AMMONIA FUELLED VESSELS

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What does it take to convert a ship to ammonia operation?

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Breeze Ship Design AS
Borggata 8
N-5417 Stord, Norway

Tel. +47 53 01 10 20
post@breeze.no
www.breeze.no

VAT Reg. No.: 925 729 655MVA
Business ID No.: 925 729 655

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ABBREVIATIONS

TCS	Tank Connection Space
LPP	Length Between Perpendiculars
IGF Code	International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels
SOLAS	International Convention for the Safety of Life at Sea
PSV	Platform Supply Vessel
NFPA	The National Fire Protection Association
AEGL	Acute Exposure Guideline Levels
DNV	Det Norske Veritas
LSA Code	International Life-Saving Appliance Code
FSS Code	Fire Safety Systems Code
VFD	Variable Frequency Drive

INTRODUCION

The transition from liquefied natural gas (LNG) to ammonia as a marine fuel is a compelling option for the shipping industry, driven by several environmental, economic, and regulatory factors. Ammonia, when used as a fuel, does not produce carbon dioxide during combustion (besides that produced due to potential pilot fuel combustion), positioning it as a pivotal solution in the pursuit of decarbonization in shipping. This attribute aligns closely with global environmental goals and the International Maritime Organization's (IMO) stringent emissions targets, which aim to reduce greenhouse gas emissions by at least 50% by 2050 compared to 2008 levels.

Economically, the shift to ammonia could offer long-term viability as a fuel choice due to its potential for scalability and the growing infrastructure being established for its production and distribution. Ammonia can be produced from renewable energy sources, which, when done sustainably, creates "green ammonia." This not only enhances the environmental credentials of ammonia but also reduces dependency on fossil fuels, mitigating risks associated with fuel price volatility.

Moreover, the maritime sector's move towards ammonia is supported by advancements in technology that make ammonia engines and fuel systems more efficient and safer to operate. Research and pilot projects are already underway, demonstrating the practical application of ammonia as a marine fuel and building confidence in its feasibility.

Ammonia is a clear, colourless, corrosive, alkaline gas with a strong odour. It is typically shipped as a liquid. Contact with the unconfined liquid can cause frostbite. Ammonia gas is generally regarded as non-flammable but does burn within certain vapor concentration limits and with a strong ignition. The NFPA 704 (Standard System for the Identification of the Hazards of Materials for Emergency Response) diamond is presented on Figure 1.

NFPA 704

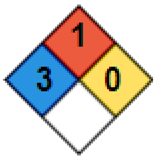
Diamond	Hazard	Value	Description
	Health	3	Can cause serious or permanent injury.
	Flammability	1	Must be preheated before ignition can occur.
	Instability	0	Normally stable, even under fire conditions.
	Special		

Figure 1 Ammonia diamond

Long-term inhalation of low concentrations of the vapours or short-term inhalation of high concentrations has adverse health effects, may be fatal if inhaled – especially in high concentrations. Fortunately, the odour threshold for ammonia is very low, typically 17 ppm (the odour detection level ranges from 5 to 53 ppm) and enables early detection by a person her/himself. Vapours cause irritation of eyes and respiratory tract. Liquid will burn skin and eyes, contact with it may cause frostbite. Acute Exposure Guideline Levels are presented in Table 1.

Table 1 Acute Exposure Guideline Levels ([1])

Classification	10 min	30 min	1h	4h	8h	End Point
AEGL-1 (nondisabling)	30 ppm 21 mg/m^3	30 ppm 21 mg/m^3	30 ppm 21 mg/m^3	30 ppm 21 mg/m^3	30 ppm 21 mg/m^3	Mild irritation
AEGL-2 (disabling)	220 ppm 154 mg/m^3	220 ppm 154 mg/m^3	160 ppm 112 mg/m^3	110 ppm 77 mg/m^3	110 ppm 77 mg/m^3	Irritation: eyes and throat; urge to cough
AEGL-3 (lethal)	2700 ppm 1888 mg/m^3	1600 ppm 1119 mg/m^3	1100 ppm 769 mg/m^3	550 ppm 385 mg/m^3	390 ppm 273 mg/m^3	Lethality

The toxicity is a reason why, aside from the known gas hazardous zones plan, a toxic zone plan is now required by Class.

Aside of toxicity, there are also major differences between natural gas and ammonia when it comes to the flammability and related explosion danger. Figure 2 presents the comparison of lower and upper flammability limits for common gas fuels. One will notice that the concentrations of ammonia where an ignitable mix with air is formed are considerably larger than for common hydrocarbon gaseous fuels. This in general translates to ammonia being much safer from the explosion/ignition perspective than those. To complement that, the ignition energy for ammonia is massive compared to the hydrocarbons, Table 2.

Gas	Lower Flammability Limit (% by volume in air)	Upper Flammability Limit (% by volume in air)
LNG (Methane)	5	15
LPG (Propane)	2.1	9.5
LPG (Butane)	1.8	8.4
Ammonia	15	28

Figure 2 Comparison of lower and upper flammability limits for common gas fuels

Table 2 Comparison of ignition energy for common gas fuels

Gas	Ignition Energy (mJ)
LNG (Methane)	0.29
LPG (Propane)	0.25
LPG (Butane)	0.25
Ammonia	15

Finally, the temperature range for LNG and ammonia storages are much different. Ammonia has a saturation temperature of about -33°C at atmospheric pressure. This means ammonia boils and turns from liquid to gas at this temperature under normal atmospheric conditions. Liquefied Natural Gas (LNG) is primarily composed of methane, which has a saturation temperature of approximately -161.5°C at atmospheric pressure – thus in cryogenic temperature range. On the other hand, ammonia is considered corrosive. For those reasons the requirements related to materials of the fuel systems are considerably different. Common materials in LNG systems include stainless steel and other alloys that retain structural integrity at cryogenic temperatures. The material selection for ammonia systems on the other hand must consider the chemical's corrosiveness, especially to copper, brass, bronze, and similar materials.

