34 Redundancy in Re-liquefaction plant<br><br>See recommendation #1 (fuel handling & bunkering) |
| Mechanical integrity / fire safety | **2.6** Tank Connection Leakage | 35 Develop specification for the stop valve. Should be high pressure integrity and maybe fire rated |
| Design / Safety | | 36 Flange connections to be specially considered |
| Procedure / Safety | | 37 In case of first connection leakage develop emergency procedure to handle leak<br><br>See recommendation #22 (dispersion analysis) |
| Mechanical Integrity | **2.7** Insulation Damage | 38 Develop plan to maintain tank, considering the spray on insulation Periodic insulation inspection procedure is to be developed |
| | **2.8** Uneven Liquid level & pressure in tanks | See recommendation #1 (fuel handling & bunkering) |
| Additional Study | **2.9** Fire in the fuel gas handling room | 39 Calculations to be conducted on fire loading conditions and for the ammonia tank protection |
| Firefighting | | 40 Consider open deck piping b/w two tanks and loading manifold to be covered by water spray system |
| Firefighting/ fire safety | | 41 Study tank protections in worst case fire scenario EG water spray, pressure release requirement |
| Firefighting | | 42 FHR to be provided with appropriate FF system |
| Safety /structural protection | **2.10** Explosion in the fuel gas handling room | 43 Fuel-handling room design to consider explosion probability and provide relief structure. Not to damage fuel tank or other equipment outside |
| Design / Additional Study | **2.11** Sloshing inside tank | 44 Dome location and sloshing study to be done to avoid liquid surge inside dome for all weather conditions and tank fill and trim conditions |
| Additional Study | **2.12** Power loss | 45 Loss of power - valve fail safe positions and backup power requirements to be studied further during the HAZOP |

| Recommendation Type | VLCC HAZID References | Recommendations (R#) |
|---|---|---|
| Additional Study | | 46 Study of power loss scenario and trapped fuel handling in the pipes |
| Safety | | 47 Any possible trapped fluid, thermal relief valve to be provided and relief valve to be vented to the vent mast<br><br>See recommendation #22 (dispersion analysis) |
| Design - Structure | **2.13** Tank Support Failure/Fatigue | 48 Tank support to be designed for fatigue loading also |
| Firefighting | **2.14** Piping leakage & Connection leakage | 49 Consider protecting single wall piping with water spray in case of liquid isolation |
| Firefighting | | 50 Consider water spray system near single wall piping to protect crew during ammonia leakage |
| Mechanical Integrity | | 51 Damage protection to be considered for single wall piping in open<br><br>See recommendation #22 (dispersion analysis) |
| Maintenance | **2.15** Deep well pump tubing pipe structural failure inside fuel tank | 52 Pump-maintenance procedures to be developed |
| Design | | 53 Consider pump seat inside fuel tank |
| Maintenance | **2.16** Deep well pump failure | 54 Pump maintenance procedures to be developed |
| **3. General Arrangement / Fuel Handling Room** | | |
| Fire safety | **3.1 Fire on VLCC** | 55 Structural fire rating to be studied and determined |
| Safety / Fire safety | | 56 Safety shutdown philosophy of FHR in case of external fire is to be developed, considering internal and external risks |
| Fire safety | | 57 System Design to consider fuel inventory in FHR and its risk in fire scenarios |
| Safety and General Arrangement | **3.2** Explosion on VLCC | 58 Consider piping and fuel tank location should be such that it is away from the opening on the cargo tanks e.g., manhole, gauging locations, piping penetrations |
| Fire Safety / Mechanical Integrity | | 59 Considering the fire scenario, study the valve ratings<br>requirements "Capacity, fire rating, etc." |
| Fire Safety | | 60 Consider the tank isolation and blow down philosophy for the fire scenario |
| Additional Study / Fire safety | | 61 Fire and explosion study to be conducted to ensure the fuel tank is not damaged in the case of explosion under FHR<br><br>See recommendation #22 (dispersion analysis) |
| Additional Study | **3.3** Fuel leak inside FHR | 62 Gas detector mapping/location study to be done |

| Recommendation Type | VLCC HAZID References | Recommendations (R#) |
|---|---|---|
| Gas Detection | **3.4** Fuel leaks inside FHR - Fire | 63 Two levels for gas detectors to be provided - alarm and shutdown (25 ppm and 300 ppm) |
| Firefighting | | 64 Consider deluge system for the entire FHR space<br>If the deluge system is provided, electrical equipment is to be appropriately IP rated |
| Ventilation | | 65 Consider emergency ventilation for FHR. (45 air changes/hour in emergency and 30 air changes/hour in normal ops)<br>In case deluge is provided, look at possibility of vacuum in the room due to absorption of ammonia in the water |
| Pollution | | 66 The dedicated bilge system should be considered for deluge water to be collected and treated before discharge |
| Personnel Safety / Procedure | | 67 FHR human entry and PPE procedures are to be developed |
| Gas detection | | 68 Two levels for gas detectors to be provided - alarm and shutdown (25 ppm and 300 ppm) |
| Personnel Safety / Firefighting | | 69 The operational philosophy of water screen is to be developed [water screen to trigger with deluge system?] |
| Gas detection | **3.5** Explosion | 70 Two levels for gas detectors to be provided - alarm and shutdown (25 ppm and 300 ppm) |
| Structural Protection / Safety | | 71 Explosion relief hatch or system to be provided to protect the structure |
| Vents / General Arrangement | **3.6** Glycol expansion tank | 72 Location of glycol expansion tank is to be determined, and venting of expansion tank to be provided |
| | **3.7** Oil/vapour leak under VLCC room | See 37 and 38 above |
| **4. General Arrangement/Fuel Handling Room/Fuel Transfer/Fuel preparation /Reliquification / Pumps / Piping** | | |
| Safety / Design | **General to node** | 73 Nitrogen purge systems are to be developed for FVT and fuel systems are to be provided with purging capabilities |
| Additional Study | | 74 When system design is developed consider performing detailed HAZOP study |
| Design | **4.1** Nitrogen in the return line from knock out drum to re-liquification plant | 75 Consider re-design of system to avoid nitrogen in re-liquification plant e.g., re-liquification plant to be separate and only to be used for fuel tank pressure/temperature management |
| Design | **4.2** Re-liquification drain not working | 76 Consider pumping back re-liquified ammonia into the fuel tank by providing a pump & expansion drum |
| Safety / Design | **4.3** Power loss or blackout | 77 Consider System design to safely evacuate fuel liquid/gas from the system in the case of power failure e.g., considering wash system |

| Recommendation Type | VLCC HAZID References | Recommendations (R#) |
|---|---|---|
| Design | **4.4** Return fuel contaminated | 78 Consider providing filter in the return line to catch the metal contaminates Consider service tank to have monitoring and draining for oil contaminate |
| Safety / Design | **4.5** Location of master shutoff valve | 79 Provide master shutoff valve per IGF and ABS requirement |
| Ventilation | **4.6** Ventilation Hazardous Area Identification | 80 Ventilation Inlets and Outlets of FHR to be identified as hazardous areas |
| **5. GA Machinery Space (ER) / Use of Fuel / Engine Maintenance Activity / Engine** | | |
| Emission / testing | **General for Node** | 81 Exhaust emissions are to be addressed by engine manufacturer after testing (NOx, $N_2O$, $NH_3$, etc.) Exhaust-related regulations are to be studied and applied e.g., 10 ppm in $NH_3$ slip |
| Additional Study / Testing | | 82 The engine is to be tested and approved by Class and FMEA is to be conducted as part of Design Approval |
| Ventilation | **5.1** Double-wall piping air circulation fail | 83 Ducting for double-wall piping ventilation to be appropriately sized to avoid high backpressure |
| Additional Study / Safety | **5.2** Inner-pipe failure in ER | 84 Considering the length of the ducting, design calculations are to address the backpressure issue for adequate design |
| Maintenance | | 85 Develop in-service maintenance inspection procedures |
| Personal Safety / Procedure | **5.3** Failure of inner and outer pipe | 86 Develop acceptable engine room entrance procedures Consider appropriate PPE |
| Design / GA | | 87 Piping arrangement is to be such that there is a low probability of damage due to dropped objects or mechanical handling |
| Safety | | 88 Consider monitoring pressure/flow differential to detect pipe failure |
| Safety / Design | **5.4** Ammonia in water-cooling system<br>**5.6** Ammonia in lubrication system | 89 Venting of $NH_3$ from auxiliary system in case of single failure to be considered and venting to be at appropriate location |
| Design / Procedure | **5.7** Fire in Engine Room | 90 Shutdown switchover philosophy to be developed, where it is recommended to have automatic switch over to fuel oil mode |
| Safety / Procedure | | 91 Consider removing $NH_3$ inventory from pipes back to FHR |
| Procedure / Maintenance | **5.10** Trapped ammonia exposure during maintenance | 92 Engine manufacturer to develop proper operational and maintenance procedures for the engine |
| Test | **5.11** Exhaust slip from engine ($CO_2$, COx, $NO_2$, $N_2O$) | 93 Engine manufacturer to provide data from engine test program |
| **6. Vent / Vent Lines / Vent Mast** | | |

| Recommendation Type | VLCC HAZID References | Recommendations (R#) |
|---|---|---|
| Vent / General Arrangement / Safety | **6.1** Ammonia release through vent mast - Ammonia in accommodations and safe spaces | 94 Current design is preliminary. VLCC cargo tank ventilation to be considered relocated to the outside of the Fuel Tank and FHR HA with appropriate distance |
| Gas Detection | | 95 PPM level for alarm and shutdown level of ammonia to be studied, considering other industries |
| Additional Study | | 96 Consider ammonia dispersion analysis from the vent mast considering normal, upset, and emergency situations |
| Additional Study | **6.1** Ammonia release through vent mast - Ammonia lifeboat area | 97 Consider ammonia dispersion analysis from the vent mast considering normal, upset, and emergency situations |
| Personnel Safety / Procedure | 6.1 Ammonia release through vent mast - Person on pilot ladder exposed to ammonia<br>People on deck exposed to ammonia | 98 Develop procedures, warning systems for the people on the deck in the case of ammonia release via vent or FHS exhaust or any other accidental scenario |
| Personnel Safety / Procedure | | 99 Develop procedures for the pilot to come aboard, considering ammonia risk |
| Personnel Safety | | 100 Consider PPE location and availability |
| Personnel Safety | | 101 Consider portable gas detectors |
| Additional Study / Personnel Safety | | 102 Emergency Escape and Rescue study to be performed |
| Additional Study | 6.1 Ammonia release through vent mast - Ammonia in VLCC Cargo Tank | 103 Consider ammonia dispersion analysis from the vent mast considering normal, upset, and emergency situations |
| Gas detection | 6.1 Ammonia release through vent mast - Ammonia in FHR | 104 Consider ammonia gas detector in FHR exhaust outlet |
| Additional study | | 105 Consider ammonia dispersion analysis from the vent mast considering normal, upset, and emergency situations to develop appropriate safety measure |
| Additional Study | 6.1 Ammonia release through vent mast - Ammonia in Cargo Pump Room | 106 Consider ammonia-dispersion analysis from the vent mast considering normal, upset, and emergency situations |
| Procedure | | 107 Develop proper operational procedures upon alarm to isolate cargo pump room |
| Procedure / Safety | **6.2** Release of ammonia through vent mast in port | 108 Proper operational procedures and warning procedures to be developed between port and vessel |
| Procedure / Safety | **6.3** Release of ammonia through vent mast during bunkering | 109 Proper operational procedures and warning procedures to be developed between bunker vessel and VLCC |
| Additional Study | | 110 Detailed HAZOP study to be conducted when system and controls are developed |
| Pollution | **6.4** System ammonia release | 111 Consider contaminated water treatment will be required and appropriate system is to be designed to comply with appropriate regulatory requirements for discharge |

| Recommendation Type | VLCC HAZID References | Recommendations (R#) |
|---|---|---|
| Pollution / Design | | 112 Catch systems are to be designed to handle the worst-case release scenario |
| Vent | | 113 Exhaust from catch system to be designed for proper ventilation (possibility of ammonia) |
| Gas detection | **6.5** Ammonia release through FHR exhaust | 114 Consider ammonia gas detector in FHR exhaust outlet |
| Additional Study | | 115 Consider ammonia dispersion analysis from the FHR vent exhaust considering normal, upset, and emergency situations |
| **7. Safety System/ Emergency** | | |
| Personnel Protection | **7.1 PPE** | 116 PPE and mask philosophy and locations are to be developed |
| Safety / Procedure | **7.2** ESD | 117 Emergency shutdown philosophy and procedures are to be developed, considering the design |
| Personnel Safety / Gas detection | **7.3** Exposure to ammonia | 118 Ammonia exposure guidelines and exposure limits are to be developed considering operation and ammonia gas alarms/shutdowns are to be designed accordingly |
| Firefighting | **7.5** Fire-fighting | 119 Appropriate fire-fighting system to be developed |
| **8. Ship's Operation / Simultaneous Operation** | | |
| Procedure and training | **8.3** Bunker area overhead lifting (bunker vessel connecting hose) | 120 Proper procedures to be developed for connection/disconnection of bunker hoses |
| Procedure | | 121 Bunker manifold should be gas free and purged during connect/disconnect |
| Design | **8.5** Gas freeing | 122 System is to be designed so ammonia can be removed safely |
| Procedure / Design | | 123 Detailed operation procedures to be developed for gas freeing operations |
| Design | **8.6** Gassing up | 124 System to be designed so nitrogen can be removed |
| Gas Detection / Safety | | 125 Consider oxygen sensor to monitor remaining air |
| Maintenance / Procedure | **8.7** Maintenance and inspection of $NH_3$ system | 126 Maintenance and inspection procedures are to be developed |
| Specification | **8.8** Fuel out of spec | 127 Fuel specification and quality monitoring is to be developed |

# Appendix IX – HAZID Register - VLCC

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking | | | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| | | | | S | L | RR | | | |
| **General Recommendations & Section Notes** | | | | | | | | 1. Fuel-handling manual to be developed including fuel handling, bunkering, and supply per IGF code requirement. "IGF Code 18.2.3 requires: the ship shall be provided with operational procedures including a suitably detailed fuel-handling manual, such that trained personnel can safely operate the fuel bunkering, storage and transfer systems…"<br>2. $NH_3$ storage tank, fuel-preparation room, and bunker area are to be located so that it does not interfere with any vent opening, manhole or other cargo tank connection on weather deck and complies with HAZ area requirements. Avoid any vent opening under fuel tank FPR. | |
| **1. General Arrangement / Bunkering** | | | | | | | | | |
| **General Recommendations & Section Notes** | | | | | | | | 3. Bunker procedures and Hose Handling to be developed | • Bunkering is not done in port and proposed to be done at anchorage<br>• During bunkering operations, ammonia not used in Engine Room(E/R)<br>• There will be no simultaneous operation of cargo transfer and bunkering<br>• Bunkering hose deployment should be done by bunker vessel<br>• Bunkering Control is located in the cargo control room and is remote controlled.<br>• Bunkering manifold monitoring by gas/liquid detection only<br>• Discharge from manifold to sea is to be reviewed in accordance to regulatory requirement<br>• Bunkering operation for ammonia will be similar to LNG and will be designed per IGF Code requirements<br>• Set pressure for relief valve on fuel tank is 4 bar |
| 1.1 Loss of containment | • Joint Failure<br>• Improper Connection<br>• Hose Failure<br>• Coupling Failure | • Fuel Spill<br>• Hazardous Atmosphere<br>• Damage to hull structure<br>Fire | • Asset<br>• Environment | 3 | C | 3C | • One gas detector<br>• Drip pan under manifold area<br>• Temperature sensor<br>• Water curtain in bunkering area side structure & underneath drip tray to protect structure against low temperature exposure | 4. Consider continuous watch of bunkering area or an equivalent method<br>5. Drip tray sizing to be based upon worst case discharge<br>6. Consider firefighting for $NH_3$ leak and fire in bunker area<br>7. Local Regulations and IMO Regulations are to be studied for discharge into the sea | QC-DC Connection |
| 1.2 Makeup and breakup of bunkering hose connection on VLCC | • Trapped gas/liquid | • Human Exposure<br>• Injury | • Human | 3 | C | 3C | • Purging of bunker header/piping | 8. Consider PPE and eyewash/shower near bunker station/manifold<br>See recommendation # 1 (Fuel handling) | |

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking S | L | RR | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| 1.3 Vessel drift away | • High Current<br>• High Wind<br>• Mooring line failure<br>• Collision | • Hose breaks away Fuel spill | • Asset<br>• Environment | 3 | B | 3B | • Ship-Shore Link<br>• ESD<br>• Dry Break Coupling<br>• One gas detector<br>• Temperature detector on drip tray | 9. Bunker transfer operation & philosophy to be developed.<br>10. Consider video camera for monitoring bunkering manifold area | |
| 1.4 Over-pressuristion of Storage Tanks | • Liquid Level Failure<br>• Pressure monitoring failure<br>• Mismanagement of BOG/vapor handling<br>• Bunker fuel is becoming warm | • Damage to equipment piping or tank<br>• Fuel release | • Asset<br>• Environment | 3 | B | 3B | • Pressure Relief Valve<br>• Pressure/Temperature monitoring/alarms<br>• Level control/alarm<br>• ESD | 11. Fuel tank filling/loading limit philosophy to be developed | See IGF Code Part A-1 /6.8 and 6.9 |
| 1.5 Pressure difference between ammonia storage & bunker vessel | • Fuel tank at higher pressure | • Reverse flow<br>• Damage to bunker vessel system<br>• $NH_3$ Release | • Asset<br>• Environment | 2 | C | 2C | • Pressure/Temperature monitoring<br>• BOG/Vapor management | 12. Fuel-handling manual to be developed including fuel handling, bunkering and supply per IGF code requirement<br>13. Consider shower and eye wash station near bunker manifold and LFSS room to decontaminate crew from ammonia exposure<br>14. Detailed bunkering procedure to be developed per applicable codes and standards<br>15. Detail HAZOP to be conducted for system design | |
| 1.6 Lightning/ Thunderstorm during bunkering | • Severe Weather<br>• poor visibility | • Fire<br>• Vessel drift away | • Asset | 1 | C | 1C | • Operational Limitations & procedures | | |
| 1.7 Overfill of tank above allowed reference limit | • level control failure<br>• Pressure/Temperature management<br>• Improper location of liquid level monitoring | • Over pressurization due over-filling<br>• Liquid discharge to vent mast or vapour lines<br>• Damage to the tank | • Asset<br>• Environment | 2 | C | 2C | • Liquid level measurement systems<br>• Liquid level alarm and ESD<br>• Cargo-handling procedure<br>• Cargo Temperature/Pressure Management<br>• Pressure Relief Valve | 16. Client to develop management system for cargo liquids<br>17. Develop liquid level measurement and control system | |
| 1.8 Over-pressurisation of bunker manifold | • Close valves | | | 3 | C | 3C | | 18. Pressure protection of Bunker manifold and pipes are to be provided against over pressurization<br>19. Detailed HAZOP study to be conducted | |
| 1.9 Emergency on bunker vessel | • Fire<br>• Power loss | • Lead to fire on VLCC | • Asset | 3 | C | 3C | • ESD<br>• Firefighting systems<br>• Operational procedures | 20. Emergency procedures are to be developed with an eye to emergencies on other vessels | |

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking S | L | RR | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| **2. General Arrangement / Fuel Storage** | | | | | | | | | |
| **General Recommendations & Section Notes** | | | | | | | | 21. Consider drip tray and catch system around all connections/dome of the fuel tanks<br>22. Dispersion analysis considering various release scenarios (including fire) conducted | • Refer to IGF: 6.7.2.2, 6.7.2.6, 6.7.2.6.2 for more guidance<br>• All fuel piping is single wall piping except in the Engine Room<br>• Fuel Valve Train (FVT) in the fuel-handling room<br>• Main shutoff valve to be considered near engine room, noting a reasonable distance between valve and engine room<br>• Valves connected to fuel tanks are Fail safe valves, which will close in the case of blackout<br>• Purge line: purge valve in FVT is fail safe open & purge the lines during blackout<br>• PRV connected to liquid line, connected to the vent mast<br>• Piping between Fuel Storage Tank and Fuel Handling room will enter the fuel handling room from the roof. |
| **2.1** Overfill of tank above allowed reference limit | • level control failure<br>• Pressure/Temperature management<br>• Improper location of liquid level monitoring | • Over-pressurisation due to warming of the cargo<br>• Liquid discharge to vent mast or vapour lines<br>• Damage to the tank<br>• High PPM level near safe spaces | • Asset<br>• Human | 4 | C | 1C | • Liquid level measurement systems<br>• Liquid level alarm and ESD<br>• Cargo handling procedure<br>• Cargo Temperature/Pressure Management<br>• Pressure Relief Valve | 23. Client to develop cargo liquid-management and liquid-level measurement systems<br>See recommendation # 22 (Dispersion analysis) | |
| **2.2** Fire on VLCC cargo tank | • Air inside cargo tank<br>• Cargo spill on the deck (cargo piping under FHR) | • Over-pressurisation of fuel tank due to heat gain<br>• BLEVE<br>• Damage to tank and piping insulation | • Asset<br>• Environment<br>• Human | 4 | D | 3D | • PRV sizing to be based on fire load case<br>• Fuel Tank Water spray system and Deck foam system for the VLCC tank protection<br>• Water fire hydrants on VLCC<br>• Manual stop of system operation upon detection of the fire<br>• PPE provided for firefighters, appropriate for ammonia leak and oil fire | 24. Calculations to be conducted on fire loading conditions and for the ammonia tank protection<br>25. Consider Open deck piping b/w two tanks and loading manifold to be covered by water spray system<br>26. Study tank protections in worst case fire scenario EG water spray, pressure release requirement<br>27. In case of fire on VLCC, possibility of BLEVE (boiling liquid expanding vapor explosion) is to be studied<br>Consider water spray capacity requirement for VLCC type fire<br>Insulation of cargo tank to be determined. Consider in relief valve capacity calculation<br>See recommendation # 22 (Dispersion analysis) | • Refer to IGF 11.5.2 for more guidance<br>• Check IGC requirement for Type-C Fuel Tank Insulation |

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking S | L | RR | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| **2.3** Explosion on VLCC cargo tank | • Air inside cargo tank<br>• Fire, leading to an explosion | • Fuel tank damage<br>• Fire<br>• Structural damage to deck structure<br>• Ammonia leakage impacting accommodations | • Asset<br>• Environment<br>• Human | 4 | C | 4C | • VLCC Cargo tank inert gas system | 28. Consider piping and fuel tank location should be such that it is away from the opening on the cargo tanks e.g., manhole, gauging locations, piping penetrations<br>29. Considering the fire scenario, study the valve ratings requirements "Capacity, fire rating, etc."<br>30. Consider the tank isolation and blow down philosophy for the fire scenario<br>31. Fire and explosion study to be conducted to ensure the fuel tank is not damaged in the case of explosion under FHR<br>See recommendation #22 (Dispersion analysis) | • Pressure relief valve is to be fire-rated. All other valves do not have this requirement<br>• IGF: 7.4.1.2 Materials having a melting point below 925°C shall not be used for piping outside the fuel tanks. |
| **2.4** Collision | • Navigation error<br>• Low visibility<br>• Weather<br>• Pilot error<br>• Loss of maneuvering functionality/steering | • Damage to the fuel tank<br>• Damage to the VLCC Structure<br>• Oil Spill<br>• Oil fire<br>• Explosion cargo tank | • Asset<br>• Environment | 3 | C | 3C | • Fuel tank locations and strength to meet IGF code requirement | 32. Emergency evacuation plan to be in place. | At this point, collision risk is identified but needs further development as risk is high due to consequence of fire/explosion from cargo |
| **2.5** Over-pressurisation of Storage Tanks | • High Temperature of fuel<br>• Re-liquification plant failure<br>• Vapour-management failure<br>• Control failure<br>• Improper bunkering operation | • Tank Damage<br>• Equipment Damage | • Asset<br>• Human | 3 | B | 3B | • Relief valve protection<br>• Re-liquification to re-liquify the boil off | 33. Fuel tank management, considering fuel consumption to be developed<br>34. Redundancy in re-liquefaction plant<br>See recommendation #1 (Fuel handling) | • Fuel usage will be from one tank at a time and redundant liquification will manage the tank pressure |
| **2.6** Tank Connection Leakage | • Improper connection<br>• Inadequate design<br>• Gasket leak<br>• Valve leak<br>• Fatigue Crack | • Ammonia leak<br>• Fuel spray | • Asset<br>• Environment<br>• Human | 3 | D | 3D | • Type C Tank complying with IGC Code<br>• All connections are in the dome<br>• Inspection and Maintenance program<br>• Water spray | 35. Develop specification for the stop valve. Should be high pressure integrity and could be fire rated<br>36. Flange connections to be specially considered<br>37. In case of first connection leakage develop emergency procedure to handle leak<br>See recommendation #22 (Dispersion analysis) | • All piping connections on fuel tanks are on the dome |
| **2.7** Insulation Damage | • Mechanical Damage<br>• Degradation of insulation due to weather effect<br>• High wind | • Heat gain<br>• Over pressurisation of the tank | • Asset | 2 | C | 2C | • Inspection and Maintenance program<br>• Protected area. Work permit required to conduct work | 38. Develop plan to maintain tank, considering the spray on insulation<br>Periodic insulation inspection procedure is to be developed | • Spray on polyurethane foam type insulation |
| **2.8** Uneven Liquid level & pressure in tanks | Both tanks are independently managed but there is not enough information to assess the hazard. At a later detailed design stage, design is to consider liquid level and pressure in the tanks. | | | | | | | | |

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking | | | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| | | | | S | L | RR | | | |
| **2.9** Fire in the fuel gas handling room | • Leak of ammonia inside fuel gas handling room<br>• Gas detection failure | • Over pressurisation of fuel tank due to heat gain from FHR fire<br>• Damage to tank and piping insulation<br>• Damage to FHR<br>• FHR over pressurisation due to pressure build-up | • Asset<br>• Environment<br>• Human | 4 | D | 3D | • FHR provided with Cat A structural Fire Protection<br>• Fuel tank PRV sizing to be based on fire load case<br>• Fuel Tank Water spray system and Deck foam system for the VLCC tank protection<br>• Water fire hydrants on VLCC<br>• Manual stop of system operation upon detection of the fire<br>• PPE provided for firefighters, appropriate for ammonia leak and oil fire<br>• 30 air change<br>• Gas detection - toxicity detection 50 ppm<br>• Electrical equipment rated for HA<br>• Fire detector | 39. Calculations to be conducted on fire-loading conditions and for the ammonia tank protection<br>40. Consider Open deck piping b/w two tanks and loading manifold to be covered by water spray system<br>41. Study tank protections in worst case fire scenario EG water spray, pressure release requirement<br>42. FHR to be provided with appropriate FF system | • Refer to IGF 11.5.2 for more guidance<br>• Check IGC requirement for Type-C Fuel Tank Insulation |
| **2.10** Explosion in the fuel gas handling room | • Leak of ammonia inside fuel gas handling room<br>• Gas detection failure | • Damage to the fuel tank<br>• Damage to FHR structure and equipment | • Asset | 4 | C | 4C | • 30 air change<br>• Gas detection - toxicity detection 50 ppm<br>• Electrical equipment rated for HA<br>• Fire detector | 43. Fuel handling room design to consider explosion probability and provide relief structure. Not to damage fuel tank or other equipment outside | • Refer to IGF 4.3.1 for more guidance |
| **2.11** Sloshing inside tank | • Motion of VLCC | • Damage to the tank<br>• liquid in the vapour line<br>• Damage of piping and pump tower damage<br>• Instrument damage<br>• Tank support damage<br>• Tank connection<br>• Damage with the deck | • Asset | 3 | C | 3C | • Slosh bulkhead<br>• Tank installation in longitudinal direction to mitigate sloshing effect<br>• Tank and Tank-supports designed to IGF criteria | 44. Dome location and sloshing study to be done to avoid liquid surge inside dome for all weather conditions and tank fill and trim conditions | |
| **2.12** Power loss | • Blackout on VLCC<br>• Power supply failure for tank connections control system | • Unable to use fuel Engine Stop or switch over<br>• Rise in fuel tank pressure due to loss of refrigeration capacity<br>• Trapped fluid equipment piping damage | • Asset | 2 | D | 2D | • Fuel tank relief valve<br>• Tank design to hold fuel without relief for 21 Day<br>• Dual fuel engine with switchover to liquid fuel<br>• Emergency power on VLCC<br>• All tank dome automatic valves are fail-safe close | 45. Loss of power valve fail safe positions and backup power requirements to be studied further during the HAZOP<br>46. Study of power loss scenario and trapped fuel handling in the pipes<br>47. Any possible trapped fluid, thermal-relief valve to be provided and relief valve to be vented to the vent mast<br><br>See recommendation #22 (Dispersion analysis) | |
| **2.13** Tank Support Failure/Fatigue | • Higher load than expected<br>• Inadequate design<br>• Marine Loads<br>• Flexibility of weather deck | • Fatigue crack<br>• connection failure b/w weather deck and supports | • Asset | 3 | C | 3C | • Tank support design to comply with IGF Code and class rules<br>• Inspection and maintenance plan | 48. Tank support to be designed for fatigue loading also | |

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking | | | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| | | | | S | L | RR | | | |
| **2.14** Piping leakage & Connection leakage | • Improper connection makeup<br>• Vibration<br>• Fatigue<br>• Inadequate design<br>• Hull Deformation<br>• Corrosion<br>• Gasket<br>• Piping expansion/contraction<br>• Piping damage | • Ammonia Leakage<br>• Human impact<br>• Weather Deck exposed to cold temperatures<br>• Fire/Explosion<br>• $NH_3$ cloud | • Asset<br>• Environment<br>• Human | 3 | D | 3D | • All piping is welded as far as possible<br>• Any connections will have a drip tray<br>• Piping will be designed to IGF Code requirements | 49. Consider protecting single-wall piping with water spray in case of liquid isolation<br>50. Consider water spray system near single wall piping to protect crew during ammonia leakage<br>51. Damage protection to be considered for single wall piping in open<br><br>See recommendation # 22 (Dispersion analysis) | • Refer **to** IGF Revision to require double wall piping<br>"9.5.3 The requirements in 9.5.4 to 9.5.6, shall apply to ships constructed on or after 1 January 2024 in lieu of the requirements in 9.5.1 and 9.5.2. |
| **2.15** Deep well pump tubing pipe structural failure inside fuel tank | • Vibration<br>• Fatigue<br>• Dynamic Motion | • Unable to pump | • Asset | 3 | B | 3B | • Redundant pump | 52. Pump maintenance procedures to be developed<br>53. Consider pump seat inside fuel tank | |
| **2.1** Deep well pump failure | • Vibration<br>• Fatigue<br>• Dynamic load | • Unable to pump | • Asset | 2 | C | 2C | • Redundant pump | 54. Pump maintenance procedures to be developed | • Pumps are deep well pumps<br>Pump change out or repair procedures to be considered during the selection of the pump |
| **3. General Arrangement / Fuel Handling Room** | | | | | | | | | |
| **General Recommendations & Section Notes** | | | | | | | | | • FHR is elevated - 3 meters distance between weather deck and FHR deck<br>• Doors located FWD and AFT<br>• Cargo Tank is installed next to FHR with 2-metre space<br>• Space below FHR can be considered semi-enclosed<br>1 metre between weather deck and fuel tank bottom<br>• Cargo piping travels below FHR<br>• Air circulation: Concerns with FHR inlet/outlet locations<br>• glycol expansion tank to be included in the design<br>• tank vent DW pipe: goes from engine room<br>Pump room vent inlet: for cargo pump<br>Glycol expansion tank in FHR<br>glycol expansion tank must have ventilation |

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking | | | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| | | | | S | L | RR | | | |
| **3.1** Fire on VLCC | • Air inside oil cargo tank<br>• Cargo spill on the deck (cargo piping under FHR) | • Heat/smoke inside FHR room<br>• Shutdown<br>• Unable to feed fuel<br>• Equipment damage<br>• Fuel release in FHR | • Asset<br>• Environment<br>• Human | 3 | D | 3D | • FHR considered Category A machinery space and will be provided with A-60 fire rated boundary<br>• VLCC Water-firefighting system<br>Water spray system per IGF code, covering externals of FHR<br>• Foam system for VLCC<br>• Manual ESD of FHR | 55. Structural fire rating to be studied and determined<br>56. Safety shutdown philosophy of FHR in case of external fire is to be developed, considering internal and external risks<br>57. System Design to consider fuel inventory in FHR and its risk in fire scenarios | • Structural fire rating to be determined based on SOLAS and IGF Code<br>• FHR is considered a category A machinery space<br>• Design is considering blowdown of the fuel tank in the case of fire emergency TBD<br>• Refer to IGF Code 11.5.2 and IGF 11.3.2 for more guidance |
| **3.2** Explosion on VLCC | • Air inside cargo tank<br>• Fire, leading to an explosion<br>• Explosion underneath FHR due to semi-enclosed nature of the space | • Damage to structure<br>• Damage to FHR structure<br>• Damage to fuel tank/structure | • Asset<br>• Environment | 4 | C | 4C | • VLCC Cargo tank inert gas system | 58. Consider piping and fuel tank location should be such that it is away from the opening on the cargo tanks e.g., manhole, gauging locations, piping penetrations<br>59. Considering the fire scenario, study the valve ratings<br>requirements "Capacity, fire rating, etc."<br>60. Consider the tank isolation and blow down philosophy for the fire scenario<br>61. Fire and explosion study to be conducted to ensure the fuel tank is not damaged in the case of explosion under FHR<br><br>See recommendation #22 (Dispersion analysis) | • Pressure relief valve is to be fire-rated. All other valves do not have such requirements<br>• IGF: 7.4.1.2 Materials having a melting point below 925°C shall not be used for piping outside the fuel tanks.<br>• Fire blast load - API RP 2FB<br>• Space between FHS room and Fuel tank is ~2 metres |
| **3.3** Fuel leak inside FHR | • Pipe connection failure<br>• Equipment leak<br>• Operation error | • ammonia in room<br>• structural damage due to cold temperatures | • Asset | 2 | D | 2D | • Two gas detectors 50 ppm alarm<br>• CCTV monitoring<br>• Ventilation 30 air change<br>• Drip trays under possible leakage area<br>• Electrical equipment rated for Hazardous area | 62. Gas-detector mapping/location study to be done | • Welded piping in FHR<br>• All piping is stainless steel in FHR<br>• IGF: 15.8.4 The detection equipment shall be located where gas may accumulate and in the ventilation outlets. Gas dispersal analysis or a physical smoke test shall be used to find the best arrangement.<br>• Refrigeration industry and fishing industry requirements and to be studied, and potentially adopted |
| **3.4** Fuel leak inside FHR - Fire | • pipe connection failure<br>• equipment leak<br>• operation error<br>• Gas detector failure | • Fire inside FHR<br>• ammonia in room<br>• structural damage due to cold temperatures | • Asset | 3 | C | 3C | • Two gas detectors<br>• Ventilation - 30 air change during normal operation<br>• Drip trays under possible leakage area<br>• Electrical equipment rated for Hazardous area<br>• Fire detector<br>• Fire-extinguishing system for the space | 63. Gas detector mapping/location study to be done<br>64. Two levels for gas detectors to be provided - alarm and shutdown (25 ppm and 300 ppm) | |

