Ocean Engineering 287 (2023) 115751

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Regulatory gap analysis for risk assessment of ammonia-fuelled ships

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ARTICLE INFO

Handling Editor: Prof. A.I. Incecik

Keywords:
Ammonia as a marine fuel
Regulations
Gap analysis
IGF code
Classification societies
Safety considerations
Risk assessment

ABSTRACT

The concept and design of ammonia as a marine fuel are still in the embryonic stage which requires an in-depth investigation of its applicability in terms of its safety and potential risks, both in the design and operational phases of a ship's lifecycle. The paper examines and compares the state-of-the-art safety regulations, rules, standards and guidelines relevant to ammonia-fuelled ships available in various classification societies reports and international regulations such as the IGF codes and summarises their gaps and limitations. The paper critically analyses three major hazards namely toxicity, chemical corrosion, fire and explosion and their potential impact on the human, environment and ship in the event of ammonia leakage. Various hazardous areas considered include ammonia leakage at the bunkering station, fuel preparation room, engine room and storage room and its impact on the ship's general arrangement. In addition, this study reviews and discusses various qualitative and quantitative risk assessment methods employed in ships using low-flashpoint fuels and their relevance and potential suitability for ships powered by ammonia. The paper concludes with important findings and recommendations to aid designers, operators, safety experts, and policymakers in the further development of safety within the framework of risk assessment and management. Overall, this study provides valuable insights into the safety considerations of using ammonia as a marine fuel and highlights the need for further research and development in this area.

1. Introduction

The IMO has set a decarbonisation goal to decrease greenhouse gas (GHG) emissions in shipping by at least 50% by 2050, compared to 2008 levels, to fulfil legal and environmental commitments (IMO, 2018). This objective has prompted research worldwide on using renewable energy and zero-carbon alternate fuels. However, energy storage and handling, as well as safe energy harnessing, are crucial to overcoming the challenges of renewable resources such as intermittency and ensuring a stable energy supply. Therefore, research on how to effectively and inexpensively store energy for the use of renewable and eco-friendly energy, which will continue to increase the proportion of use in the energy system, is indispensable. Currently, the most popular energy storage method is chemical storage, which stores the energy produced through hydrogen or carbon-neutral hydrogen derivatives. Ammonia, identified as a sustainable fuel, is an excellent hydrogen carrier, a fuel that can be obtained from fossil fuels, biomass or other renewable sources such as wind and solar power. Ammonia can be stored using one of the chemical energy storage methods that can convert surplus electrical energy into zero-carbon fuel (Gil Posada et al., 2016).

At present, there are no ships that run on ammonia fuel in service, but several projects are underway to develop ammonia-fuelled ships. Several maritime companies are exploring the potential of ammonia as a clean energy source. Mitsubishi Heavy Industries and MOL (Mitsui O.S. K. Lines) have completed a concept study for an ammonia/liquefied CO_2 carrier (MOL, 2022), while China State Shipbuilding Corporation (CSSC) has received Approval in Principal from DNV for an ammonia-fuelled, 7000 unit car carrier design (DNV, 2022). Lloyd's Register, Samsung Heavy Industries, and MISC Berhad have signed an MoU to develop and construct two Very Large Crude Carriers (VLCC) that run on ammonia fuel as part of the Castor Initiative (LR, 2022). NYK (Nippon Yūsen

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https://doi.org/10.1016/j.oceaneng.2023.115751
Received 24 May 2023; Received in revised form 12 August 2023; Accepted 30 August 2023
Available online 27 September 2023