An intermediate solution to address the need for more environmental friendly and environmentally sustainable operation can be converting existing LNG fuelled vessels to ammonia.

This work deals with vessels equipped with internal combustion engines fed with gas fuel in gaseous form as their prime movers and provides a general description on what topics need to be addressed when considering such an upgrade.

The document is divided into Chapters. Each chapter addresses a different aspect of such conversion.

1 GENERAL ARRANGEMENT

The main purpose of the platform supply vessel is to supply offshore installations with necessary supplies for the complement and operation of the offshore installations. Lifting of cargo to and from the cargo deck by crane is a daily occurrence, both in open sea and while alongside key. Permanent installations introduced in the vicinity of and on the cargo deck are consequently highly exposed to impact from such operations unless properly protected.

1.1 Accommodation, service control spaces

Because of the toxicity of ammonia all air intakes, outlets and other openings into the accommodation spaces, service spaces and control stations shall be fitted with closing devices and be capable of being operated from inside the space.

1.2 Personal protective equipment onboard

In general (requirements for the specific cases are given later, in respective chapters), at least two sets of air breathing apparatuses with spare air bottles shall be available on board. The breathing apparatuses may be the same as those required for other purposes, e.g. SOLAS, provided the ship is equipped with an air compressor for recharging the air bottles.

Suitable respiratory and eye protection for emergency escape purposes shall be provided for every person on board. Filter-type respiratory protection is unacceptable. Self-contained breathing apparatus shall have at least 15 minutes of service time. Emergency escape respiratory protection shall not be used for firefighting or cargo-handling purposes and shall be clearly distinguished from those (clearly marked).

1.3 Survival craft and muster stations

Arrangement of survival craft and muster stations shall be considered in the alternative design analysis as required by the IGF Code Ch.2 2-3. In connection with subject analysis, the following may be used as examples for items relevant to consider:

- The need for life boats provided with a self-contained air support system complying with the requirements of the international life-saving appliance (LSA) code.
- The need for enclosed and in other ways protected muster stations.
- Safe escape from accommodation/muster stations to survival craft.

The analysis should utilize the results from dispersion studies discussed in Section 7.4 of the document. In case alternative dispersion scenarios play a role in the personnel evacuation, those should be also carried.

1.4 Stability

In general, the total weight value and its distribution is not expected to change considerably due to conversion from LNG to ammonia fuel. The ammonia installation requires a set of additional equipment and some compartments; however their cumulative weight is expected to have negligible impact on the stability of the vessel.

2 BUNKERING STATION

In case of ammonia fuelled vessels the bunkering station shall be designed to safely contain ammonia leakages. In principle, it shall be arranged as enclosed, with an opening for the hoses located on the ship side, normally closed, and two doors opening to the cargo rail. Boundaries shall be gas tight towards other spaces on the ship. Arrangement of bunkering station as open, typical for LNG is subject to special consideration and is not a favoured solution from the safety point of view, as it provides little control over where the toxic vapours travel in case of a leak.

The entire piping and valves arrangement will be replaced with a ammonia – dedicated one.

2.1 Ventilation

Ammonia bunkering station is a space designed to safely contain ammonia leakages. As such it shares the ventilation requirements common for this type of compartments.

Bunkering station shall be arranged with a separate ventilation system, in order to eliminate the possibility of ammonia gas spreading to other spaces. The space shall be continuously ventilated, for that purpose, the closing appliances shall be avoided. For that purpose, it is essential that the concerned area is considered a deckhouse with no access to below where green sea may enter, and that the deckhouse is not regarded as buoyant nor in load line or stability calculations. In such case it would be acceptable to arrange ventilation outlet that is not in compliance with the International Load Line Convention, without the need to apply for exemption. However, overboard drainage shall be arranged in case water enters via these vent openings.

Regular and catastrophe ventilation shall be arranged. For that purpose two, VFD driven, fans supplied from different redundancy groups shall be installed, combined capacity of which shall cover the requirements for catastrophe ventilation. A single fan should cover the needs of at least regular ventilation at its top speed. If possible serial operation of fans should be arranged, to avoid the need for backflow preventing devices. The ventilation shall be of extraction type, with the fans located outside the compartment. The outlet pipe downstream of the fans cannot be led through any closed compartment.