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking S | L | RR | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| | • pipe connection failure<br>• equipment leak<br>• operation error<br>• improper maintenance | • Human exposure<br>• Low temperature exposure | • Human | 4 | C | 4C | • Low toxicity ppm detection drip trays<br>• 2 means of escape<br>• Eyewash and decontamination shower near exit door, outside of the space<br>• Water screen at each door entrance<br>• Electrical equipment rated for Hazardous area | 65. Consider deluge system for the entire FHR space<br>If deluge system is provided, electrical equipment is to be appropriated IP rated<br>66. Consider emergency ventilation for FHR. (45 air change in emergency and 30 air change in normal ops)<br>In case deluge is provided, look at possibility of vacuum in the room due to absorption of ammonia in the water<br>67. Dedicated bilge system should be considered for deluge water to be collected and treated before discharge<br>68. FHR human entry and PPE procedures are to be developed<br>69. Two levels for gas detectors to be provided - alarm and shutdown (25 ppm and 300 ppm)<br>70. Operational philosophy of water screen is to be developed (i.e., water screen to trigger with deluge system) | • FHR is to be negatively pressurised per IEC 60079-502<br>• Consider gas detection in exhaust |
| **3.5** Explosion | • Gas inside the space<br>• Electrical spark | • Damage to structure<br>• Damage to FHR structure<br>• Damage to fuel tank/structure | • Asset<br>• Human | 4 | C | 4C | • Electrical equipment is appropriately IP rated<br>• Two gas detectors<br>• Ventilation - 30 air change during normal operation | 71. Two levels for gas detectors to be provided - alarm and shutdown (25 ppm and 300 ppm)<br>72. Explosion relief hatch or system to be provided to protect the structure | • Refer to IGF 4.3.1 for more guidance |
| **3.6** Glycol expansion tank | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | 73. Glycol expansion tank location is to be determined and venting of expansion tank to be provided | • Refer to IGF: 10.3.1.4 and ABS 5C-13-9/4.14: 4.14 for more guidance |
| **3.7** Oil/vapour leak under VLCC room | See scenario **3.3** Fuel leak inside FHR and **3.4** Fuel leak inside FHR - Fire | | | | | | | | |
| **4. General Arrangement/Fuel-Handling Room/Fuel Transfer/Fuel preparation /Reliquification/Pumps/Piping** | | | | | | | | | |

| ***System Level Nodes - Hazard Scenario*** | **Potential Cause** | **Consequences** | **Category** | ***Risk Ranking*** ***S*** | ***L*** | ***RR*** | **Effective Safeguard** | **Recommendations (R#)** | **Comments** |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | 74. Nitrogen purge systems are to be developed for FVT and fuel systems are to be provided with purging capabilities<br>75. When system design is developed, consider performing detailed HAZOP study | • Pressure monitoring on engine may be considered to detect leakage of piping. Piping to be properly designed (316L material)<br>• Decontaminated fuel is filtered after the heat exchanger. Additional filter on the return line to be incorporated.<br>• Small quantities of oil may leak into the return line, which will accumulate in the service tank. Consideration to this accumulation to be made<br>• Engine philosophy: ammonia and $N_2$ to knock out drum, ammonia catching system (nitrogen vented and ammonia absorbed).<br>• MARIC philosophy: ammonia and n2 to knock out drum, re-liquification will not work properly if $N_2$ is included after re-liquification of ammonia, the inventory should not be sent back to fuel tanks due to the potential for contamination. Design is to be further discussed.<br>Elevation difference of equipment in FHR to be considered during the detailed design phase |
| **4.1** Nitrogen in the return line from knock out drum to re-liquification plant | • Standard purging process using nitrogen on ESD shutdown | • Re-liquification plant inoperable | • Asset<br>• Environment | 3 | E | 3E | | 76. Consider re-design of system to avoid nitrogen in re-liquification plant e.g., re-liquification plant to be separate and only to be used for fuel tank pressure/temperature management | • Engine manufacturer is introducing the liquid-catch system and it is not yet integrated<br>Location of liquid catch system, whether inside or outside of FHR, is to be determined liquid catch system design is in development, once designed it is to be considered in the next round of HAZID |
| **4.2** Re-liquification drain not working | • Re-liquification plant elevation is lower than tank inlet | • Higher static head at JT valve<br>unable to operate plant<br>lower efficiency | • Asset<br>• Environment | 3 | E | 3E | | 77. Consider pumping back re-liquified ammonia into the fuel tank by providing a pump & expansion drum | |
| **4.3** Power loss or blackout | • Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | 78. Consider System design to safely evacuate fuel liquid/gas from the system in the case of power failure e.g., considering wash system | |
| **4.4** Return fuel contaminated | • Oil from engine<br>• Metal shavings from engine | • Equipment failure (pump) | • Asset | 3 | D | 3D | • Filter in the discharge line | 79. Consider providing filter in the return line to catch the metal contaminates<br>Consider service tank to have monitoring and draining for oil contaminate | |
| **4.5** Location of master shutoff valve | • Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | 80. Provide master shutoff valve per IGF and ABS requirement | • Refer to IGF: 9.4.9 and ABS 5C-13-9/4.2: 4.2 for more guidance |

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking | | | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| | | | | S | L | RR | | | |
| **4.6** Ventilation Hazardous Area Identification | • Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | 81. Ventilation Inlets and Outlets of FHR to be identified as hazardous areas | • Refer to IGF: 13.6.1, 13.6.2, 13.6.3, 12.5.2.4, 12.5.2.3 for more guidance |
| | | | | | | | | | |
| | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | 82. Exhaust emissions are to be addressed by engine manufacturer after testing (NOx, $N_2O$, $NH_3$, etc.) Exhaust-related regulations are to be studied and applied e.g., 10 ppm in $NH_3$ slip<br>83. Engine is to be tested and approved by Class and FMEA is to be conducted as part of Design Approval | • Refer to IGF 3.1.4 for more guidance |
| **5.1** Double-wall piping air circulation fail | • Extraction fan failure<br>• Electrical power loss<br>• Electrical fault<br>• Blackout | • unsafe atmosphere<br>• unable to extract air<br>• unable to use ammonia | • Asset | 1 | C | 1C | • redundant fans<br>• alarm and automatic shutdown of ammonia fuel supply<br>• fan connected to emergency power<br>• dual fuel engine switchover to liquid fuel | 84. Ducting for double-wall piping ventilation to be appropriately sized to avoid high backpressure | |
| **5.2** Inner pipe failure in ER | • Corrosion<br>• 800:1 expansion ratio can lead to over pressurization of annulus<br>• Overstress<br>• Vibration<br>• Unable to inspect | • ammonia in engine room<br>• outer pipe failure due to over pressurization of annulus | • Asset<br>• Human | 1 | C | 1C | • Both piping is stainless steel double wall piping will be designed for worst case release scenario<br>• double wall piping ventilation exhaust gas detector alarm & shutdown<br>• Engine room gas detector<br>• Annular space is negatively pressurised | 85. Considering the length of the ducting, design calculations are to address the backpressure issue for adequate design<br>86. Develop in-service maintenance inspection procedures | • Outer pipe will be designed to survive worst case pressure<br>• Refer to IGF: 9.8.1 for more guidance |
| **5.3** Failure of inner and outer pipe | • Outer pipe failure due to over pressurisation of annulus due to inner pipe failure<br>• Guillotine failure<br>• Dropped object<br>• Rough seas | • Ammonia in engine room<br>• Human exposure<br>• Toxic gas atmosphere | • Asset<br>• Human | 3 | C | 3C | • Machinery space gas detection shutdown system | 87. Develop acceptable engine room entrance procedures Consider appropriate PPE<br>88. Piping arrangement is to be such that there is a low probability of damage due to dropped objects or mechanical handling<br>89. Consider monitoring pressure/flow differential to detect pipe failure | • Refer to IGF 7.3.4.4, IGF 9.6.1 for more guidance |
| **5.4** Ammonia in water cooling system | • Team discussed high-level recommendations to improve design. Design will comply with IGC/IGF Code and standard practices. | | | | | | | 90. Venting of $NH_3$ from auxiliary system in case of single failure to be considered and venting to be placed at appropriate location | • Refer to IGF 3.1.4 for more guidance |
| **5.6** Ammonia in lubrication system | • Team discussed high-level recommendations to improve design. Design will comply with IGC/IGF Code and standard practices. | | | | | | | | |
| **5.7** Fire in Engine Room | • Oil in contact with high temp surface<br>• Electrical fire in engine room<br>• Oil leakage | • Smoke/fire | • Asset | 2 | C | 2C | • Fire alarm<br>• Manual shutdown<br>• Water mist/fog system<br>• Machinery space fire extinguishing system | 91. Shutdown switchover philosophy to be developed, where it is recommended to have automatic switch over to fuel oil mode<br>92. Consider removing $NH_2$ inventory from pipes back to FHR | • This node is ranked considering the risk due to ammonia system or ammonia release |

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking S | L | RR | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| **5.8** flooding and grounding in Engine Room | • No additional risks identified by the team. Design will comply with IGC/IGF Code and standard practices. | | | | | | | | |
| **5.9** Glycol system | • Ammonia carryover<br>• Cross-contamination | • Ammonia in unexpected system | • Asset | 1 | C | 1C | • Glycol system is in the FHR Glycol system has expansion tank with gas detector | | • System is designed so that GW system is in FHR |
| **5.10** Trapped ammonia exposure during maintenance | • No additional risks identified by the team. Design will comply with IGC/IGF Code and standard practices. | | | | | | | 93. Engine Manufacturer to develop proper operational and maintenance procedures for the engine | |
| **5.11** Exhaust slip from engine ($CO_2$, COx, $NO_2$, $N_2O$) | • No additional risks identified by the team. Design will comply with IGC/IGF Code and standard practices | | | | | | | 94. Engine Manufacturer to provide data from engine test programme | |
| **6. Vent / Vent Lines / Vent Mast** | | | | | | | | | |
| **6.1** Ammonia release through vent mast | • Over pressurisation of fuel tank<br>• Relief valve malfunction<br>• Reliquification system over pressurisation<br>• Re-liquefaction system failure<br>• Power Loss<br>• Fuel over fill<br>• Bunkering operation | • Ammonia in accommodations and safe spaces | • Asset<br>• Human | 4 | C | 4C | • No opening in front wall of accommodations<br>• Accommodation is positively pressurised<br>• Ammonia detector at accommodation A/C inlet and entrance - 50 ppm alarm | 95. Current design is preliminary. VLCC Cargo tank ventilation to be considered relocated to the outside of the Fuel Tank and FHR HA with appropriate distance<br>96. PPM level for Alarm and shutdown level of ammonia to be studied, considering other industries<br>97. Consider ammonia-dispersion analysis from the vent mast considering normal, upset, and emergency situations | • All Ammonia venting is via vent mast. The fuel handling system venting with be absorbed in the ammonia catching system<br>• ABS is working on ammonia alarm levels and will provide additional guidance |
| | | • Ammonia lifeboat area | • Asset<br>• Human | 4 | C | 4C | | 98. Consider ammonia dispersion analysis from the vent mast considering normal, upset, and emergency situations | |
| | | • Person on pilot ladder exposed to ammonia<br>• People on deck exposed to ammonia | • Human | 4 | C | 4C | • Gas detector<br>• Alarms<br>• Operational Procedures<br>• PPE | 99. Develop procedures, warning systems for the people on the deck in the case of ammonia release via vent or FHS exhaust or any other accidental scenario<br>100. Develop procedures for the pilot to come aboard, considering ammonia risk<br>101. Consider PPE location and availability<br>102. Consider portable gas detectors<br>103. Emergency Escape and Rescue study to be performed | • Pilot transfer may have additional people on deck. During cargo transfer there may be a deck watch. Maintenance may require people on the deck Escape route drawings are to be developed |
| | | • Ammonia in VLCC Cargo Tank | • Asset | 3 | C | 3C | • Cargo tank vents are as far away from vent mast as reasonably possible | 104. Consider ammonia dispersion analysis from the vent mast considering normal, upset, and emergency situations | • Ammonia compatibility with oil to be studied If the ammonia is migrating into any additional area, ammonia compatibility with material is to be studied |
| | | • Ammonia in FHR | • Asset | 2 | D | 2D | • Two gas detectors in FHR Appropriate procedures for gas detection | 105. Consider ammonia gas detector in FHR exhaust outlet<br>106. Consider ammonia dispersion analysis from the vent mast considering normal, upset, and emergency situations to develop appropriate safety measures | |

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking S | L | RR | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| | • Cargo pump room is negatively pressurized<br>• Over pressurisation of fuel tank<br>• Relief valve malfunction<br>• Reliquification system over pressurisation<br>• Re-liquefaction system failure<br>• Power Loss<br>• Fuel over fill | • Ammonia in Cargo Pump Room | • Asset<br>• Human | 4 | C | 4C | • Cargo pump room inlet has gas detector - 50 ppm alarm<br>• Cargo pump room inlet and vents as far away from vent mast as reasonably possible | 107. Consider ammonia-dispersion analysis from the vent mast considering normal, upset, and emergency situations<br>108. Develop proper operational procedures upon alarm to isolate cargo pump room | • Refer to IGF:15.8.4 for more guidance<br>• There may be a possibility of personnel in cargo pump room, therefore the alarm will alert & the person will take action. |
| **6.2** Release of ammonia through vent mast in port | • Ammonia release | • Impact on port operations | • Asset<br>• Human | 3 | C | 3C | • Refrigeration system will keep fuel tank pressure under control, minimising the possibility of ammonia gas release | 109. Proper operational procedures and warning procedures to be developed between port and vessel | • When vessel is in port, fuel-processing system is shut down. Refrigeration systems may be functional to manage fuel tank pressure |
| **6.3** Release of ammonia through vent mast during bunkering | • Over pressurization of fuel tank | • Impact on bunkering operations | • Asset<br>• Human | 2 | D | 2D | • Gas detector | 110. Proper operational procedures and warning procedures to be developed between bunker vessel and VLCC<br>111. Detailed HAZOP study to be conducted when system and controls are developed | |
| **6.4** System ammonia release | • System over pressurisation<br>• Improper operation<br>• Valve malfunction<br>• Engine shutdown<br>• Engine switchover | • Ammonia release through PRV | • Asset | 1 | D | 1D | • Ammonia diverted to catch system and absorbed in water | 112. Consider contaminated water treatment will be required and appropriate system is to be designed to comply with appropriate regulatory requirements for discharge | |
| | | • Ammonia release through catch system | • Asset<br>• Environment | 3 | C | 3C | | 113. Catch systems are to be designed to handle the worst-case release scenario<br>114. Exhaust from catch system to be designed for proper ventilation (possibility of ammonia) | • Catch system is still in developmental stage. HAZID to be updated when system is designed |
| **6.5** Ammonia release through FHR exhaust | • Ammonia released inside FHS room e.g., connection failure, pipe failure, valve leak | • Ammonia venting through FHR exhaust<br>• Higher PPM at safe area e.g., accommodation, pump room etc.<br>• Fire<br>• Explosion | • Asset<br>• Human | 3 | D | 3D | • Gas detector insider FHR<br>• Deluge system<br>• Fire detector in FHR<br>• 30 air change ventilation | 115. Consider ammonia gas detector in FHR exhaust outlet<br>116. Consider ammonia dispersion analysis from the FHR vent exhaust considering normal, upset, and emergency situations | • See previous node for FHS where fire explosion study is to be conducted & release hatch provided |
| **6.6** Vent Mast ignited | • Lightning and thunderstorm release of ammonia through vent system | • Vent mast ignited | • Asset | 1 | D | 1D | • $CO_2$ fire-extinguishing system provided | | • Check IGC for vent mast flame arrest |
| **6.7** Rough weather | • Heavy rain | • Water in vent mast water can migrate into other systems | • Asset | 1 | D | 1D | • Vent drain provided | | |
| **7. Safety System/ Emergency** | | | | | | | | | |
| **7.1** PPE | Team discussed high-level recommendations to improve design. | | | | | | | 117. PPE and mask philosophy and locations are to be developed | |
| **7.2** ESD | | | | | | | | 118. Emergency shutdown philosophy and procedures are to be developed, considering the design | |

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking | | | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| | | | | S | L | RR | | | |
| **7.3** Exposure to ammonia | Not discussed further. | | | | | | | 119. Ammonia exposure guidelines and exposure limits are to be developed considering operation and ammonia gas alarms/shutdowns are to be designed accordingly | |
| **7.4** Structural Fire Protection | | | | | | | | | • For the FHS room, see the previous node. Follow SOLAS requirement |
| **7.5** Fire-Fighting | | | | | | | | 120. Appropriate Firefighting system to be developed | |
| **8. Ship's Operation / Simultaneous Operation** | | | | | | | | | |
| **8.1** Simultaneous Operation | • No additional risks identified by the team. No simultaneous operations e.g., cargo fuel loading/unloading and bunkering allowed | | | | | | | | |
| **8.2** Overhead lifting over fuel tank and FHR and piping | • No additional risks identified by the team. No overhead lifting allowed. | | | | | | | | |
| **8.3** Bunker area overhead lifting (bunker vessel connecting hose) | • Dropped object damage manifold | • Ammonia release<br>• Unable to transfer bunker<br>• Human exposure to ammonia | • Asset<br>• Human | 3 | C | 3C | | 121. Proper procedures to be developed for connection/disconnection of bunker hoses<br>122. Bunker manifold should be gas free and purged during connect/disconnect | |
| **8.4** Rough weather | • High wind<br>• $NH_3$ release can migrate into accommodations and other areas | • Previous node | | | | | | | |
| | • High waves | • Previous node | | | | | | | |
| **8.5** Gas freeing | • Unable to gas free remaining air - explosion hazard remaining moisture - material issue | • Discharge of ammonia into atmosphere via vent mast during gas freeing<br>• Human exposure<br>• Fire<br>• Explosion | • Asset<br>• Environment<br>• Human | 2 | C | 2C | • Gas detector installed in vent mast | 123. System is to be designed so ammonia can be removed safely<br>124. Detailed operation procedures to be developed for gas freeing operations | • Discharge of ammonia into the atmosphere during the gas freeing is a special consideration. Check any potential regulation that may prohibit this practice. |
| **8.6** Gassing up | • Unable to remove air and nitrogen Potential for air or $N_2$ in system - explosion hazard, contamination of fuel<br>• Remaining moisture - material issue | • Discharge of ammonia into atmosphere<br>• Fire<br>• Explosion | • Asset<br>• Environment | 2 | C | 2C | • Gas detector installed in vent mast | 125. System is to be designed so nitrogen can be removed<br>126. Consider oxygen sensor to monitor remaining air | |
| **8.7** Maintenance and inspection of $NH_3$ system | | | | | | | | 127. Maintenance and inspection procedures are to be developed | |
| **8.8** Fuel out of spec | • Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | 128. Fuel specification and quality monitoring is to be developed | |

# Appendix X – List of Recommendations BC Proposal I

| Recommendation Type | BC 1 HAZID References | Recommendation |
|---|---|---|
| **1. General Arrangement/Bunkering** | | |
| Hazardous area | **General** | **1.** Considering cargo carriage (coal), Hazardous Area if any with regards to the cargo is to be considered |
| Procedure | **2.9** Over-pressurisation of Storage Tanks<br><br>**2.10** Overfill of tank above allowed reference limit | **2.** Fuel handling manual to be developed including fuel handling, bunkering, and supply per IGF code requirement. "IGF Code 18.2.3 requires: the ship shall be provided with operational procedures including a suitably detailed fuel-handling manual, such that trained personnel can safely operate the fuel bunkering, storage and transfer systems…" |
| Procedure / additional study | | **3.** Once the bunkering philosophy is developed, bunkering operations to be further studied |
| Design / procedure | | **4.** Develop purging monitoring requirement to confirm that purging process removed all ammonia |
| Additional Study | **1.1 Loss of containment - Bunker Manifold** | **5.** Cause and effects of ESD system is to be further evaluated considering ammonia and its toxicity |
| Emission / Additional Study | | **6.** Drip tray sizing and philosophy of collected fluid handling to be studied |
| Gas detection / Additional study | | **7.** Further analysis of number and placement of gas detectors around bunker stations to be conducted |
| Pollution | | **8.** Local Regulations and IMO Regulations are to be studied for discharge into the sea |
| Personnel Safety | | **9.** Bunker station locations and crew presence are to be studied considering potential ammonia release |
| Personnel Safety | | **10.** Crew near bunker manifold are to be provided with appropriate PPE and portable gas detectors |
| Firefighting | | **11.** consider providing water spray system for local control station |
| Safety | **1.2 Bunker Manifold over-pressurisation during bunkering operation** | **12.** If there is a possibility of Trapped fluid due to various operational condition, proper relief arrangement is to be provided (i.e., QC-DC operations between pop-it and ESD valve, ESD, loss of power etc.) |
| Design / Safety | **1.3 Trapped fluid in bunker piping** | **13.** Manifold is to be designed for the maximum vapour pressure buildup at 45 $^{0}$C for Trapped fluid or for emergency shutdown with the possibility of trapped fluid |

| Recommendation Type | BC 1 HAZID References | Recommendation |
|---|---|---|
| Safety | | **14.** For trapped fluid, thermal expansion is to be considered and thermal relief valve to be provided |
| Safety | | **15.** For various ESD scenarios, study to be conducted on the scenarios and the potential for trapped fluid in the different scenarios |
| Vent / safety | | **16.** Any thermal relief provided to be vented properly in to vent mast |
| Safety / Design | **1.5 Unable to get ammonia back to tank during purging** | **17.** How to purge and handle inventory in bunker piping during ESD and normal operation is to be considered and proper design is to be developed. (The issue is a difference in gravity and volume of inventory in the piping) |
| Inspection | **1.6 Loss of containment - Piping between bunker station and fuel tank** | **18.** consider including visual inspection of the bunker piping from manifold to tank before bunkering when developing the operations manual |
| Additional analysis | | **19.** consider the need for piping stress analysis to address pipe failure due to overstress, fatigue, etc. and justification to be provided. |
| Maintenance / inspection | | **20.** inspection and maintenance plan for this piping is to be developed considering fatigue fracture failure |
| Additional study / Design | | **21.** Evaluate adequacy of proposed pipe protection considering risk of ammonia and dropped object damage |
| Procedure | **1.7 Make & Break of bunkering hose during normal operations** | **22.** Proper connect/disconnect procedures are to be developed to prevent trapped fluid |
| Personnel safety | **1.8 Emergency Breakaway** | **23.** Investigate how much ammonia can be released during emergency disconnect and if this will affect any crew in the bunkering control station |
| design | | **24.** Dry breakaway coupling is to be provided |
| Fire safety | **1.9** Emergency on the Bulk Carrier | **25.** piping insulation has to consider the fire rating |
| Fire safety / additional study | | **26.** fire scenario on the bulk carrier during bunkering is to be investigated |
| Personnel safety / emergency | **1.10 Emergency on bunker supply ship** | **27.** Emergency procedures are to be developed considering an emergency on the bunker vessel |
| Personnel safety | **1.11 Vessel Drifts Away** | **28.** Investigate how much ammonia can be released during emergency disconnect and if this will affect any crew in the bunkering control station |
| Design / safety | | **29.** Dry breakaway coupling is to be provided |
| Safety / venting | **1.13 Over-pressurisation of tank during bunkering** | **30.** Investigate Type-A tank secondary barrier ventilation which is discharge into the vent mast with all other |

| Recommendation Type | BC 1 HAZID References | Recommendation |
|---|---|---|
| | | venting and there is potential for high backpressure and reverse flow in to secondary barrier |
| Additional study | **1.14 Freeboard height difference between bunkering vessel and Bulk Carrier** | **31.** Conduct compatibility study between the two vessels and evaluate need for crane on bulk carrier |
| **2. General Arrangement / Fuel Storage** | | |
| Personnel safety / Additional Analysis / safety | | **32.** Dispersion analysis for $NH_3$ release considering normal, upset, emergency and fire scenario to be performed to estimate $NH_3$ exposure to various area. |
| Personnel safety / emergency | **2.1** Fire in Accommodations, Service, Control Stations | **33.** Emergency procedures are to be developed taking into consideration the fire scenarios |
| Safety | | **34.** Evaluate ingress protection ratings of the equipment |
| Additional study / personnel safety | | **35.** Dispersion analysis for $NH_3$ release considering normal, upset, emergency and fire scenario to be performed to estimate $NH_3$ exposure to various area. |
| Safety / fore protection | **2.2** Fire in Cat-A Machinery Space | **36.** $NH_3$ Tanks are to be segregated with cofferdam and cofferdam should be measured from secondary barrier (900 mm cofferdam, boundary of cofferdam to machinery space to be A-60) |
| Design / Safety | | **37.** Secondary barrier should be gas tight |
| Safety | | **38.** Inter-barrier space between the primary and secondary barriers to be inerted and maintained at positive pressure |
| Fire Safety | | **39.** All tank boundaries exposed to CAT-A machinery space are to be provided with A-60 boundary |
| Ventilation / safety | **2.3** Fire in FSS Room | **40.** Reconsider shutdown of ventilation philosophy for FFSS room (due to 800 to 1 expansion ration of $LNH_3$ can create over pressure)<br>If water spray system is activated in NHS room full of $NH_3$ gas it can create Vacuum due to solubility of $NH_3$ in water, pressure vacuum protection should be considered |
| Gas detection / safety | | **41.** Gas detection, alarm and shut down philosophy for ammonia are to be based on toxicity level not LEL level |
| Additional study | | **42.** Require dispersion analysis see general recommendation |
| Hazardous area / fire protection | **2.4** Fire in Fuel Tank/Cargo Area | **43.** IMO/IACS is in discussion to interpret inter-barrier space between the primary and secondary barriers as Zone 0, this will make outside space zone 1, in that |

| Recommendation Type | BC 1 HAZID References | Recommendation |
|---|---|---|
| | | case cofferdam will be needed between zone 0 and other enclosed space Consider A-60/cofferdam protection for $NH_3$ Tank to protect against cargo area fire above deck |
| Structural protection | **2.5** Explosion in FSS Room | **44.** Consider explosion relief hatch to limit explosion consequences |
| Structural fire protection | **2.6** $NH_3$ tank Primary barrier failure | **45.** Consider providing cofferdam between secondary barrier and machinery space |
| Vent / Emergency | | **46.** Consider emergency evacuation of NH3 tank and inter-barrier space and provide proper arrangement to handle such event |
| Vent | | **47.** Venting system to be designed such that in worst case situation (inter-barrier space full of $NH_3$) can safely vent $NH_3$ without exceeding toxic exposure limit |
| Design | **2.7** $NH_3$ leak at tank connection/dome | **48.** Tank connection space arrangement to be developed |
| Procedure | | **49.** Restrict any lifting over cargo tank when tank has $NH_3$ |
| Additional study | | **50.** Gas dispersion analysis to be performed and venting details to be developed for TCS room |
| Personnel safety / emergency | **2.8** Collision | **51.** Emergency evacuation plan to be in place. |
| Personnel safety / emergency | | **52.** Look at worst-case scenario and the volume of gas released in case of incident in port/economic zone concerned with the port authorities |
| Procedure / Safety | **2.9** Over-pressurisation of Storage Tanks | **53.** Fuel tank management considering two separate tanks, considering fuel consumption to be developed |
| Design / Safety | | **54.** Redundancy in Re-liquefaction plant to be considered<br><br>See recommendation #1 (hazardous areas) |
| Procedure | **2.10** Overfill of tank above allowed reference limit | **55.** Client to develop cargo-liquid management and liquid-level measurement system and detailed procedure<br><br>See recommendation #1 (hazardous areas) |
| Additional study | **2.11** Sloshing inside tank | **56.** Dome location and sloshing study to be done to avoid liquid surge inside dome for all weather conditions and tank fill and trim conditions |
| Additional study | **2.13** Power loss | **57.** Loss of power - valve fail safe positions and backup power requirements to be studied further during the HAZOP |
| Safety / additional study | | **58.** Study of power loss scenario and trapped fuel handling in the pipes |

| Recommendation Type | BC 1 HAZID References | Recommendation |
|---|---|---|
| safety | | **59.** Any possible trapped fluid, thermal relief valve to be provided and relief valve to be vented to the vent mast |
| | **3. General Arrangement/Fuel Handling Room** | |
| Personnel safety | **3.1** Exhaust location | **60.** Recommend having toxic zone area plan developed to access HAZ. |
| Design | **3.2** $NH_3$ leak in FSS room | **61.** FSS room is to be under pressurised (extraction ventilation) |
| Design / Safety | | **62.** Consider FSS room door are to be gas tight |
| Ventilation | | **63.** Reconsider ventilation philosophy instead of shutting down consider additional air circulation to disperse $NH_3$ |
| Ventilation | | **64.** Reconsider exhaust location |
| Pollution | | **65.** philosophy for ammonia catch system to consider leakage scenario |
| Safety / Additional study / Design | | **66.** Hazards associated with FSS room (emission) with respect to all other spaces and openings are to be reconsidered and relooked Hazards associated with FSS room (leak, fire, explosion etc.) with respect to all other spaces and openings are to be reconsidered and relooked |
| Design / Safety | | **67.** Consider tank management equipment to be located in separate space Consider IGF requirement to have redundancy in static equipment from reliquefication system Consider conducting HAZOP/FMEA to prove availability of the reliquefication and BOG management system for P-T management of $NH_3$ tanks.<br><br>See recommendation #73 (tank pressure) |
| | **4. General Arrangement/Fuel Handling Room/Fuel Transfer/Fuel preparation /Reliquification/pumps/piping** | |
| ventilation | General | **68.** Engine room double-wall piping exhaust inlet to be provided and HA drawing to be updated |
| Design | **4.2** Poor ventilation | **69.** Consider redundancy requirements of IGF Code or equivalent |
| Ventilation | | **70.** Consider Emergency additional ventilation upon detection of $NH_3$ |
| Fire safety / Additional study | **4.3** Fire in FSS Room | **71.** Fire safety shutdown safety philosophy and detailed HAZOP to be conducted |
| Firefighting | | **72.** Application of water mist system to be reevaluated considering that ammonia can dissolve in water and |

| Recommendation Type | BC 1 HAZID References | Recommendation |
|---|---|---|
| | | create a vacuum or over pressurisation due to high expansion ratio and damper closure |
| Design / Safety | **4.4** Re-liquification plant failure | **73.** Re-evaluate single re-liquification plant philosophy with respect to maintaining tank pressure for all conditions (IGF Code requirement applies) |
| Design | **4.6** Contaminated return fuel | **74.** Engine manufacturer to address detection of contaminated ammonia fuel and separation philosophy |
| Fire safety | **4.7** Explosion in FSS Room | **75.** Consider cofferdam between FSS Room and tank secondary barrier |
| Pollution | **4.12** Drainage in FSS Room | **76.** Consider drain provision and drain collection from FSS Room and evaluate the capacity required for drainage collection<br>Consider inventory monitoring in the drain tank drain treatment to be provided to meet regulations to protect aqua-life |
| Pollution | **4.13** Ammonia catch system drainage | **77.** ammonia catch system contaminated water collection and treatment to be provided to meet discharge standard and protect aqua life<br>ammonia catch system to be designed to provide monitoring of the system, to determine when to recharge catch fluid |
| Vent / Additional study | **4.14** Gas blow by from ammonia catch system | **78.** to be addressed in HAZOP<br>vent from ammonia catch systems to be identified as HA |
| Personnel safety / design | **4.15** Liquid ammonia leaking in FSS Room | **79.** Consider Liquid leakage collection and monitoring to be designed to address the toxicity issue<br>Study to be done to address the risk due to the leakage in the FSS room considering pressurized cold leakage and ventilation and firefighting philosophy |
| Design | **4.16** Purging capabilities | **80.** Purging capabilities of the system to be developed |
| Additional study | **4.17** Dropped object on FSS Room | **81.** Dropped object study to be performed |
| **5. GA Machinery space (ER) / Use of Fuel / Engine Maintenance Activity / Engine** | | |
| Additional study | **General** | **82.** The engine is under development and therefore the engine risk will be addressed in a later FMEA<br>Engine manufacturers are to conduct component level FMEA to see if ammonia can migrate into other systems and areas |
| Maintenance / inspection | **5.2** Inner wall pipe failure | **83.** inspection and maintenance plan and procedures are to be developed |
| Inspection | | **84.** post-maintenance inspection |
| Personnel safety / procedure | **5.4** Inner and outer wall pipe failure | **85.** piping arrangement to be such that there is low probability of dropped object damage<br>develop appropriate engine room entrance procedures considering necessary PPE |
| Additional study | **5.6** Ammonia in the cooling water system | **86.** Engine FMEA to be conducted<br>venting of $NH_3$ from engine auxiliary system in case of single failure to be designed and appropriate venting to be provided |
| Procedure | **5.8** Fire in the engine room | **87.** Shutdown switchover philosophy to be developed and $NH_3$ fuel to be purged back to FSS Room |
| Safety / procedure | **5.10**<br>Trapped ammonia during exposure during maintenance | **88.** develop proper operational and maintenance procedures for the system and ensure there is no trapped ammonia |

| Recommendation Type | BC 1 HAZID References | Recommendation |
|---|---|---|
| Testing | **5.11** Exhaust slip | **89.** During testing, man to collect data and address accordingly |
| **6. Vent/Vent Lines/Vent Mast** | | |
| Gas Detection | **General** | **90.** All gas detection etc., for venting systems to comply with ABS Ammonia Guide<br>Vent mast system drainage to be provided and considering that ammonia dissolved in water |
| Additional study | **6.1** Location of vent mast | **91.** dispersion analysis to be conducted to justify the height of the mast<br>consider defining toxic zones and personnel safety based upon the PPE level exposure for worst case discharge of ammonia |
| Procedure / design | **6.2.1** Ammonia release to vent mast at port | **92.** Operational and safety procedures while in port are to consider port requirements and be incorporated into the design |
| Additional study | **6.2.2** Ammonia release to vent mast during bunkering | **93.** Dispersion analysis to be conducted |
| Ventilation | **6.2.3** Ammonia release to FSS Room exhaust | **94.** consider exhaust fan to exhaust in the upward direction, to have a better gas dispersion in the case of leakage |
| Ventilation | **6.2.4** Ammonia release to double walled piping exhaust | **95.** Exhaust location from double walled pipe to be determined and exposure to accommodations to be considered |
| Ventilation | **6.4** Ammonia catch system exhaust<br>**6.5** Glycol water system exhaust | **96.** Exhaust locations to be determined according to IGF Requirement |
| **7. Safety System/ Emergency** | | |
| Personnel safety | **7.1** Escape - Cat A machinery space fire | **97.** Consider LSA to be provided with self-contain breathing PPE etc. suitable for $NH_3$ considering risk of exposure - SOLAS for gas carrier |
| Personnel safety / additional study | | **98.** Consider conducting EER study considering fire, $NH_3$ release, other emergencies |
| Fire safety | | **99.** Consider applying A-60 boundary around containment system or any escape route with possibility to direct fire exposure or possibility of $NH^3$ - IGF 11.3.2 |
| Personnel safety | **7.2** PPE Requirement | **100.** PPE and mask requirement/philosophy are to be developed and locations to be determined |
| Design / procedure | **7.3** ESD Philosophy | **101.** Emergency shutdown philosophy and procedures are to be developed and to be considered during the design |
| Structural fire protection | **7.4** Structural fire protection | **102.** FSS Room structural requirements are to comply with IGF Requirements |
| Firefighting | **7.5** Firefighting | **103.** Appropriate firefighting systems to be provided considering ammonia leak and ammonia fire<br>Emergency evacuation and rescue procedures for worst case discharge to be developed |
| **8. Ship's Operation / Simultaneous Operation** | | |
| Additional study | **8.3** Damage to deck piping due to cargo loading/unloading | **104.** Dropped object study to be performed considering cargo loading/unloading and maintenance<br>Consider breakage of piping and perform dispersion analysis to consider exposure to humans and toxicity |

| Recommendation Type | BC 1 HAZID References | Recommendation |
|---|---|---|
| | | zone<br>Consider the alternative to capture the fluid and reuse it |
| Design / procedure | **8.5** Gas freeing<br>**8.6** gassing up | **105.** Gas freeing and gassing up operations are to be studied for emergency, maintenance, dry docking situation and appropriate solutions are to be developed<br>Consider addressing the ammonia discharge issue during gas freeing<br>Evaluate need for nitrogen if doing independently |
| Maintenance | **8.7** Maintenance and inspection | **106.** Maintenance and inspection procedures are to be developed |
| Quality control | **8.8** Out of spec fuel | **107.** Fuel quality control and fuel spec to be developed |
| Safety /emergency | **8.9** Port entry | **108.** local authorities are to be consulted for grounding risk and proper procedures are to be developed |
| Design | **8.11** heavy weather - failure of equipment/piping | **109.** Equipment foundations/supports are to be designed considering heavy weather dynamic loads<br>Ammonia equipment is to be designed for full operations considering heavy dynamic loads and heave/roll/pitch for the expected operating conditions in heavy weather |

# Appendix XI – Hazard Register BC Proposal I – Fuel Storage tank port/starboard of Accommodation and penetrating Engine Room