Nomenclature

ABCU	Automatic Bridge Centralized Control Unmanned
ABS	American Bureau of Shipping
ACC	Automatic Centralized Control
ACCU	Automatic Centralized Control Unmanned
AEGL	Acute Exposure Guideline Levels
B	Breadth
BLEVE	Boiling Liquid Evaporating Vapour Explosion
BN	Bayesian Network
BV	Bureau Veritas
CASS	Complete Accident Scenario Set
CCC	Carriage of Cargoes and Containers
CFD	Computational Fluid Dynamics
CO_2	Carbon Dioxide
DNV	Det Norske Veritas
DPS	Dynamic Process Simulation
ESD	Emergency Shutdown
ETA	Event Tree Analysis
EU	European Union
f_{cn}	Collision Damage Factor
FEPQPM	Fire Explosion Poisoning Quantitative Probability Model
FHIA	FMECA and HAZOP integrated analysis
f_l	Longitudinal Factor
FMEA	Failure Mode and Effects Analysis
FMECA	Failure Modes, Effects and Criticality Analysis
FSS Code	International Code for Fire Safety Systems
f_t	Transverse (Inboard Penetration) Factor
FTA	Fault Tree Analysis
f_v	Vertical Factor
GHG	Greenhouse Gas
HAZID	Hazard Identification
HAZOP	Hazard and Operability Analysis
HHV	High Heating Value
HVO	Hydrotreated Vegetable Oil
H_2	Hydrogen
IACS	International Association of Classification Societies
ICI	Imperial Chemical Industries
IBC Code	International Code for the Construction and Equipment of Ships Carrying Dangerous Chemicals in Bulk
IGC Code	International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk
IGF Code	International Code of Safety for Ship Using Gases or Other Low-Flashpoint Fuels
IMO	International Maritime Organization
ISO	International Organization for Standardization
KR	Korean Register
LFL	Lower Flammability Limit
LHV	Low Heating Value
LNG	Liquefied Natural Gas
LOPA	Layers of Protection Analysis
LPG	Liquefied Petroleum Gas
LR	Lloyd's Register
MCS	Monte Carlo Simulation
MGO	Marine Gas Oil
MOL	Mitsui O.S.K. Lines
MSC	Maritime Safety Committee
MVR	Rules for Building and Classing Marine Vessels
NASA	National Aeronautics and Space Administration
NH_3	Ammonia
NK	Nippon Kaiji Kyokai (also known as ClassNK)
NYK	Nippon Yūsen Kabushiki Kaisha
OSHA	Occupational Safety and Health Administration
P&IDs	Process and Instrumentation Diagrams
PRV	Pressure Relief Valve
QpsRA	Quantitative Probabilistic Seismic Risk Analysis
QRA	Quantitative Risk Assessment
RINA	Registro Italiano Navale
RPN	Risk Priority Number
SOLAS	Safety of Life at Sea
SCC	Stress Corrosion Cracking
SSL	Ship-Shore Link
STPA	System Theoretical Process Analysis
UFL	Upper Flammability Limit

Kabushiki Kaisha) Line, MTI, and Elomatic (a Finnish maritime consulting and engineering firm) have completed a concept design for an ammonia-ready, LNG-fuelled vessel and plan to extend the concept to two more vessel types and they aim to launch the first ammonia-fuelled vessel by 2025 (NYK, 2022).

On the other hand, ammonia is highly toxic and can cause serious injuries and fatalities to humans depending on the level of ammonia concentration exposed. The use of ammonia as a marine fuel is still in the early stages, and stringent safety measures are required for its bunkering, storage, and handling onboard during both the design and operational phases. International organizations such as IMO and various class societies have been working to develop and update the rules and regulations specific to ammonia-fuelled ships. Until now, regulations for low flash point fuels such as LNG or methyl alcohol/ethyl alcohol have been developed under the IGF code (MSC, 2015) and MSC circular (IMO, 2020), while there are no officially agreed safety guidelines for ammonia to be used as ship fuel. Instead, only safety guidelines from various independent classification societies such as ABS (ABS, 2021a, ABS, 2021b), DNV (DNV GL, 2020), KR (KR, 2021), and RINA (RINA, 2021) are available. In other words, there is currently no common international code for ammonia-fuelled ships, each regulation is slightly different. Therefore, a thorough review and understanding of the existing and upcoming rules, standards, and guidelines are necessary to identify any gaps and ensure coherence before finally applying them to the design and operational phases. In the context of the gap analysis, defining the 'gap' involves highlighting areas where the existing rules and regulations fall short in adequately addressing the unique demands and safety considerations posed by ammonia-fuelled ships. This paper serves as a common platform for readers, including designers and safety experts, to easily access and compare different regulations to achieve a safe and efficient installation of ammonia fuel storage onboard.

The remaining section of the paper is structured as follows: Section 2 covers the general characteristics of ammonia, major hazards, and accident statistics. Section 3 introduces various international regulations, ISO standards, EU legislations, class rules and guidelines that are considered in the study. Section 4 provides a detailed gap analysis of the different safety considerations. Section 5 summarises the different risk assessment approaches used and their relevance to ammonia-fuelled ships. Finally, Section 6 offers conclusions and recommendations that were developed from the study.

2. Background

2.1. General characteristics of ammonia

Ammonia (NH_3) is a colourless gas and has a lower density than air. When it leaks, it gets dispersed into the atmosphere easily. The boiling point of ammonia is −33.3 °C, and therefore, when a pressure of 8.6 bar or more is applied at 20 °C, ammonia changes to a liquid state with a density of 0.68 t/m^3. The lower calorific value of ammonia is approximately 18.6 MJ/kg, and compared to MGO (marine gas oil), the energy content is less than half by mass in the liquid state and about 30% by volume. Table 1 summarises and compares the different characteristics of ammonia with other alternate fuels.