2.2 Water safety systems

In the current Rules state the emergency release response and damage control relies heavily on the water spray systems, that are not present in such variety in case of LNG fuel. In case of bunkering station a number of water spray systems is required:

1. bunkering station entrances shall be arranged with water screens having constantly available water supply. The water screen shall be possible to activate from a safe location outside the bunkering station toxic zone if an ammonia leak occurs. The water screens shall be arranged on the outside of the bunkering station access,
2. a water spray system intended for limiting the amount of toxic vapours to be arranged above the bunker manifold and cover all possible leakage points,
3. a water distribution system shall be fitted over the bulkhead opening for shore connections to provide a low-pressure water curtain for protection of the hull steel and the ship's side structure

and for the purpose of limiting the amount of toxic vapours exiting the bunkering station opening in a leakage scenario. This system shall be operated when fuel transfer is in progress,

4. for the purpose of limiting the amount of toxic vapours spreading from bunkering station ventilation system outlet, a water mist system shall be provided and located inside the compartment at the suction inlet of the ventilation system outlet. The water mist system shall be automatically activated if an ammonia concentration exceeding 350 ppm is detected in the ventilated space. Due consideration shall be taken towards the vacuum generating effect upon combining ammonia gas and water.

Suitably marked decontamination showers and eyewashes shall be available close to bunkering station. Water supply capacity shall be sufficient for simultaneous use of the unit close to the bunkering station and the unit at the exit from the TCS.

Water safety systems for limiting the spread of toxic ammonia gas, eye washes and decontamination showers shall be operable in all ambient conditions. A heating system with temperature control shall be installed for water supply piping exposed to the freezing conditions. Thermal insulation is not considered as an alternative to a system with temperature control.

Remote start of pumps supplying the water spray systems (besides the low-pressure water curtain on the ship side opening) and remote operation of any normally closed valves to the system shall be located in a readily accessible position, which likely to be accessible in case of fire or leakage of toxic gases in the areas protected. Remote operation of valves shall be possible from the control location for bunkering.

2.3 Fire protection

Bunkering station shall be provided with a fixed dry powder fire-extinguishing system complying with the provisions of the FSS code and taking into account the necessary concentrations/application rate required for extinguishing fires in spaces with ammonia.

2.4 Personal protective equipment

For the protection of crew members who are engaged in bunkering operations, the ship shall have on board suitable protective equipment consisting of large aprons, special gloves with long sleeves, suitable footwear, coveralls of chemical-resistant material, and face shields. The protective clothing and equipment shall cover all skin so that no part of the body is unprotected.

2.5 Purging and gas freeing

An arrangement for purging and gas freeing fuel bunkering lines shall be arranged. When not engaged in bunkering the bunkering pipes shall be free of gas. The nitrogen system utilized for that purpose shall be of sufficient capacity to purge fuel bunkering lines, supply lines and return lines.

Bunkering lines shall in general be arranged as self-draining towards the tank. For that purpose, the pipes shall generally be arranged with a downwards slope or horizontal sections only.

2.6 Detection and alarm

Bunkering station shall have a permanently installed gas detection system. Gas detection system shall continuously monitor for gas.

Control of bunkering shall be possible from a safe location for bunkering operations. At this location, tank pressure, tank level and overfill alarm shall be available.

3 TANK HOLD SPACE

The fuel tanks on offshore and special vessels are typically located in a tank hold space under the main deck. Tank hold space is arranged similarly for LNG and ammonia. In general, it should not serve any other purposes and contain minimum combustible materials that could sustain fire. As the tank is not located on open deck, no water spray for tank cooling is required. As the amount of the combustible material in the tank hold space is to be minimized, the large-scale heat ingress to the tank can only be caused by fires in engine room or in the cargo space. For such cases, the benefits of installing the spray system should be evaluated as part of the dispersion analysis.

Tank hold space will act as the protective cofferdam, providing necessary spacing from the engine room (machinery space of category A). For that it needs to be assured, that the bulkhead dividing the two compartments is at least 900 mm from the outer shell of the tank.

4 TANK AND TANK CONNECTION SPACE

The tank and the tank connection space are closely related. Typically, the TCS is delivered mounted directly on the engine, and thus the two form a one part. The TCS will contain the piping, valves and other equipment closely related to the carried fluid storage and delivery state properties and as such, it will not be reusable when switching from the LNG to ammonia. The tank is typically also not considered to be reused.

4.1 Tank & endurance

Typically, the existing LNG tank, and associated TCS will not be used to store ammonia fuel. The replacement of tank requires a check with regards to the supporting structure underneath.

4.2 Type of storage

The tasks required for converting from LNG to ammonia will vary somewhat depending on the type of storage considered. Pressurized and refrigerated storage are outlined in Sections 4.2.1 and 4.2.2 below.

4.2.1 Pressurized storage

The tank system contains the ammonia under a combination of pressure and ambient temperature. The tank system is designed to safely contain the ammonia vapor pressure at a temperature of 47°C (design pressure of 18 barg). Due to high design pressure, there is no need for a pressure maintenance system. The tank is not thermally insulated. Depending on the required engine delivery pressure it may be required to provide the tank with capability to pressurize it with nitrogen - in case the tank pressure can, in any circumstances be lower than the required engine delivery pressure level.

4.2.2 Refrigerated storage

The system capable of controlling the tank pressure to provide correct driving pressure and quantity of the fuel gas to the engines at all relevant operating conditions shall be provided. Means shall be provided to keep the fuel tank pressure and temperature within their design range at all times, and for that purpose two redundant reliquification units are required. The tank is thermally insulated. Thermal insulation is required in order to reduce heat ingress, thus reducing the running of reliquification plant and to avoid condensation of water from air and icing. The latter would require spaces surrounding fuel tank be filled with dry air and be maintained in this condition with dry air provided by suitable air-drying equipment according to DNV Rules for Ships Part 6 Chapter 2 Section 14 [3.3.3.3].