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking S | L | RR | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| **0. Introductory Notes** | | | | | | | | | |
| **General Arrangement Notes** | • Distance between the FSS Room and accommodation boundary is about 11 m<br>• FSS Room entrance faces aft<br>• FSS air outlet is on the port side of the room and inlet is in the aft, stbd side<br>• One escape route is on C-Deck, STBD Side of Engine Casing.<br>• There is to be a total of two escape routes per class and regulatory requirement<br>• Piping from bunkering station to the cargo tank is routed along weather deck to the accommodations and then up the side of the accommodations to the dome. Elevation of piping to be discussed further<br>• Deckhouse has an entrance door, which should be above the piping to the ammonia tank. The door is weathertight.<br>• Distance between Ammonia Tank enclosure and Accommodations is 1.1 m<br>• Access hatch to cargo hold in the fwd. section of the deckhouse<br>• There are two entrances to the FSS Room. Consider moving the Port side entrance as far outboard as practicable to comply with SOLAS Regulations<br>• Type-A Tanks... The rectangular prism enclosures seen on the GA are secondary barriers, not the primary barriers.<br>• Piping from the FSS Room to the ER is double-walled piping<br>• No redundancy is currently planned for re-liquification. Only ammonia consumer is the main engine. Type of re-liquification plant is to be sub-cooler<br>• Connections from tank dome to the FSS Room are located on the side of the room<br>• Suggest to investigate NH3 toxic limit by NIOSH : REL 25ppm (8hr), PEL 50ppm, IDLH 300ppm. https://www.cdc.gov/niosh/idlh/7664417.html | | | | | | | | |
| **Engine Notes** | • Ammonia Catch system is a water absorber. Water will need to be replaced occasionally, with the rate to be determined.<br>• Size of catch tank to be designed for worst-case venting scenario. The current design capacity is only to handle fuel supply system. Not included are refrigeration, cargo maintenance, BOG etc.<br>• Absorption rate to be considered for the ammonia catch system in determining when to recharge and replace water<br>• ABS Has no direct specification for the water absorption system. However, this would be indirectly addressed during a required FMEA.<br>• Piping from Engine to FSS Room is currently double-walled<br>• Piping between bunker manifold and fuel tank is single walled. IGF Code amendment will require double-walled piping on the open deck for LNG<br>• Ammonia slip from engine could be handled by SCR.<br>• MSC.458(101), entry into force 1 Jan 2024: ... "9.5.6 Liquefied fuel pipes shall be protected by a secondary enclosure able to contain leakages. If the piping system is in a fuel preparation room or a tank connection space, the Administration may waive this requirement. Where gas detection as required in 15.8.1.2 is not fit for purpose, the secondary enclosures around liquefied fuel pipes shall be provided with leakage detection by means of pressure or temperature monitoring systems, or any combination thereof. The secondary enclosure shall be able to withstand the maximum pressure that may build up in the enclosure in case of leakage from the fuel piping. For this purpose, the secondary enclosure may need to be arranged with a pressure relief system that prevents the enclosure from being subjected to pressures above their design pressures." | | | | | | | | |
| **1. General Arrangement/Bunkering** | | | | | | | | | |
| **General Recommendations & Section Notes** | | | | | | | | **1.** Considering cargo carriage (coal), Hazardous Area if any with regards to the cargo is to be considered.<br>**2.** Fuel-handling manual to be developed including fuel handling, bunkering, and supply per IGF code requirement. "IGF Code 18.2.3 requires: the ship shall be provided with operational procedures including a suitably detailed fuel handling manual, such that | • Bunkering is not done in port and proposed to be done at anchorage<br>• During bunkering operations, ammonia not used in Engine Room(E/R)<br>• There will be no simultaneous operation of cargo loading/unloading and bunkering<br>• Bunkering hose deployment |

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking S | L | RR | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | trained personnel can safely operate the fuel bunkering, storage and transfer systems…"<br>**3.** Once the bunkering philosophy is developed, bunkering operations to be further studied<br>**4.** Develop purging monitoring requirement to confirm that purging process removed all ammonia | should be done by bunker vessel<br>• Bunkering Control is located in remote-controlled station.<br>• Bunkering manifold monitoring by gas/liquid detection only<br>• Discharge from manifold to sea is to be reviewed in accordance with regulatory requirement<br>• Bunkering operation for ammonia will be similar to LNG and will be designed per IGF Code requirements<br>• Bunker manifold will be purged of nitrogen after each bunkering operation, therefore no ammonia in bunker manifold<br>• Two isolation valves at tank dome to isolate bunker piping (liquid/vapour)<br>• Bunker hose to be handled and provided by bunker vessel crane |
| **1.1 Loss of containment - Bunker Manifold** | • Joint Failure<br>• Mechanical Damage<br>• Improper connection Fatigue<br>• Temperature Variation<br>• Vibration<br>• Hose failure | • Fuel Spill<br>• Toxic Atmosphere<br>• Hazardous Atmosphere<br>• Hull Structure Exposed to cold temperature | Asset | 3 | C | 3C | • Drip Tray<br>• Water Spray System<br>• ESD System (Manual/Auto)<br>• SSL (Ship to Shore Link)<br>• Ammonia gas detector (1 Port and 1 Stbd)<br>• Water curtain to protect side shell<br>• Quick disconnect flange<br>• Eye wash and shower near bunker manifold<br>• Portable foam system | **5.** Cause and effects of ESD system is to be further evaluated considering ammonia and its toxicity<br>**6.** Drip tray sizing and philosophy of collected fluid handling to be studied<br>**7.** Further analysis of number and placement of gas detectors around bunker stations to be conducted | • Assumption is that bunkering will be controlled remotely after connection is made from control station<br>• Bunker manifold is visible from control station<br>• Refer to IGF 8.5.3, IGF 8.5.5 for more guidance |

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking S | L | RR | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | **8.** Local Regulations and IMO Regulations are to be studied for discharge into the sea | • IGF requires gas test or further analysis to determine gas detector location<br>• The distance between the bunker control station and bunker manifold is about 10 m |
| | | • Ammonia at control station<br>• Human exposure | • Human | 3 | C | 3C | • Fixed gas detector at bunker manifold<br>• Manual emergency stop<br>• Tank pressure and level monitoring<br>• Local control of water spray system from control station<br>• Fire and Gas detector | **9.** Bunker station locations and crew presence are to be studied considering potential ammonia release<br>**10.** Crew near bunker manifold are to be provided with appropriate PPE and portable gas detectors<br>**11.** consider providing water spray system for local control station | • Distance between the bunker control station and bunker manifold is about 10 m<br>• Current plan is to have the bunker control station, which is location near Cargo Tank #8, is to be manned to control bunker operations<br>• Water-spray system at the bunker station can be isolated from the rest of the water-spray system |
| **1.2 Bunker Manifold over-pressurisation during bunkering operation** | • Blocked flow (e.g., Tank valve closed, bunker manifold closed) | • Pipe breakage<br>• Release of ammonia<br>• Hull Structure Exposed to cold temperature | • Asset<br>• Human | 1 | D | 1D | • High-pressure alarm<br>• Design pressure of 10 bar (max supply pressure of 6 bar from bunker vessel) | **12.** If there is a possibility of trapped fluid due to various operational condition, proper relief arrangement is to be provided (i.e., QC-DC operations between pop-it and ESD valve, ESD, loss of power etc.) | • From bunker flange to tank dome, no pressure relief valve is provided |

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking | | | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| | | | | S | L | RR | | | |
| **1.3 Trapped fluid in bunker piping** | • Emergency shutdown – manual<br>• High level in the tank<br>• Over-pressurisation in the tank<br>• Power loss | • Over-pressurisation of the pipe<br>• Damage to piping/equipment<br>• Release of ammonia | • Asset<br>• Human | 4 | D | 4D | • ESD Trigger only bunker manifold shutdown (tank valve will still be open) | **13.** Manifold is to be designed for the maximum vapour pressure buildup at 45 $^0$C for Trapped fluid or for emergency shutdown with the possibility of trapped fluid<br>**14.** For trapped fluid, thermal expansion is to be considered and thermal relief valve to be provided<br>**15.** For various ESD scenarios, study to be conducted on the scenarios and the potential for trapped fluid in the different scenarios<br>**16.** Any thermal relief provided to be vented properly in to vent mast | • Refer to IGF Code: 7.3.1.3 for more guidance |
| **1.4 Overfilling of the tank due to draining of the bunker piping** | • inventory inside bunker piping drained | • Overfilling of tank | Asset | 2 | B | 2B | • Design in compliance with IGC Code | | • Current proposal is to drain back bunker piping inventory back to tank |
| **1.5 Unable to get ammonia back to tank during purging** | • height difference between tank connections and bunker manifold | • Unable to safely handle inventory due to gravity difference<br>• Nitrogen in ammonia cargo tank | • Asset | 3 | E | 3E | | **17.** How to purge and handle inventory in bunker piping during ESD and normal operation is to be considered and proper design is to be developed. (Issue is a gravity difference & volume of inventory in the piping) | • tanks height is 10 m relative to the deck<br>• Current proposal is to drain back bunker piping inventory back to tank |

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking S | Risk Ranking L | Risk Ranking RR | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| **1.6 Loss of containment - Piping between bunker station and fuel tank** | • mechanical damage during cargo ops<br>• fatigue<br>• overstress<br>• corrosion | • leakage at the pipe due to mechanical or fatigue damage<br>• gas leak near non-hazardous spaces<br>• toxic hazardous atmosphere<br>• human exposure to toxic gas<br>• fire/explosion in safe space<br>• hull, accommodation, and/or other structural damage | • Asset<br>• Human | 4 | C | 4C | • Pipe is protected by angle bar<br>• piping designed to handle all loads<br>• bunker piping is all welded (no threaded connections)<br>• piping thermal expansion study to be done<br>• piping specification meets IGF criteria<br>• During bunkering no cargo handling allowed | **18.** consider including visual inspection of the bunker piping from manifold to tank before bunkering when developing the operations manual<br>**19.** consider need for piping stress analysis to address pipe failure due to overstress, fatigue, etc. and justification to be provided.<br>**20.** inspection and maintenance plan for this piping is to be developed considering fatigue fracture failure<br>**21.** Evaluate adequacy of proposed pipe protection considering risk of Ammonia and dropped object damage | • During bunkering no cargo operations allowed within the vicinity of the ammonia piping<br>• during cargo operations, there is a possibility of damaging the piping on the deck, which should be analysed by the shipyard/owner<br>• Refer to IGF Code: 7.3.4.4 , IGF 7.3.4.5, IGF Code: 7.3.4.2 for more guidance<br>• During purging, the ammonia in bunker piping is returned to the tank |
| **1.7 Make & Break of bunkering hose during normal operations** | • Trapped liquid ammonia | • damage to the equipment<br>• human exposure | • Asset<br>• Human | 2 | B | 2B | • bunkering procedures require inerting prior to 'make' or 'break'<br>• crew provided with appropriate PPE and a gas detector | **22.** Proper connect/disconnect procedures are to be developed to prevent trapped fluid | |
| **1.8 Emergency Breakaway** | • emergency on bulk carrier<br>• emergency on bunker vessel<br>• mooring line failure | • Ammonia spill (due to breakaway coupling design)<br>• Toxic atmosphere | • Human | 2 | D | 2D | | **23.** Investigate how much ammonia can be released during emergency disconnect and if this will affect any crew in the bunkering control station<br>**24.** Dry breakaway coupling is to be provided | • In emergency, dry break coupling can release a fixed amount of ammonia to the atmosphere |
| **1.9 Emergency on the Bulk Carrier** | • Fire in accommodations<br>• Fire in FSS room<br>• Fire in Cargo Area<br>• Fire in Cat-A machinery space | • loss of ammonia containment<br>• heat gain to the tank<br>• Trapped ammonia inventory in the piping<br>• excess boil off gas | • Asset<br>• Human | 2 | C | 2C | • ESD for bunkering<br>• SSL Link<br>• Bunkering ceases<br>• tank is designed considering heat gain due to fire | **25.** piping insulation has to consider the fire rating<br>**26.** fire scenario on the bulk carrier during bunkering is to be investigated | |
| **1.10 Emergency on bunker supply ship** | • fire<br>• power loss<br>• Ammonia release | • loss of ammonia containment<br>• heat gain to the tank<br>• Trapped ammonia inventory in the piping<br>• excess boil off gas | • Asset<br>• Human | 2 | C | 2C | • SSL Link<br>• ESD<br>• operational procedures<br>• water spray for tank protection | **27.** Emergency procedures are to be developed considering an emergency on the bunker vessel | |

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking | | | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| | | | | S | L | RR | | | |
| **1.11 Vessel Drift Away** | • extreme weather<br>• mooring line failure<br>• collision<br>• high wind | • hose break away<br>• fuel spill | • Asset<br>• Human | 2 | D | 2D | • monitoring and operational procedures<br>• ESD<br>• SSL<br>• Dry break coupling<br>• fixed gas detector<br>• bunkering is limited to safe-operating environment | **28.** Investigate how much ammonia can be released during emergency disconnect and if this will affect any crew in the bunkering control station<br>**29.** Dry breakaway coupling is to be provided | • No additional risk compared to the LNG<br>• Refer to IGF Code: 8.4.1 for more guidance |
| **1.12 Extreme weather event** | | | | | | | | | • Procedures will restrict bunkering operations during extreme weather events |
| **1.13 -ver pressurisation of tank during bunkering** | • Operational malfunction<br>• liquid level failure<br>• Operator error<br>• pressure control failure<br>• Tanks maintained at different levels during bunkering | • damage to tank structure<br>• ammonia in the atmosphere<br>• Toxic atmosphere | • Asset<br>• Human | 2 | C | 2C | • Type-A tank is provided with a secondary barrier that is fully inerted and slightly pressurised<br>• secondary barrier is provided with venting<br>• Tank is protected by PRV<br>• High pressure alarm<br>• High pressure shutdown<br>• High level redundant alarm system | **30.** Investigate Type-A tank secondary barrier ventilation which is discharge into the vent mast with all other venting and there is potential for high backpressure and reverse flow in to secondary barrier | • vent from secondary barrier goes into the vent mast |
| **1.14 Freeboard height difference between bunkering vessel and Bulk Carrier** | • Handling of hose | | | 4 | B | 4B | | **31.** Conduct compatibility study between the two vessels and evaluate need for crane on bulk carrier | |
| **2. General Arrangement / Fuel Storage** | | | | | | | | | |
| **General Recommendations & Section Notes** | | | | | | | | **32.** Dispersion analysis for $NH_3$ release considering normal, upset, emergency and fire scenario to be performed to estimate $NH_3$ exposure to various area. | • Considering proximity of Tank, vent system wrt accommodation and Cat A machinery etc. risk is high and recommended that further analysis to be conducted. Exposure level guide per NISH to be considered in analysis<br>• IGF safety function fuel supply: 9.4.1 Fuel storage tank inlets and outlets shall be provided with valves |

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking S | L | RR | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | located as close to the tank as possible. Valves required to be operated during normal operation16 which are not accessible shall be remotely operated. Tank valves, whether accessible or not, shall be automatically operated when the safety system required in 15.2.2 is activated. |
| **2.1** Fire in Accommodations, Service, Control Stations | • short circuit<br>• electromagnetic fire<br>• galley fire | • smoke<br>• evacuation<br>• ammonia tank exposed to high temperature/radiant heat<br>• smoke migrating into FSS Room<br>• Ammonia tank PRV discharging to the vent mast<br>• FSS air intake may draw water into FSS Room<br>• LSA exposed to ammonia due to venting<br>• egress routes exposed to large amounts of water spray and will be a challenge for the crew to escape | • | 3 | D | 3D | • fire detector<br>• fire alarm<br>• smoke detector<br>• portable firefighting equipment<br>• A-60 boundaries inside accommodation boundaries between accommodations/services/control stations and tank side<br>• fire main<br>• fire hydrant<br>• water spray system for ammonia tanks exposed to the weather<br>• water spray system for accommodations/services/control stations | **33.** Emergency procedures are to be developed taking into consideration the fire scenarios<br>**34.** Evaluate ingress protection ratings of the equipment<br>**35.** Dispersion analysis for $NH_3$ release considering normal, upset, emergency and fire scenario to be performed to estimate $NH_3$ exposure to various area. | • Refer to IGF Code: 11.5.1 and IGF Code: 11.5.2 for more guidance<br>• Vent mast height is approximately 20 metres<br>• Considering proximity of tank, vent system wrt accommodation and Cat A machinery etc. risk is high and recommended that further analysis to be conducted. Exposure level guide per NISH to be considered in analysis. |
| **2.2** Fire in Cat-A Machinery Space | • Hot surface<br>• Fuel/Oil Spray<br>• Electrical short<br>• Boiler explosion<br>• Hydraulic fluid leak<br>• $NH_3$ leak | • Fire<br>• Explosion<br>• High temperature<br>• Radian heat<br>• $NH_3$ tank fuel warming up and exposure to high temperature<br>• Damage to secondary barrier<br>• PRV discharging to vent mast<br>• Damage to fuel supply room<br>• Release of $NH_3$ | • Asset<br>• Human | 4 | C | 4C | • Cat A m/c space provided with fire/gas detection<br>• Water mist<br>• Hydrant<br>• Fixed ff system - $CO_2$<br>• M/C space in compliance with SOLAS and class rules<br>• Water spray system for fuel tank (boundary on open deck) | **36.** $NH_3$ Tanks are to be segregated with cofferdam and cofferdam should be measured from secondary barrier (900 mm cofferdam, boundary of cofferdam to machinery space to be A-60)<br>**37.** Secondary barrier should be gas tight | • $NH_3$ tanks are separated by cofferdam and A-60 bulkhead<br>• Type - A requires complete secondary barrier, if hull is considered as secondary barrier is boiling temp is not less than -55. |

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking S | L | RR | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | **38.** Inner-barrier space to be inerted and maintained at positive pressure<br>**39.** All tank boundaries exposed to Cat-A machinery space are to be provided with A-60 boundary | • 2nd deck is A-60 from machinery space<br>• At the moment, outer hull is the secondary barrier<br>• IMO/IACS is in discussion to interpret inter-barrier space as Zone 0<br>• Refer to IGF 11.3.3, IGF 6.11.1, ABS ammonia as fuel guide 12/6.4, SOLAS III/31.1.6 and LSA IV/4.8 for more guidance |
| **2.3** Fire in FSS Room | • $NH_3$ leak<br>• Connection failure<br>• Pipe failure/crack<br>• Fatigue<br>• Seal failure (compressor and other rotating machinery)<br>• Over-pressurisation | • Toxic atmosphere<br>• Fire<br>• Explosion<br>• $NH_3$ escaping due to over pressure of room<br>• FFS room can be over-pressurised and collapse<br>• Toxic zone around FSS room expanding<br>• Human exposure/injury/fatality<br>• Damage to $NH_3$ storage tank | • Asset<br>• Human | 4 | C | 4C | • Gas detection (based on LEL)<br>• Fire detection<br>• Shutdown of ventilation<br>• Shutdown of damper<br>• Water spray<br>• Water curtain at entrance<br>• PPE, eyewash, shower outside FSS room entrance<br>• Automatic shutdown of tank valves and fuel supply valves | **40.** Reconsider shutdown of ventilation philosophy for FFSS room (due to 800 to 1 expansion ratio of $LNH_3$ can create over pressure)<br>If water spray system is activated in NHS room full of $NH_3$ gas, it can create Vacuum due to solubility of $NH_3$ in water, pressure vacuum protection should be considered<br>**41.** Gas detection, alarm and shot-down philosophy for ammonia are to be based on toxicity level not LEL level<br>**42.** Require dispersion analysis see general recommendation | • FSS design philosophy is to upon LEL level detection of $NH_3$ shutdown ventilation, close damper. Upon fire detection same with spray water come automatically<br>• For liquified or pressurised gas in closed space leakage can create high pressure if all openings are shut down due to volume expansion ($NH_3$ volume expansion approximately 800 - 1.<br>• If water deluge is activated in FSS room with room full of $NH_3$ can create vacuum due to $NH_3$ dissolving in water (Pressure vacuum protection is recommended |

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking S | L | RR | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | • Present philosophy for $NH_3$ detection is based on SOLAS. which is based on LEL type philosophy and is not suitable for $NH_3$ due to toxicity of $NH_3$<br>• Present design FSS room ventilation inlet is aft and exhaust on side (port side) |
| **2.4** Fire in Fuel Tank/Cargo Area | • HFO Fuel/coal tank fire | • $NH_3$ tank directly exposed to fire<br>• $NH_3$ tank heat gain due to direct exposure or radian heat<br>• High temperature exposure can lead to $NH_3$ tank failure | • Asset<br>• Human | 3 | C | 3C | • Water spray system<br>• Fire hydrant | **43.** IMO/IACS is in discussion to interpret inter-barrier space as Zone 0, this will make outside space zone 1, in that case cofferdam will be needed between zone 0 and other enclosed space Consider A-60/cofferdam protection for $NH_3$ Tank to protect against cargo area fire above deck | • Refer to IGF Code: 11.3.3 for more guidance |
| **2.5** Explosion in FSS Room | • $NH_3$ leak<br>• Connection failure<br>• Pipe failure/crack<br>• Fatigue<br>• Seal failure (compressor and other rotating machinery)<br>• Over-pressurisation | • Collapse of structure<br>• Damage to $NH_3$ tank<br>• $NH_3$ leakage<br>• Secondary barrier break<br>• EER impaired | • Asset<br>• Human | 3 | C | 3C | • Gas detection (based on LEL)<br>• Electrical equipment suitable for HAZ area<br>• Fire detection<br>• Shutdown of ventilation<br>• Shutdown of damper<br>• Water spray<br>• Water curtain at entrance<br>• PPE, eyewash, shower outside FSS room entrance<br>• Automatic Shutdown of tank valves and fuel supply valves | **44.** Consider explosion relief hatch to limit explosion consequences | • Refer to IGF Code: 4.3 for more guidance |
| **2.6** $NH_3$ tank primary barrier failure | • Corrosion<br>• Fatigue<br>• Overstress<br>• Over-pressurisation<br>• Manufacturing defect<br>• Dropped object | • Failure of inner barrier led to $NH_3$ leak in secondary barrier<br>• $NH_3$ vented to atmosphere via vent mast from secondary barrier<br>• Gas migration to machinery space can lead to explosion in machinery space<br>• Lead to long lasting event as $NH_3$ continuously leaking | • Asset<br>• Human | 4 | C | 4C | • Secondary barrier provided to contain primary barrier leak<br>• Secondary barrier is designed to withstand low temperature<br>• Gas detector in secondary barrier<br>• Temperature detection in secondary barrier<br>• Level alarm<br>• Vent to vent mast secondary barrier | **45.** Consider providing cofferdam between secondary barrier and machinery space<br>**46.** Consider emergency evacuation of $NH_3$ tank and inner barrier space and provide proper arrangement to handle such event<br>**47.** Venting system to be designed such that in | • Proposed arrangement does not include cofferdam required to separate machinery space and secondary barrier |

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking S | Risk Ranking L | Risk Ranking RR | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | • Pressure/Temperature/level monitoring of tank<br>• ESD provision | worst case situation (inner barriers space full of $NH_3$) can safely vent $NH_3$ without exceeding toxic exposure limit | |
| **2.7** $NH_3$ leak at tank connection/dome | • tank connection leak/failure<br>• Fatigue<br>• Overstress<br>• Valve leaking<br>• Gland leaking | • Hazardous atmosphere due to $NH_3$ leak<br>• Toxic atmosphere<br>• Human exposure | • Asset<br>• Human | 3 | C | 3C | • Design complies with IGC code<br>• Inspection and maintenance | **48.** Tank connection space arrangement to be developed<br>**49.** Restrict any lifting over cargo tank when tank has $NH_3$<br>**50.** Gas dispersion analysis to be performed and venting details to be developed for TCS room | • Refer to IGF Code: 6.3.4, IACS UI GF3: 1 for more guidance<br>• Tank connection space is located AFT part of the tank in center, but current documentation does not show tank connection arrangement<br>• Tank connection will be provided in TCS room type arrangement, current arrangement do not show such |
| **2.8** Collision | • Navigation error<br>• Low visibility<br>• Weather<br>• Pilot error<br>• Loss of maneuvering functionality/steering | • Damage to the fuel tank<br>• Damage to the BC Structure<br>• Fuel Oil Spill<br>• Oil fire<br>• Damage/Explosion cargo tank | • Asset<br>• Environment<br>• Human | 3 | C | 3C | • Fuel tank locations and strength to meet IGF code requirement | **51.** Emergency evacuation plan to be in place.<br>**52.** Look at worst case scenario and the volume of gas released in case of incident in port/economic zone concerned with the port authorities | • At this point, collision risk is identified but needs further development as risk is high due to consequences |
| **2.9** Over-pressurisation of Storage Tanks | • High temperature of fuel<br>• Re-liquification plant failure<br>• Vapour-management failure<br>• Control failure<br>• Improper bunkering operation<br>• liquid level not managed<br>• cargo coming at wrong temperature | • Tank Damage<br>• Equipment Damage<br>• Hazardous atmosphere<br>• Toxic atmosphere | • Asset<br>• Human | 3 | B | 3B | • Relief valve protection<br>• Re-liquification to re-liquify the boil off<br>• Pressure /temperature monitoring and alarm<br>• Design complies with IGF code requirements | **53.** Fuel tank management considering two separate tanks, considering fuel consumption to be developed<br>**54.** Redundancy in re-liquefaction plant to be considered<br>See recommendation # 1 | • Fuel usage will be from one tank at a time and redundant liquification will manage the tank pressure |
| **2.10** Overfill of tank above allowed reference limit | • level control failure<br>• Pressure/Temperature management | • Over-pressurisation due to warming of the cargo<br>• Liquid discharge to vent mast or vapour lines<br>• Damage to the tank<br>High PPM level near safe spaces | • Asset<br>• Human | 4 | C | 4C | • Liquid level measurement systems<br>• Liquid level alarm and ESD<br>• Cargo handling procedure | **55.** Client to develop cargo liquid management and liquid level | |

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking S | Risk Ranking L | Risk Ranking RR | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| | • Both tank levels not managed properly<br>• Human error | | | | | | • Cargo Temperature/Pressure Management<br>• Pressure Relief Valve | measurement system and detailed procedure | |
| **2.11** Sloshing inside tank | • Motion of BC | • Damage to the tank<br>• liquid in the vapour line<br>• Damage of piping and pump tower damage<br>• Instrument damage<br>• Tank support damage<br>• Tank connection | • Asset | 3 | C | 3C | • Slosh bulkhead<br>• Tank and tank supports designed to IGF criteria | **56.** Dome location and sloshing study to be done to avoid liquid surge inside dome for all weather conditions and tank fill and trim conditions | |
| **2.12** Liquid management between the two ammonia tanks | No risks identified by the team because there is not enough information available at this stage. | | | | | | | | |
| **2.13** Power loss | • Blackout on BC<br>• Power supply failure for tank connections control system | • Unable to use fuel<br>• Engine Stop or switch over<br>• Rise in fuel tank pressure due to loss of refrigeration capacity<br>• Trapped fluid equipment piping damage | • Asset | 2 | D | 2D | • Fuel tank relief valve<br>• Tank design to hold fuel without relief for 21 Day (IGF /IGC requirement)<br>• Dual fuel engine with switchover to liquid fuel<br>• Emergency power on BC<br>• All tank dome automatic valves are fail-safe closed | **57.** Loss of power valve fail safe positions and backup power requirements to be studied further during the HAZOP<br>**58.** Study of power loss scenario and trapped fuel handling in the pipes<br>**59.** Any possible trapped fluid, thermal relief valve to be provided and relief valve to be vented to the vent mast | |
| **2.14** Escape route | No risks identified by the team because there is not enough information available at this stage. | | | | | | | | |
| **2.15** Submerged pump failure | No risks identified by the team because there is not enough information available at this stage. | | | | | | | | |
| **3. General Arrangement/Fuel Handling Room** | | | | | | | | | |
| **3.1** Exhaust location | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | **60.** Recommend having toxic zone area plan developed to access HAZ. | • ABS $NH_3$ Guide to be used for guidance |

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking | | | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| | | | | S | L | RR | | | |
| **3.2** $NH_3$ leak in FSS room | • $NH_3$ leak<br>Connection failure<br>Pipe failure/crack<br>Fatigue<br>Seal failure (compressor and other rotating machinery)<br>Over-pressurisation | • Fire<br>• Explosion<br>• High temperature<br>• Radian heat<br>• $NH_3$ tank fuel warming up and exposure to high temperature<br>• Damage to secondary barrier<br>• PRV discharging to vent mast<br>• Damage to fuel supply room<br>• Release of $NH_3$ | • Asset | 2 | D | 2D | • Gas detection (based on LEL)<br>• Fire detection<br>• Shutdown of ventilation<br>• Shutdown of damper<br>• Water spray<br>• Water curtain at entrance<br>• PPE, eyewash, shower outside FSS room entrance<br>• Automatic Shutdown of tank valves and fuel supply valves | **61.** FSS room is under pressurised (extraction ventilation)<br>**62.** Consider FSS room door are to be gas tight<br>**63.** Reconsider ventilation philosophy instead of shutting down consider additional air circulation to disperse $NH_3$<br>**64.** Reconsider exhaust location<br>**65.** philosophy for ammonia catch system to consider leakage scenario | • Fire dampers are gas tight<br>• Refer to IGF: 5.11.1 for more guidance<br>• Eyewash and shower outside FSS room is in a Hazardous area. Is this allowed |
| | | • Gas in emergency generator room | • Asset | 3 | D | 3D | | **66.** Hazards associated with FSS room (emission) with respect to all other spaces and openings are to be reconsidered and re-examined<br>Hazards associated with FSS room (leak, fire\explosion, etc.) with respect to all other spaces and openings are to be reconsidered and relooked | • Refer to ABS $NH_3$ Guidance |
| | | • Gas in $CO_2$ room | • Asset | 3 | D | 3D | | | |
| | | • Gas in engine room | • Asset | 4 | D | 4D | | | |
| | | • Gas in steering room | • Asset | 4 | D | 4D | | | |
| | • Shutdown of reliquification room | • Loss of boil off gas management system i.e., reliquification<br>• Tank PRV will open<br>• Tank over-pressurisation<br>• $NH_3$ vent to atmosphere via vent mast | • Asset | 3 | C | 3D | • Single reliquifaction plant<br>• | **67.** Consider tank management equipment to be located in separate space<br>Consider IGF requirement to have redundancy in static equipment from reliquefication system<br>Consider conducting HAZOP/FMEA to prove availability of the reliquefication and BOG management system for P-T management of $NH_3$ tanks.<br><br>See recommendation #73 | • Current design takes credit for managing P-T of tank<br>• Current proposal is only single train for reliquefication equipment<br>• Refer to IGF Code 6.91 (IACS), IGF Code 6.9.6:9.6.1 for more guidance<br>• If system is design not to vent tank relief due to liquefaction failure can be diverted to $NH_3$ catch system |
| No PFD/GA available therefore other HAZ was not identified at this stage | | | | | | | | | |

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking S | Risk Ranking L | Risk Ranking RR | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| **4. General Arrangement/Fuel Handling Room/Fuel Transfer/Fuel preparation /Reliquification/pumps/piping** | | | | | | | | | |
| **General Recommendations & Section Notes** | | | | | | | | **68.** Engine room double wall piping exhaust inlet to be provided and HA drawing to be updated | |
| **4.1** Ammonia leak | | | | | | | | | • See previous node 3.2 |
| **4.2** Poor ventilation | • loss of power<br>• fan breakage | • loss of air circulation<br>• buildup of ammonia in FSS Room<br>• fire<br>• explosion<br>• loss of reliquification<br>• tank pressure rising | • Asset | 2 | C | 2C | • Complies with IGF Code<br>• Alarms upon loss of ventilation<br>• Switch over to fuel over mode & shutdown of FSS Room<br>• 2*100% exhaust fans<br>• fans are on emergency power circuit | **69.** Consider redundancy requirements of IGF Code or equivalent<br>**70.** Consider Emergency additional ventilation upon detection of $NH_3$ | • FSS Room is maintained with a negative pressure Shipyard is considering that during an emergency BOG will go to the ammonia catch system |
| **4.3** Fire in FSS Room | • ammonia leak<br>• overheating of electrical circuit<br>• overheating of rotating equipment<br>• short circuit | • heat radiation impacting ammonia fuel storage tank<br>• loss of reliquification | | 2 | C | 2C | • gas detection<br>• fire detection<br>• shutdown<br>• automatic water mist system<br>• ventilation stop and fire dampers close | **71.** Fire safety shutdown safety philosophy and detailed HAZOP to be conducted<br>**72.** Application of water mist system to be reevaluated considering that ammonia can dissolve in water and create a vacuum or over pressurisation due to high expansion ratio and damper closure | • all valves in FSS Room are pneumatic IGF Explosion prevention safety principles |
| **4.4** Re-liquification plant failure | • Leak<br>• Electrical fault<br>• Loss of power | • Loss of Boil off gas management system i.e., reliquification<br>• Tank PRV will open<br>• Tank over-pressurisation<br>$NH_3$ vent to atmosphere via vent mast | Asset | 3 | C | 3D | | **73.** Re-evaluate single re-liquification plant philosophy with respect to maintaining tank pressure for all conditions (IGF Code requirement applies) | • IGF Code redundancy requirements or equivalent Consider zero discharge ammonia philosophy into system design |
| **4.5** Power loss | No additional risks identified by the team. See previous nodes for related power loss scenarios. Design will comply with IGC/IGF Code and standard practices. | | | | | | | | |

| ***System Level Nodes - Hazard Scenario*** | ***Potential Cause*** | ***Consequences*** | ***Category*** | ***Risk Ranking*** | | | ***Effective Safeguard*** | ***Recommendations (R#)*** | ***Comments*** |
|---|---|---|---|---|---|---|---|---|---|
| | | | | ***S*** | ***L*** | ***RR*** | | | |
| **4.6** Contaminated return fuel | No risks identified by the team because the system is still under development. Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | **74.** MAN has to address detection of contaminated ammonia fuel and separation philosophy | |
| **4.7** Explosion in FSS Room | • $NH_3$ leakage | • damage to Generator room/ER Room<br>• damage to structure<br>• damage to fuel ammonia tank | • Asset<br>• Human | 4 | B | 4B | • electrical equipment suitable for HA<br>• gas detector<br>• continuous ventilation<br>• safety shutdown | **75.** Consider cofferdam between FSS Room and tank secondary barrier | • TCS room is on weather deck, which is the secondary barrier for the Type-A tank |
| **4.12** Drainage in FSS Room | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | **76.** Consider drain provision and drain collection from FSS room and evaluate the capacity required for drainage collection Consider inventory monitoring in the drain tank drain treatment to be provided to meet regulations to protect aqua life | • drainage from FSS room collected in one drainage tank drain from FSS Room will be considered hazardous and will be separated from other drainage. Code requirements to be applied |
| **4.13** Ammonia catch system drainage | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | **77.** ammonia catch system contaminated water collection and treatment to be provided to meet discharge standard and protect aqua life ammonia catch system to be designed to provide monitoring of the system, to determine when to recharge catch fluid | • Ammonia catch system is in the design development stage. Further HAZID/HAZOP to be conducted once developed |
| **4.14** Gas blow by from ammonia catch system | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | **78.** to be addressed in HAZOP vent from ammonia catch systems to be identified as HA | |
| **4.15** Liquid ammonia leaking in FSS Room | • pipe break<br>• connection failure<br>• sealing failure<br>• fatigue | • gas in FSS Room<br>• low temperature exposure to deck structure | • Asset<br>• Human | 3 | C | 3D | • low temperature carbon steel<br>• gas detection<br>• shutdown | **79.** Consider Liquid leakage collection and monitoring to be designed to address the toxicity issue Study to be done to address the risk due to the leakage in the FSS room considering pressurised cold leakage and ventilation and firefighting philosophy | • Liquid ammonia can be pressurised |