Although ammonia has a much lower energy content per unit weight compared to hydrogen, the density of the fuel is high, and the volume required for storage is much smaller than that of compressed/liquid hydrogen. On the other hand, since the energy density is smaller than that of MGO and LPG, one of the disadvantages is that additional storage space of about three times that of MGO and about twice that of LPG/LNG is required.

Ammonia has the main advantage of being easier to store than hydrogen in almost the same form as LPG at low pressure if ambient conditions are similar. In fact, in terms of storage cost, ammonia costs about 0.5 \$/kg-H_2, whereas hydrogen requires 15 \$/kg-H_2. In other words, ammonia is much cheaper to store for a long period compared to hydrogen and can be transported about three times cheaper by sea or land (Bartels, 2008). Therefore, since the storage cost per unit of energy is low, it can have a great advantage as a fuel for ships. In addition, although ammonia is presently produced through natural gas in an industrial process through steam reforming and the Haber-Bosch process, the fuel itself does not contain carbon, so it is in the spotlight as an eco-friendly fuel. Besides, when ammonia is produced through renewable energy, it is expected that greater environmental benefits will be obtained from the lifecycle perspective (DNV GL, 2020).

However, there are certain disadvantages associated with the use of ammonia as a fuel. Ammonia is highly toxic and characterised as a low flash point fuel. Another disadvantage is the lack of experience in using ammonia as a ship fuel and the relatively low energy density, so additional analysis is required. Therefore, an overall understanding of ammonia as a marine fuel is important, including ammonia production and utilization, engine and tank technology, safety considerations including toxicity, environmental performance, and economic feasibility.

In this regard, the International Maritime Organization (IMO) has developed the international code of safety for ships using gases or other low-flashpoint fuels (IGF code) (MSC, 2015) for essential provisions such as the arrangement, installation, control and monitoring of fuel equipment for ships using gas or other low flash point fuels. However, the IGF code was established based on the safety of LNG-fuelled ships, and detailed safety guidelines for ammonia have not yet been developed.

2.2. Major hazards of using ammonia as a fuel for shipping

The relevant ship safety regulations of using ammonia as an alternative marine fuel should be introduced however, with due consideration of its potential hazards in terms of its toxicity, corrosive and flammability/explosion. Until now, international regulations for ammonia-fuelled ships must satisfy the IGF code as a basis, but it is a fact that the current IGF code is insufficient to ensure the safety of ammonia-fuelled ships. For this reason, the development of detailed safety guidelines for ammonia fuel should proceed as soon as possible, and sufficient risk assessment is required to develop them (DNV GL, 2020).

2.2.1. Explosion and fire

According to Table 1, the flammability limits of ammonia at standard atmospheric conditions range from 15.0% (lower flammability limit, LFL) to 28.0% (upper flammability limit, UFL). This implies that 15%–28% of ammonia mixed with air in the atmosphere can lead to potential fire and explosion hazards depending on the presence or absence of an ignition source. In addition, a phenomenon called BLEVE (boiling liquid evaporating vapour explosion) can occur, in which fatal accidents such as fires and explosions are triggered by the storage tank rupture and its associated gas released because the cylinder cannot maintain its structural integrity. It is caused by the rising internal pressure due to the boiling of the saturated liquid inside the storage container when heat is applied from the outside.

On the other hand, ammonia has a significantly higher flash point and auto-ignition temperature compared to other alternative energy sources. In addition, the reaction of the fuel is slow, and the minimum ignition energy is 8.0 MJ, which is much higher than that of LNG 0.28 MJ, methanol 0.14 MJ, and hydrogen 0.011 MJ. Further, in comparison to other fuels such as LPG (0.43 m/s), LNG (0.37 m/s), methanol (0.36 m/s), and hydrogen (3.51 m/s), ammonia has a relatively low laminar burning velocity of 0.07 m/s. This indicates that ammonia is relatively difficult to ignite compared to other fuels, and the above-mentioned fire and explosion potential and severity are somewhat mitigated due to these fuel characteristics.

It is worth noting that the calorific value has a strong correlation with the effect of an actual fire and explosion, and the higher the calorific value, the greater the effect on fire and explosion. While ammonia and methanol are at a similar level, overall, other low flash point fuels have a calorific value that is more than twice that of ammonia. In particular, in the case of hydrogen, the calorific value is more than 6 times that of ammonia, which indirectly suggests that the risk of hydrogen explosion is quite large. Thus, it can be concluded that the probability of fire and explosion of ammonia is less compared to other alternative fuels.