4.3 Tank connection space (TCS)

In case of LNG, Tank connection spaces are arranged to be able to safely contain leakages of cryogenic liquids and arranged to prevent the surrounding hull structure from being exposed to unacceptable cooling. Tank connection spaces in ammonia case are designed to safely contain fuel leakages, but due to higher temperatures involved and lower flammability the focus is more on the ammonia toxicity.

In LNG case, unless the access to the tank connection space is independent and direct from open deck, it shall be arranged as a bolted hatch. In case of ammonia gas-tight doors are acceptable, however an air lock is required, separating TCS from any other compartment.

4.3.1 Ventilation

The ammonia tank TCS is a space designed to safely contain ammonia leakages. As such it shares the ventilation requirements common for this type of compartments.

It shall be arranged with a separate ventilation system, in order to eliminate the possibility of ammonia gas spreading to other spaces. As such it can reuse a part of the ventilation system of the existing TCS. However, the space shall be continuously ventilated, for that purpose, the closing appliances shall be avoided and ventilation inlets and outlets for such spaces shall be located at sufficient height above deck to avoid closing appliances according to the Regulation 19 of the International Load Line Convention, Figure 3.

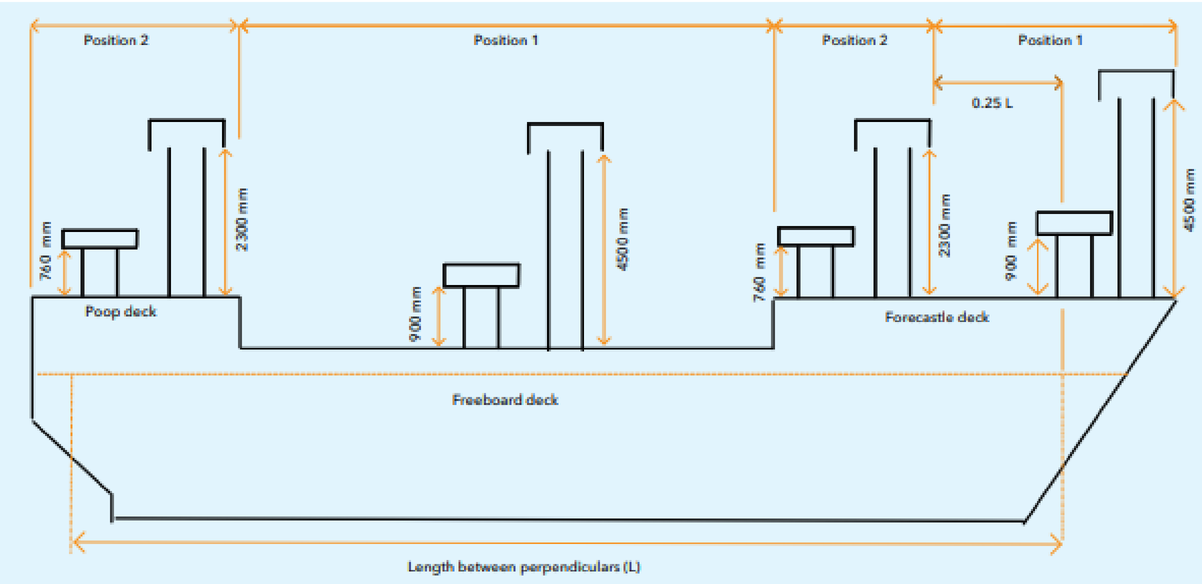


Figure 3 Regulation 19 of the International Load Line Convention

Regular and catastrophe ventilation shall be arranged. For that purpose two, VFD driven, fans supplied from different redundancy groups could be installed, combined capacity of which shall cover the requirements for catastrophe ventilation. A single fan should cover the needs of at least regular ventilation at its top speed. If possible serial operation of fans should be arranged, to avoid the need for backflow preventing devices. The ventilation shall be of extraction type, with the fans located outside the compartment. The outlet pipe downstream of the fans cannot be led through any closed compartment.

4.3.2 Water safety systems

In the current DNV ammonia rules the ammonia release response and damage control relies heavily on the water spray systems. In case of TCS a number of water spray systems is required:

1. The entrances shall be arranged with water screens having constantly available water supply. The water screen shall be possible to activate from a safe location outside the TCS toxic zone if an ammonia leak occurs. The water screens shall be arranged on the outside of the TCS,

2. for the purpose of limiting the amount of toxic vapours spreading from bunkering station ventilation system outlet, a water mist system shall be provided and located inside the compartment at the suction inlet of the ventilation system outlet. The water mist system shall be automatically activated if an ammonia concentration exceeding 350 ppm is detected in the ventilated space. Due consideration shall be taken towards the vacuum generating effect upon combining ammonia gas and water.

Suitably marked decontamination showers and eyewashes shall be available close to the TCS. Water supply capacity shall be sufficient for simultaneous use of the unit close to the bunkering station and the unit at the exit from the TCS.

Water safety systems for limiting the spread of toxic ammonia gas, eye washes and decontamination showers shall be operable in all ambient conditions. A heating system with temperature control shall be installed for water supply piping exposed to the freezing conditions. Thermal insulation is not considered as an alternative to a system with temperature control.