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking S | L | RR | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| **4.16** Purging capabilities | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | **80.** Purging capabilities of the system to be developed | |
| **4.17** Dropped object on FSS Room | • Cargo handling operations | • No impact. | Asset | 3 | B | 2C | • No cargo handling allowed above FSS room | **81.** Dropped object study to be performed | |
| **5. GA Machinery space (ER) / Use of Fuel / Engine Maintenance Activity / Engine** | | | | | | | | | |
| **General Recommendations & Section Notes** | | | | | | | | **82.** Engine is under development and therefore the engine risk will be addressed in a later FMEA Engine manufacturers are to conduct component-level FMEA to see if ammonia can migrate into other systems and areas | • Design complies with IGF and class society rules |
| **5.1** Double-walled pipe air circulation failure | • exhaust fan failure<br>• power loss<br>• electrical fault<br>• blackout<br>• improper maintenance | • unsafe atmosphere in annulus space | Asset | 2 | C | 2C | • Flow switch<br>• Emergency shutdown<br>• Pressure differential<br>• switch to liquid fuel<br>• alarms<br>• fans on emergency power | | |
| **5.2** Inner wall pipe failure | • corrosion<br>• overstress<br>• fatigue<br>• vibration<br>• uninspectable system<br>• condensation in the annular space | • Annular space full of ammonia gas<br>• Over-pressurisation of annular space<br>• Outer pipe failure due to over-pressurisation | Asset | 2 | C | 2C | • Outer pipe designed to withstand worst case inner failure<br>• alarms - flow and pressure<br>• shutdown of gas supply<br>• gas detector in annular space<br>• gas detector in engine room<br>• annular space is negatively pressurised<br>• annular space ventilation is provided with dry air<br>• proper material selection | **83.** inspection and maintenance plan and procedures are to be developed<br>**84.** post-maintenance inspection | • Outer pipe will be designed to survive worst case pressure<br>• Refer to IGF: 9.8.1 for more guidance. |
| **5.3** Failure of outer pipe | • corrosion<br>• overstress<br>• fatigue<br>• vibration<br>• uninspectable system<br>• condensation in the annular space | • loss of annular space negative pressure<br>• ammonia leaking into engine room | Asset | 3 | B | 2C | • periodic testing of annular space with pressure<br>• visual inspection<br>• automatic sequence to test annular space tightness | | |
| **5.4** Inner and outer wall pipe failure | • Dropped object<br>• outer pipe failure due to over-pressurisation<br>• parts from rotating equipment, Stopped object<br>• overstress | • Human exposure<br>• Ammonia in engine room<br>• toxic atmosphere | Asset | 3 | C | 3C | • gas detector<br>• shutdown<br>• pressure and flow switch | **85.** piping arrangement to be such that there is low probability of Dropped object damage develop appropriate engine room entrance procedures considering necessary PPE | • Engine room only has a cooling water system, which will cool the glycol water system in the FSS Room |

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking S | L | RR | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | • Refer to IGF 7.3.4.4, IGF 9.6.1 for more guidance |
| **5.6** Ammonia in the cooling water system<br>**5.7** Ammonia in the lubricating system | No additional risks identified by the team. Design will comply with IGC/IGF Code and standard practices. | | | | | | | **86.** Engine FMEA to be conducted venting of $NH_3$ from engine auxiliary system in case of single failure to be designed and appropriate venting to be provided | • Refer to IGF 3.1.4 for more guidance |
| **5.8** Fire in the engine room | • overheating of equipment<br>• lubricating oil leak on hot surface<br>• electrical fire | • smoke<br>• fire | Asset<br>Human | 4 | C | 4C | • fire alarm<br>• manual shutdown<br>• water mist system<br>• SOLAS compliant firefighting systems | **87.** Shutdown switchover philosophy to be developed and $NH_3$ fuel to be purged back to FSS Room | • See node 2.2 |
| **5.9** Flooding | No additional risks identified by the team. Design will comply with IGC/IGF Code and standard practices. | | | | | | | | |
| **5.10** Trapped ammonia during exposure during maintenance | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | **88.** develop proper operational and maintenance procedures for the system and ensure there is no trapped ammonia | • Trapped ammonia can occur if design is improper. FMECA to be conducted to address the issue |
| **5.11** Exhaust slip | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | **89.** During testing, engine manufacturer to collect data and address accordingly | |
| **6. Vent / Vent lines /Vent Mast** | | | | | | | | | |
| **General Recommendations & Section Notes** | | | | | | | | **90.** All gas detection etc., for the venting systems is to comply with ABS Ammonia Guide Vent mast system drainage to be provided and considering that ammonia dissolved in water | |
| **6.1** Vent mast location | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | **91.** dispersion analysis to be conducted to justify the height of the mast: consider defining toxic zones are to be defined and safety to the human is to be based upon the PPE level exposure for worst case discharge of ammonia | • consider following ABS ammonia guide |

| *System Level Nodes - Hazard Scenario* | *Potential Cause* | *Consequences* | *Category* | *Risk Ranking* | | | *Effective Safeguard* | *Recommendations (R#)* | *Comments* |
|---|---|---|---|---|---|---|---|---|---|
| | | | | *S* | *L* | *RR* | | | |
| **6.2** Ammonia release to vent mast during operation | No additional risks identified by the team. Design will comply with IGC/IGF Code and standard practices. | | | | | | | | |
| **6.2.1** Ammonia release to vent mast at port | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | **92.** Operational and safety procedures while in port are to consider port requirements and be incorporated into the design | |
| **6.2.2** Ammonia release to vent mast during bunkering | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | **93.** Dispersion analysis to be conducted | • Fill in nodes from previous discussion |
| **6.2.3** Ammonia release to FSS Room exhaust | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | **94.** consider exhaust fan to exhaust in the upward direction, to have a better gas dispersion in the case of leakage | • The exhaust fans are venting in the horizontal direction |
| **6.2.4** Ammonia release to double walled piping exhaust | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | **95.** Exhaust location from double-walled pipe to be determined and exposure to accommodations to be considered | |
| **6.3** Vent mast ignited | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | | • Check IGF/IGC Code for vent mast fire requirement |
| **6.4** Ammonia catch system exhaust | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | | |
| **6.5** Glycol water system exhaust | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | **96.** Exhaust locations to be determined according to IGF Requirement | |
| **7. Safety System/ Emergency** | | | | | | | | | |
| **7.1** Escape - Cat A machinery space fire | • Fire in CAT A space (ER, FSS) | • Unable to escape<br>• LSA expose to ammonia release from vent mast<br>• Water on escape route | Human | 4 | C | 4C | | **97.** Consider LSA to be provided with self-contain breathing PPE etc. suitable for $NH_3$ considering risk of exposure - SOLAS for gas carrier<br>**98.** Consider conducting EER study considering | • A this point design is not clear or enough information available to evaluate escape route<br>• Refer to SOLAS III/31.1.6 and LSA IV/4.8, ABS |

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking S | L | RR | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | fire, $NH_3$ release, other emergencies<br>**99.** Consider applying A-60 boundary around containment system or any escape route with possibility to direct fire exposure or possibility of $NH_3$ - IGF 11.3.2 | ammonia as fuel guide 12/6.4 for more guidance |
| **7.2** PPE Requirement | | | | | | | | **100.** PPE and mask requirement/philosophy are to be developed and locations to be determined | |
| **7.3** ESD Philosophy | | | | | | | | **101.** Emergency shutdown philosophy and procedures are to be developed and to be considered during the design | |
| **7.4** Structural fire protection | | | | | | | | **102.** FSS Room structural requirements are to comply with IGF requirements | |
| **7.5** Firefighting | | | | | | | | **103.** Appropriate firefighting systems to be provided considering ammonia leaks and ammonia fire Emergency evacuation and rescue procedures for worst case discharge to be developed | |
| **8. Ship's Operation / Simultaneous Operation** | | | | | | | | | |
| **General Recommendations & Section Notes** | | | | | | | | | • During cargo loading/unloading no crew on the deck |
| **8.1** Bunkering and Cargo Loading | | | | | | | | | • Bunkering and cargo operations will not be done simultaneously. One operation at a time |
| **8.2** Crew change & pilotage | | | | | | | | | • No new issue identified |
| **8.3** Damage to deck piping due to cargo loading/unloading | • Dropped object<br>• Over-pressurisation<br>• inappropriate assembly<br>• improper maintenance<br>• vibration<br>• fatigue<br>Trapped inventory | • ammonia on the deck<br>• toxic cloud<br>• fire<br>exposure to people at port and on ships | Asset<br>Human | 3 | C | 3C | • thermal relief<br>• mechanical protection (100 mm angle bar)<br>• piping is provided with an expansion loop<br>all welded piping on deck | **104.** Dropped object study to be performed considering cargo loading/unloading and maintenance Consider breakage of piping and perform dispersion analysis to | • 100-mm angle bar is provided for the piping on deck<br>• Consider restricting inventory during cargo operations |

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking | | | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| | | | | S | L | RR | | | |
| | | | | | | | | consider exposure to humans and toxicity zone<br>Consider the alternative to capture the fluid and reuse it | deck piping is single walled piping<br>• During the cargo loading/unloading consider de-inventorying the on-deck ammonia piping |
| **8.4** Cargo loading/unloading overhead lifting over bunker area | No additional risks identified by the team. Design will comply with IGC/IGF Code and standard practices. | | | | | | | | |
| **8.5** Gas freeing | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | **105.** Gas freeing and gassing up operations are to be studied for emergency, maintenance, dry docking situation and appropriate solutions are to be developed<br>Consider addressing the ammonia discharge issue during gas freeing<br>Evaluate need for nitrogen if doing independently | • ammonia tank is 12,000 $m^3$<br>• gas freeing operation will be done using bunkering vessels nitrogen system |
| **8.6** gassing up | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | | |
| **8.7** Maintenance and inspection | | | | | | | | **106.** Maintenance and inspection procedures are to be developed | |
| **8.8** Out of spec fuel | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | **107.** Fuel quality control and fuel spec to be developed | |
| **8.9** Port entry | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | **108.** local authorities are to be consulted for grounding risk and proper procedures are to be developed | |
| **8.10** Port departure | No additional risks identified by the team. Design will comply with IGC/IGF Code and standard practices. | | | | | | | | |
| **8.11** heavy weather - failure of equipment/piping | • extreme dynamic load high rolling | • component comes loose<br>• gas leakage<br>• Ammonia leak from piping | Asset | 3 | C | 3C | | **109.** Equipment foundations/supports are to be designed considering heavy weather dynamic loads<br>Ammonia equipment ais to be designed for full operations | • Engine and ammonia tank design to comply with IGC Code which considers pitch, roll, etc. |

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking | | | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| | | | | S | L | RR | | | |
| | | | | | | | | considering heavy dynamic loads and heave/roll/pitch for the expected operating conditions in heavy weather | |

# Appendix XII – List of Recommendations BC Proposal II

| Recommendation Type | BC II HAZID References | Recommendations |
|---|---|---|
| **1. General Arrangement/Bunkering** | | |
| Safety / Additional Study | **General Recommendations** | **1.** Considering cargo carriage (coal), hazards if any with regards to the cargo is to be considered. |
| Procedure/ Additional Study | | **2.** Once the bunkering philosophy is developed, bunkering operations to be further studied |
| Design | | **3.** Develop bunkering piping arrangement between bunker manifold and TCS/FSS Room |
| Design | | **4.** Develop detailed GA for FSS/TCS Rooms |
| Design / procedure | | **5.** Develop purging monitoring requirement to confirm that purging process removes all ammonia |
| Additional study | **1.1** Bunker Manifold | **6.** Cause and effects of ESD system is to be further evaluated considering ammonia and its toxicity |
| Emission/additional study | | **7.** Drip tray sizing and philosophy of collected fluid handling to be studied |
| Gas detection / additional study | | **8.** Further analysis of number and placement of gas detectors around bunker stations to be conducted |
| Pollution | | **9.** Local Regulations and IMO Regulations are to be studied for discharge into the sea |
| Design | | **10.** Develop detailed GA for FSS/TCS Room's |
| Personnel safety | | **11.** Bunker station locations and crew presence are to be studied considering potential ammonia release |
| Personnel safety | | **12.** crew near bunker manifold are to be provided with appropriate PPE and gas detectors |
| Firefighting | | **13.** consider providing water spray system for local control station |
| Safety | **1.2** Bunker Manifold over-pressurisation during bunkering operation | **14.** If there is a possibility of Trapped fluid, proper relief arrangement is to be provided (i.e., QC-DC operations between pop-it and ESD valve) |
| Design / Safety | **1.3** Trapped fluid in bunker piping | **15.** Manifold is to be designed for the maximum vapour pressure buildup at 45 0C for Trapped fluid or for emergency shutdown with the possibility of Trapped fluid |
| Safety | | **16.** For Trapped fluid, thermal expansion is to be considered and thermal relief valve to be provided |
| Safety | | **17.** For various ESD scenarios, study to be conducted on the scenarios and the potential for Trapped fluid in the different scenarios |
| Vent / safety | | **18.** Any thermal relief provided to be vented properly in to vent mast |
| Safety / Design | | **19.** How to purge and handle inventory in bunker piping during ESD and normal operation is to be considered and proper design is to be developed |
| Inspection | **1.5** Loss of containment - Piping between bunker station and fuel tank | **20.** consider including visual inspection of the ammonia on deck piping before bunkering when developing the operations manual |
| Additional analysis | | **21.** consider the need for piping stress analysis to address pipe failure due to overstress, fatigue, etc. and justification to be provided. |

| Recommendation Type | BC II HAZID References | Recommendations |
|---|---|---|
| Maintenance / inspection | | **22.** inspection and maintenance plan for this piping is to be developed considering fatigue fracture failure |
| Procedure | **1.6** Make & Break of bunkering hose during normal operations | **23.** Proper connect/disconnect procedures are to be developed to prevent Trapped fluid |
| Personnel safety | **1.7** Emergency Breakaway | **24.** Investigate how much ammonia can be released during emergency disconnect and if this will affect any crew in the bunkering control station |
| Design | | **25.** Dry breakaway coupling is to be provided |
| Fire safety | **1.8** Emergency on the Bulk Carrier | **26.** piping insulation has to consider the fire rating |
| Fire safety / Additional study | | **27.** fire scenario on the bulk carrier during bunkering is to be investigated |
| Personnel safety / emergency | **1.9** Emergency on bunker supply ship | **28.** Emergency procedures are to be developed considering an emergency on bunker vessel |
| Personnel safety | **1.10** Vessel Drift Away | **29.** Investigate how much ammonia can be released during emergency disconnect and if this will affect any crew in the bunkering control station |
| Design / safety | | **30.** Dry breakaway coupling is to be provided |
| Safety / venting | **1.12** Over-pressurisation of tank during bunkering | **31.** Investigate Type-A tank secondary barrier ventilation discharge into the vent mast with all other venting and potential for high backpressure and reverse flow |
| Additional study | **1.13** Freeboard height difference between bunkering vessel and Bulk Carrier | **32.** Conduct compatibility study between the two vessels and evaluate need for crane on bulk carrier |
| Additional study / safety | **1.14** Location of mooring line and snapping of mooring line | **33.** Evaluate the location of the moorings line with respect to the breaking hazard and risk to the bunker manifold and hoses during bunkering operations |
| **2. General Arrangement / Fuel Storage** | | |
| Personnel safety / additional analysis / safety | **General** | **34.** Dispersion analysis for $NH_3$ release considering normal, upset, emergency and fire scenario to be performed to estimate $NH_3$ exposure to various area. |
| Design | | **35.** Based upon proposed GA, consider fuel oil as primary fuel and ammonia as secondary source of fuel |
| Additional study | **2.1** Dropped Object | **36.** Dropped object study considering cargo handling are to be developed considering port operations |
| Additional study / hazardous area | **2.3** Hatch Operation | **37.** Re-evaluate the arrangement or conduct a study to show that sparking will not cause a fire hazard |
| Structural protection / dire safety | **2.4** Fire in cargo hold | **38.** Consider cofferdam between cargo hold space and ammonia fuel tank space with A-60 boundary |
| Design / safety | | **39.** tank relief valve calculations to include cargo fire and heat load |
| Hazardous area | **2.5** HAZ extended over cargo tank | **40.** Consider electrical equipment to be safe certified (coal and ammonia) |
| Ventilation / safety | **2.6** Fire in FSS Room | **41.** Reconsider shutdown of ventilation philosophy for FFSS room (due to 800 to 1 expansion ration of $LNH_3$ can create over pressure)<br>If water spray system is activated in NHS room full of $NH_3$ gas it can create vacuum due to solubility of $NH_3$ in water, pressure vacuum protection should be considered |

| Recommendation Type | BC II HAZID References | Recommendations |
|---|---|---|
| Gas detection / safety | | **42.** Gas detection, alarm and shut down philosophy for ammonia are to be based on toxicity level not LEL level |
| Additional study | | **43.** Require dispersion analysis see general recommendation |
| Structural protection | | **44.** FSS Room is considered a category A machinery space and has to be provided with an A-60 boundary |
| Structural protection | **2.7** Explosion in FSS Room (FSS Room location on top of secondary barrier) | **45.** FSS Room has to be separated by a cofferdam. See IGF 11.3.1 and 11.3.3 |
| Design | | **46.** TCS arrangement to be developed per IGF Requirements |
| Structural protection | | **47.** Consider explosion relief hatch to limit explosion consequences |
| Safety / emergency | **2.8** $NH_3$ tank primary barrier failure | **48.** primary barrier failure when ship is in port, emergency procedures are to be developed |
| Additional study / personnel safety | | **49.** gas dispersion analysis to be considered if there is a potential for human exposure or toxicity exceeding limit |
| Design / Ven / emergency | | **50.** Consider emergency evacuation of NH3 tank and inner-barrier space and provide proper arrangement to handle such event |
| Design | **2.9** Tank connection failure | **51.** Tank connection space arrangement to be developed |
| Design | | **52.** TCS Arrangement to be developed |
| Personnel safety / Procedure / safety | **2.10** Collision | **53.** Emergency procedures are to be developed |
| Personnel safety / emergency | | **54.** Look at worst case scenario and the volume of gas released in case of incident in port/economic zone concerned with the port authorities. |
| Procedure / safety | **2.11** **O**ver-pressurisation of tank | **55.** Fuel tank management considering fuel consumption to be developed |
| Design / safety | | **56.** Redundancy in Re-liquefaction plant to be considered<br><br>See recommendation # 1 (hazardous areas) |
| Procedure | **2.12** **O**verfilling of tank | **57.** Client to develop cargo liquid management and liquid level measurement system and detailed procedure |
| Structural protection / safety | **2.13** Secondary barrier damage | **58.** provide cofferdam between cargo tank and ammonia tank |
| Inspection / procedure | | **59.** Develop procedures to detect any damage to secondary barrier |
| Gas detection / inspection | | **60.** Upon detection of gas in secondary barrier, all surrounding area is to be inspected for damage |
| Design / safety | **2.16** Power loss | **61.** Consider providing redundancy to maintain tank pressure/temperature<br>Consider catch system design to handle relief vent from ammonia |
| **3. General Arrangement/Fuel Handling Room** | | |
| Personnel safety | **3.1** Exhaust location | **62.** Recommend to have toxic zone area plan developed to access HAZ. |
| Design | **3.2** $NH_3$ leak in FSS room | **63.** FSS room is to be under pressurised (extraction ventilation) |

| Recommendation Type | BC II HAZID References | Recommendations |
|---|---|---|
| Design / safety | | **64.** Consider FSS room door are to be gas tight |
| Ventilation | | **65.** Reconsider ventilation philosophy instead of shutting down consider additional air circulation to disperse $NH_3$ |
| Pollution | | **66.** philosophy for ammonia catch system to consider leakage scenario |
| Design / safety | | **67.** Consider tank management equipment to be located in separate space<br>Consider IGF requirement to have redundancy in static equipment from reliquefication system |
| Additional study | | **68.** Consider conducting HAZOP/FMEA to prove availability of the reliquefication and BOG management system for P-T management of NH3 tanks |
| Design / additional study | **3.3** $NH_3$ Leak in TCS (Tank Connection Space) | **69.** TCS arrangement with respect to FSS Room is to be further developed to conduct a proper HAZID |
| Gas detection / personnel safety | **3.4** Vent inlet/outlet and vent mast location | **70.** Gas detection and alarm philosophy to be based on PPE level considering human exposure, not on LEL<br>further study to be considered to see the possibility of vent gas getting into the FSS Room |
| Additional study | **3.5** Cargo loading and unloading/ dust | **71.** Further study to be done to see if dust will migrate to FSS Room and create a safety issue |
| **4. General Arrangement/Fuel Handling Room/Fuel Transfer/Fuel preparation /Reliquification / pumps / piping** | | |
| Ventilation | - **General** | **72.** Engine room double-wall piping exhaust inlet to be provided and HA drawing to be updated |
| Additional study / safety | **4.1** distance between engine room and FSS Room & Trapped inventory unable to purge the system in emergency | **73.** further study to be conducted for draining of fuel supply system between purging FSS Room and engine connection |
| Additional study | | **74.** Once the system has been designed, detailed HAZOP to be conducted |
| Procedure / design | | **75.** During the system design, consider how to drain the system during an emergency |
| Additional study | **4.2** Damage to $NH_3$ piping on deck | **76.** Dropped object study to be performed considering cargo loading/unloading and maintenance |
| Design / safety | **4.4** Poor ventilation | **77.** Consider redundancy requirements of IGF Code or equivalent |
| Ventilation | | **78.** Consider Emergency additional ventilation upon detection of $NH_3$ |
| Fire safety / Additional study | **4.5** Fire in FSS Room | **79.** Fire safety shutdown safety philosophy and detailed HAZOP to be conducted |
| Firefighting | | **80.** Application of water mist system to be reevaluated considering that ammonia can dissolve in water and create a vacuum or over pressurisation due to high expansion ratio and damper closure |
| Design / safety | **4.6** Re-liquification plant failure | **81.** Re-evaluate single re-liquification plant philosophy with respect to maintaining tank pressure for all conditions (IGF Code requirement applies) |
| Design | **4.8** Contaminated return fuel | **82.** Engine manufacture has to address detection of contaminated ammonia fuel and separation philosophy |
| Ventilation / design / procedure | **4.9** Location of master shutoff valve is in FSS Room therefore large | **83.** Shipyard and engine manufacturer have to provide detailed information of the location of the master shutoff valve relative to the FVT<br>Consider Fuel handling systems to be designed to handle 2*180-meter length of inventory or re-design to reduce the |

| Recommendation Type | BC II HAZID References | Recommendations |
|---|---|---|
| | inventory between valve and engine connection | inventory<br>Double walled piping ventilation locations are a hazardous zone and are to be evaluated for worst case failure scenario (complete failure of inner wall) |
| Structural safety | **4.10** Explosion in FSS Room | **84.** Consider cofferdam between FSS Room and tank secondary barrier |
| Pollution | **4.11** Drainage in FSS Room | **85.** Consider drain provision and drain collection from FSS Room and evaluate the capacity required for drainage collection<br>Consider inventory monitoring in the drain tank drain treatment to be provided to meet regulations to protect aqua life |
| Pollution | **4.12** Ammonia catch system drainage | **86.** ammonia catch system contaminated water collection and treatment to be provided to meet discharge standard and protect aqua life<br>ammonia catch system to be designed to provide monitoring of the system, to determine when to recharge catch fluid |
| Vent / additional study | **4.13** Gas blow by from ammonia catch system | **87.** to be addressed in HAZOP<br>vent from ammonia catch systems to be identified as HA |
| Personnel safety / design | **4.14** Liquid ammonia leaking in FSS Room | **88.** Consider Liquid leakage collection and monitoring to be designed to address the toxicity issue<br>Study to be done to address the risk due to the leakage in the FSS room considering pressurised cold leakage and ventilation and firefighting philosophy |
| Design | **4.15** Purging capabilities | **89.** Purging capabilities of the system to be developed |
| Additional study | **4.16** Dropped object on FSS Room | **90.** Dropped object study to be performed |
| **5. GA Machinery space (ER) / Use of Fuel / Engine Maintenance Activity / Engine** | | |
| Additional study | **General** | **91.** Engine is under development and therefore the engine risk will be addressed in a later FMEA<br>Engine manufacturers are to conduct component level FMEA to see if ammonia can migrate into other systems and areas |
| Maintenance / inspection | **5.2** Inner wall pipe failure | **92.** inspection and maintenance plan and procedures are to be developed |
| Inspection | | **93.** post-maintenance inspection |
| Personnel safety / procedure | **5.4** Inner and outer wall pipe failure | **94.** piping arrangement to be such that there is low probability of Dropped object damage<br>develop appropriate engine room entrance procedures considering necessary PPE |
| Additional study | **5.6** Ammonia in the cooling water system<br>**5.7** Ammonia in the lubricating system | **95.** Engine FMEA to be conducted<br>venting of $NH_3$ from engine auxiliary system in case of single failure to be designed and appropriate venting to be provided |
| Procedure | **5.8 F**ire in the engine room | **96.** Shutdown switchover philosophy to be developed and $NH_3$ fuel to be purged back to FSS Room |
| Additional study | **5.9** Flooding | **97.** Special study and dispersion analysis to be performed considering accidental scenarios such as grounding, collision, tank damage |
| Safety / procedure | **5.10** Trapped ammonia during exposure during maintenance | **98.** develop proper operational and maintenance procedures for the system and ensure there is no Trapped ammonia |
| Testing / Pollution | **5.11** Exhaust slip | **99.** During testing, man to collect data and address accordingly |

| Recommendation Type | BC II HAZID References | Recommendations |
|---|---|---|
| **6. Vent / Vent lines /Vent Mast** | | |
| Gas detection | **General** | **100.** All gas detection etc. for the venting systems to comply with ABS Ammonia Guide<br>Vent mast system drainage to be provided and considering that ammonia dissolved in water |
| Additional study | **6.1** Vent mast location | **101.** dispersion analysis to be conducted to justify the height of the mast<br>consider defining a toxic zones and safety to the human based upon the PPE level exposure for worst-case discharge of ammonia |
| Procedure / design | **6.2.1** Ammonia release to vent mast at port | **102.** Operational and safety procedures while in port are to consider port requirements and be incorporated into the design |
| Additional study | **6.2.2** Ammonia release to vent mast during bunkering | **103.** Dispersion analysis to be conducted |
| Ventilation | **6.2.3** Ammonia release to FSS Room exhaust | **104.** Consider exhaust fan to exhaust in the upward direction, to have a better gas dispersion in the case of leakage |
| Ventilation | **6.2.4** Ammonia release to double walled piping exhaust | **105.** Exhaust location from double walled pipe to be determined and exposure to accommodations to be considered |
| Ventilation | **6.4** Ammonia catch system exhaust<br>**6.5** Glycol water system exhaust | **106.** Exhaust locations to be determined according to IGF Requirement |
| **7. Safety System/ Emergency** | | |
| Personnel safety | **7.1** Escape - Cat A machinery space fire | **107.** Consider LSA to be provided with self-contain breathing PPE etc. suitable for NH3 considering risk of exposure - SOLAS for gas carrier |
| Personnel safety / additional study | | **108.** Consider conducting EER study considering fire, NH3 release, other emergencies |
| Fire safety | | **109.** Consider applying A-60 boundary around containment system or any escape route with possibility to direct fire exposure or possibility of $NH_3$ - IGF 11.3.2 |
| Personnel safety | **7.2** PPE Requirement | **110.** PPE and mask requirement/philosophy are to be developed and locations to be determined |
| Design / procedure | **7.3** ESD Philosophy | **111.** Emergency shutdown philosophy and procedures are to be developed and to be considered during the design |
| Structural fire protection | **7.4** Structural fire protection | **112.** FSS Room structural requirements are to comply with IGF Requirements |
| Firefighting | **7.5** firefighting | **113.** Appropriate firefighting systems to be provided considering ammonia leak and ammonia fire<br>Emergency evacuation and rescue procedures for worst case discharge to be developed |
| **8. Ship's Operation / Simultaneous Operation** | | |
| | **8.3** Cargo loading/unloading overhead lifting over cargo tank and FSS Room | **114.** If planned to have maintenance in FSS Room during loading/unloading, then dropped-object study to be conducted |

| Recommendation Type | BC II HAZID References | Recommendations |
|---|---|---|
| Additional study | **8.4** Damage to deck piping due to cargo loading/unloading | **115.** Dropped-object study to be performed considering cargo loading/unloading and maintenance Consider breakage of piping and perform dispersion analysis to consider exposure to humans and toxicity zone Consider the alternative to capture the fluid and reuse it |
| Design / procedure | **8.6** Gas freeing<br>**8.7** gassing up | **116.** Gas freeing and gassing up operations are to be studied for emergency, maintenance, dry docking situation and appropriate solutions are to be developed Consider addressing the ammonia discharge issue during gas freeing<br>Evaluate need for nitrogen if doing independently |
| Maintenance | **8.8** Maintenance and inspection | **117.** Maintenance and inspection procedures are to be developed |
| Quality control | **8.9** Out of spec fuel | **118.** Fuel quality control and fuel spec to be developed |
| Safety / emergency | **8.10** Port entry<br>**8.11** Port departure | **119.** local authorities are to be consulted for grounding risk and proper procedures are to be developed |
| Design | **8.12** Heavy weather - failure of equipment/piping | **120.** Equipment foundations/supports are to be designed considering heavy weather dynamic loads Ammonia equipment is to be designed for full operations considering heavy dynamic loads and heave/roll/pitch for the expected operating conditions in heavy weather |

# Appendix XIII – Hazard Register BC Proposal II – Fuel Storage Tank in Cargo Area

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking S | Risk Ranking L | Risk Ranking RR | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| **0. Introductory Notes** | | | | | | | | | |
| **General Arrangement Notes** | • Distance between FSS Room and Engine Room is approximately 162 metres<br>• FSS Room mounted on the weather deck<br>• Vent mast is about 12 metres above weather deck<br>• TCS in FSS Room<br>• TCS Room has airlock access<br>• Suggest keeping in mind NIOSH limits: REL 25ppm (8hr), PEL 50ppm, IDLH 300ppm. https://www.cdc.gov/niosh/idlh/7664417.html | | | | | | | | |
| **Re-liquification System Notes** | • No redundancy currently planned for re-liquification. Only ammonia consumer is the main engine. Type of re-liquification plant is to be sub-cooler<br>• Connections from tank dome to the FSS Room are located on the side of the room | | | | | | | | |
| **Engine Notes** | • Ammonia Catch system is a water absorber. Water will need to be replaced occasionally, with the rate to be determined. Size of tank to be designed for worst case venting scenario. Considerations to be made for the FSS<br>• Room ammonia payload for ammonia catch.<br>• Absorption rate to be considered for the ammonia catch system<br>• ABS Has no direct specification for the water seal system. However, this would be indirectly addressed during a required FMEA.<br>• Piping from Engine to FSS Room is currently double-walled in enclosed spaces, but single walled in open spaces. IGF Code amendment will require double-walled piping on the open deck for LNG<br>• During ammonia slip, ammonia could be handled by SCR.<br>• MSC.458(101), entry into force 1 Jan 2024 : ... "9.5.6 Liquefied fuel pipes shall be protected by a secondary enclosure able to contain leakages. If the piping system is in a fuel preparation room or a tank connection space, the Administration may waive this requirement. Where gas detection as required in 15.8.1.2 is not fit for purpose, the secondary enclosures around liquefied fuel pipes shall be provided with leakage detection by means of pressure or temperature monitoring systems, or any combination thereof. The secondary enclosure shall be able to withstand the maximum pressure that may build up in the enclosure in case of leakage from the fuel piping. For this purpose, the secondary enclosure may need to be arranged with a pressure relief system that prevents the enclosure from being subjected to pressures above their design pressures." | | | | | | | | |
| **1. General Arrangement/Bunkering** | | | | | | | | | |
| **General Recommendations & Section Notes** | | | | | | | | **1.** Considering cargo carriage (coal), HA if any with regards to the cargo is to be considered.<br>**2.** Once the bunkering philosophy is developed, bunkering operations to be further studied<br>**3.** Develop bunkering piping arrangement between bunker manifold and TCS/FSS Room<br>**4.** Develop detailed GA for FSS/TCS Room's<br>**5.** Develop purging monitoring requirement to confirm that purging process removed all ammonia | • Bunker manifold will be nitrogen purged after each bunkering operation, therefore no ammonia in bunker manifold<br>• Two isolation valves at tank dome to isolate bunker piping (liquid/vapour)<br>• bunker hose to be handled and provided by bunker vessel crane<br>• Bunker space is in an open area (Port & Stbd) |

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking S | Risk Ranking L | Risk Ranking RR | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| **1.1** Bunker Manifold | • Joint Failure<br>• Mechanical Damage<br>• Improper connection<br>• Fatigue<br>• Temperature Variation<br>• Vibration<br>• Hose failure | • Fuel Spill<br>• Toxic Atmosphere<br>• Hazardous Atmosphere<br>• Hull Structure Exposed to cold temperature | • Asset | 3 | C | 3C | • Drip Tray<br>• Water Spray System<br>• ESD System (Manual/Auto)<br>• SSL (Ship to Shore Link)<br>• Ammonia gas detector (1 Port and 1 Stbd)<br>• water curtain to protect side shell<br>• Quick disconnect flange<br>• eye wash and shower near bunker manifold<br>• portable foam system | **6.** Cause and effects of ESD system is to be further evaluated considering ammonia and its toxicity<br>**7.** Drip tray sizing and philosophy of collected fluid handling to be studied<br>**8.** Further analysis of number and placement of gas detectors around bunker stations to be conducted<br>**9.** Local Regulations and IMO Regulations are to be studied for discharge into the sea | • Assumption is that bunkering will be controlled remotely after connection is made<br>• Bunker manifold is visible from control station<br>• Drip tray diverts ammonia liquid overboard and side shell is protected by water curtain<br>• IGF requires gas test or further analysis to determine gas detector location<br>• Distance between the bunker control station and bunker manifold is about 10 m<br>• Refer to IGF bunkering system: 8.5.3, 8.5.5 for more guidance |
| | | • Ammonia leakage inside FSS Room | • Asset | 2 | C | 2C | • All welded piping in FSS Room<br>• fixed gas detectors<br>• fixed fire detectors<br>• Fire fighting<br>• Continuous ventilation | | • Not enough information to do a proper hazard assessment at this stage |
| | | • Ammonia leakage inside TCS Room | • Asset | 3 | C | 3C | • FCS Space designed for over pressurisation | **10.** Develop detailed GA for FSS/TCS Room's | • Not enough information to do a proper hazard assessment at this stage |
| | | • ammonia at control station<br>• human exposure | • Human | 3 | C | 3C | • fixed gas detector at bunker manifold<br>• Manual emergency stop<br>• tank pressure and level monitoring<br>• local control of water spray system from control station<br>• Fire and Gas detector | **11.** Bunker station locations and crew presence are to be studied considering potential ammonia release<br>**12.** crew near bunker manifold are to be provided with appropriate PPE and gas detectors<br>**13.** consider providing water spray system for local control station | • Distance between the bunker control station and bunker manifold is about 10 m<br>• Current plan is to have the bunker control station, which is location on Tank #4, is to be manned to control bunker operations |

| *System Level Nodes - Hazard Scenario* | *Potential Cause* | *Consequences* | *Category* | *Risk Ranking S* | *L* | *RR* | *Effective Safeguard* | *Recommendations (R#)* | *Comments* |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | • Water spray system at the bunker station can be isolated from the rest of the water spray system |
| **1.2** Bunker Manifold over-pressurisation during bunkering operation | • Blocked flow (e.g., Tank valve closed, bunker manifold closed) | • pipe breakage<br>• release of ammonia<br>• Hull Structure Exposed to cold temperature | • Asset<br>• Human | 1 | D | 1D | • High-pressure alarm<br>• design pressure of 10 bar (max supply pressure of 6 bar from bunker vessel) | **14.** If there is a possibility of trapped fluid, proper relief arrangement is to be provided (i.e., QC-DC operations between pop-it and ESD valve) | • From bunker flange to tank dome, no pressure relief valve is provided, |
| **1.3** Trapped fluid in bunker piping | • Emergency shutdown – manual<br>• high level in the tank<br>• Over-pressurisation in the tank<br>• Power loss | • Over-pressurisation of the pipe<br>• damage to piping/equipment<br>• release of ammonia | • Asset<br>• Human | 4 | D | 4D | • ESD Trigger only bunker manifold shutdown (tank valve will still be open) | **15.** Manifold is to be designed for the maximum vapour pressure buildup at 45 ° C for Trapped fluid or for emergency shutdown with the possibility of trapped fluid<br>**16.** For trapped fluid, thermal expansion is to be considered and thermal relief valve to be provided<br>**17.** For various ESD scenarios, study to be conducted on the scenarios and the potential for Trapped fluid in the different scenarios<br>**18.** Any thermal relief provided to be vented properly in to vent mast<br>**19.** How to purge and handle inventory in bunker piping during ESD and normal operation is to be considered and proper design is to be developed | • IGF Code: 7.3.1.3 All pipelines or components which may be isolated in a liquid full condition shall be provided with relief valves. |
| **1.4** Overfilling of the tank due to draining of the bunker piping | • inventory inside bunker piping drained | | Asset | 1 | B | 1B | • Design in compliance with IGC Code | | • Not credible event<br>• Current proposal is to drain back bunker piping inventory back to tank |

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking S | L | RR | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| **1.5** Loss of containment - Piping between bunker station and fuel tank | • mechanical damage<br>• fatigue<br>• overstress<br>• corrosion | • leakage at the pipe due to mechanical or fatigue damage<br>• gas leak near non-hazardous spaces<br>• toxic hazardous atmosphere<br>• human exposure to toxic gas<br>• fire/explosion in safe space<br>• hull, accommodation, and/or other structural damage<br>• Gas inside FSS Room or TCS Space | • Asset<br>• Human | 4 | C | 4C | • piping designed to handle all loads<br>• bunker piping is all welded (no threaded connections)<br>• piping thermal expansion study to be done<br>• piping specification meets IGF criteria<br>• During bunkering no cargo handling allowed | **20.** consider including visual inspection of the ammonia on deck piping before bunkering when developing the operations manual<br>**21.** consider need for piping stress analysis to address pipe failure due to overstress, fatigue, etc. and justification to be provided.<br>**22.** inspection and maintenance plan for this piping is to be developed considering fatigue fracture failure | • During bunkering no cargo operations allowed within the vicinity of the ammonia piping<br>• during the cargo operations there is a possibility of damaging the piping on the deck, which should be analysed by the shipyard/owner<br>• IGF Code: 7.3.4.4 High pressure fuel piping systems shall have sufficient constructive strength. This shall be confirmed by carrying out stress analysis and taking into account: .1 stresses due to the weight of the piping system; .2 acceleration loads when significant; and .3 internal pressure and loads induced by hog and sag of the ship.<br>• 7.3.4.5 When the design temperature is minus 110°C or colder, a complete stress analysis, taking into account all the stresses due to weight of pipes, including acceleration loads if significant, internal pressure, |

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking S | L | RR | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | thermal contraction and loads induced by hog and sag of the ship shall be carried out for each branch of the piping system.<br>• IGF Code: 7.3.4.2 Where necessary for mechanical strength to prevent damage, collapse, excessive sag or buckling of pipes due to superimposed loads, the wall thickness shall be increased over that required by 7.3.2 or, if this is impracticable or would cause excessive local stresses, these loads shall be reduced, protected against or eliminated by other design methods. Such superimposed loads may be due to; supports, ship deflections, liquid pressure surge during transfer operations, the weight of suspended valves, reaction to loading arm connections, or otherwise. length of piping between bunker manifold to tank is<br>• During purging, the ammonia payload is |

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking S | Risk Ranking L | Risk Ranking RR | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | returned to the tank |
| **1.6** Make & Break of bunkering hose during normal operations | • Trapped liquid ammonia | • damage to the equipment human exposure | • Asset<br>• Human | 2 | B | 2B | • bunkering procedures require inerting prior to make or break<br>• crew provided with appropriate PPE and a gas detector | **23.** Proper connect/disconnect procedures are to be developed to prevent Trapped fluid | |
| **1.7** Emergency Breakaway | • emergency on bulk carrier<br>• emergency on bunker vessel<br>• mooring line failure | • Ammonia spill (due to breakaway coupling design)<br>• Toxic atmosphere | • Human | 2 | D | 2D | | **24.** Investigate how much ammonia can be released during emergency disconnect and if this will affect any crew in the bunkering control station<br>**25.** Dry breakaway coupling is to be provided | • In emergency, dry break coupling can release a fixed amount of ammonia to the atmosphere |
| **1.8** Emergency on the Bulk Carrier | • Fire in accommodations<br>• Fire in FSS room<br>• Fire in Cargo Area<br>• Fire in Cat-A machinery space | • loss of ammonia containment<br>• heat gain to the tank<br>• tracked PPE ammonia inventory in the piping excess boil off gas | • Asset<br>• Human | 2 | C | 2C | • ESD for bunkering<br>• SSL Link<br>• Bunkering ceases<br>• tank is designed considering heat gain due to fire | **26.** piping insulation has to consider the fire rating<br>**27.** fire scenario on the bulk carrier during bunkering is to be investigated | |
| **1.9** Emergency on bunker supply ship | • fire<br>• power loss<br>• ammonia release | • emergency on bulk carrier | • Asset<br>• Human | 2 | C | 2C | • SSL Link<br>• ESD<br>• operational procedures<br>• water spray for tank protection | **28.** Emergency procedures are to be developed considering emergency on bunker vessel | |

| *System Level Nodes - Hazard Scenario* | *Potential Cause* | *Consequences* | *Category* | *Risk Ranking* S | L | RR | *Effective Safeguard* | *Recommendations (R#)* | *Comments* |
|---|---|---|---|---|---|---|---|---|---|
| **1.10** Vessel Drift Away | • extreme weather<br>• mooring line failure<br>• collision<br>• high wind | • hose break away<br>• fuel spill | • Asset<br>• Human | 2 | D | 2D | • monitoring and operational procedures<br>• ESD<br>• SSL<br>• Dry break coupling<br>• fixed gas detector<br>• bunkering is limited to during safe operating environment | **29.** Investigate how much ammonia can be released during emergency disconnect and if this will affect any crew in the bunkering control station<br>**30.** Dry breakaway coupling is to be provided | • No additional risk compared to the LNG application<br>• IGF Code: 8.4.1 The bunkering manifold shall be designed to withstand the external loads during bunkering. The connections at the bunkering station shall be of dry-disconnect type equipment with additional safety dry break-away coupling/ self-sealing quick release. The couplings shall be of a standard type. |
| **1.11** Extreme weather event | | | | | | | | | • Procedures will restrict bunkering operations during extreme weather events |
| **1.12** Over-pressurisation of tank during bunkering | • Operational malfunction<br>• liquid level failure<br>• bunker fuel coming onboard<br>• pressure control failure | • damage to tank primary barrier/ structure<br>• ammonia in the atmosphere<br>• | • Asset | 2 | C | 2C | • Type-A tank is provided with a secondary barrier that is fully inserted and slightly pressurised<br>• secondary barrier is provided with venting<br>• Tank is protected by PRV<br>• High pressure alarm<br>• High pressure shutdown | **31.** Investigate Type-A tank secondary barrier ventilation discharge into the vent mast with all other venting and potential for high backpressure and reverse flow | • vent from secondary barrier goes into the vent mast |
| **1.13** Freeboard height difference between bunkering vessel and Bulk Carrier | • Handling of hose | • | | 4 | B | 4B | | **32.** Conduct compatibility study between the two vessels and evaluate need for crane on bulk carrier | |
| **1.14** Location of mooring line and snapping of mooring line | • Overload<br>• mooring line failure | • damage to bunker manifold<br>• damage to bunker hoses | | 3 | C | 3C | | **33.** Evaluate the location of the moorings line with respect to the breaking hazard and risk to the bunker manifold and hoses during bunkering operations | |
| **2. General Arrangement / Fuel Storage** | | | | | | | | | |

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking S | Risk Ranking L | Risk Ranking RR | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| **General Recommendations & Section Notes** | | | | | | | | **34.** Dispersion analysis for $NH_3$ release considering normal, upset, emergency and fire scenario to be performed to estimate $NH_3$ exposure to various area.<br>**35.** Based upon proposed GA, consider fuel oil as primary fuel and ammonia as secondary source of fuel | • Exposure level guide per NISH to be considered in analysis.<br>• No cofferdam between Ammonia tank & Cargo holds<br>• There is a double bottom<br>• Distance between main deck and the primary barrier > 900 mm<br>• Weather deck is secondary barrier<br>• Longitudinal bulkheads provided to mitigate sloshing effects<br>• Refer to IGF safety function fuel supply: 9.4.1 for more guidance |
| **2.1** Dropped Object | • Cargo Loading/Unloading<br>• Hatch cover removal & putting back | • Damage to tank primary and secondary barrier<br>• Uncontrolled release of ammonia in the port<br>• human exposure/fatality | • Asset<br>• Human | 4 | C | 4C | • Hatches are hydraulically operated and don't require lifting | **36.** Dropped object study considering cargo handling are to be developed considering port operations | • Weather deck is secondary barrier for the cargo tank<br>• Hatches are hydraulically operated and do not require lifting<br>• Depending on port loading equipment possibility of cargo moving over tank during cargo loading/unloading operation |
| **2.2** Location of mooring line | No additional risks identified by the team. Design will comply with IGC/IGF Code and standard practices. | | | | | | | | |
| **2.3** Hatch Operation | • Sparking due to hatch wheels | • fire | • Asset | 3 | C | 2C | | **37.** Re-evaluate the arrangement or conduct a study to show that sparking will not cause a fire hazard | • Cargo hatch wheels are within the Hazardous area per submitted document |

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking S | Risk Ranking L | Risk Ranking RR | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| **2.4** Fire in cargo hold | • Ignition<br>• Coal fire/cargo fire | • heat gain into tank<br>• damage to ammonia fuel tank<br>• FSS Room exposed to heat | • Asset<br>• Human | 4 | B | 4B | | **38.** Consider cofferdam between cargo hold space and ammonia fuel tank space with A-60 boundary<br>**39.** tank relief valve calculations to include cargo fire and heat load | • Current design consider transverse bulkhead between ammonia fuel tank and cargo hold is secondary barrier |
| **2.5** HAZ extended over cargo tank | • Ammonia leak | • Ammonia migration into cargo hold | Asset | 3 | C | 3C | | **40.** Consider electrical equipment to be safe certified (coal and ammonia) | • Refer to ABS ammonia as fuel guide 12/6.4, SOLAS III/31.1.6 and LSA IV/4.8 for more guidance |
| **2.6** Fire in FSS Room | • $NH_3$ leak<br>• Connection failure<br>• Pipe failure/crack<br>• Fatigue<br>• Seal failure (compressor and other rotating machinery)<br>• Over-pressurisation<br>• Gland leak | • Toxic atmosphere<br>• Fire<br>• Explosion<br>• $NH_3$ escaping due to over pressure of room<br>• FFS room can be over-pressurised and collapse<br>• Toxic zone around FSS room expanding<br>• Human exposure/injury/fatality<br>• Damage to $NH_3$ storage tank | • Asset | 3 | C | 3C | • Gas detection (based on LEL)<br>• Fire detection<br>• Shutdown of ventilation<br>• Shutdown of damper<br>• Water spray<br>• Water curtain at entrance<br>• PPE, eyewash, shower outside FSS room entrance<br>• Automatic Shutdown of tank valves and fuel supply valves | **41.** Reconsider shutdown of ventilation philosophy for FFSS room ( because 800 to 1 expansion ratio of $LNH_3$ can create excessive pressure) If water spray system is activated in NHS room full of $NH_3$ gas it can create vacuum due to solubility of $NH_3$ in water; pressure vacuum protection should be considered<br>**42.** Gas detection, alarm and shut down philosophy for ammonia is to be based on toxicity level, not LEL level<br>**43.** Require dispersion analysis see general recommendation<br>**44.** FSS Room is considered a Category A machinery space and has to be provided with an A-60 boundary | • FSS design philosophy is, upon LEL level detection of $NH_3$, shutdown ventilation, close damper. Upon fire detection, spray water should come automatically<br>• For liquified or pressurised gas in closed space, leakage can create high pressure if all openings are shut down due to volume expansion ($NH_3$ volume expansion approximately 800 – 1).<br>• If water deluge is activated in FSS room with room full of $NH_3$, it can create a vacuum due to $NH_3$ dissolving in water (Pressure vacuum protection is recommended<br>• Present philosophy for $NH_3$ detection is based on SOLAS. which is |

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking S | L | RR | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | based on LEL type philosophy and is not suitable for $NH_3$ due to toxicity of $NH_3$<br>• Present design FSS room ventilation inlet is aft and exhaust on side (port side) |
| **2.7** Explosion in FSS Room (FSS Room location on top of secondary barrier) | • $NH_3$ leak<br>• Connection failure<br>• Pipe failure/crack<br>• Fatigue<br>• Seal failure (compressor and other rotating machinery)<br>• Over-pressurisation | • Collapse of structure<br>• Damage to $NH_3$ tank<br>• $NH_3$ leakage<br>• Secondary barrier break<br>• EER impaired | Asset | 3 | C | 3C | • Gas detection (based on LEL)<br>• Electrical equipment suitable for HAZ area<br>• Fire detection<br>• Shutdown of ventilation<br>• Shutdown of damper<br>• Water spray<br>• Water curtain at entrance<br>• PPE, eyewash, shower outside FSS room entrance<br>• Automatic shutdown of tank valves and fuel supply valves | **45.** FSS Room has to be separated by a cofferdam. See IGF 11.3.1 and 11.3.3<br>**46.** TCS arrangement to be developed per IGF Requirements<br>**47.** Consider explosion relief hatch to limit explosion consequences | • Refer to IGF code 11.3.1, 11.3.3, 4.3 for more guidance |
| **2.8** $NH_3$ tank primary barrier failure | • Corrosion<br>• Fatigue<br>• Overstress<br>• Over-pressurisation<br>• Manufacturing defect<br>• Dropped object | • Failure of inner barrier led to $NH_3$ leak in secondary barrier<br>• $NH_3$ vented to atmosphere via vent mast from secondary barrier<br>• Gas can migrate into hydraulic pump room and other safe spaces<br>• Lead to long lasting event as $NH_3$ continuously leaking<br>• Human exposure | Asset<br>Human | 4 | C | 3C | • Secondary barrier provided to contain primary barrier leak<br>• Secondary barrier is designed to withstand low temperature<br>• Gas detector in secondary barrier<br>• Temperature detection n secondary barrier<br>• Level alarm<br>• Vent to vent mast secondary barrier<br>• Pressure/Temperature/level monitoring of tank<br>• ESD provision | **48.** primary barrier failure when ship is in port, emergency procedures are to be developed<br>**49.** gas dispersion analysis to be considered if there is a potential for human exposure or toxicity exceeding limit<br>**50.** Consider emergency evacuation of $NH_3$ | • Secondary barrier space venting to the vent mast<br>• Vent mast height is about 12 metres |

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking S | L | RR | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | tank and inner-barrier space and provide proper arrangement to handle such event | |
| **2.9** Tank connection failure | • tank connection leak/failure<br>• Fatigue<br>• Overstress<br>• Valve leaking<br>• Gland leaking | • Hazardous atmosphere due to $NH_3$ leak<br>• Toxic atmosphere Human exposure | Asset Human | 4 | B | 4B | | **51.** Tank connection space arrangement to be developed<br>**52.** TCS Arrangement to be developed | • Refer to<br>• IGF Code: 6.3.4 and IACS UI GF3: 1 for more guidance |
| **2.10** Collision | • navigation error<br>• Low visibility<br>• Weather<br>• Pilot error<br>• Loss of maneuvering functionality/steering | • Damage to the fuel tank<br>• Damage to the BC Structure<br>• Damage/Explosion cargo tank<br>• Toxic atmosphere | • Asset<br>• Human | 3 | C | 3C | • Tank complies with IGF Code requirements | **53.** Emergency procedures are to be developed<br>**54.** Look at worst case scenario and the volume of gas released in case of incident in port/economic zone concerned with the port authorities. | • Port entry procedures are to be developed considering port authority restrictions |
| **2.11 O**ver-pressurisation of tank | • High temperature of fuel<br>• Re-liquification plant failure<br>• Vapor management failure<br>• Control failure<br>• Improper bunkering operation<br>• liquid level not managed<br>• cargo coming at wrong temperature | • damage to tank<br>• ammonia spill into secondary barrier<br>• gas venting through vent mast<br>• Toxic atmosphere | • Asset<br>• Human | 3 | B | 3B | • PRV on tank<br>• Operational and emergency procedures<br>• level control<br>• pressure control<br>• Re-liquefaction plant | **55.** Fuel tank management considering fuel consumption to be developed<br>**56.** Redundancy in Re-liquefaction plant to be considered<br>See recommendation # 1 | • Fuel usage will be from one tank at a time and redundant liquification will manage the tank pressure |
| **2.12 O**verfilling of tank | • level control failure<br>• Pressure/Temperature management<br>• Both tank levels not managed properly<br>• Human error | • Over pressurisation due to warming of the cargo<br>• Liquid discharge to vent mast or vapor lines<br>• Damage to the tank<br>• High PPM level near safe spaces | • Asset<br>• Human | 4 | C | 4C | • Liquid level measurement systems<br>• Liquid level alarm and ESD<br>• Cargo handling procedure<br>• Cargo Temperature/Pressure Management<br>• Pressure Relief Valve | **57.** Client to develop cargo liquid management and liquid level measurement system and detailed procedure | • IGF Code Reference to be provided |
| **2.13** Secondary barrier damage | • damage to transverse bulkhead<br>• damage to side shell<br>• damage to weather deck | • in case of primary barrier leakage, gas can migrate outside of secondary barrier | • Asset | 4 | B | 4B | • 5-year inspection<br>• regular maintenance | **58.** provide cofferdam between cargo tank and ammonia tank<br>**59.** Develop procedures to detect any damage to secondary barriers<br>**60.** Upon detection of gas in secondary barrier, all surrounding area is to be inspected for damage | • If there is an undetected crack then it will be unnoticed until the 5-year inspection. |
| **2.14** Tank pressure/temperature management | No additional risks identified by the team. Design will comply with IGC/IGF Codes and standard practices. | | | | | | | | |

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking S | Risk Ranking L | Risk Ranking RR | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| **2.15** Mechanical Damage | No additional risks identified by the team. Tank is enclosed inside secondary barriers. Damage is not probable. See dropped object and collision nodes for more information | | | | | | | | |
| **2.16** Power loss | • loss of power | • loss of refrigeration<br>• ammonia tank warming up<br>• ammonia release to the atmosphere via vent mast | • Asset<br>• Human | 2 | C | 2C | • Tank-relief valve venting to vent mast | **61.** Consider providing redundancy to maintain tank pressure/temperature Consider catch system design to handle relief vent from ammonia | • Copy IGF Code reference for redundancy ABS philosophy is to not vent ammonia in normal operations, unless it is an emergency |
| 2.17 Tank support failure | No additional risks identified by the team. Design will comply with IGC/IGF Code and standard practices. | | | | | | | | |
| **2.18** Escape route | No additional risks identified by the team. Design will comply with IGC/IGF Code and standard practices. | | | | | | | | |
| **2.19** Extreme Weather | No additional risks identified by the team. Design will comply with IGC/IGF Code and standard practices. | | | | | | | | |
| **2.20** Submerged pump failure | No additional risks identified by the team. Design will comply with IGC/IGF Code and standard practices. | | | | | | | | |
| **6.2 General Arrangement/Fuel Handling Room** | | | | | | | | | |
| **General Recommendations & Section Notes** | | | | | | | | | vent outlet on port. Vent inlet is on the stbd/aft side. FSS room sides are not A-60, but the base will be A-60 to comply with IGC 11.3.1 and 11.3.3 |
| **3.1** Exhaust location | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | **62.** Recommend to have toxic zone area plan developed to access HAZ. | ABS $NH_3$ Guide to be used for Guidance |
| **3.2** $NH_3$ leak in FSS room | • $NH_3$ leak<br>• Connection failure<br>• Pipe failure/crack<br>• Fatigue<br>• Seal failure (compressor and other rotating machinery)<br>• Over pressurisation | • Fire<br>• Explosion<br>• High temperature<br>• Radian heat<br>• $NH_3$ tank fuel warming up and exposure to high temperature<br>• Damage to secondary barrier<br>• PRV discharging to vent mast<br>• Damage to fuel supply room<br>• Release of $NH_3$ | • Asset<br>• Human | 2 | D | 2D | • Gas detection (based on LEL)<br>• Fire detection<br>• Shutdown of ventilation<br>• Shutdown of damper<br>• Water spray<br>• Water curtain at entrance<br>• PPE, eyewash, shower outside FSS room entrance<br>• Automatic shutdown of tank valves and fuel supply valves | **63.** FSS room is under pressurised (extraction ventilation)<br>**64.** Consider FSS room door are to be gas tight<br>**65.** Reconsider ventilation philosophy instead of shutting down consider additional air circulation to disperse $NH_3$<br>**66.** philosophy for ammonia catch system to consider leakage scenario | • Eyewash and shower outside FSS room is in a Hazardous area.<br>• Refer to IGF: 5.11.1 for more guidance on fire dampers |

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking S | L | RR | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| | • Shutdown of reliquification room | • Loss of Boil off gas management system i.e., reliquification<br>• Tank PRV will open<br>• Tank over pressurisation<br>• $NH_3$ vent to atmosphere via vent mast | • Asset | 2 | D | 2D | | **67.** Consider tank management equipment to be located in separate space<br>Consider IGF requirement to have redundancy in static equipment from reliquefication system<br>**68.** Consider conducting HAZOP/FMEA to prove availability of the reliquefication and BOG management system for P-T management of $NH_3$ tanks. | • Current design takes credit for managing P-T of tank<br>• Current proposal is only single train for reliquefication equipment<br>• Refer to IGF Code 6.91 (IACS) and IGF Code 6.9.6:9.6.1 for more guidance |
| **3.3** $NH_3$ Leak in TCS (Tank Connection Space) | • $NH_3$ leak<br>• Connection failure<br>• Pipe failure/crack<br>• Fatigue<br>• Seal failure (compressor and other rotating machinery)<br>• Over-pressurisation | • Pressure builds up in the TCS<br>• Fire<br>• Explosion | • Asset | 2 | C | 2C | | **69.** TCS arrangement with respect to FSS Room is to be further developed in order to conduct a proper HAZID | • Refer to IGC 11.3.1 for more guidance |
| **3.4** Vent inlet/outlet and vent mast location | • Ammonia release from vent mast entering into FSS Room | • Gas in FSS Room | Asset | 3 | C | 3C | • Gas detection in vent mast and FSS Room<br>FSS air inlet provided with gas detector and damper<br>• Upon gas detection at FSS inlet, fuel handling system will be shutdown | **70.** Gas detection and alarm philosophy to be based on PPE level considering human exposure, not on LEL further study to be considered to see the possibility of vent gas getting into the FSS Room | • Vent mast height is the same as the top of the FSS Room & inlet/outlet of FSS Room is at the top level vent mast outlet and air inlet to FSS Room distance is approximately 12 metres |
| **3.5** Cargo loading and unloading/ dust | • dust migrating to FSS Room (iron ore and coal) | • Coal dust can be hazardous and can be a fire/blast hazard Cleanliness issue<br>• Contamination of FSS equipment | Asset | 3 | C | 3C | | **71.** Further study to be done to see if dust will migrate to FSS Room and create a safety issue | • Consider filtering arrangement if dust is an issue |
| **4. General Arrangement/Fuel Handling Room/Fuel Transfer/Fuel preparation /Reliquification / pumps / piping** | | | | | | | | | |
| **General Recommendations & Section Notes** | | | | | | | | **72.** Engine room double wall piping exhaust inlet to be provided and HA drawing to be updated | |

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking | | | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| | | | | S | L | RR | | | |
| **4.1** Distance between engine room and FSS Room & Trapped inventory unable to purge the system in emergency | • length of piping<br>• elevation difference | • Trapped inventory unable to drain piping can create a safety and fire hazard | • Asset | 3 | E | 3E | • Thermal relief valve<br>• $N_2$ Purge capability | **73.** further study to be conducted for draining and of fuel supply system between purging FSS Room and engine connection<br>**74.** Once the system has been designed, detailed HAZOP to be conducted<br>**75.** During the system design, consider how to drain the system during an emergency | • All piping on weather deck is single-walled piping<br>• Engine system can only handle 100 m of piping between engine and FSS Room Approximately 2 $m^3$ of liquid inventory between engine connection and FSS Room<br>• Engine manufacturer proposes to use $N_2$ to purge the liquid. Trials at this length are to be conducted. lots of high-pressure inventory between FVT and FSS<br>• Purging at pressure 7 bar greater than inventory is enough to purge LPG |
| **4.2** Damage to $NH_3$ piping on deck | • dropped object<br>• over pressurisation<br>• inappropriate assembly<br>• improper maintenance<br>• vibration<br>• fatigue<br>• Trapped inventory | • ammonia on the deck<br>• toxic cloud<br>• fire<br>• exposure to people on ports and ships | Asset | 2 | D | 2D | • thermal relief<br>• mechanical protection (100 mm angle bar)<br>• piping is provided with an expansion loop<br>• all welded piping on deck | **76.** Dropped object study to be performed considering cargo loading/unloading and maintenance | • 100 mm angle bar is provided for the piping on deck<br>• Consider restricting inventory during cargo operations<br>• deck piping is single walled piping<br>• IGF Code amendment requiring double walled piping |
| **4.3** Ammonia leak | No additional risks identified by the team. See previous nodes. | | | | | | | | |

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking S | L | RR | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| **4.4** Poor ventilation | • loss of power<br>• fan breakage | • loss of air circulation<br>• buildup of ammonia in FSS Room<br>• fire<br>• explosion<br>• loss of reliquification<br>• tank pressure rising | • Asset | 2 | C | 2C | • Complies with IGF Code<br>• Alarms upon loss of ventilation<br>• Switch over to fuel over mode & shutdown of FSS Room<br>• 2*100% exhaust fans<br>• fans are on emergency power circuit | **77.** Consider redundancy requirements of IGF Code or equivalent<br>**78.** Consider Emergency additional ventilation upon detection of $NH_3$ | • FSS Room is maintained with a negative pressure<br>• Shipyard should consider that, during an emergency, BOG will go to the ammonia catch system |
| **4.5** Fire in FSS Room | • ammonia leak<br>• overheating of electrical circuit<br>• overheating of rotating equipment<br>• short circuit | • heat radiation impacting ammonia fuel storage tank<br>• loss of reliquification | Asset | 2 | C | 2C | • gas detection<br>• fire detection<br>• shutdown<br>• automatic water mist system<br>• ventilation stop and fire dampers close | **79.** Fire safety shutdown safety philosophy and detailed HAZOP to be conducted<br>**80.** Application of water mist system to be reevaluated considering that ammonia can dissolve in water and create a vacuum or over pressurisation due to high expansion ratio and damper closure | • all valves in FSS Room are pneumatic<br>IGF Explosion prevention safety principles |
| **4.6** Re-liquification plant failure | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | **81.** Re-evaluate single re-liquification plant philosophy with respect to maintaining tank pressure for all conditions (IGF Code requirement applies) | • IGF Code redundancy requirements or equivalent<br>Consider zero discharge ammonia philosophy into system design |
| **4.7** Power loss | No additional risks identified by the team. See previous nodes. | | | | | | | | |
| **4.8** Contaminated return fuel | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | **82.** Engine Manufacturer has to address detection of contaminated ammonia fuel and separation philosophy | |
| **4.9** Location of master shutoff valve is in FSS Room, therefore large inventory between valve and engine connection | • Over pressurisation<br>• inappropriate assembly<br>• improper maintenance<br>• vibration<br>• fatigue | • gas in the engine room<br>• gas on open deck<br>• toxic zone | • Asset | 2 | D | 2D | • Double-walled piping in engine room<br>• gas detection for double walled piping annulus space | **83.** Shipyard and engine manufacturer have to provide detailed information of the location of the master shutoff valve relative to the FVT<br>Consider Fuel handling systems to be designed to handle 2*180-meter length of inventory or re-design to reduce the inventory<br>Double-walled piping ventilation locations | • Copy IGF Code Requirement<br>Engine room ammonia piping is double walled<br>Upon failure of double walled piping potential for purging inventory to be addressed<br>IGF: 9.4.9 For single-engine installations and multi-engine |

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking S | L | RR | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | are a hazardous zone and are to be evaluated for worst case failure scenario (complete failure of inner wall) | installations, where a separate master valve is provided for each engine, the master gas fuel valve and the double block and bleed valve functions can be combined. ABS 5C-13-9/4.2: 4.2 Interpretation (ABS) If the master fuel valve is located in an enclosed space such as a gas valve unit room, that space is to be protected against gas leakage by another automatic shutdown valve arranged for closure in the event that gas leakage is detected within the enclosed space or loss of ventilation for the duct or casing or loss of pressurisation of the double wall gas fuel piping occurs |
| **4.10** Explosion in FSS Room | • $NH_3$ leakage | • damage to TCS Room<br>• damage to structure<br>• damage to fuel ammonia tank | Asset | 4 | B | 4B | • electrical equipment suitable for HA<br>• gas detector<br>• continuous ventilation<br>• safety shutdown | **84.** Consider cofferdam between FSS Room and tank secondary barrier | TCS room is on weather deck, which is the secondary barrier for the Type-A tank |
| **4.11** Drainage in FSS Room | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | **85.** Consider drain provision and drain collection from FSS Room and evaluate the capacity required for drainage collection Consider inventory monitoring in the drain tank drain treatment to be | drainage from FSS Room collected in one drainage tank drain from FSS Room will be considered hazardous and will be separated from other drainage. |

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking S | Risk Ranking L | Risk Ranking RR | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | provided to meet regulations to protect aqua life | Code requirements to be applied |
| **4.12** Ammonia catch system drainage | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | **86.** ammonia catch system contaminated water collection and treatment to be provided to meet discharge standard and protect aqua life ammonia catch system to be designed to provide monitoring of the system, to determine when to recharge catch fluid | Ammonia-catch system is in the design development stage. Further HAZID/HAZOP to be conducted once developed |
| **4.13** Gas blow by from ammonia catch system | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | **87.** to be addressed in HAZOP vent from ammonia catch systems to be identified as HA | |
| **4.14** Liquid ammonia leaking in FSS Room | • pipe break<br>• connection failure<br>• sealing failure<br>• fatigue | • Ammonia in FSS Room<br>• low temperature exposure to deck structure | Asset | 2 | C | 2C | • low temperature carbon steel<br>• gas detection<br>• shutdown<br>• Ventilation<br>• | **88.** Consider Liquid leakage collection and monitoring to be designed to address the toxicity issue Study to be done to address the risk due to the leakage in the FSS room considering pressurised cold leakage and ventilation and firefighting philosophy | Liquid ammonia can be pressurised |
| **4.15** Purging capabilities | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | **89.** Purging capabilities of the system to be developed | |
| **4.16** Dropped object on FSS Room | • Cargo handling operations | • Damage to FSS Room<br>• Ammonia leakage<br>• Damage to tank/dome | Asset Human | 4 | C | 4C | • electrical equipment suitable for HA<br>• gas detector<br>• continuous ventilation safety shutdown | **90.** Dropped object study to be performed | • Consider restricting any lifting over cargo tank and FAA room |
| **5. GA Machinery space (ER) / Use of Fuel / Engine Maintenance Activity / Engine** | | | | | | | | | |
| **General Recommendations & Section Notes** | | | | | | | | **91.** Engine is under development and therefore the engine risk will be addressed in a later FMEA Engine manufacturers are to conduct | • Design complies with IGF and class society rules |

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking | | | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| | | | | S | L | RR | | | |
| | | | | | | | | component level FMEA to see if ammonia can migrate into other systems and areas | |
| **5.1** Double-walled pipe ventilation failure | • exhaust fan failure<br>• power loss<br>• electrical fault<br>• blackout<br>• improper maintenance | • unsafe atmosphere in annulus space | Asset | 2 | C | 2C | • Flow switch<br>• Emergency shutdown<br>• Pressure differential<br>• switch to liquid fuel<br>• alarms<br>• fans on emergency power | | |
| **5.2** Inner wall pipe failure | • corrosion<br>• overstress<br>• fatigue<br>• vibration<br>• uninspectable system<br>• condensation in the annular space | • Annular space full of ammonia gas<br>• Over pressurisation of annular space<br>• Outer pipe failure due to over pressurisation | | 2 | C | 2C | • Outer pipe designed to withstand worst case inner failure<br>• alarms - flow and pressure<br>• shutdown of gas supply<br>• gas detector in annular space<br>• gas detector in engine room<br>• annular space is negatively pressurised<br>• annular space ventilation is provided with dry air<br>• proper material selection | **92.** inspection and maintenance plan and procedures are to be developed<br>**93.** post-maintenance inspection | • Outer pipe will be designed to survive worst case pressure<br>• Refer to IGF: 9.8.1 for more guidance |
| **5.3** Failure of outer pipe | • corrosion<br>• overstress<br>• fatigue<br>• vibration<br>• uninspectable system<br>• condensation in the annular space | • loss of annular space negative pressure<br>• ammonia leaking into engine room | | 2 | C | 2C | • periodic testing of annular space with pressure<br>• visual inspection<br>• automatic sequence to test annular space tightness | | |
| **5.4** Inner and outer wall pipe failure | • Dropped object<br>• outer pipe failure due to over pressurisation<br>• parts from rotating equipment, stopped object<br>• overstress | • Human exposure<br>• Ammonia in engine room<br>• toxic atmosphere | | 3 | C | 3C | • gas detector<br>• shutdown<br>• pressure and flow switch | **94.** piping arrangement to be such that there is low probability of Dropped object damage develop appropriate engine room entrance procedures considering necessary PPE | • Engine room only has a cooling water system, which will cool the glycol water system in the FSS Room<br>• Refer to IGF 7.3.4.4 and IGF 9.6.1 for more guidance |
| **5.6** Ammonia in the cooling water system | Team discussed high-level recommendations to improve design. Design will comply with IGC/IGF Code and standard practices. Not discussed further. | | | | | | | **95.** Engine FMEA to be conducted venting of $NH_3$ from engine auxiliary system in case of single failure to be designed and appropriate venting to be provided | • Refer to IGF 3.1.4 for more guidance |
| **5.7** Ammonia in the lubricating system | | | | | | | | | |
| **5.8** Fire in the engine room | • overheating of equipment<br>• lubricating oil leak on hot surface<br>• electrical fire | • smoke<br>• fire | Asset | 2 | B | 2B | • fire alarm<br>• manual shutdown<br>• water mist system | **96.** Shutdown switchover philosophy to be developed and $NH_3$ | |

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking S | L | RR | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | • SOLAS Compliant firefighting systems | fuel to be purged back to FSS Room | |
| **5.9** Flooding | • Collision<br>• Grounding<br>• Hull failure<br>• Damage to secondary barrier | Ammonia release<br>High vapourisation rate<br>Surrounding is impacted due to large release of ammonia | Asset<br>Human<br>Environment | 4 | C | 4C | • Tank location and side clearance in compliance with IGF code requirements<br>• Good navigation practice | **97.** Special study and dispersion analysis to be performed considering accidental scenarios such as grounding, collision, tank damage | |
| **5.10** Trapped ammonia during exposure during maintenance | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | **98.** develop proper operational and maintenance procedures for the system and ensure there is no Trapped ammonia | • Trapped ammonia can occur if design is improper. FMECA to be conducted to address the issue |
| **5.11** Exhaust slip | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | **99.** During testing, engine manufacturer to collect data and address accordingly | |
| **6. Vent / Vent lines /Vent Mast** | | | | | | | | | |
| **General Recommendations & Section Notes** | | | | | | | | **100.** All gas detection etc. for the venting systems to comply with ABS Ammonia Guide Vent mast system drainage to be provided and considering that ammonia dissolved in water | |
| **6.1** Vent mast location | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | **101.** dispersion analysis to be conducted to justify the height of the mast consider defining toxic zones and human safety based upon the PPE level exposure for worst case discharge of ammonia | • consider following ABS ammonia guide |
| **6.2** Ammonia release to vent mast during operation | No additional risks identified by the team. Design will comply with IGC/IGF Code and standard practices. | | | | | | | | |
| **6.2.1** Ammonia release to vent mast at port | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | **102.** Operational and safety procedures while in port are to consider port requirements and be incorporated into the design | |
| **6.2.2** Ammonia release to vent mast during bunkering | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | **103.** Dispersion analysis to be conducted | • Fill in nodes from previous discussion |

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking S | Risk Ranking L | Risk Ranking RR | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| **6.2.3** Ammonia release to FSS Room exhaust | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | **104.** consider exhaust fan to exhaust in the upward direction, to have a better gas dispersion in the case of leakage | • The exhaust fans are venting in the horizontal direction |
| **6.2.4** Ammonia release to double walled piping exhaust | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | **105.** Exhaust location from double-walled pipe to be determined and exposure to accommodations to be considered | |
| **6.3** Vent mast ignited | No additional risks identified by the team. Design will comply with IGC/IGF Code and standard practices. | | | | | | | | |
| **6.4** Ammonia catch system exhaust<br>**6.5** Glycol water system exhaust | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | **106.** Exhaust locations to be determined according to IGF Requirement | |
| **7. Safety System/ Emergency** | | | | | | | | | |
| **General Recommendations & Section Notes** | | | | | | | | | |
| **7.1** Escape - Cat A machinery space fire | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | **107.** Consider LSA to be provided with self-contain breathing PPE etc. suitable for $NH_3$ considering risk of exposure - SOLAS for gas carrier<br>**108.** Consider conducting EER study considering fire, $NH_3$ release, other emergencies<br>**109.** Consider applying A-60 boundary around containment system or any escape route with possibility to direct fire exposure or possibility of $NH_3$ - IGF 11.3.2 | A this point design is not clear or enough information available to evaluate escape route<br><br>Refer to SOLAS III/31.1.6 and LSA IV/4.8, ABS ammonia as fuel guide 12/6.4 |
| **7.2** PPE Requirement | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | **110.** PPE and mask requirement/philosophy are to be developed and locations to be determined | |
| **7.3** ESD Philosophy | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | **111.** Emergency shutdown philosophy and procedures are to be developed and to be considered during the design | |
| **7.4** Structural fire protection | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | **112.** FSS Room structural requirements | |