Remote start of pumps supplying the water spray systems (besides the low-pressure water curtain on the ship side opening) and remote operation of any normally closed valves to the system shall be located in a readily accessible position, which likely to be accessible in case of fire or leakage of toxic gases in the areas protected. Remote operation of valves shall be possible from the control location for bunkering.

4.3.3 Fire protection

Fixed fire-extinguishing system complying with the provisions of the FSS code and taking into account the necessary concentrations/application rate required for extinguishing fires in spaces with ammonia. An approved automatic fail-safe fire dampers shall be fitted in the ventilation trunk for the TCS.

4.3.4 Personal protective equipment

Gas masks and hermetically sealed filters shall be available in a permanently marked, transparent door case located immediately outside entrance to tank connection space. Additionally, at least two sets of suitable protective clothing shall be available on board and located in the vicinity of TCS. The two sets of protective clothing shall be gas tight suits with permanently attached boots and gloves and suitable for use in combination with the air breathing apparatuses.

4.3.5 Air lock

The air locks shall be of simple geometrical form. They shall be enclosed by gas tight bulkheads with two substantially gas tight doors spaced at least 1.5 m and not more than 2.5 m apart. The door shall be of self-closing type without any holding back arrangements. Deck area shall be not less than 1.5 m^2. Air locks shall not be used for any other purposes, for instance as stores, and shall provide free and easy passage.

4.3.5.1 Ventilation

Air locks are hazardous areas zone 2. They shall be separately mechanically ventilated at an overpressure relative to the adjacent hazardous area or space. The ventilation inlets and outlets for air locks shall be located in open air.

It is not however a space designed to safely contain ammonia leakages and hence its ventilation outlet should not be combined with outlets from such spaces.

4.3.5.2 Detection and alarm

An ammonia sensor shall be installed inside the airlock.

An audible and visual alarm system to give a warning on both sides of the air lock shall be provided to indicate if more than one door is moved from the closed position. Audible and visual alarms shall be given at a manned location to indicate loss of pressure in air lock and if both air lock doors are open at the same time. Access to the hazardous space shall be restricted until the ventilation has been reinstated.

4.4 Gas valve unit (GVU)

Tank connection space can also contain the gas valve unit. Such an arrangement is the length of the piping between gas valve unit and the engine is limited (approx. 10 m). This needs to be verified with a fuel system and engine supplier.

5 FUEL SUPPLY SYSTEM

This chapter outlines the safety aspects related to the ammonia fuel supply system in light of major differences between ammonia and LNG as fuels. The fuel supply system for this purpose is defined as ammonia fuel piping after leaving the storage tank.

5.1 Evaporation and heating

A shell-and-plate type heat exchangers located in TCS are used to vaporize and superheat the ammonia to the required temperatures. The heating medium is a water-glycol (50%wt - 50%wt) mix. The water-glycol mix is delivered to the TCS from the dedicated loop, isolated from all other systems by a dedicated heat exchanger connected to the vessel central heating/heat recovery system on its secondary side. This arrangement is essentially the same as for the LNG. However, utilizing heat recovery is of paramount importance for fuel economy, due to the heat requirements for the evaporation of ammonia.

Due to higher temperatures associated with ammonia, the danger of freezing in the heating/evaporation loop is lower. The glycol/water mix can be composed to have freezing temperatures below saturation temperature of ammonia, even at atmospheric pressure hence, lowest expected -33°C, Figure 4.