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking S | L | RR | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | are to comply with IGF Requirements | |
| **7.5** Firefighting | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | **113.** Appropriate firefighting systems to be provided considering ammonia leak and ammonia fire Emergency evacuation and rescue procedures for worst case discharge to be developed | |
| **8. Ship's Operation / Simultaneous Operation** | | | | | | | | | |
| **General Recommendations & Section Notes** | | | | | | | | | During cargo loading/unloading no crew on the deck |
| **8.1** Bunkering and Cargo Loading | Bunkering and cargo operations will not be done simultaneously. One operation at a time | | | | | | | | |
| **8.2** Crew change & pilotage | No additional risks identified by the team. Design will comply with IGC/IGF Code and standard practices. | | | | | | | | |
| **8.3** Cargo loading/unloading overhead lifting over cargo tank and FSS Room | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | **114.** If planned to have maintenance in FSS Room during loading/unloading then Dropped object study to be conducted | |
| **8.4** Damage to deck piping due to cargo loading/unloading | • Dropped object<br>• over pressurisation<br>• inappropriate assembly<br>• improper maintenance<br>• vibration<br>• fatigue<br>• Trapped inventory | • ammonia on the deck<br>• toxic cloud<br>• fire<br>• exposure to people on ports and ships | Asset Human | 4 | D | 4D | • thermal relief<br>• mechanical protection (100 mm angle bar)<br>• piping is to be provided with an expansion loop<br>• all welded piping on deck | **115.** Dropped object study to be performed considering cargo loading/unloading and maintenance Consider breakage of piping and perform dispersion analysis to consider exposure to humans and toxicity zone Consider the alternative to capture the fluid and reuse it | • 100 mm angle bar is provided for the piping on deck<br>• Consider restricting inventory during cargo operations<br>• deck piping is single walled piping<br>• During the cargo loading/unloading consider de-inventorying the on-deck ammonia piping |
| **8.5** Cargo loading/unloading overhead lifting over bunker area | No additional risks identified by the team. Design will comply with IGC/IGF Code and standard practices. | | | | | | | | |
| **8.6** Gas freeing | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | **116.** Gas freeing and gassing up operations are to be studied for emergency, maintenance, dry | • ammonia tank is 12,000 m$^3$<br>• gas freeing operation will be done using |

| System Level Nodes - Hazard Scenario | Potential Cause | Consequences | Category | Risk Ranking | | | Effective Safeguard | Recommendations (R#) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| | | | | S | L | RR | | | |
| **8.7** Gassing up | | | | | | | | docking situation and appropriate solutions are to be developed<br>Consider addressing the ammonia discharge issue during gas freeing<br>Evaluate need for nitrogen, if doing independently | bunkering vessels nitrogen system |
| **8.8** Maintenance and inspection | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | **117.** Maintenance and inspection procedures are to be developed | |
| **8.9** Out of spec fuel | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | **118.** Fuel quality control and fuel spec to be developed | |
| **8.10** Port entry<br>**8.11** Port departure | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | **119.** local authorities are to be consulted for grounding risk and proper procedures are to be developed | |
| **8.12** Heavy weather - failure of equipment/piping | • extreme dynamic load<br>• high rolling | • component comes loose<br>• gas leakage | | | | | | **120.** Equipment foundations/supports are to be designed considering heavy weather dynamic loads<br>Ammonia equipment is to be designed for full operations considering heavy dynamic loads and heave/roll/pitch for the expected operating conditions in heavy weather | • Engine and ammonia tank design to comply with IGC Code which considers pitch, roll, etc. |

# Appendix XIV – List of Recommendations RO-Pax

| Recommendation Type | References | | Recommendations |
|---|---|---|---|
| Safety – GA/ | 2.1 Ammonia leakage in TCS space – $NH_3$ fuel storage tank A (engine room) | 1 | Classify whether TCS is a hybrid TCS/ fuel preparation room or if they are separate spaces |
| Further Engineering Analysis – mechanical integrity | 2.1 Ammonia leakage in TCS space – $NH_3$ fuel storage tank A (engine room) | 2 | Evaluate insulation requirement due to condensation and liquid ammonia |
| Further Engineering Analysis – mechanical integrity | 2.1 Ammonia leakage in TCS space – $NH_3$ fuel storage tank A (engine room) | 3 | Evaluate TCS space for moisture condensation due to low temperature ammonia piping |
| Human Safety | 2.1 Ammonia leakage in TCS space – $NH_3$ fuel storage tank A (engine room) | 4 | Consider passengers on board, look at detecting ammonia at 5 or 10 ppm |
| Mechanical integrity and safety | 2.1 Ammonia leakage in TCS space – $NH_3$ fuel storage tank A (engine room) | 5 | First stop valve after tank required to be high reliability and gas tight |
| Ventilation | 2.1 Ammonia leakage in TCS space – $NH_3$ fuel storage tank A (engine room) | 6 | Ventilation of TCS space needs to be evaluated |
| Ventilation | 2.1 Ammonia leakage in TCS space – $NH_3$ fuel storage tank A (engine room) | 7 | Reevaluate venting location, consider upon gas detection divert ventilation through scrubber |
| Gas detection | 2.1 Ammonia leakage in TCS space – $NH_3$ fuel storage tank A (engine room) | 8 | Tank and first stop valve inner and outer pipe monitoring needs to be considered for ammonia leak in vacuum space |
| Safety - GA | 2.1 Ammonia leakage in TCS space – $NH_3$ fuel storage tank A (engine room) | 9 | Expansion tank location with regards to regulations needs to be considered for final location and installation |
| Fluid Suitability and testing | 2.1 Ammonia leakage in TCS space – $NH_3$ fuel storage tank A (engine room) | 10 | Expansion tank fluid to be looked at for use with ammonia/solubility/disposal |

| **Recommendation Type** | **References** | | **Recommendations** |
|---|---|---|---|
| Ventilation | 2.1 Ammonia leakage in TCS space – $NH_3$ fuel storage tank A (engine room) | 11 | Ventilation exhaust from any hazardous area (ammonia) discharges into the same vent mast, possibility of reverse flow to be studied. (ABS Guide 12/6.3, ABS guide 12/6.4) |
| Ventilation | 2.1 Ammonia leakage in TCS space – $NH_3$ fuel storage tank A (engine room) | 12 | Ensure ventilation exhaust is clear of any ammonia e.g., consider exhaust to be diverted into scrubber (can be 99.9% efficient) |
| Ventilation | 2.1 Ammonia leakage in TCS space – $NH_3$ fuel storage tank A (engine room) | 13 | To avoid any condensation issues, consider dry ventilation air |
| Containment Barrier | 2.2 Leak from tank – $NH_3$ fuel storage tank A (engine room)<br>3.2 Leak from tank – NH3 fuel storage tank B (on open deck) | 14 | For a vacuum-insulated tank, the second layer should be designed to withstand leakage from the first layer. |
| Gas detection | 2.2 Leak from tank – $NH_3$ fuel storage tank A (engine room)<br>3.2 Leak from tank – $NH_3$ fuel storage tank B (on open deck) | 15 | Fuel tank vacuum space to be monitored for leakage |
| Hazardous area classification | 2.2 Leak from tank – $NH_3$ fuel storage tank A (engine room)<br>3.2 Leak from tank – $NH_3$ fuel storage tank B (on open deck) | 16 | Study the area classification for the ammonia tank in fuel storage area |
| Fire | 2.2 Leak from tank – $NH_3$ fuel storage tank A (engine room)<br>2.4 Fire in machinery space aft of ammonia tank hold space – $NH_3$ fuel storage tank A (engine room)<br>3.2 Leak from tank – $NH_3$ fuel storage tank B (on open deck) | 17 | To minimise fire risks, the fuel storage hold space shall not be used for machinery or equipment that may have a fire risk (Compliance to IGF 11.3.4 ) |
| Training and Procedures | 2.2 Leak from tank – $NH_3$ fuel storage tank A (engine room) | 18 | Considering risks if tank primary boundary has leak emergency procedure are to be developed to address emptying fuel tank, safety and safe evacuation |

| Recommendation Type | References | | Recommendations |
|---|---|---|---|
| | 3.2 Leak from tank – $NH_3$ fuel storage tank B (on open deck) | | |
| Firefighting Systems | 2.3 Fire on deck 3 (deck above cargo hold space) – $NH_3$ fuel storage tank A (engine room) | 19 | Ammonia tank room fire-fighting requirement to be evaluated |
| Ventilation | 2.4 Fire in machinery space aft of ammonia tank hold space – $NH_3$ fuel storage tank A (engine room) | 20 | Upon loss of burner, determine where the ammonia between the engine and main shutdown valve is vented |
| Fire Protection | 2.5 Fire explosion in reliquification plant – $NH_3$ fuel storage tank A (engine room) | 21 | Structural fire protection requirement for room to be A-60 rated |
| Further Detailed Analysis | 2.5 Fire explosion in reliquification plant – $NH_3$ fuel storage tank A (engine room) | 22 | Fuel change over philosophy and engine capacity need to be worked out |
| Mechanical integrity and protection | 2.5 Fire explosion in reliquification plant – $NH_3$ fuel storage tank A (engine room) | 23 | Piping between TCS and reliquification plant to be protected (mechanical protection) |
| Structural fire protection | 2.5 Fire explosion in reliq plant – $NH_3$ fuel storage tank A (engine room) | 24 | Consider separation between boundary of Reliq plant and fuel tank |
| Personnel Safety Protections | 2.5 Fire explosion in reliq plant – $NH_3$ fuel storage tank A (engine room) | 25 | Consider eye wash and PPE located near to potential ammonia exposure area |
| Firefighting Systems | 2.5 Fire explosion in reliq plant – $NH_3$ fuel storage tank A (engine room) | 26 | Fire-fighting philosophy and equipment to be provided for reliq plant space |
| Safety Systems | 2.6 Grounding/collision – $NH_3$ fuel storage tank A (engine room)<br>2.9 Over-pressurisation of the tank – $NH_3$ fuel storage tank A (engine room) | 27 | Relief valve capacity should consider complete flooding of compartment |
| Safety Systems | 2.6 Grounding/collision – $NH_3$ fuel storage tank A (engine room) | 28 | Ensure tank shut-off valves are failsafe close |

| Recommendation Type | References | | Recommendations |
|---|---|---|---|
| Safety/emergency/Further Detailed Analysis | 2.6 Grounding/collision – $NH_3$ fuel storage tank A (engine room) | 29 | Calculation to be done to estimate vapourisation time of tank |
| Safety/Further Detailed Analysis | 2.6 Grounding/collision – $NH_3$ fuel storage tank A (engine room) | 30 | Dispersion analysis for worst-case scenario to be performed for toxic zone and hazardous zone |
| Structural fire protection | 2.7 Fire in battery compartment between frame 108-120 – $NH_3$ fuel storage tank A (engine room) | 31 | Battery compartment structural protections are to be studied to ensure they comply with class requirement |
| Personnel Safety | 2.7 Fire in battery compartment between frame 108-120 – $NH_3$ fuel storage tank A (engine room) | 32 | Escape routes from battery compartments to be studied to ensure they meet SOLAS requirement |
| Firefighting Systems | 2.7 Fire in battery compartment between frame 108-120 – $NH_3$ fuel storage tank A (engine room) | 33 | Battery compartment firefighting equipment to be provided |
| Compliance with IGF codes, Class Requirements, Industry Best Practices | 2.7 Fire in battery compartment between frame 108-120 – $NH^3$ fuel storage tank A (engine room) | 34 | Battery location to comply with statutory and class requirements |
| Safety/Compliance with IGF codes, Class Requirements, Industry Best Practices | 2.10 Overfilling tank – $NH_3$ fuel storage tank A (engine room) | 35 | Any penetration (e.g., level gauge) is to be justified through alternative arrangement (IMO MSC 1455) |
| Safety/fire/General Arrangements | 3.3 Fire on deck – $NH_3$ fuel storage tank B (on open deck) | 36 | Storage of dangerous cargo next to ammonia tank to be studied for fire risk |
| Structural fire protection/ | 3.3 Fire on deck – $NH_3$ fuel storage tank B (on open deck) | 37 | Structural fire protection at the tank boundary to be studied based on IMDG cargo and fire load |
| Personnel Safety Protections | 3.3 Fire on deck – $NH_3$ fuel storage tank B (on open deck) | 38 | Ensure personnel areas are not in toxic zones unless PPE provided |
| Structural fire protection/Further Detailed Analysis | 3.4 Fire from deck below – $NH_3$ fuel storage tank B (on open deck) | 39 | Fire-load analysis to be done to determine the structural integrity of fuel-tank deck |

| Recommendation Type | References | | Recommendations |
|---|---|---|---|
| Fire safety/General Arrangements | 3.9 Dangerous goods close to ammonia tank – $NH_3$ fuel storage tank B (on open deck) | 40 | Proper study to be done for category of IMDG goods next to ammonia tank considering fire and explosion risk |
| Fire and Gas Detection | 3.10 Escape routes in area – $NH_3$ fuel storage tank B (on open deck) | 41 | Proper gas dispersion analysis to be conducted considering ammonia leak, venting and results are to be considered for layout of walkway and passenger traffic area |
| Collision/Safety/Further Detailed Analysis | 3.15 Damage to ammonia tank due to vehicle traffic – $NH_3$ fuel storage tank B (on open deck) | 42 | Study to be conducted to prevent damage to tank due to vehicle collision and additional safeguards provided |
| Personnel safety/Fire and Gas Detection | 3.16 Passengers around ammonia tank – $NH_3$ fuel storage tank B (on open deck) | 43 | Consider ammonia gas detection at detection level of personnel (5 ppm) |
| Further Detailed Analysis | 4. Bunkering in port from shore – Bunkering Arrangement (tank in hold) | 44 | Bunkering using port facility is to be addressed with a separate study with the port operators and local requirements |
| Structural protection / Safety | 4.1 Bunkering in port from shore – Bunkering Arrangement (tank in hold) | 45 | The water curtain on a site cell is a preferred option to vapourise an ammonia leak |
| Firefighting Systems | 2.5 Fire explosion in reliq plant – $NH_3$ fuel storage tank A (engine room)<br>4.1 Bunkering in port from shore – Bunkering Arrangement (tank in hold) | 46 | Fire-fighting and fire-suppression systems need to be developed e.g., water- spray system to dissolve ammonia gas |
| Fire and Gas Detection | 4.2 Bunkering in port from shore – Bunkering Arrangement (tank in hold)<br>4.3 Ship-to- ship bunkering outside of port – Bunkering Arrangement (tank in hold) | 47 | Dispersion analysis for maximum credible/worst case scenario to determine impact on ship, passengers and personnel |
| Safety/ | 4.1 Bunkering in port from shore – Bunkering Arrangement (tank in hold) | 48 | Bunkering study to develop safety/ exclusion zones criteria |
| Further Detailed Analysis | 4.2 Bunkering in port from shore – Bunkering Arrangement (tank in hold) | 49 | SIMOPS study considering ammonia bunkering and passengers to be conducted |

| Recommendation Type | References | | Recommendations |
|---|---|---|---|
| Personnel safety/Further Detailed Analysis | 4.1 Bunkering in port from shore – Bunkering Arrangement (tank in hold) | 50 | Study to be done for bunker line failure and impact on ship with solutions e.g., double-wall piping, leak before break criteria for design, proper material selection |
| Safety Systems | 4.1 Bunkering in port from shore – Bunkering Arrangement (tank in hold) | 51 | Consider over-pressure protection and venting of void spaces |
| Preventive measure/port control | 4.2 Bunkering in port using barge – Bunkering Arrangement (tank in hold) | 52 | Port to establish protocols for distance and speed of passing vessels to avoid surges |
| Preventive measure/port control | 4.2 Bunkering in port using barge – Bunkering Arrangement (tank in hold) | 53 | Establish safety zones around bunkering vessels |
| Further Detailed Analysis | 4.2 Bunkering in port using barge – Bunkering Arrangement (tank in hold) | 54 | Compatibility study between bunkering vessel and Ro-Pax to be performed |
| Training and Procedures | 4.2 Bunkering in port using barge – Bunkering Arrangement (tank in hold) | 55 | Emergency procedures to be developed for bunkering vessel emergency in consultation with port and Ro-Pax |
| Preventive measures and port control/ | 4.3 Ship-to-ship bunkering outside of port – Bunkering Arrangement (tank in hold) | 56 | Safety zones are established for ship-to-ship bunkering |
| Preventive measures/safety/ | 4.3 Ship-to-ship bunkering outside of port – Bunkering Arrangement (tank in hold) | 57 | SIMOP safety study to determine risks of ship-to-ship bunkering with passengers and cargo on board |
| Hazardous zone/ Further Detailed Analysis | 4.3 Ship-to-ship bunkering outside of port – Bunkering Arrangement (tank in hold) | 58 | Hazardous areas on bunkering vessel to be studied |
| Preventive measures/safety | 4.3 Ship-to-ship bunkering outside of port – Bunkering Arrangement (tank in hold) | 59 | Bunkering to be avoided mid journey |
| Training and Procedures/safety | 4.4 Simultaneous Operation ($NH_3$/MGO) – Bunkering Arrangement (tank in hold) | 60 | All simultaneous operation scenarios to be studied and proper mitigation measures determined - bunkering, cargo and passenger load/unload, supply |
| Personnel safety/toxic zone/Further Detailed Analysis | 5.1 Ammonia leak – Bunkering arrangement (on deck) | 61 | Gas-dispersion analysis considering bunkering location study to be conducted with passenger area/traffic for potential exposure of passenger to ammonia |
| Training and Procedures | 7.1 Ammonia slip from the engine – Machinery space (ER) | 62 | Proper maintenance and testing procedures to be developed |

| Recommendation Type | References | | Recommendations |
|---|---|---|---|
| | 10.1 Port entry/departure – Ship's Operation | | |
| Emission/Further Detailed Analysis and testing | 7.1 Ammonia slip from the engine – Machinery space (ER) | 63 | Study to be performed to determine how to handle ammonia slip from engine exhaust e.g., catalyst or scrubber |
| Emission/Further Detailed Analysis | 7.1 Ammonia slip from the engine – Machinery space (ER) | 64 | Study to be performed for the maximum release of ammonia into the air |
| Safety/fire and explosion/Further Detailed Analysis | 7.1 Ammonia slip from the engine – Machinery space (ER) | 65 | Engine manufacturer to address issue of ammonia release into engine room e.g., crank case explosion |
| Emission/Safety/toxic zone/Further Detailed Analysis | 7.1 Ammonia slip frm the engine – Machinery space (ER)<br>7.6 Engine exhaust explosion – Machinery space (ER) | 66 | Discharge from exhaust to be studied and the hazardous and toxic zones developed during explosion in exhaust. |
| Ventilation | 7.1 Ammonia slip from the engine – Machinery space (ER) | 67 | Explosion relief valve venting to be provided to lead to outside engine room |
| Venting/ Safety Systems | 7. Ammonia slip from the engine – Machinery space (ER) | 68 | Purging capability to be provided to purge any trapped ammonia in piping |
| Emission/Further Detailed Analysis | 7.7 $N_2O$ and NOx emissions from engine – Machinery space (ER) | 69 | SCR/NOx monitoring to be confirmed |
| Emissions Testing | 7.7 $N_2O$ and NOx emissions from engine – Machinery space (ER) | 70 | During type testing/emission testing of engine manufacturer has to determine normal and maximum level of NOx from engine |
| Safety/Further Detailed Analysis | 7.8 Cylinder cover lift – Machinery space (ER) | 71 | Engine manufacturer need to provide details about possibility of ammonia leak inside engine |
| Ventilation | 8.1 TCS Ventilation – Ventilation<br>8.2 Reliq plant ventilation – Ventilation<br>8.3 Double-walled pipe ventilation – Ventilation | 72 | Ventilation exhaust ppm level to be studied for worse case discharge scenario |
| Safety Systems | 9.1 Ammonia pressure relief – Safety Systems | 73 | Thermal and pressure relief to be designed to handle worst case scenario considering toxic zone requirement |
| Firefighting Systems | 9.3 Fire-fighting system – Safety Systems | 74 | Firefighting philosophy to be developed |

| Recommendation Type | References | | Recommendations |
|---|---|---|---|
| Personnel Protection | 9.4 Structural fire protection – Safety Systems | 75 | PPE suitable for ammonia to be provided |
| Personnel Protection/IGF codes, Class Requirements, Industry Best Practices | 9.4 Structural fire protection – Safety Systems | 76 | Eye wash and shower to be provided close to ammonia bunker, Fuel preparation room, TCS space, reliq palt etc. |
| Personnel Protection/ IGF codes, Class Requirements, Industry Best Practices | 9.5 PPE – Safety Systems | 77 | Follow class requirement for PPE to be provided at all the locations where exposure to ammonia is possible |
| Training and Procedures | 10.1 Port entry/departure – Ship’s Operation | 78 | Management and crew to be trained for ammonia related hazards and operational/handling procedures for ammonia to be developed |

# Appendix XV – Ro-Pax HAZID Register

| | |
|---|---|
| 1 | General Arrangement Ro-Pax |
| | |

| **No.:** 1 | General Arrangement Ro-Pax | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Item** | **Deviation** | **Causes** | **Consequences** | **Matrix** | **Severity** | **Likelihood** | **Risk** | **Safeguards** | **Recommendations** |
| 1.1 | No new risk identified.<br>Not discussed further. | | | | | | | | |

| 2 | NH3 fuel storage tank A (engine room) |
|---|---|

Section notes:
- $NH_3$ tank next to engine room inside structure Deck
- Bunker piping goes to tank through void, all piping is protected.
- Type C tank, 6 barg design pressure, -33 oC, 1 barg normal pressure.
- TCS space connected to tank which will contain any leaks with instrumentation to notify of any leaks. TCS is designed to contain ammonia.
- TCS vent independent.
- TCS zone 1 space.
- Bottom connection on tank with stop valve for fuel supply.
- Tank location will comply with IGF requirements.
- Between frame 108-120 there is battery energy storage (Li-Ion) 2x5 MWh capacity.
- Additional structural requirement form IGF code to be applied.
- Ensure ventilation exhaust is clear of any ammonia e.g., consider exhaust to be diverted into scrubber
- Valve has welding on inner and outer pipes (connection between tank and first valve is double valve)
- Connection between tank and first valve is double wall
- All TCS piping designed for -33 °C
- All piping for TCS space is stainless steel and designed to Leak before fail (LBF) principle
- IGF/IGC Type C tank has additional safety margin compared to standard pressure vessels
- 2 types of tanks are considered, single-wall tank with insulation or double wall tank with vacuum insulation
- Ship is designed for MGO so no heating circuit
- Ammonia will not be used in port and the changeover philosophy needs to be developed
- Heating circuit is intermediate circuit to reduce risk of contamination of cooling/heating liquid from ship

| **No.:** 2 | | NH3 fuel storage tank A (engine room) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Item** | **Deviation** | **Causes** | **Consequences** | **Matrix** | **Severity** | **Likelihood** | **Risk** | **Safeguards** | **Recommendations** |
| 2.1 | Ammonia leakage in TCS space | 1. Leak in welded first valve<br>**Comment:** Dual fuel engine | 1. Gaseous ammonia inside the TCS space | Asset | S4-Major | LB-Unlikely | High | 1. Continuous ventilation of space normal 30 air change and emergency upon gas detection<br>2. Gas doctor in ventilation inlet/outlet<br>3. Fire and gas detectors inside TCS space<br>4. TCS space is gas and liquid tight<br>5. Designed to comply with ABS/IGF code<br>6. Space is protected against over-pressurisation<br>8. TCS space is designed for zone 1<br>15. Maintenance and inspection<br>19. Dual Fuel engine can switch over to backup fuel | 4. Consider passengers on board, look at detecting ammonia at 5 or 10 ppm<br>5. First stop valve after tank required to be high reliability and gas tight<br>6. Ventilation of TCS space needs to be evaluated<br>7. Reevaluate venting location, consider upon gas detection divert ventilation through scrubber |
| | | | 2. Liquid ammonia in TCS space | Asset | S4-Major | LB-Unlikely | High | | |
| | | | 3. Fire/Explosion | Overall | S4-Major | LA-Rare | High | | |
| | | | 4. Damage to fuel tank | Asset | S4-Major | LA-Rare | High | | |
| | | | 5. Damage to TCS Space | Asset | S4-Major | LB-Unlikely | High | | |
| | | | 6. Ammonia gas in fuel tank holding space | Asset | S3-Moderate | LB-Unlikely | Moderate | | |
| | | | 7. Ammonia in ventilation exit leads to hazardous and toxic zone | Human | S2-Minor | LC-Possible | Moderate | | |
| | | | 8. Ammonia in ventilation exit leads to wider low concentration ammonia zone- passenger perception | Human | S4-Major | LC-Possible | Extreme | | |
| | | 2. Leak in other equipment/valves inside TCS | 1. Gaseous ammonia inside the TCS space | Asset | S4-Major | LB-Unlikely | High | 1. Continuous ventilation of space normal 30 air change and emergency upon gas detection<br>2. Gas doctor in ventilation inlet/outlet<br>3. Fire and gas detectors inside TCS space<br>4. TCS space is gas and liquid tight<br>5. Designed to comply with ABS/IGF code<br>6. Space is protected against over pressurisation<br>7. ESD on detection of fire or gas (closure of valve closest to tank)<br>8. TCS space is designed for zone 1<br>9. Sump with level or temperature detection (IGF requirement) | 4. Considering passengers onboard, consider detecting ammonia at 5 or 10 ppm<br>6. Ventilation of TCS space needs to be evaluated<br>7. Reevaluate venting location, consider upon gas detection divert ventilation through scrubber |

| **No.:** 2 | | NH3 fuel storage tank A (engine room) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Item** | **Deviation** | **Causes** | **Consequences** | **Matrix** | **Severity** | **Likelihood** | **Risk** | **Safeguards** | **Recommendations** |
| | | | | | | | | 10. TCS space is designed to hold liquid ammonia<br>17. First valve is welded to tank piping and tank piping has double wall construction<br>19. Dual Fuel engine can switch over to backup fuel | |
| | | | 2. Liquid ammonia in TCS space | Asset | S4-Major | LB-Unlikely | High | | |
| | | | 3. Fire/Explosion | Overall | S4-Major | LA-Rare | High | | |
| | | | 4. Damage to fuel tank | Asset | S4-Major | LA-Rare | High | | |
| | | | 5. Damage to TCS Space | Asset | S4-Major | LB-Unlikely | High | | |
| | | | 6. Ammonia gas in fuel tank holding space | Asset | S3-Moderate | LB-Unlikely | Moderate | | |
| | | | 7. Ammonia in ventilation exit leads to hazardous and toxic zone | Human | S2-Minor | LC-Possible | Moderate | | |
| | | | 8. Ammonia in ventilation exit leads to wider low concentration ammonia zone- passenger perception | Human | S4-Major | LC-Possible | Extreme | | |
| | | 3. TCS piping overload/fatigue | 1. Gaseous ammonia inside the TCS space | Asset | S4-Major | LB-Unlikely | High | 1. Continuous ventilation of space normal 30 air change and emergency upon gas detection<br>2. Gas doctor in ventilation inlet/outlet<br>3. Fire and gas detectors inside TCS space<br>4. TCS space is gas and liquid tight<br>5. Designed to comply with ABS/IGF code<br>6. Space is protected against over-pressurisation<br>7. ESD on detection of fire or gas (closure of valve closest to tank)<br>8. TCS space is designed for zone 1<br>9. Sump with level or temperature detection (IGF requirement)<br>10. TCS space is designed to hold liquid ammonia<br>11. Proper selection of materials used<br>12. Piping designed to leak before fail and stainless steel<br>15. Maintenance and inspection<br>18. Piping is designed for leak-before-break criteria and stainless steel construction<br>19. Dual Fuel engine can switch over to backup fuel | |
| | | | 2. Liquid ammonia in TCS space | Asset | S4-Major | LB-Unlikely | High | | |
| | | | 3. Fire/Explosion | Overall | S4-Major | LA-Rare | High | | |
| | | | 4. Damage to fuel tank | Asset | S4-Major | LA-Rare | High | | |
| | | | 5. Damage to TCS Space | Asset | S4-Major | LB-Unlikely | High | | |
| | | | 6. Ammonia gas in fuel tank holding space | Asset | S3-Moderate | LB-Unlikely | Moderate | | |
| | | | 7. Ammonia in ventilation exit leads to hazardous and toxic zone | Human | S2-Minor | LC-Possible | Moderate | | |
| | | | 8. Ammonia in ventilation exit leads to wider low concentration ammonia zone- passenger perception | Human | S4-Major | LC-Possible | Extreme | | |
| | | 4. Failure of inner/outer pipe (between tank and first valve)<br>**Comment:** Double-wall piping only up to first valve in TCS (IGF: 6.3.6/IGF: 6.3.9/CABS Guide: 9/5.14) | 1. Gaseous ammonia inside the TCS space | Asset | S4-Major | LB-Unlikely | High | 1. Continuous ventilation of space normal 30 air change and emergency upon gas detection<br>3. Fire and gas detectors inside TCS space<br>4. TCS space is gas and liquid tight<br>5. Designed to comply with ABS/IGF code<br>6. Space is protected against over-pressurisation | 8. Tank and first stop valve Inner and outer pipe monitoring needs to be considered for ammonia leak in vacuum space |

| **No.:** 2 | NH3 fuel storage tank A (engine room) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Item** | **Deviation** | **Causes** | **Consequences** | **Matrix** | **Severity** | **Likelihood** | **Risk** | **Safeguards** | **Recommendations** |
| | | | | | | | | 7. ESD on detection of fire or gas (closure of valve closest to tank)<br>8. TCS space is designed for zone 1<br>9. Sump with level or temperature detection (IGF requirement)<br>10. TCS space is designed to hold liquid ammonia<br>11. Proper selection of materials used<br>12. Piping designed to leak-before-fail and stainless steel<br>15. Maintenance and inspection<br>18. Piping is designed for leak-before-break criteria and stainless-steel construction<br>19. Dual Fuel engine can switch over to backup fuel | |
| | | | 2. Liquid ammonia in TCS space | Asset | S4-Major | LB-Unlikely | High | | |
| | | | 3. Fire/Explosion | Overall | S4-Major | LA-Rare | High | | |
| | | | 4. Damage to fuel tank | Overall | S4-Major | LA-Rare | High | | |
| | | | 5. Damage to TCS Space | Overall | S4-Major | LB-Unlikely | High | | |
| | | | 6. Ammonia gas in fuel tank holding space | Asset | S3-Moderate | LB-Unlikely | Moderate | | |
| | | | 7. Ammonia in ventilation exit leads to hazardous and toxic zone | Human | S2-Minor | LC-Possible | Moderate | | |
| | | | 8. Ammonia in ventilation exit leads to wider low concentration ammonia zone - passenger perception | Human | S4-Major | LC-Possible | Extreme | | |
| | | | 10. Ammonia not available for engine | Overall | S2-Minor | LC-Possible | Moderate | | |
| | | 5. Wrong material used in flange seals | 1. Gaseous ammonia inside the TCS space | Asset | S4-Major | LB-Unlikely | High | 1. Continuous ventilation of space normal 30 air change and emergency upon gas detection<br>2. Gas doctor in ventilation inlet/outlet<br>3. Fire and gas detectors inside TCS space<br>4. TCS space is gas and liquid tight<br>5. Designed to comply with ABS/IGF code<br>6. Space is protected against over-pressurisation<br>7. ESD on detection of fire or gas (closure of valve closest to tank)<br>8. TCS space is designed for zone 1<br>11. Proper selection of materials used<br>18. Piping is designed for leak-before-break criteria and stainless-steel construction<br>19. Dual Fuel engine can switch over to backup fuel | |
| | | | 2. Liquid ammonia in TCS space | Asset | S4-Major | LB-Unlikely | High | | |
| | | 6. Tube failure of the heater<br>**Comment:** ABS Guide: 9/5.14 | 9. Ammonia in adjacent space where heating equipment is located | Asset | S2-Minor | LC-Possible | Moderate | 1. Continuous ventilation of space normal 30 air change and emergency upon gas detection<br>7. ESD on detection of fire or gas (closure of valve closest to tank)<br>16. Intermediate circuit expansion tank with ammonia detection is provided<br>19. Dual Fuel engine can switch over to backup fuel | 9. Expansion tank location (wrt regulations) needs to be considered for final location and installation<br>10. Expansion tank fluid to be looked at for use with ammonia/solubility/disposal<br>11. Ventilation exhaust from any hazardous area (ammonia) discharges into the same vent mast, possibility of reverse flow to be studied. (ABS Guide 12/6.3, ABS guide 12/6.4) |
| | | | 11. Ammonia in heating circuit | Asset | S2-Minor | LC-Possible | Moderate | | |
| | | 7. Failure of the centrifugal pump | 1. Gaseous ammonia inside the TCS space | Asset | S4-Major | LB-Unlikely | High | 1. Continuous ventilation of space normal 30 air change and emergency upon gas detection<br>2. Gas doctor in ventilation inlet/outlet | |

| No.: 2 | NH3 fuel storage tank A (engine room) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Item** | **Deviation** | **Causes** | **Consequences** | **Matrix** | **Severity** | **Likelihood** | **Risk** | **Safeguards** | **Recommendations** |
| | | | | | | | | 3. Fire and gas detectors inside TCS space<br>4. TCS space is gas and liquid tight<br>5. Designed to comply with ABS/IGF code<br>6. Space is protected against over-pressurisation<br>7. ESD on detection of fire or gas (closure of valve closest to tank)<br>8. TCS space is designed for zone 1<br>9. Sump with level or temperature detection (IGF requirement)<br>10. TCS space is designed to hold liquid ammonia<br>15. Maintenance and inspection<br>19. Dual Fuel engine can switch over to backup fuel | |
| | | | 2. Liquid ammonia in TCS space | Asset | S4-Major | LB-Unlikely | High | | |
| | | | 3. Fire/Explosion | Overall | S4-Major | LA-Rare | High | | |
| | | | 4. Damage to fuel tank | Asset | S4-Major | LA-Rare | High | | |
| | | | 5. Damage to TCS Space | Asset | S4-Major | LB-Unlikely | High | | |
| | | | 6. Ammonia gas in fuel tank holding space | Asset | S3-Moderate | LB-Unlikely | Moderate | | |
| | | | 7. Ammonia in ventilation exit leads to hazardous and toxic zone | Human | S2-Minor | LC-Possible | Moderate | | |
| | | | 8. Ammonia in ventilation exit leads to wider low concentration ammonia zone- passenger perception | Human | S4-Major | LC-Possible | Extreme | | |
| | | | 10. Ammonia not available for engine | Asset | S2-Minor | LC-Possible | Moderate | | |
| | | 8. Instrument/instrument connection leak | 1. Gaseous ammonia inside the TCS space | Asset | S4-Major | LB-Unlikely | High | 1. Continuous ventilation of space normal 30 air change and emergency upon gas detection<br>2. Gas doctor in ventilation inlet/outlet<br>3. Fire and gas detectors inside TCS space<br>4. TCS space is gas and liquid tight<br>5. Designed to comply with ABS/IGF code<br>6. Space is protected against over-pressurisation<br>7. ESD on detection of fire or gas (closure of valve closest to tank)<br>8. TCS space is designed for zone 1<br>9. Sump with level or temperature detection (IGF requirement)<br>10. TCS space is designed to hold liquid ammonia<br>12. Piping designed to leak-before-fail and stainless steel<br>15. Maintenance and inspection<br>19. Dual Fuel engine can switch over to backup fuel | |
| | | | 5. Damage to TCS Space | Asset | S4-Major | LB-Unlikely | High | | |
| | | | 6. Ammonia gas in fuel tank holding space | Asset | S3-Moderate | LB-Unlikely | Moderate | | |
| | | | 7. Ammonia in ventilation exit leads to hazardous and toxic zone | Human | S2-Minor | LC-Possible | Moderate | | |
| | | | 8. Ammonia in ventilation exit leads to wider low concentration ammonia zone- passenger perception | Human | S4-Major | LC-Possible | Extreme | | |
| | | 9. Stress corrosive cracking due to ammonia | 1. Gaseous ammonia inside the TCS space | Asset | S4-Major | LB-Unlikely | High | 9. Sump with level or temperature detection (IGF requirement)<br>10. TCS space is designed to hold liquid ammonia | |