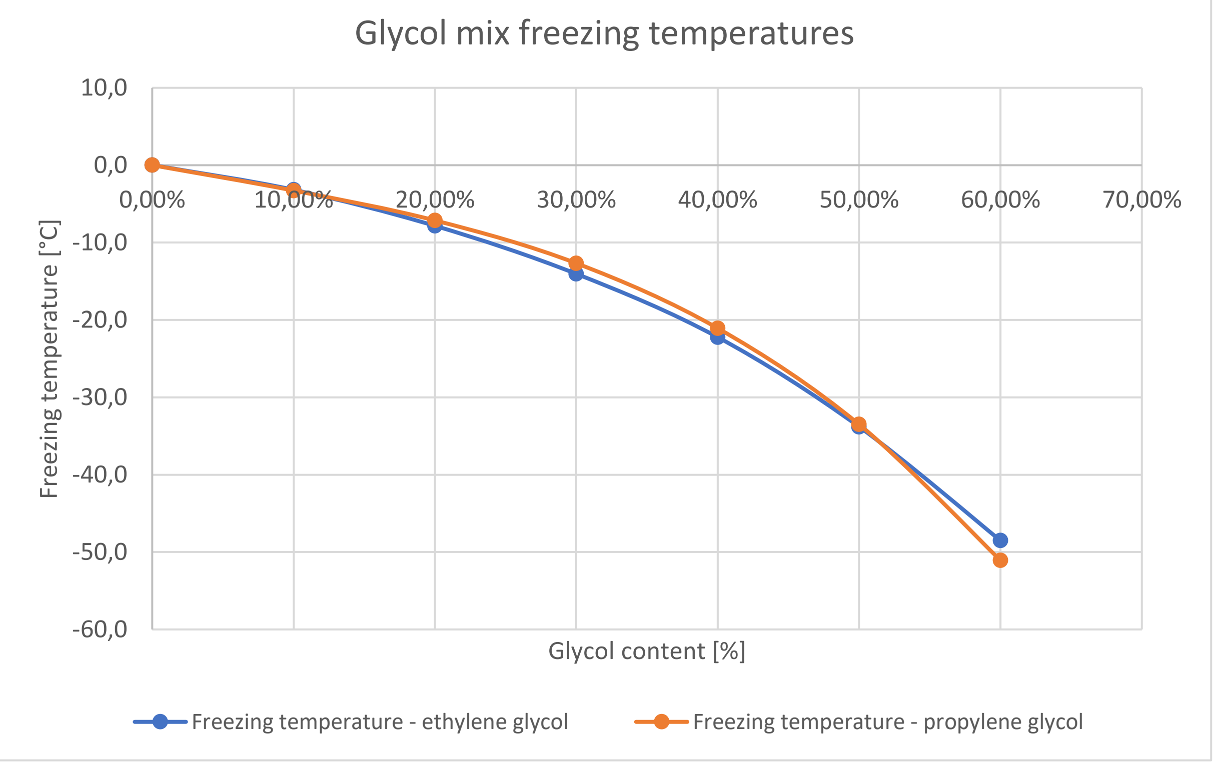


Figure 4 Freezing temperatures of glycol/water mix at different compositions

For glycol-water mixtures with concentrations higher than 60%, the freezing points continue to decrease, but the change becomes less drastic as you approach pure propylene glycol, hence such mixes are not justified and rarely used.

5.2 Fuel supply piping between TCS and engine

Ammonia fuel piping between the TCS (valve unit) and the engine shall be protected by a secondary enclosure able to contain leakages, enable effective detection of leakages and lead the leaked content to open air. Vent line shall be sized to prevent overpressure in a maximum probable leakage scenario, like in case of the LNG. However, in case of ammonia the vent pipe opening in open air shall be arranged with a water spray system having constantly available water supply. The water spray system shall be automatically activated if an ammonia concentration exceeding 350 ppm is detected in the annular space. The water spray system shall be arranged over the vent opening.

The higher temperatures involved in the ammonia fuel also bare some negative consequences. Due to them, the dew point is much closer and there is a significant danger of liquid fuel droplets forming and depositing inside the gas fuel pipes. There is a rule requirement dictating that the fuel pipe wall temperature should not drop lower than the dew point + a 10°C margin. For that reason, as opposed to the LNG installation trace heating and thermal insulation shall be arranged for the fuel supply piping. According to the experience in Breeze, the trace heating shall be designed to ensure that the inner pipe wall temperature never falls below 20°C above the dew point at the maximum expected pressure at the consumer inlet, to ensure that transients and short term anomalies will not lead to an emergency shutdown.

Drain pot fitted with level switch needs to be fit on fuel supply piping before the engine. Additional drain pot needs to be installed for the secondary enclosure, to allow removal of condensate water, should it deposit under certain conditions.

5.3 Fuel gas parameters monitoring

It is expected that ammonia fuel used in the gaseous state will have a dew point higher than ambient temperature at the maximum expected pressure at the engine inlet. For the purpose of securing that its temperature does not fall below the dew point, previously mentioned trace heating and insulation are planned. However, necessary monitoring equipment needs to be installed in order to verify that and monitor the parameters of the gas supplied to the engine:

- monitoring of fuel pipe wall temperature
- monitoring of fuel pressure

The control system shall be capable of calculating the dynamic dew point based on measurements of fuel pressure and fuel pipe wall temperature.

6 ENGINE ROOM

The engine room containing parts of the ammonia system, e.g. ammonia fuel pipes led to ammonia fuelled engine is required to be arranged such that the space may be considered gas safe under all conditions. This implies that all leakage sources shall be protected by a secondary enclosure in order to ensure that a single failure will not lead to release of fuel into the machinery space. A gas safe machinery space may be arranged as a conventional machinery space. In comparison, the LNG fuelled vessels are allowed to have an engine room arranged as an ESD protected machinery space as an alternative.

Suitably marked decontamination shower and eyewash shall be available in the engine room.

7 VENTING AND VENT MAST

Due to toxicity of ammonia, venting of the fuel system elements needs extra attention. It is in general in venting and bunkering that the biggest differences can be found between the two fuels. This chapter discusses the venting arrangement from the fuel system.

7.1 ARMS

A major difference between the ammonia and LNG fuel is the necessity to instal an ammonia release mitigation system (ARMS). The ARMS (ammonia release mitigation system) is a system capable of collecting and handling ammonia from:

- purging or draining operations of fuel pipes,
- bleeding operations from double block and bleed arrangements on the fuel piping systems,
- releases from opening of pressure relief valves on the fuel piping system,
- any other releases of ammonia occurring from normal operation of the system.

There are two major types of ARMS systems:

- dilution-based systems and
- combustion-based systems.

The dilution-based systems utilize the relative ease with which ammonia is bound in water. Those systems essentially vent all the vents though a water contained. The challenge associated with them is that the water-ammonia mix that is formed needs to be properly stored onboard and later to be dispensed with.

The combustion-based systems gain much popularity due to the above shortcoming of the dilution-based systems, and it is this solution that is advised here. Preferably the combustion-based cracker solutions, where the control over the emissions is much better. The combustion-based systems produce exhaust gasses, so care needs to be taken to avoid creating NO_x but overall, they provide a much more reliable and compact solution.

To avoid intermittent operation of the system a holding tank should be installed. ARMS shall be capable of safely handling ammonia, purge gas (N_2 + NH_3), air mixtures resulting from gas freeing. Ammonia should be considered as a pilot fuel for the system, if needed. Proper consideration needs to be made on how to handle purging after the emergency shut down (ESD) when the tank valve is closed, and the ammonia supply is cut. Some alternative source needs then to be considered. The ARMS shall be capable of reducing the amount of ammonia discharged to air from the above operations to a concentration not exceeding 300 ppm. Discharges from the ARMS shall be led to a vent mast.

The ARMS compartment shall contain a combustion-based cracker and include a holding tank. Since the combustion-based ARMS is not arranged following the double wall principle, the room shall be arranged as a hazardous zone 1.

7.2 Fuel supply line secondary enclosure vent

The secondary enclosure around fuel piping shall be provided with a vent pipe led to open air, sized to prevent overpressure in a maximum probable leakage scenario and protected with a water spray at its outlet.

7.3 Vent mast

Both fuel installations require having a fuel tank vent mast, there are however different requirements due to the distinct properties of each fuel, particularly regarding their vapor densities, flammability, and toxicity:

- Vent masts for LNG tanks are primarily designed to safely discharge LNG vapours into the atmosphere, ensuring that they are released at a safe height and distance from potential ignition sources. Made of materials compatible with cryogenic temperatures of LNG, vent masts must withstand the low temperatures without cracking or becoming brittle.
- Vent masts for ammonia are also designed to release vapours into the atmosphere but with additional consideration for the toxic nature of ammonia. These systems must ensure that ammonia is released in a way that minimizes exposure to the crew and environment.

Although the materials used for the construction of the LNG vent mast are potentially compatible also with ammonia, the properties of ammonia generally dictate larger distances from air intakes, air outlets or openings to accommodation, service and control spaces etc. Which is why, it is most likely that an entirely new vent mast is planned for and installed.

In principle the vent mast shall be located at least B (greatest moulded breadth) or 25.0 m (whichever is less) from the nearest air intake, air outlet or opening to enclosed spaces on the vessel. At the current stage it is believed that the safest place is the remote location on the top of wheelhouse. However, dispersion studies shall be carried to establish the safest location of the vent mast outlet.

In practice the venting to air is preferred over the venting to sea, that has been proposed for a number of projects, especially considering the toxicity of ammonia to aquatic life and difficulty of controlling and handling the spill. Predicting the direction of spill travel may be impossible in practical scenarios, and that may have dire consequences in case the ship needs to be abandoned to (open) life boats. Conversely, the ammonia in a gaseous form is relatively easily dispersed in air, especially that the releases from the storage tank pressure relieve system are always buoyant in air and the time constant of the tank, measured as time from inception of fire to the start of pressure release is considerable. That gives ample time to terminate operations and move to a safe distance from the offshore installation. The ship will also normally be downwind from the installation, meaning that the cloud of ammonia will not reach it.

The venting shall be to open air, directly upwards and undisturbed by any structure.

7.4 Dispersion studies

One of the important differences between LNG and ammonia resulting mostly from the later being poisonous to humans is that possible releases are required to be analysed in more formal way. Current DNV Rules for ammonia as fuel directly require preparing a dispersion analysis in which tank venting release and maximum probable leakage scenario(s) are considered. Those should be done in a way to be able to affect the design process, and not only as a "book-keeping" exercise to maximise the gain from them for sake of human safety.

In our opinion at least the following scenarios should be considered as part of the dispersion studies for the project:

1. Opening of tank pressure relief valves due to a fire load case.
2. Maximum probable leakage scenario in TCS.
3. Maximum probable leakage scenario in Bunkering Station.

The behaviour of the gas should be studied in several wind directions and speeds. Speed range should include still atmosphere and an average expected wind speed. Middle steps can be added on a need-to-have basis.

As mentioned, the dispersion analyses should not be treated as an accounting activity, documenting the obtained, final state of the design. It should rather be used to actively influence the design process, gradually leading to enhanced levels of safety in the final design. The dispersion study should dynamically follow the design process to be able to effectively affect the decisions being made. For that to be possible the dispersion analysis activities should be introduced early in the design process and constantly react to and suggest design decisions. As such it should be a part of internal competencies in the design office – what is the case in Breeze Ship Design.

8 BILGE SYSTEM

Ammonia tank TCS shall be served by a separate bilge system, segregated from other bilge systems. System operation shall be remote controlled but not automatic. The piping and valves material shall be suitable for use with ammonia and ammonia/water solutions.

There are currently discussions if it should be allowed to dispense this water outboards or should it be collected at the shore. To prepare for the latter it can be wise to consider a TCS bilge holding tank of capacity sufficient to hold 150% of the 30 minutes discharge from water spray systems required by the rules. Ammonia tank TCS bilge pump shall be used for emptying the bilge wells in TCS and, possibly, other spaces designed to safely contain ammonia leakages. Due care shall be given to the spaces being gas tight. The same pump shall be also used for shore delivery of the drained water.

Bilge wells in tank connection spaces and or other spaces containing fuel systems without secondary enclosures shall be provided with level sensors. Alarm shall be given at high level in bilge well. Bilge wells shall be as small as practicable, not more than 25 litres.

9 OVERALL VIEW ON THE ENERGY CONVERSION SYSTEMS

Due to relatively high cost of ammonia fuel, it is advisable to reconsider the service speed, by carefully analysing the operational profile. It might be possible to lower the fuel consumption considerably by lowering the typical service speed, especially supplemented with bulbous bow retrofit, as well as considering other fuel saving devices.