| **No.:** 2 | NH3 fuel storage tank A (engine room) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Item** | **Deviation** | **Causes** | **Consequences** | **Matrix** | **Severity** | **Likelihood** | **Risk** | **Safeguards** | **Recommendations** |
| | | | | | | | | 11. Proper selection of materials used<br>12. Piping designed to leak before fail and stainless steel<br>13. Quality of ammonia is monitored<br>14. Proper insulation used on TCS piping<br>15. Maintenance and inspection<br>19. Dual Fuel engine can switch over to backup fuel | |
| | | | 2. Liquid ammonia in TCS space | Asset | S4-Major | LB-Unlikely | High | | |
| | | | 3. Fire/Explosion | Overall | S4-Major | LA-Rare | High | | |
| | | | 4. Damage to fuel tank | Asset | S4-Major | LA-Rare | High | | |
| | | | 5. Damage to TCS Space | Asset | S4-Major | LB-Unlikely | High | | |
| | | | 6. Ammonia gas in fuel tank holding space | Asset | S3-Moderate | LB-Unlikely | Moderate | | |
| | | | 7. Ammonia in ventilation exit leads to hazardous and toxic zone | Human | S2-Minor | LC-Possible | Moderate | | |
| | | | 8. Ammonia in ventilation exit leads to wider low concentration ammonia zone- passenger perception | Human | S4-Major | LC-Possible | Extreme | | |
| | | | 10. Ammonia not available for engine | Asset | S2-Minor | LC-Possible | Moderate | | |
| | | 10. Low temperature | 12. Ice formation/condensation on TCS piping and accumulation of water on floor | Asset | S3-Moderate | LD-Likely | High | 1. Continuous ventilation of space normal 30 air change and emergency upon gas detection<br>14. Proper insulation used on TCS piping | 2. Evaluate insulation requirement due to condensation and liquid ammonia<br>3. Evaluate TCS space for moisture condensation due to low-temperature ammonia piping<br>13. To avoid any condensation issues, consider dry ventilation air |
| | | | 13. Condensation in TCS space due to low temperature inside | Asset | S3-Moderate | LC-Possible | High | | |
| 2.2 | Leak from tank | 1. Metal fatigue (2 types of tanks are considered, single-wall tank with insulation or double-wall tank with vacuum insulation) | 1. Ammonia leak in fuel storage space for insulated tank | Asset | S4-Major | LA-Rare | High | 1. IGF/IGC Tank Type C has additional safety margin compared to standard pressure vessels, probability of structural failure is extremely low<br>2. IGC/IGF code requires proper material selection<br>3. Proper design meeting class and statutory requirements (IGC 4.4.4)<br>4. Regular inspection, maintenance and testing<br>5. Gas detector in fuel storage space<br>6. Operational procedure and requirements for entrance into fuel storage space (IGC/IGF specific requirement) | 14. For vacuum-insulated tank, the second layer should be designed to withstand leakage from first layer.<br>15. Fuel tank vacuum space to be monitored for leakage<br>16. Study the area classification for the ammonia tank in fuel storage area<br>17. To minimise fire risks, the fuel storage hold space shall not be used for machinery or equipment that may have a fire risk (Compliance to IGF 11.3.4) |
| | | | 2. Ammonia leak will be held in vacuum space in double-wall tank for vacuum insulated tank | Asset | S3-Moderate | LA-Rare | Moderate | | |
| | | 2. Stress corrosion | 1. Ammonia leak in fuel storage space for insulated tank | Asset | S4-Major | LA-Rare | High | 1. IGF/IGC Tank Type C has additional safety margin compared to standard pressure vessels, probability of structural failure is extremely low<br>2. IGC/IGF code requires proper material selection<br>3. Proper design meeting class and statutory requirements (IGC 4.4.4)<br>4. Regular inspection, maintenance and testing<br>5. Gas detector in fuel storage space<br>6. Operational procedures and requirements for entrance into fuel storage space (IGC/IGF specific requirement) | 14. For vacuum- insulated tank, the second layer should be designed to withstand leakage from the first layer.<br>15. Fuel tank vacuum space to be monitored for leakage<br>16. Study the area classification for the ammonia tank in fuel storage area<br>17. To minimise fire risks, the fuel storage hold space shall not be used for machinery or equipment that may have a fire risk (Compliance to IGF 11.3.4) |
| | | | 2. Ammonia leak will be held in vacuum space in double wall tank for vacuum insulated tank | Asset | S3-Moderate | LA-Rare | Moderate | | |

| **No.:** 2 | NH3 fuel storage tank A (engine room) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Item** | **Deviation** | **Causes** | **Consequences** | **Matrix** | **Severity** | **Likelihood** | **Risk** | **Safeguards** | **Recommendations** |
| | | 3. Failure at support | 1. Ammonia leak in fuel storage space for insulated tank | Asset | S4-Major | LA-Rare | High | 1. IGF/IGC Tank Type C has additional safety margin compared to standard pressure vessels, probability of structural failure is extremely low<br>2. IGC/IGF code requires proper material selection<br>3. Proper design meeting class and statutory requirements (IGC 4.4.4)<br>4. Regular inspection, maintenance and testing<br>5. Gas detector in fuel storage space<br>6. Operational procedure and requirements for entrance into fuel storage space (IGC/IGF specific requirement) | 14. For vacuum-insulated tank, the second layer should be designed to withstand leakage from the first layer.<br>15. Fuel tank vacuum space to be monitored for leakage<br>16. Study the area classification for the ammonia tank in fuel storage area<br>17. To minimize fire risks, the fuel storage hold space shall not be used for machinery or equipment that may have a fire risk (Compliance to IGF 11.3.4)<br>18. Considering risk, if tank's primary boundary has leak, emergency procedures are to be developed to address emptying fuel tank, safety and safe evacuation |
| 2.3 | Fire on deck 3 (deck above cargo hold space) | 1. Cargo fire<br>**Comment:** Cargo mainly vehicles/hazardous cargo in container/IMDG cargo/ reefer units on deck 3 | 1. High heat | Asset | S3-Moderate | LB-Unlikely | Moderate | 1. Deluge system on cargo deck<br>2. Fire/smoke detectors for cargo space<br>3. Higher risk cargo not allowed on deck 3<br>4. Deck is protected with A-60 underneath (ammonia tank situated underneath) | 19. Ammonia tank room firefighting requirement to be evaluated |
| | | | 2. Integrity of deck compromised | Asset | S4-Major | LB-Unlikely | High | | |
| | | | 3. Smoke leading to personnel exposure | Human | S2-Minor | LC-Possible | Moderate | | |
| 2.4 | Fire in machinery space aft of ammonia tank hold space | 1. Failure of equipment and fire<br>**Comment:** Contains separators, filters, pumps, heater/burner for ammonia tank | 1. Damage to bulk head due to heat | Asset | S3-Moderate | LC-Possible | High | 1. Structural fire protection in machinery space<br>2. Dampers in machinery space<br>3. Fire detection in machinery space<br>4. Water spray system<br>5. CCTV in machinery space<br>6. Oil mist detection system<br>7. Back up fuel<br>8. Dual Fuel engine can switch over to backup fuel | 17. To minimise fire risks, the fuel storage hold space shall not be used for machinery or equipment that may have a fire risk (Compliance to IGF 11.3.4)<br>20. Upon loss of burner, determine where the ammonia between the engine and main shutdown valve is vented |
| | | | 2. Ammonia fuel system will be shut down due to loss of heater/burner | Asset | S3-Moderate | LC-Possible | High | | |
| 2.5 | Fire explosion in reliq plant | 1. Leakage due to connection/flange/seal failure<br>**Comment:** Reliq plant considered fuel-preparation room under ABS requirement and maybe consider it to be a Category A machinery space | 1. Fire and explosion | Overall | S3-Moderate | LC-Possible | High | 2. Fire and gas detector<br>3. Ventilation (normal and emergency)<br>4. Air locks for entry into plant<br>5. Reliq plant space maintained at negative pressure | 21. Structural fire protection requirement for room to be A-60 rated<br>22. Fuel changeover philosophy and engine capacity need to be worked out<br>23. Piping between TCS and reliq plant to be protected (mechanical protection)<br>24. Consider separation between boundary of reliq plant and fuel tank<br>25. Consider eye wash and PPE near to potential ammonia exposure area<br>26. Firefighting philosophy and equipment to be provided for reliq plant space<br>46. Firefighting and fire suppression systems need to be developed e.g., water-spray system to dissolve ammonia gas |
| | | | 2. Damage to TCS | Asset | S3-Moderate | LB-Unlikely | Moderate | | |
| | | 2. Electrical fire | 1. Fire and explosion | Overall | S3-Moderate | LC-Possible | High | 1. Classified as Zone 1 area<br>2. Fire and gas detector<br>3. Ventilation (normal and emergency) | 26. Firefighting philosophy and equipment to be provided for reliq plant space<br>46. Firefighting and fire suppression systems need to be developed e.g., water-spray system to dissolve ammonia gas |
| | | | 2. Damage to TCS | Asset | S3-Moderate | LB-Unlikely | Moderate | | |

| **No.:** 2 | NH3 fuel storage tank A (engine room) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Item** | **Deviation** | **Causes** | **Consequences** | **Matrix** | **Severity** | **Likelihood** | **Risk** | **Safeguards** | **Recommendations** |
| | | | 3. Damage to MGO tank | Asset | S4-Major | LB-Unlikely | High | | |
| 2.6 | Grounding/collision | 1. Grounding | 1. Flooding of fuel tank space | Asset | S3-Moderate | LC-Possible | High | 1. Tank location meets IGF/IGC requirement and passenger vessel damage stability requirement, designed for 0.5G<br>2. Tank support designed to withstand complete flooding/upward force<br>3. Relief valve and venting designed for maximum worst case discharge capacity<br>4. Navigation and route planning<br>5. Vertical damage penetration requirements are b/10 (IGC/IGF requirements)<br>6. Bottom damage penetration requirement meet IGF code and other standard<br>7. Opening of safety valve | 27. Relief valve capacity should consider complete flooding of compartment<br>28. Ensure tank shut-off valves are fail-safe close<br>29. Calculation to be done to estimate vapourisation time of tank<br>30. Dispersion analysis for worst case scenario to be performed for toxic zone and hazardous zone |
| | | | 2. Rise of pressure due to heat gain in Ammonia tank | Asset | S3-Moderate | LC-Possible | High | | |
| | | | 4. Loss of tank support/tank floating | Asset | S4-Major | LB-Unlikely | High | | |
| | | | 5. Gas discharge to vent mast | Environment | S3-Moderate | LC-Possible | High | | |
| | | | 6. Damage to tank | Asset | S4-Major | LB-Unlikely | High | | |
| | | | 7. Damage to TCS equipment | Asset | S3-Moderate | LC-Possible | High | | |
| | | 2. Collision | 1. Flooding of fuel tank space | Asset | S3-Moderate | LC-Possible | High | 1. Tank location meets IGF/IGC requirement and passenger vessel damage stability requirement, designed for 0.5G<br>2. Tank support designed to withstand complete flooding/upward force<br>3. Relief valve and venting designed for maximum worst case discharge capacity<br>4. Navigation and route planning<br>5. Vertical damage penetration requirements are b/10 (IGC/IGF requirements) | 27. Relief valve capacity should consider complete flooding of compartment<br>28. Ensure tank shut-off valves are fail-safe close<br>29. Calculation to be done to estimate vapourisation time of tank<br>30. Dispersion analysis for worst-case scenario to be performed for toxic zone and hazardous zone |
| | | | 2. Rise of pressure due to heat gain in ammonia tank | Asset | S3-Moderate | LC-Possible | High | | |
| | | | 4. Loss of tank support/tank floating | Asset | S4-Major | LB-Unlikely | High | | |
| | | | 5. Gas discharge to vent mast | Environment | S3-Moderate | LC-Possible | High | | |
| | | | 6. Damage to tank | Asset | S4-Major | LB-Unlikely | High | | |
| | | | 7. Damage to TCS equipment | Asset | S3-Moderate | LC-Possible | High | | |
| | | | 8. Damage to vent mast (passing under bridge) | Asset | S3-Moderate | LB-Unlikely | Moderate | | |
| | | | 9. Life boat may be in toxic zone | Overall | S4-Major | LB-Unlikely | High | | |
| 2.7 | Fire in battery compartment between frame 108-120 | 1. Thermal overrun<br>**Comment:** Battery will be powered at port or using engine power, EMSA studies available for battery compartments. | 1. Fire/Explosion | Overall | S3-Moderate | LC-Possible | High | 1. Battery room A-60 rated boundary<br>2. Battery management system<br>3. Battery compartment has ventilation system to keep battery cool<br>4. Each module will be ventilated separately | 31. Battery compartment structural protections are to be studied to ensure they comply with class requirement<br>32. Escape routes from battery compartments to be studied to ensure they meet SOLAS requirement<br>33. Battery compartment firefighting equipment to be provided |
| | | | 2. Release of toxic gas | Human | S2-Minor | LB-Unlikely | Low | | |

**No.:** 2 NH3 fuel storage tank A (engine room)

| Item | Deviation | Causes | Consequences | Matrix | Severity | Likelihood | Risk | Safeguards | Recommendations |
|---|---|---|---|---|---|---|---|---|---|
| | | | 3. High heat leads to damage of the battery compartment | Asset | S3-Moderate | LB-Unlikely | Moderate | | |
| | | 2. Collision | 1. Fire/Explosion | Overall | S3-Moderate | LC-Possible | High | | 34. Battery location to comply with statutory and class requirements |
| | | | 4. Damage to side shell will lead to flooding of compartment | Asset | S3-Moderate | LC-Possible | High | | |
| | | | 5. Submerged battery can lead to thermal overrun | Asset | S3-Moderate | LC-Possible | High | | |
| | | | 6. Flooding of battery compartment | Asset | S3-Moderate | LC-Possible | High | | |
| | | 3. Grounding | 1. Fire/Explosion | Overall | S3-Moderate | LC-Possible | High | | 34. Battery location to comply with statutory and class requirements |
| | | | 5. Submerged battery can lead to thermal overrun | Asset | S3-Moderate | LC-Possible | High | | |
| | | | 6. Flooding of battery compartment | Asset | S3-Moderate | LC-Possible | High | | |
| 2.8 | GVU (Gas valve unit) | 1. No risk identified. Not discussed further. GVU is acceptable for ABS ammonia guide (ABS 9/5.8) | | | | | | | |
| 2.9 | Over-pressurisation of the tank | 1. Operator error | 1. Tank failure | Asset | S4-Major | LB-Unlikely | High | 1. Pressure relief valve<br>2. Pressure monitoring<br>3. Level monitoring<br>5. Gas detector in hold space<br>6. Training | |
| | | | 2. Ammonia in hold space | Asset | S3-Moderate | LB-Unlikely | Moderate | | |
| | | | 3. Fire/Explosion | Overall | S4-Major | LA-Rare | High | | |
| | | 2. Fire in hold space or surrounding (deck 3, engine room etc.) | 4. Heat gain in tank leads to over-pressurisation | Asset | S2-Minor | LC-Possible | Moderate | 1. Pressure relief valve<br>2. Pressure monitoring<br>4. Reliq plant for pressure management<br>5. Gas detector in hold space | |
| | | 3. Failed sensors<br>**Comment:** Cargo management procedures for IGF code will be developed | 1. Tank failure | Asset | S4-Major | LB-Unlikely | High | 1. Pressure relief valve<br>2. Pressure monitoring<br>3. Level monitoring<br>4. Reliq plant for pressure management<br>5. Gas detector in hold space<br>6. Training | 27. Relief valve capacity should consider complete flooding of compartment |
| | | | 2. Ammonia in hold space | Asset | S3-Moderate | LB-Unlikely | Moderate | | |
| | | | 3. Fire/Explosion | Overall | S4-Major | LA-Rare | High | | |
| 2.10 | Overfilling tank | 1. Level sensor failure | 1. Liquid ammonia in relief valve and vent | Asset | S3-Moderate | LB-Unlikely | Moderate | 1. Redundant liquid level measurement<br>2. Alarms and automatic shutdown<br>3. Continuous monitoring through control panel and CCTV | 35. Any penetration (e.g., level gauge) is to be justified through alternative arrangement (IMO MSC 1455) |
| | | 2. Operator error | 1. Liquid ammonia in relief valve and vent | Asset | S3-Moderate | LB-Unlikely | Moderate | 1. Redundant liquid level measurement<br>2. Alarms and automatic shutdown<br>3. Continuous monitoring through control panel and CCTV<br>4. Training | |

| **No.:** 2 | NH3 fuel storage tank A (engine room) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Item** | **Deviation** | **Causes** | **Consequences** | **Matrix** | **Severity** | **Likelihood** | **Risk** | **Safeguards** | **Recommendations** |
| 2.11 | Escape routes in area | 1. No risk identified.<br>**Comment:** Design to be in compliance with IGF and SOLAS requirement. Two means of escape for spaces. | | | | | | 1. All PPE provided where ammonia gas expected | |
| 2.12 | Power loss | 1. Loss of power due to electrical fault, generator failure | 1. Loss of reliq plant leads to pressure rise in tank | Asset | S2-Minor | LC-Possible | Moderate | 1. Ship will meet safe return to port regulations<br>2. Dual fuel engine in a separate compartment and the battery has auxiliary power<br>3. Reliq plant is connected to emergency power also | |
| 2.13 | Sloshing inside tank | 1. Movement of fuel inside tank due to ship motion - sloshing load | 1. Tank damage | Asset | S3-Moderate | LB-Unlikely | Moderate | 1. Internal baffles provided to minimise sloshing load | |
| 2.14 | Pressure, temperature, level management of tank | 1. No risk identified.<br>**Comment:** Vessel to comply with IGF requirement and current industry practices. | | | | | | | |

| | |
|---|---|
| 3 | NH3 fuel storage tank B (on open deck) |
| Section notes:<br>- $NH_3$ tank open on deck at aft for Ro-Pax ship<br>- Vent mast location may differ for open deck arrangement<br>- Unknown if tank will be in open or closed environment<br>- Space below ammonia tank is a closed space with limited ventilation<br>- Compartment next to battery assumed to be empty space | |

| **No.:** 3 | NH3 fuel storage tank B (on open deck) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Item** | **Deviation** | **Causes** | **Consequences** | **Matrix** | **Severity** | **Likelihood** | **Risk** | **Safeguards** | **Recommendations** |
| 3.1 | Ammonia leakage from tank connections in TCS space | 1. Ammonia leakage in TCS space - $NH_3$ fuel storage tank A (engine room) (linked from 2.1)<br>**Comment:** Risk in deck configuration is lower | | | | | | | |
| 3.2 | Leak from tank | 1. Metal fatigue<br>**Comment:** 2 types of tanks are considered, single-wall tank with insulation or double-wall tank with vacuum insulation | 1. Ammonia leak from tank to atmosphere for insulated tank | Asset | S4-Major | LA-Rare | High | 1. IGF/IGC Tank Type C has additional safety margin compared to standard pressure vessels, probability of structural failure is extremely low<br>2. IGC/IGF code requires proper material selection<br>3. Proper design meeting class and statutory requirements (IGC 4.4.4)<br>4. Regular inspection, maintenance and testing | 14. For vacuum-insulated tanks, the second layer should be designed to withstand leakage from the first layer.<br>15. Fuel tank vacuum space to be monitored for leakage<br>16. Study the area classification for the ammonia tank in fuel storage area<br>17. To minimise fire risks, the fuel storage hold space shall not be used for machinery or equipment that may have a fire risk (Compliance to IGF 11.3.4)<br>18. Consider risk if the tank's primary boundary has leak emergency; procedure is to be developed to address emptying fuel tank, safety and safe evacuation |
| | | | 2. Ammonia leak will be held in vacuum space in double-wall tank for vacuum-insulated tank | Asset | S3-Moderate | LA-Rare | Moderate | | |
| | | 2. Stress corrosion | 1. Ammonia leak from tank to atmosphere for insulated tank | Asset | S4-Major | LA-Rare | High | 1. IGF/IGC tank Type C has additional safety margin compared to standard pressure vessels, probability of structural failure is extremely low<br>2. IGC/IGF codes require proper material selection<br>3. Proper design meeting class and statutory requirements (IGC 4.4.4)<br>4. Regular inspection, maintenance and testing<br>5. Gas detector in fuel storage space<br>6. Operational procedure and requirements for entrance into fuel storage space (IGC/IGF specific requirement) | 14. For vacuum-insulated tanks, the second layer should be designed to withstand leakage from the first layer.<br>15. Fuel tank vacuum space to be monitored for leakage<br>16. Study the area classification for the ammonia tank in fuel storage area<br>17. To minimise fire risks, the fuel storage hold space shall not be used for machinery or equipment that may have a fire risk (Compliance to IGF 11.3.4)<br>18. Consider risk if the tank's primary boundary has a leak; emergency procedures are to be developed to address emptying fuel tank, safety and safe evacuation |
| | | | 2. Ammonia leak will be held in vacuum space in double-wall tank for vacuum insulated tank | Asset | S3-Moderate | LA-Rare | Moderate | | |
| 3.3 | Fire on deck | 1. IMDG cargo fire<br>**Comment:** On deck IMGD cargoes are allowed | 1. Fuel tank exposed to high temperature | Asset | S3-Moderate | LC-Possible | High | 1. Water deluge system protecting boundary/tank<br>2. Fire and heat detection on open deck<br>3. CTTV on open deck<br>4. Water cannon and fire monitor | 36. Storage of dangerous cargo next to ammonia tank to be studied for fire risk<br>37. Structural fire protection at the tank boundary to be studied based on IMDG cargo and fire load<br>38. Ensure personnel areas are not in toxic zones unless PPE is provided |
| | | | 2. High tank pressure will cause relief valve to vent ammonia | Asset | S3-Moderate | LC-Possible | High | | |
| 3.4 | Fire from deck below | 1. Vehicle/cargo fire<br>**Comment:** Below deck cargo is normal cars/trucks | 1. Damage to open deck/damage to tank | Asset | S5-Critical | LC-Possible | Extreme | 1. Fuel tank deck has A-60 insulation<br>2. Firefighting water spray system (drencher system)<br>3. Space below fuel tank is closed space<br>4. Fire and smoke detection | 39. Fire-load analysis to determine the structural integrity of fuel tank deck |

**No.:** 3 NH3 fuel storage tank B (on open deck)

| Item | Deviation | Causes | Consequences | Matrix | Severity | Likelihood | Risk | Safeguards | Recommendations |
|---|---|---|---|---|---|---|---|---|---|
| | | | 2. Ammonia in atmosphere and on deck | Human | S5-Critical | LC-Possible | Extreme | | |
| 3.5 | Fire explosion in reliq plant | 1. Leakage due to connection/flange/seal failure **Comment:** Reliq plant considered; fuel preparation room under ABS requirement and may be consideredr as a Category A machinery space | 1. Damage to IMDG cargo | Asset | S3-Moderate | LB-Unlikely | Moderate | 1. reliq plant are inside A-60 rated enclosed space<br>2. Classified as Zone 1 area<br>3. Fire and gas detector<br>4. Ventilation (normal and emergency)<br>5. Air locks for entry into plant<br>6. Reliq plant space maintained at negative pressure<br>7. Vents are vented to vent mast | |
| | | | 2. Fire and explosion | Overall | S3-Moderate | LB-Unlikely | Moderate | | |
| 3.6 | Grounding/collision | 1. No risk identified. Not discussed further. | | | | | | | |
| 3.7 | Over-pressurisation of the tank | 1. No risk identified. Not discussed further. **Comment:** Vessel complied with IGF and industry practice. | | | | | | | |
| 3.8 | Overfilling tank | 1. No risk identified. Not discussed further. **Comment:** Complied with IFG and industry practices. | | | | | | | |
| 3.9 | Dangerous good close to ammonia tank | 1. Cargo | 1. fire/explosion | Overall | S3-Moderate | LB-Unlikely | Moderate | | 40. Proper study to be done for category of IMDG goods next to ammonia tank, considering fire and explosion risk |
| 3.10 | Escape routes in area | 1. Ammonia leak | 1. Passengers exposed to ammonia | Human | S4-Major | LB-Unlikely | High | | 41. Proper gas-dispersion analysis to be conducted considering ammonia leak, venting; results are to be considered for layout of walkway and passenger traffic area |
| 3.11 | Power loss | 1. No risk identified. Not discussed further. **Comment:** Vessel complied with IGF codes and industry practices | | | | | | | |
| 3.12 | Sloshing inside tank | 1. No risk identified. Not discussed further. **Comment:** Tank has baffle inside. | | | | | | | |
| 3.13 | Pressure, temperature, level management of tank | 1. No risk identified. Not discussed further. | | | | | | | |
| 3.14 | Dropped Objects | 1. Dropped object | 1. Damage to tank | Asset | S4-Major | LB-Unlikely | High | 1. No lifting allowed around fuel tank area | |
| 3.15 | Damage to ammonia tank due to vehicle traffic | 1. Accident involving vehicle and ammonia tank | 1. Damage to tank/Ammonia leak | Asset | S3-Moderate | LC-Possible | High | | 42. Study to be conducted to prevent damage to tank due to vehicle collisions and additional safeguards provided |
| 3.16 | Passengers around ammonia tank | 1. Passengers on deck during loading/unloading of ship **Comment:** Passengers are not allowed close to ammonia tank except during loading/unloading at port | 1. Passenger exposure to risk/ammonia | Human | S3-Moderate | LC-Possible | High | 1. Potential leak points in enclosed area and vented (TCS and reliq plant)<br>2. Passengers are not allowed on deck where ammonia tank is located except during loading/unloading at port<br>3. All piping is double-walled and protected | 43. Consider ammonia gas detection at detection level of personnel (5 ppm) |
| 3.17 | Fire in battery compartment between frame 108-120 | 1. Fire in battery compartment between frame 108-120 - $NH_3$ fuel storage tank A (engine room) (linked from 2.7) | | | | | | | |
| 3.18 | GVU (Gas valve unit) | 1. No risk identified. Not discussed further. **Comment:** Vessel complied with IGF codes and industry practices | | | | | | | |

| 4 | Bunkering Arrangement (tank in hold) |
|---|---|

Section notes:
- During Bunkering, it is assumed that passengers and cargo will load/unload simultaneously.
- Assume MGO and ammonia Bunkering may occur simultaneously, but at a sufficiently safe distance that it's not considered a hazard.
- Bunker station is enclosed space with ventilation, there are 2 lines for Bbunkering and ammonia vapor
- Side shell designed to withstand -33° C

**No.:** 4 Bunkering Arrangement (tank in hold)

| Item | Deviation | Causes | Consequences | Matrix | Severity | Likelihood | Risk | Safeguards | Recommendations |
|---|---|---|---|---|---|---|---|---|---|
| 4.1 | Bunkering in port from shore | 1. Bunker hose failure | 1. Cold Liquid ammonia on water | Asset | S4-Major | LC-Possible | Extreme | 1. Gas detection<br>2. ESD systems (1 and 2)<br>3. CCTV monitoring<br>4. Appropriate PPE<br>5. Training of crew for ammonia handling<br>6. Procedures for ammonia handling and Bunkering<br>7. Procedure for breakaway/ coupling<br>10. Safety zones/exclusion zones around bunkering operations<br>11. hazardous area electrical equipment classification<br>13. Emergency response protocols for crew and port<br>20. Inspection and maintenance | |
| | | | 2. Evaporation of ammonia into air | Asset | S2-Minor | LC-Possible | Moderate | | |
| | | | 3. Ammonia gas on vessel, exposure to personnel on board | Human | S4-Major | LC-Possible | Extreme | | |
| | | | 4. Impact of ammonia gas on personnel in port | Human | S4-Major | LC-Possible | Extreme | | |
| | | | 5Ignition/fire of ammonia if concentration within flammable range | Asset | S3-Moderate | LB-Unlikely | Moderate | | |
| | | | 6. Environmental impact (marine life) | Environment | S3-Moderate | LC-Possible | High | | |
| | | 2. Bunker connection leak outside bunker station<br>**Comment:** Assume Bunkering can be done using loading arm, trucks, hoses etc. | 1. Cold Liquid ammonia on water | Asset | S4-Major | LC-Possible | Extreme | 1. Gas detection<br>2. ESD systems (1 and 2)<br>3. CCTV monitoring<br>4. Appropriate PPE<br>5. Training of crew for ammonia handling<br>6. Procedures for ammonia handling and Bunkering<br>7. Procedure for breakaway/ coupling<br>8. Drip tray to collect ammonia inside bunker station<br>9. Suction type ventilation system in bunker station with 30-45 air change<br>10. Safety zones/exclusion zones around bunkering operations<br>11. hazardous area electrical equipment classification<br>12. SIMOPS risk mitigation measures<br>13. Emergency response protocols for crew and port<br>23. The water curtain on a site cell | 44. Bunkering using port facility is to be addressed with a separate study with the port operators and local requirements<br>46. Firefighting and fire-suppression system needs to be developed e.g., water-spray system to dissolve ammonia gas<br>47. Dispersion analysis for maximum credible/worst case scenario to determine impact on ship, passengers and personnel<br>48. Bunkering study to develop safety/ exclusion zones criteria<br>49. SIMOPS study considering ammonia bunkering and passengers to be conducted |
| | | | 2. Evaporation of ammonia into air | Asset | S2-Minor | LC-Possible | Moderate | | |
| | | | 3. Ammonia gas on vessel, exposure to personnel on board | Human | S4-Major | LC-Possible | Extreme | | |
| | | | 4. Impact of ammonia gas on personnel in port | Human | S4-Major | LC-Possible | Extreme | | |

| No.: 4 | Bunkering Arrangement (tank in hold) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Item** | **Deviation** | **Causes** | **Consequences** | **Matrix** | **Severity** | **Likelihood** | **Risk** | **Safeguards** | **Recommendations** |
| | | | 5. Ignition/fire of ammonia if concentration within flammable range | Asset | S3-Moderate | LB-Unlikely | Moderate | | |
| | | | 6. Environmental impact (marine life) | Environment | S3-Moderate | LC-Possible | High | | |
| | | 3. Bunker connection leak inside bunker station | 2. Evaporation of ammonia into air | Asset | S2-Minor | LC-Possible | Moderate | 3. CCTV monitoring<br>4. Appropriate PPE<br>5. Training of crew for ammonia handling<br>6. Procedures for ammonia handling and Bunkering<br>7. Procedure for breakaway/coupling<br>8. Drip tray to collect ammonia inside bunker station<br>9. Suction type ventilation system in bunker station with 30-45 air change<br>10. Safety zones/exclusion zones around bunkering operations<br>11. hazardous area electrical equipment classification<br>12. SIMOPS risk mitigation measures<br>13. Emergency response protocols for crew and port<br>20. Inspection and maintenance<br>21. Drip tray under bunker manifold | |
| | | | 5. Ignition/fire of ammonia if concentration within flammable range | Asset | S3-Moderate | LB-Unlikely | Moderate | | |
| | | | 7. gaseous ammonia inside bunker station | Asset | S2-Minor | LB-Unlikely | Low | | |
| | | | 8. Cold liquid ammonia inside bunker | Asset | S1-Low | LC-Possible | Low | | |
| | | 4. Bunker line failure from bunker station to tank (material issues, stress, corrosion, mechanical damage) | 9. Over-pressurisation of void space | Asset | S3-Moderate | LC-Possible | High | 14. Bunker line routed through void spaces, avoids cargo or high-traffic areas | 50. Study to be done for bunker-line failure and impact on ship with solutions e.g., double-wall piping, leak-before-break criteria for design, proper material selection<br>51. Consider over pressure protection and venting for cold spaces |
| | | 5. Bunker line over-pressurisation | 10. Line failure | Asset | S4-Major | LB-Unlikely | High | 3. CCTV monitoring<br>15. Pressure relief valve vented to safe location<br>16. Pressure/temperature monitoring and alarms | |
| | | 6. Trapped fluid in bunker line | 9. Over-pressurisation of void space | Asset | S3-Moderate | LC-Possible | High | 17. Bunker lines are emptied after each bunker operation<br>22. Bunker line purged after each operation | |
| | | | 10. Line failure | Asset | S4-Major | LB-Unlikely | High | | |
| | | 7. Ship movement during Bunkering (improper ballasting operations, wave effect of passing ship) | 11. Higher load on transfer hose or arm | Asset | S3-Moderate | LB-Unlikely | Moderate | 18. Breakaway coupling | |
| | | 8. High wind during Bunkering | | | | | | 19. Operational restrictions considering environmental parameters e.g., wind speed | |
| 4.2 | Bunkering in port using barge | 1. Mooring line failure | 2. Barge movement creating a high load on transfer hoses leading to hose failure | Asset | S3-Moderate | LC-Possible | High | 1. Barge crew response and procedures | 54. Compatibility study between bunkering vessel and Ro-Pax to be performed |
| | | | 3. Barge personnel exposed to ammonia | Human | S3-Moderate | LB-Unlikely | Moderate | | |
| | | 2. Fire explosion emergency on barge | 4. Ammonia leak from bunkering vessel | Asset | S4-Major | LB-Unlikely | High | | 55. Emergency procedures to be developed for bunkering vessel emergency in consultation with port and Ro-Pax |
| | | 3. Passing vessel creating wave surge | 2. Barge movement creating a high load on transfer hoses leading to hose failure | Asset | S3-Moderate | LC-Possible | High | | 52. Port to establish protocols for distance and speed of passing vessels to avoid surges |

| **No.:** 4 | Bunkering Arrangement (tank in hold) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Item** | **Deviation** | **Causes** | **Consequences** | **Matrix** | **Severity** | **Likelihood** | **Risk** | **Safeguards** | **Recommendations** |
| | | | 3. Barge personnel exposed to ammonia | Human | S3-Moderate | LB-Unlikely | Moderate | | |
| | | 4. High wind during bunkering | 2. Barge movement creating a high load on transfer hoses leading to hose failure | Overall | S3-Moderate | LC-Possible | High | 2. Operational restrictions considering environmental parameters e.g., wind speed<br>3. Mooring analysis and safeguards | 52. Port to establish protocols for distance and speed of passing vessels to avoid surges<br>53. Establish safety zone around bunkering vessels |
| 4.3 | Ship-to-ship bunkering outside of port | 1. Hose/loading arm failure<br>**Comment:** Assume passengers and cargo are on board, client don't think this is a realistic scenario | 1. Ammonia in air | Environment | S3-Moderate | LB-Unlikely | Moderate | 3. Inspection and maintenance | 47. Dispersion analysis for maximum credible/worst-case scenario to determine impact on ship, passengers and personnel<br>56. Safety zones are established for ship-to-ship bunkering<br>57. SIMOP safety study to determine risks of ship-to-ship bunkering with passengers and cargo on board<br>58. Hazardous areas on bunkering vessel to be studied |
| | | | 2. Ammonia in water | Environment | S4-Major | LC-Possible | Extreme | | |
| | | | 3. Ammonia impacting Ro-Pax passengers | Human | S4-Major | LC-Possible | Extreme | | |
| | | 2. Rough weather | 1. Ammonia in air | Environment | S3-Moderate | LB-Unlikely | Moderate | 1. Operational restrictions considering environmental parameters e.g., wind speed<br>2. Weather forecasting | |
| | | | 2. Ammonia in water | Environment | S4-Major | LC-Possible | Extreme | | |
| | | | 3. Ammonia impacting Ro-Pax passengers | Human | S4-Major | LC-Possible | Extreme | | |
| | | | 4. Mooring failure | Asset | S3-Moderate | LB-Unlikely | Moderate | | |
| | | | 5. High movement between vessels | Asset | S3-Moderate | LB-Unlikely | Moderate | | |
| | | 3. High sea current | 1. Ammonia in air | Environment | S3-Moderate | LB-Unlikely | Moderate | 1. Operational restrictions considering environmental parameters e.g., wind speed<br>2. Weather forecasting | |
| | | | 2. Ammonia in water | Environment | S4-Major | LC-Possible | Extreme | | |
| | | | 3. Ammonia impacting Ro-Pax passengers | Human | S4-Major | LC-Possible | Extreme | | |
| | | | 4. Mooring failure | Asset | S3-Moderate | LB-Unlikely | Moderate | | |
| | | | 5. High movement between vessels | Asset | S3-Moderate | LB-Unlikely | Moderate | | |
| | | 4. Stop during journey | 6. Bunkering operation mid journey will lead to bad perception from passengers | Human | S3-Moderate | LC-Possible | High | | 59. Bunkering to be avoided mid journey |
| 4.4 | Simultaneous Operation (NH3/MGO) | The team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | 60. All simultaneous operation scenarios to be studied and proper mitigation measures determined - bunkering, cargo and passenger load/unload, supply |

| **No.:** 4 | Bunkering Arrangement (tank in hold) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Item** | **Deviation** | **Causes** | **Consequences** | **Matrix** | **Severity** | **Likelihood** | **Risk** | **Safeguards** | **Recommendations** |
| 5 | Bunkering arrangement (on deck) | | | | | | | | |