9.1 Endurance

The energy content of ammonia is much different than the same volume of LNG, this requires reconsideration of endurance. As liquefied natural gas primarily consists of methane the energy density of LNG is approximately 22 200 kJ/L. Ammonia on the other hand has an energy density of about 11 500 kJ/L, Figure 5. Therefore, on a volumetric basis, LNG stores almost twice as much energy per cubic meter as ammonia.

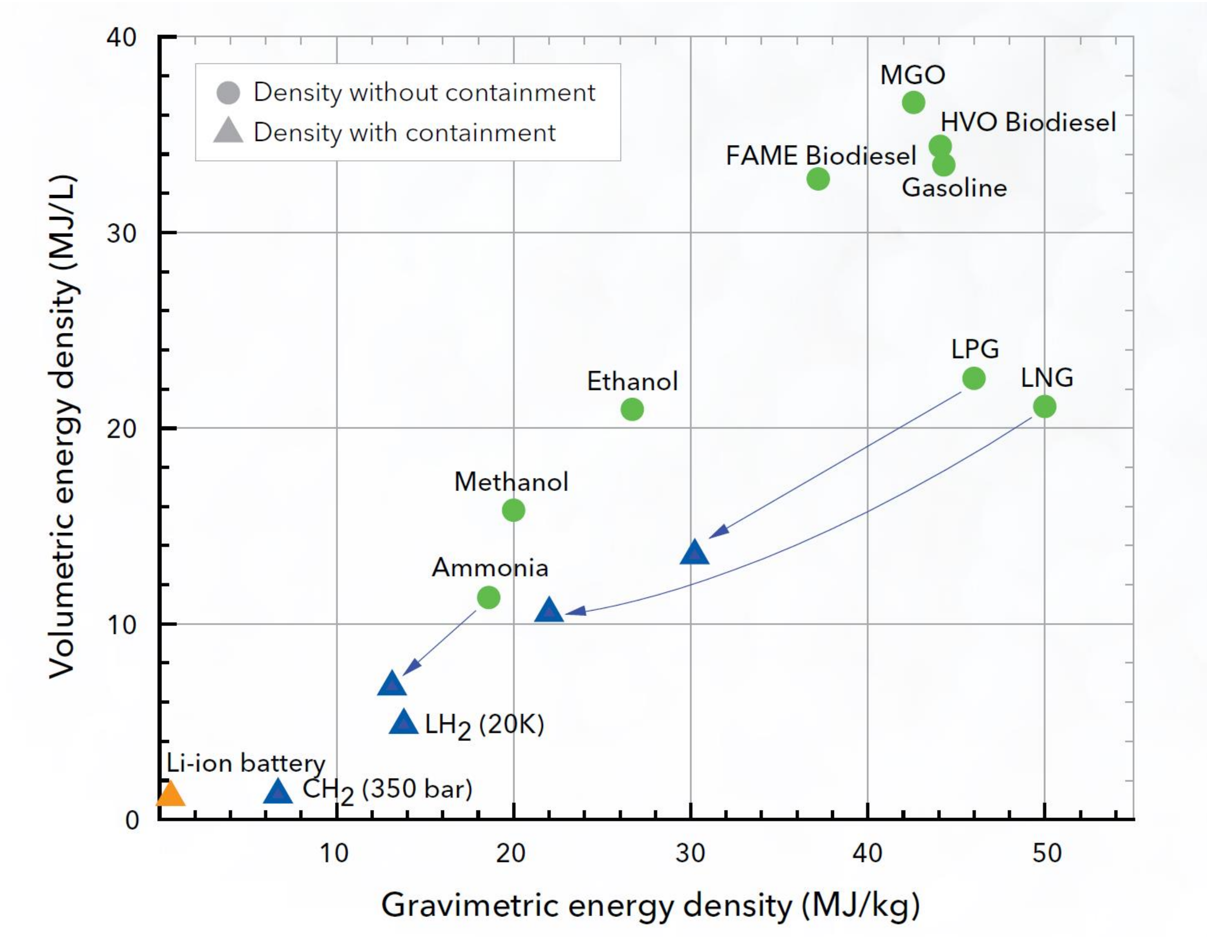


Figure 5 Densities for selected alternative fuel with and without containment on lower heating value basis [2]

9.2 Fuel efficiency & fuel saving measures

High cost of ammonia fuel enables and necessitates review of energy saving devices and solutions. Considering that the vessel under investigation is an offshore vessel of moderate size, the following could be considered:

- Slow steaming combined with reconsidering of hull appendages and features (bulbous bow, sponsons) and propeller redesign,
- Numerous energy saving/efficiency improvement devices as boss cap fins, propeller inflow stators,
- Advanced coatings (anti-fouling and low-friction coatings),
- Exploring synergies between the energy conversion systems (heating, ventilation, cooling etc).

10 REFERENCES

[1] National Research Council (U.S.). Subcommittee on Acute Exposure Guideline Levels., National Research Council (U.S.). Committee on Toxicology., and National Research Council (U.S.). Board on Environmental Studies and Toxicology., *Acute exposure guideline levels for selected airborne chemicals. Volume 6*. National Academies Press, 2008.

[2] DNVGL, "Ammonia as a Marine Fuel," 2020.