Section Notes:
- Connection for nitrogen in bunker station, the nitrogen is used to push the ammonia inside the tank.
- Assume no vapour return line in bunker station.
- Normal bunker station exhaust leads to the top of the gas-ventilation room (separate from TCS vent). Emergency relief valve will vent to gas-ventilation room and then gas vent mast.

| **No.:** 5 | Bunkering arrangement (on deck) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Item** | **Deviation** | **Causes** | **Consequences** | **Matrix** | **Severity** | **Likelihood** | **Risk** | **Safeguards** | **Recommendations** |
| 5.1 | Ammonia leak | 1. Ammonia leak | 1. passenger exposure to ammonia | Human | S3-Moderate | LC-Possible | High | 1. Ammonia is vented to vent mast<br>2. Piping on deck is double-wall and protected | 61. Gas-dispersion analysis considering bunkering location study to be conducted with passenger area/traffic for potential exposure of passenger to ammonia |

| 6 | Fuel preparation room |
|---|---|
| Section notes:<br>- node covers Fuel Transfer/Fuel preparation /Reliquification/pumps/piping<br>- Need to check if shell type GVUs are suitable for ammonia in general machinery space rather than in a dedicated room.<br>- No dedicated fuel-transfer space, TCS space is considered as a fuel-preparation room which is already covered | |

| **No.:** 6 | Fuel preparation room | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Item** | **Deviation** | **Causes** | **Consequences** | **Matrix** | **Severity** | **Likelihood** | **Risk** | **Safeguards** | **Recommendations** |
| 6.1 | No new risk identified.<br>Not discussed further. | | | | | | | | |

| 7 | Machinery space (ER) |
|---|---|
| Section Notes:<br>- node covers Use of Fuel/Engine Maintenance Activity/Engine<br>- Type C tanks used here are not expected to leak. Air locks not required for flammable purposes, but could help with toxicity, air locks pre-existing from LNG fuel. TCS is liquid and gas tight. Any fuel piping in engine room is double-wall piping.<br>- Master gas valve is in TCS<br>- Piping between GVU and engine will be vented via burner in case of engine shutdown; if this is not available, the gas is routed to the vent mast. This pipe is vented, not purged.<br>- All piping between GVU and engine will be purged<br>- Double-wall pipe between TCS and GVU is designed for 18 bar, 45 °C to hold gas and thermal relief is provided in case of emergency.<br>- Ammonia fuel supplied at ~8 bar | |

| **No.:** 7 | Machinery space (ER) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Item** | **Deviation** | **Causes** | **Consequences** | **Matrix** | **Severity** | **Likelihood** | **Risk** | **Safeguards** | **Recommendations** |
| 7.1 | Ammonia slip from the engine | 1. Ammonia in crank case | 1. Ammonia slip in engine exhaust | Asset | S2-Minor | LC-Possible | Moderate | 2. Explosion relief valve on crank case | 62. Proper maintenance and testing procedures to be developed<br>65. Engine manufacturer to address issue of ammonia release into engine room e.g., ,crank case explosion<br>67. Explosion-relief valve venting to be provided to lead to outside engine room<br>68. Purging capability to be provided to purge any trapped ammonia in piping |
| | | | 3. Ammonia inside the engine room | Asset | S3-Moderate | LB-Unlikely | Moderate | | |
| | | | 4. Ammonia exposure to crew during maintenance | Human | S3-Moderate | LB-Unlikely | Moderate | | |
| | | 2. Engine emergency stop (sudden or controlled) | 1. Ammonia slip in engine exhaust | Asset | S2-Minor | LC-Possible | Moderate | 3. Piping between GVU and engine has the capability to send the gas to .collection | 64. Study to be performed for the maximum release of ammonia into the air |
| | | | 2. Concentration (>5 ppm) can be detected by passengers | Human | S4-Major | LC-Possible | Extreme | | |
| | | | 5. Ammonia at supply pressure (~8 bar) trapped in engine | Asset | S3-Moderate | LC-Possible | High | | |
| | | | 6. Ammonia at supply pressure (~8 bar) trapped in pipes | Asset | S3-Moderate | LC-Possible | High | | |
| | | | 7. Unburnt ammonia in exhaust | Asset | S2-Minor | LD-Likely | High | | |
| | | | 8. Stuck ammonia in engine cylinders in case of emergency stop | Asset | S3-Moderate | LC-Possible | High | | |
| | | 3. Otto cycle will not burn 100% ammonia | 1. Ammonia slip in engine exhaust | Asset | S2-Minor | LC-Possible | Moderate | 1. SCR is provided | 63. Study to be performed to determine how to handle ammonia slip from engine exhaust e.g., catalyst or scrubber<br>64. Study to be performed for the maximum release of ammonia into the air<br>66. Discharge from exhaust to be studied and the hazardous and toxic zones developed during explosion in exhaust. |
| | | | 2. Concentration (>5 ppm) can be detected by passengers | Human | S4-Major | LC-Possible | Extreme | | |
| | | | 7. Unburned ammonia in exhaust | Asset | S2-Minor | LD-Likely | High | | |
| 7.2 | GVU (Gas valve unit) | No additional risks identified by the team. Design will comply with IGC/IGF Code and standard practices. | | | | | | | |
| 7.3 | Double-Wall Piping | 1. Corrosion/stress cracking<br>**Comment:** Current plan is to purge with air. Alternative can be nitrogen system for double-wall piping | 1. Inner pipe failure | Asset | S2-Minor | LC-Possible | Moderate | 1. Gas detector in the annulus space<br>2. Continuous ventilation<br>3. Proper selection of material addressing material degradation issue<br>4. System is tested before every startup | |
| | | | 2. Ammonia in double-wall space | Asset | S2-Minor | LC-Possible | Moderate | | |

| **No.:** 7 | Machinery space (ER) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Item** | **Deviation** | **Causes** | **Consequences** | **Matrix** | **Severity** | **Likelihood** | **Risk** | **Safeguards** | **Recommendations** |
| | | 2. Dropped object/mechanical damage causing complete failure of double wall pipe | 3. Gas in engine room | Asset | S3-Moderate | LB-Unlikely | Moderate | 5. No overhead lifting allowed above ammonia pipe in engine room<br>6. Engine can switch over to backup fuel | |
| | | | 4. Loss of ammonia supply to engine | Asset | S3-Moderate | LC-Possible | High | | |
| 7.4 | Auxiliary system (cooling/ lubrication system) | 1. Cooling system Failure | 1. ammonia in auxiliary system | Asset | S3-Moderate | LB-Unlikely | Moderate | 1. Cooling circuit is intermediate circuit<br>2. Expansion tank with Gas detection and venting | |
| 7.5 | Engine room ventilation | | | | | | | | |
| 7.6 | Engine exhaust explosion | 1. Malfunction of engine | 1. Ammonia released into exhaust | Overall | S2-Minor | LB-Unlikely | Low | 1. Explosion relief valve on exhaust | 66. Discharge from exhaust to be studied and the hazardous and toxic zones developed during explosion in exhaust. |
| | | | 2. Ammonia exposure to personnel | Overall | S3-Moderate | LB-Unlikely | Moderate | | |
| 7.7 | $N_2O$ and NOx emissions from engines | 1. Bi-product of combustion | 1. $N_20$ and NOx emission leading to environmental issues | Environment | S3-Moderate | LC-Possible | High | | 69. SCR/NOx monitoring to be confirmed<br>70. During type testing/emission testing of engine manufacturer has to determine normal and maximum level of NOx from engine |
| | | 2. Malfunction of engine leads to abnormal level in emissions | 1. $N_20$ and NOx emission leading to environmental issues | Environment | S3-Moderate | LC-Possible | High | 1. General engine control system | 69. SCR/NOx monitoring to be confirmed<br>70. During type testing/emission testing of engine manufacturer has to determine normal and maximum level of NOx from engine |
| 7.8 | Cylinder cover lift | 1. Mechanical damage to cylinder cover | 1. Ammonia in engine room | Asset | S3-Moderate | LB-Unlikely | Moderate | 1. Engine monitoring system<br>2. Gas detection in engine room (just above cylinder cover)<br>3. Fuel shutdown<br>5. gas detector in engine room | 71. Engine manufacturer needs to provide details about the possibility of ammonia leak inside engine |
| | | | 2. Exhaust gas in engine | Asset | S2-Minor | LB-Unlikely | Low | | |
| | | 2. Injection timing malfunction | 1. Ammonia in engine room | Asset | S3-Moderate | LB-Unlikely | Moderate | 4. Engine control system | |
| | | 3. Improper design | 1. Ammonia in engine room | Asset | S3-Moderate | LB-Unlikely | Moderate | | 71. Engine manufacturer need to provide details about possibility of ammonia leak inside engine |
| | | | 2. Exhaust gas in engine | Asset | S2-Minor | LB-Unlikely | Low | | |
| 7.9 | Release of ammonia inside engine room | 1. Leakage from engine<br>**Comment:** Designed so that all ammonia in engine room is in gaseous form, which is easier to dilute with water | 1. Gas in engine room | Asset | S2-Minor | LC-Possible | Moderate | 1. Water-mist system in engine room<br>2. Gas detector<br>3. Fire detector | |
| | | | 2. Fire in engine room | Asset | S3-Moderate | LB-Unlikely | Moderate | | |
| | | 2. Leakage form piping/ connections | 1. Gas in engine room | Asset | S2-Minor | LC-Possible | Moderate | 1. Water-mist system in engine room<br>2. Gas detector<br>3. Fire detector | |
| | | | 2. Fire in engine room | Asset | S3-Moderate | LB-Unlikely | Moderate | | |

| 8 | Ventilation |
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Section notes:
- node covers Vent Vent lines/Vent Mast
- In the event of a leak, ammonia may be vented to air in current setup, so that needs to be addressed. TCS and GVU will be venting somewhere; need to establish where the gas will go.
- Ventilation in these spaces will be extraction type ventilation for normal and emergency situations. All exhausts vented together to go to ammonia treatment
- Ventilation inlet is required to be 10 m away from key areas
- zone 1 for ammonia is 6 m
- zone 2 for ammonia is 10 m

**No.:** 8 Ventilation

| Item | Deviation | Causes | Consequences | Matrix | Severity | Likelihood | Risk | Safeguards | Recommendations |
|---|---|---|---|---|---|---|---|---|---|
| 8.1 | TCS Ventilation | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | 72. Ventilation exhaust ppm level to be studied for worst-case discharge scenario |
| 8.2 | Reliq plant ventilation | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | 72. Ventilation exhaust ppm level to be studied for worst-case discharge scenario |
| 8.3 | Double-wall pipe ventilation | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | 72. Ventilation exhaust ppm level to be studied for worst-case discharge scenario |
| 8.4 | Bunker station ventilation | 1. No risk identified. Not discussed further.<br>**Comment:** Enclosed area with airlock and dedicated ventilation | | | | | | 1. Ventilation air inlet is from a safe area near to the bunker station<br>2. Exhausts into the vent mast | |

| 9 | Safety Systems |
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| Section notes:<br>- node covers Safety System/ Emergency, fire and gas detection, firefighting system, structural fire protection, PPE | |

| **No.:** 9 | Safety Systems | | | | | | | | |
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| **Item** | **Deviation** | **Causes** | **Consequences** | **Matrix** | **Severity** | **Likelihood** | **Risk** | **Safeguards** | **Recommendations** |
| 9.1 | Ammonia pressure relief | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | 73. Thermal and pressure relief to be designed to handle worst=case scenario considering toxic zone requirement |
| 9.2 | Gas detection | No additional risks identified by the team. Design will comply with IGC/IGF Code and standard practices. | | | | | | | |
| 9.3 | Firefighting system | 1. No requirement developed at this time. Not discussed further. | | | | | | | 74. Firefighting philosophy to be developed |
| 9.4 | Structural fire protection | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | 75. PPE suitable for ammonia to be provided<br>76. Eye wash and shower to be provided close to ammonia bunker, fuel-preparation room, TCS space, reliq palt etc. |
| 9.5 | PPE | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | 77. Follow class requirement for PPE to be provided at all the locations where exposure to ammonia is possible |

| 10 | Ship's Operation |
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| Ship's Operation / Simultaneous Operation | |

| **No.:** 10 | Ship's Operation | | | | | | | | |
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| **Item** | **Deviation** | **Causes** | **Consequences** | **Matrix** | **Severity** | **Likelihood** | **Risk** | **Safeguards** | **Recommendations** |
| 10.1 | Port entry/departure | Team discussed high-level recommendations to improve design. Not discussed further. | | | | | | | 62. Proper maintenance and testing procedures to be developed<br>78. Management and crew to be trained for ammonia-related hazards, and operational/handling procedures for ammonia to be developed |

| 11 | Biofuel |
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| **No.:** 11 | Biofuel | | | | | | | | |
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| **Item** | **Deviation** | **Causes** | **Consequences** | **Matrix** | **Severity** | **Likelihood** | **Risk** | **Safeguards** | **Recommendations** |
| 11.1 | No new risk identified.<br>Not discussed further. | | | | | | | | |

| 12 | Engines |
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| No.: 12 | Engines | | | | | | | | |
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| **Item** | **Deviation** | **Causes** | **Consequences** | **Matrix** | **Severity** | **Likelihood** | **Risk** | **Safeguards** | **Recommendations** |
| 12.1 | No new risk identified.<br>Not discussed further. | | | | | | | | |

# Appendix XVI – Detailed Regulatory Gap Analysis

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| No Gap or Changes needed to address ammonia |
| Small Gap or Minor Change to address ammonia |
| Medium Gap or Some Challenging Change to address ammonia |
| Large Gap or Many Challenging Changes to address ammonia |

| Subject | Code/Standard Title | Comment on Code/Standard - Benefits | Comment on Code/Standard - Gaps | General Comments | Contribute / Restrain uptake of Ammonia as Marine Fuel |
|---|---|---|---|---|---|
| Sustainability and Emissions Regulations | EU 'Fit-for-55' FuelEU Maritime | - Considers ammonia as one of the hydrogen-derived fuels or e-ammonia.<br>- Supports setting clear regulatory environment for ammonia as marine fuel<br>- Economic incentives for positive change or to adopt ammonia | - Focus is only on decarbonised (green) ammonia produced from hydrogen<br>- Focus is only on well-to-wake emission, does not incorporate emissions from production | International regulators are pivoting to adopt more stringent emissions regulations to reduce the impacts to climate change. Various efforts in the European Union to adopt more renewable energy sources throughout its industrial and transportation markets can include the increased use of renewable fuels of non-biological origin (RFNBO). RFNBOs include | <u>Contribute</u>. International policy which drives the adoption of renewable ammonia in various industries can increase the uptake of the fuel in all industries. The regulations force industries to look to renewable solutions or face consequences by using or continuing to use polluting fuels. |
| | EU Emissions Trading System (ETS) | - Economic incentives for positive change or to adopt ammonia | - Not directly applicable to shipping industry (until 2023 adoption of the 'Fit-for-55' package)<br>- Only focused on tank-to-wake emissions, does not incorporate emissions from consumption | | |
| | EU Energy Taxation Directive | - Economic incentives for positive change or to adopt ammonia | - Maritime sector fully exempt<br>- Member states independently implement national policy | | |
| | EU RED III | - Considers ammonia as a marine fuel produced from decarbonised hydrogen<br>- Supports renewable | - Divided incentives for shipowners and operators do not stimulate the deployment of renewable fuels<br>- Member states independently implement national policy | | |

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| | | fuels<br>- Economic incentives for positive change or to adopt ammonia | | renewable ammonia as fuel, and this is being considered as one which can meet the goals for reduced emissions. | |
| | MARPOL Annex VI EEDI, EEXI, CII & DCS | - Carbon Indexing and limits for ships is met by using ammonia as fuel, even though ammonia fuel does not have a Carbon Factor | - No explicit provision in IMO regulations and guidelines for the direct use of an ammonia carbon factor in EEDI, EEXI, CII and DCS<br>- Provision for well-to-wake emissions considerations should be taken into account in these instruments | | |
| | MARPOL Annex VI and NOx Technical Code (NTC) | | - Requires NTC amendment to include $NH_3$ analysers, measurement and calculation provisions for ammonia as fuel to enable NOx certification to regulation 13<br>- Air emissions limits for $NH_3$ and $N_2O$ from marine engines, and associated measurement and calculation procedures, are missing from Annex VI and the NTC<br>- Regulation 18 of Annex VI would benefit from clarification on BDN and fuel sampling obligations for ammonia as fuel<br>- Application of ammonia as fuel (particularly for retrofits) would benefit from clarification on application of regulation 18.3.2.2 for NOx implications where ammonia is derived from methods other than petroleum refining<br>- No limits or guidelines exist for environmental impacts of potential $NH_3$ emissions to water in normal or emergency operations from exhaust cleaning or fuel system cleaning systems. Precedent exists for water quality limits for SOx EGCS under Annex VI but unclear which is appropriate instrument to regulate $NH_3$ discharges to water | | |
| | ISO 17179:2016 - Stationary source emissions - Determination of the mass concentration of ammonia in flue gas - Performance characteristics of automated measuring systems | | - May be considered or referenced in development of IMO marine standards | | |

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| | ISO 21877:2019 - Stationary source emissions - Determination of the mass concentration of ammonia - Manual method | | - May be considered or referenced in development of IMO marine standards | | |
| Storage – Land | ANSI K61.1-1999 / CGA G-2.1 Requirements for the Storage and Handling of Anhydrous Ammonia | | - Not applicable to ammonia storage on ships | Where ammonia has been used in industry in the past, for example, imported into the United States as a key component to produce fertiliser, land-based storage of the chemical for industrial purposes has been done for many years. | Contribute. Previous land-based experience and existing standards for storing anhydrous ammonia can promote the uptake of the chemical as a marine fuel, not only to improve probabilities of availability, but also to share lessons learned of storing and handling the chemical with the marine regulatory community. |
| | U.S. 33 U.S.C. §1251 – Clean Water Act | - Considers ammonia as pollutants to water and wastewater | - No significant gaps for supporting the application of ammonia | | |
| | U.S. EPA 822-R-18-002 - Aquatic Life Ambient Water Quality Criteria for Ammonia - Freshwater 2013 | - Considers ammonia as pollutants to water | - No significant gaps for supporting the application of ammonia | | |
| | U.S. 40 CFR Ch. I Subchapter J Part 372 - Toxic Chemical Release Reporting: Community Right-To-Know | - Considers ammonia as marine fuel | - No significant gaps for supporting the application of ammonia | | |
| Storage – Onboard | IMO IGF Code | - Ammonia considered as marine fuel under alternative approval scheme | - IGF Code Part A-1 prescriptive provisions are specifically for natural gas (methane). Alternative Design process enables approval of other gases and low flashpoint fuels, but could be revised to include specific provisions for ammonia in the longer term. Development of interim guidelines is now added to the CCC workplan, commencing CCC 8 in September 2022. | As discussed in Section 3.4.2, the inclusion of ammonia in the IMO's low-flashpoint fuels codes (IGF/IGC) has highlighted | Contribute. Onboard storage rules and regulations from Marine Regulatory Bodies (international, national, and regional) |
| | IMO IGC Code | - Ammonia considered as Special marine cargo | - Provisions could be added to allow toxic anhydrous ammonia to be used as fuel. Review of IGC Code is now added to CCC workplan, commencing CCC 8 in September 2022. | | |

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| | | under Chapter 17 | | the practice and understanding of using the chemical as a marine fuel, especially considering it has been carried as cargo, and those carriers are considering using the cargo as fuel, both for convenience and to decarbonise or reduce emissions according to the IMO and other decarbonisation goals and initiatives. | support the uptake of the chemical as a marine fuel. Whether for specific applications or general directives, available codes of practice for safely storing anhydrous ammonia on board ships (for cargo or as fuel) can help designers, users, and owners understand the realistic considerations of adopting ammonia as marine fuel on marine assets. |
| | U.S. CFR 46 98.25 | - Specific to ships carrying anhydrous ammonia | - No details of anhydrous ammonia as marine fuel<br>- National regulation not applicable to international vessels | | |
| | U.S. CFR 46 151.50-32 | - Specific to barges carrying anhydrous ammonia | - No details of anhydrous ammonia as marine fuel<br>- National regulation not applicable to international vessels | | |
| Quality | International Bunker Industry Association | - Future Fuels Working group assesses ammonia as alternative marine bunker fuel, preparing to develop position papers and consultancy for the IMO | - No specific guidance for ammonia. Missing ISO fuel quality standard together with missing BDN and sampling requirements under Annex VI Regulation 18 hinders consistent implementation | Historically, ammonia has been produced, transported, and used in industrial processes such that its quality is standardised as either aqueous or anhydrous ammonia. For transportation and use on ships, anhydrous ammonia is | Contribute. Existing standards for the quality of ammonia can contribute to the uptake of ammonia as marine fuel, as it sets foundational chemical quality standards, production and testing procedures |
| | ISO 8217:2017 Petroleum Products - Fuels (class F) - Specifications of Marine Fuels | | - Not applicable to and does not discuss ammonia marine fuel<br>- Additional provisions for ammonia as marine fuel could be developed as a new standard | | |

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| | ISO 7103:1982 - Liquefied anhydrous ammonia for industrial use - Sampling - Taking a laboratory sample | - Specifies test procedure for liquefied anhydrous ammonia for industrial use from a container | - May be referenced in marine standards | used, with contaminant levels typically low by nature of ammonia production. | for the marine industry to adopt. Since the chemical is typically "industrially pure" there is little concern of production contaminants that require special handling procedures or storage requirements. |
| | ISO 7106:1985 - Liquefied anhydrous ammonia for industrial use - Determination of oil content - Gravimetric and infra-red spectrometric methods | - Specifies test procedure for liquefied anhydrous ammonia for industrial use | - May be referenced in marine standards | | |
| | ISO 7105:1985 - Liquefied anhydrous ammonia for industrial use - Determination of water content - Karl Fischer method | - Specifies test procedure for liquefied anhydrous ammonia for industrial use | - May be referenced in marine standards | | |
| | IMO MARPOL Annex VI | - Requires all marine fuel to meet specific standard of low sulfur limit | - Regulation 18 for fuel oil availability and quality requires onboard fuel to be tested for sulphur content and seal fuel samples for the record. While regulation 18.4 exempts gas fuels from BDN and fuel sample requirements, regulation 18 would benefit from explicit clarification on BDN and fuel sampling obligations for ammonia as fuel | | |
| Transportation & Handling | ASME B31.3-2020 Process Piping | - Includes provisions for anhydrous ammonia pipelines in general | - Not specific to marine, may be referenced in marine standards | Considering the historical experience from industry of best practices to transport and handle ammonia safely, from the design of pipelines to health codes of toxicity, the marine industry | Contribute. Industrial practices for handling and transporting ammonia can translate into and contribute to marine rules and regulations covering the safe handling of the chemical on |
| | ISO 5771:2008 - Rubber hoses and hose assemblies for transferring anhydrous ammonia | - Applicable to anhydrous ammonia (in general) | - Subject limited to hose performance and hose assemblies, may be referenced in marine standards | | |
| | ISO 6957:1988 - Copper alloys - Ammonia test for stress corrosion resistance. | | - May be referenced in marine standards | | |

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| | SIGTTO Liquefied Gas Sampling Procedures | | - Not applicable to ammonia. SIGTTO could produce similar recommendations for ammonia gas cargo or fuel | can benefit from existing experience standardised codes and practices for transporting and handling of ammonia. | board vessels and streamline the process of adopting ammonia as marine fuel. |
| | U.S. CFR § 130.230 – Protection from Refrigerants | - Provisions for PPE near ammonia storage | - National regulation not applicable to international vessels<br>- Not specific or considering marine applications | | |
| | U.S. CFR 29 1910.111 Storage and Handling of anhydrous ammonia | - Includes provisions for anhydrous ammonia safe handling and storage | - Not specific to marine | | |
| Bunkering | ISO 20159:2021 - Ships and Marine Technology - Specification for bunkering of liquefied natural gas fueled vessels | - Standard related to liquefied gas bunkering | - Not applicable to liquefied anhydrous ammonia. Could be modified or used to develop liquefied ammonia bunkering guidelines | Various global uses and phases of ammonia for industry or other use may lead to the use of non-standard or incompatible bunkering and transfer mechanisms. This issue was observed during the adoption of LNG as marine fuel, where industrial quality standards, handling, storage, and consumption codes or practices exist, but a disconnect in transfer practices was a major hurtle to achieve the widespread adoption and use of | <u>Restrain</u>. Non-uniform international standards or codes for chemical transfer technology and compatible bunkering infrastructure can make it difficult to adopt ammonia as a fuel. Similar to standard international requirements for fuel oil manifolds or shore connection boxes, the development of specific designs for transferring and bunkering anhydrous ammonia may be essential to |
| | ISO/TS 18683:2021 - Guidelines for safety and risk assessment of LNG fuel bunkering operations | - Standard related to liquefied gas bunkering | - Not applicable to liquefied anhydrous ammonia. Could be modified or used to develop liquefied ammonia bunkering guidelines | | |
| | ISO 21593:2019 - Ships and Marine Technology - Technical requirements for dry-disconnect/connect couplings for bunkering liquefied natural gas | | - Not applicable to liquefied anhydrous ammonia. Could be modified or used to develop liquefied ammonia bunkering coupling standard | | |
| | SIGTTO Ship/Shore Interface for LPG/Chemical Gas Carriers and Terminals | - Related to IGC code for LPG and chemical gas carriers | - SIGTTO publications address liquefied gases including anhydrous ammonia, so no big gaps, but could provide specific guidance for ammonia gas cargo or fuel | | |
| | SIGTTO Recommendations for Liquefied Gas | - Related to LPG and LNG carrier manifolds | | | |

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| | Carrier Manifolds | and safe cargo transfer equipment | | it as marine fuel. | adopt the chemical as marine fuel. |
| | SIGTTO Liquefied Gas Handling Principles on Ships and Terminals (LGHP4) | - Related to LNG, LPG and chemical gases on ships and at the shore interface | | | |
| | SIGTTO, CDI, ICS, OCIMF: Ship-to-Ship Transfer Guide for Petroleum, Chemicals and Liquefied Gases | - Related to all ships involved in transfer activities of all types of bulk liquid cargoes | - Could be modified or used to develop recommendations for ammonia bunkering | | |
| | SGMF Bunkering Area Safety information LNG | - Related to bunkering interface, port permitting and establishing safety and security zones of ISO standards | - Not applicable to ammonia. SGMF could expand these tools and guidelines, or develop new ones, to cover ammonia as fuel | | |
| | SGMF FP05-01 Ver1.0 Gas as a marine fuel: Recommendation of Controlled Zones during LNG bunkering; May 2018 | - Related to safe bunkering of LNG as marine fuel | - Not applicable to ammonia. SGMF could expand these tools and guidelines, or develop new ones, to cover ammonia as fuel | | |
| | SGMF FP07-01 Ver3.0 LNG as a marine fuel: Safety and Operational Guidelines - Bunkering; December 2021 | - Related to safe bunkering of LNG as marine fuel | - Not applicable to ammonia. SGMF could expand these tools and guidelines, or develop new ones, to cover ammonia as fuel | | |
| | SGMF FP-08-01 Ver1.0 Gas as a marine fuel: Simultaneous Operations (SIMOPs) during LNG | - Related to safe bunkering of LNG as marine fuel | - Not applicable to ammonia. SGMF could expand these tools and guidelines, or develop new ones, to cover ammonia as fuel | | |

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| | bunkering; May 2018 | | | | |
| | SGMF FP05-01 Ver1.0 Gas a a marine fuel: Contractual guidelines; September 2015 | - Related to safe bunkering of LNG as marine fuel | - Not applicable to ammonia. SGMF could expand these tools and guidelines, or develop new ones to cover ammonia as fuel | | |
| | SGMF TGN06-04 Ver1.0 Gas as a marine fuel: manifold arrangements for gas-fuelled vessels; May 2019 | - Related to manifold arrangement of gas-fueled vessels | - Not applicable to ammonia. SGMF could expand these tools and guidelines, or develop new ones to cover ammonia as fuel | | |
| | SGMF TGN06-06 Ver1.0 Gas as a marine fuel: LNG bunkering with hose bunker systems: considerations and recommendations; February 2020 | - Related to safe bunkering of LNG as marine fuel | - Not applicable to ammonia. SGMF could expand these tools and guidelines, or develop new ones to cover ammonia as fuel | | |
| | SGMF TGN06-07 Ver1.0 Gas as a marine fuel: Bunker station location: Considerations and Recommendations: January 2021 | - Related to safe bunkering of LNG as marine fuel | - Not applicable to ammonia. SGMF could expand these tools and guidelines, or develop new ones to cover ammonia as fuel | | |
| | EMSA *Guidance on LNG Bunkering to Port Authorities and Administrations*; January 2018 | - Related to safe bunkering of LNG as marine fuel | - Not applicable to ammonia. EMSA could expand or use this tool to develop ammonia guidance | | |
| Use & Consumption | IMO IGF Code | - Ammonia considered as marine fuel under alternative approval scheme | - IGF Code Part A-1 prescriptive provisions are specifically for natural gas (methane). Alternative Design process enables approval of other gases and low-flashpoint fuels, but could be revised to include specific provisions for ammonia in the longer term. Development of interim guidelines is now added to the CCC | Historical and continuous experience, research, published studies and | Contribute. Codes, standards and regulations covering the subject |

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| | | | workplan, commencing CCC 8 in September 2022. | codes of practice for consuming ammonia for power generation, either by the use of internal combustion engines or with a fuel cell, can contribute to global knowledge databases on the chemical as a fuel.<br><br>However, experience with the design and use of internal combustion engines running on ammonia is small but growing, as engine manufacturers begin to examine what technical specifications are required for engines to run on pure or dual fuel with ammonia.<br><br>When considering emissions from ammonia engines or fuel cells, there may develop | of fuel supply to consumers, and details about optimisation of the chemical in the combustion cycle or reformation withing fuel cells all contribute to global knowledge and understanding of ammonia as marine fuel.<br><br>Ongoing studies and research to support the implementation of ammonia in large engines and fuel cells onboard vessels will continue to grow the industry's collective experience for further adoption and widespread use of ammonia as marine fuel.<br><br>Restrain. Where standards exist for marine emissions, the |
| | IMO MARPOL Annex VI and NOx Technical Code | - All marine fuels including ammonia must comply with pollution/emission requirements | - Could include specific provisions for using and consuming anhydrous ammonia onboard ships<br>- Air emissions limits for $NH_3$ and $N_2O$ from marine engines, and associated measurement and calculation procedures, are missing from Annex VI and the NTC. To consider in-service monitoring of $NH_3$ emissions.<br>- Regulation 18 of Annex VI would benefit from clarification on BDN and fuel sampling and storage obligations of for ammonia as fuel onboard<br>- No limits or guidelines exist for environmental impacts of potential $NH_3$ emissions to water in normal or emergency operations from exhaust-cleaning or fuel-system cleaning systems. Precedent exists for water quality limits for SOx EGCS under Annex VI but unclear which is appropriate instrument to regulate $NH_3$ discharges to water | | |
| | ISM Code | - Standard for ship management and operation includes provisions to protect against pollution | Development of operational requirements under IGF Code, or Interim Guidelines, would facilitate operators undertaking obligations under ISM Code | | |
| | SGMF FP00-01-06 Ver4.0 LNG as a marine fuel: An Introductory Guide; June 2021 | - Related to LNG only, providing general recommendations on the use of LNG as marine fuel and safety and environmental consideration s of its use | - Not applicable to ammonia. SGMF could expand, or develop new, publications for ammonia as fuel | | |
| | SGMF FP10-01 Ver1.0 Gas as a marine fuel: Work practices for maintenance, repair and dry-dock operations; May 2020 | - Related to operations of LNG fueled vessel. | | | |

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| | SGMF FP14-01 Ver1.0 Gas as a marine fuel: Operations of ships with Liquefied Natural Gas (LNG) competency and assessment guidelines; May 2021 | - Related to operations of LNG-fuelled vessel. | | resistance if ammonia slip or emissions from nitrogen in combustion (resulting in NOx or $N_2O$) cannot be contained or controlled. Care must be taken that in the attempt to reduce carbon emissions, other – potentially more dangerous emissions – are not allowed to be released. Some emissions regarding ammonia consumption can be addressed using selective catalytic reduction (SCR) technology post-combustion, but these may be prohibitively expensive to allow for economic feasibility using ammonia as fuel. | adoption of ammonia as fuel may be restricted. Limited experience using ammonia as fuel (especially for internal combustion) may lead to unknown or unexpected emissions, including nitrogen oxides (NOx), $N_2O$ (nitrous oxide, a chemical with the GHG potential to be almost 300 times more potent than $CO_2$), and possible ammonia slip. Where these emissions are regulated, specifically from international marine codes, and the emissions are found to be difficult to limit or manage, the adoption of ammonia as marine |
| | SGMF TGN06-05 Ver1.0 Gas as a marine fuel: recommendations for linked emergency shutdown (ESD) arrangements for LNG bunkering; May 2019 | - Related to LNG ESD Procedures | | | |
| | IMO STCW Convention | | - Regulation for training of crew for IGF Code ships exists under STCW Convention. Question mark remains on application of ammonia under IGF Code, but development of training courses by flag Administrations is still required to enable crew certification for ammonia as fuel under STCW. | | |
| | SIGTTO ESD Systems - Recommendations for Emergency Shutdown and Related Safety Systems | | - SIGTTO publications cover gas carriers and carriage of anhydrous ammonia but could benefit from specific consideration for ammonia gas cargo or fuel | | |
| | SIGTTO Recommendations for Relief Valves on Gas Carriers | | | | |
| | SIGTTO Guidelines for the Alleviation of Excessive Surge Pressures on ESD for Liquified Gas Transfer Systems | | | | |

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| | IACS Unified Requirement M57 *Use of ammonia as a refrigerant*; 1993 | - Guidance on safety risks when using ammonia as refrigerant | - No significant gaps for supporting the application of ammonia as a refrigerant, however, this publication has not been updated since original publication in 1993 and would benefit from updating | | fuel may experience resistance. |
| | IMO draft *Interim Guidelines for the Safety of Ships using Fuel Cell Power Installations* | - Applicable to ammonia systems being used in fuel cells for power generation on ships | No significant gaps for supporting the application of marine fuel cells, however these guidelines do not cover fuel storage and distribution and therefore application is limited by lack of those IMO requirements | | |
| | IACS UR M78 *Safety of Internal Combustion Engines Supplied with Low Pressure Gas* | - Related to low pressure trunk piston engines using gas (methane) as fuel. | - Does not cover high-pressure and cross-head (2-stroke slow speed) engines burning methane.<br>- Does not cover other low flashpoint fuels.<br>- Could be updated to include all engine types and fuels in a more general way | | |
| | IACS Recommendation No.146 *Risk assessment as required by the IGF Code*. | - Specific to fuels covered by IGF Code. | - Could be updated to include specific requirements for ammonia | | |
| | IACS Recommendation Nos.26, 27 and 30; recommended spare parts for IC main and auxiliary engines and essential auxiliary machinery | | - Could be updated to cover spare parts for DF engines and fuel supply systems | | |
| | IACS Recommendation No.138 Recommendation for the FMEA process for diesel engine control systems | | - Could be updated to cover DF engines and fuel supply systems | | |
| | IACS *Ammonia bunkering guidelines* | - Covers general guidelines to ammonia bunkering | - Could be updated to cover bunkering guidelines for all liquefied gases or new publication could be developed | | |

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| | IACS Classification Societies Rules | | Harmonisation of Class Society rules or guidelines, through the development of Unified Requirements, would facilitate harmonised application of ammonia as fuel | | |

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