2.2.2. Health and safety

Even though ammonia has a lower fire and explosion potential than other low-flammability fuels, unlike other fuels, it can pose risks such as suffocation and cryogenic burns when exposed to normal atmospheric conditions.

Ammonia is a toxic gas and basic compound that can cause asphyxiation. The severity of its effects on humans depends on the route of exposure, dose and duration of exposure. However, exposure to high concentrations of ammonia in the air can cause immediate burns to the eyes, nose, throat, and respiratory tract, and may cause corrosive injuries including skin burns, blindness, lung damage, or even death. Because of this effect, much more careful management in terms of toxicity than other fuels is required.

In general, the concentration of ammonia in the blood is less than 50 μmol/L, which is generated from waste products obtained from protein and is metabolised by the liver to urea or glutamine and excreted in the

Table 1
Typical characteristics of ammonia (Aatola et al., 2009; DNV, 2019; Herdzik, 2021; Speight, 2011; Valera-Medina et al., 2018; Haynes, 2016; MAN, 2019).

Fuel properties	MGO	Diesel	LPG	LNG	Methanol	HVO	Liquid hydrogen	Ammonia
Flash point (°C)	60–75	52	−104	−188	11–12	>61	Not defined	132
Auto-ignition temperature (°C)	250	210	410–580	537	470	204	500	630
LHV (MJ/kg)	42.7	43.4	46	48.6	19.9	37.8	120	18.6
HHV (MJ/kg)	45.9	46	49.3	55.2	22.7	40.2	141.8	22.5
Flammability range (% volume in air, LFL-UFL)	0.4–8	0.6–7.5	1.8–10.1	4–15	6.7–36	0.6–7.5	4–74.2	15–28
Density (t/m^3)	0.835	0.832	0.49	0.49	0.79	0.78	0.071	0.68
Energy density (GJ/m^3)	35.7	38.6	25.3	22.2	15.6	34.3	8.5	11.4
Volume per unit energy (m^3/GJ)	Standard (1)	0.92	1.41	1.61	2.29	1.04	4.18	3.14
Toxicity	No	No	No	No	Low acute toxicity	No	No	High

urine. Most of the ammonia inhaled, not the ammonia generated by the human body, is in the form of gas or vapour, which immediately interacts with moisture in the skin, eyes, mouth, respiratory tract, and especially the mucous membranes to form ammonium hydroxide. Ammonium hydroxide causes tissue necrosis through cell membrane destruction to destroy cells, and as cellular proteins are decomposed, water is extracted, causing an inflammatory response, causing further damage. Concentrations of ammonia above 100 μmol/L may cause disturbance of consciousness, and from 200 μmol/L, coma or convulsions may occur. When ammonia gas is inhaled, the airways are blocked, breathing becomes difficult, and laryngitis or bronchitis occurs. Exposure to ammonia can be treated by immediately flushing the skin and eyes with plenty of water (Public Health England, 2015).

Table 2 summarises the different levels of ammonia exposure time and concentrations and their corresponding effects on humans. AEGL (acute exposure guideline levels) indicate acute exposure threshold levels to ammonia and measures risks ranging from stage 1 to stage 3, where stage 3 is fatal. Accordingly, if a human is exposed for about 20 min at an ammonia concentration of 1600 ppm, it may cause life-threatening effects). In addition, at a concentration of 5000 ppm or more, a risk of respiratory arrest may be induced regardless of the exposure time, and at a concentration of 10,000 ppm or more, a burn may occur immediately upon contact with the skin (National Research Council, 2009).

Due to these serious concerns, ammonia-fuelled ships should be built with the aim of zero leakage. Reflecting this need for fuel management, BV classification established regulations such as prohibiting direct venting under normal conditions and venting for the purpose of tank pressure control, ensuring emission concentration of less than 30 ppm from the vent mast, requiring a dilution device prior to venting through combustion/water/air and so on, and permitting direct venting only in case of fire (BV, 2022).

Ammonia possesses the distinct quality of not only dispersing into the atmosphere due to its lower density compared to air but also exhibiting solubility in water. To put it differently, in case of a leakage, ammonia can readily be absorbed by a considerable amount of moisture, causing the resultant mixture to become denser and prone to settling aboard the ship. These attributes must also be taken into account when assessing the potential risk of ammonia dispersion.

2.2.3. Corrosion

Ammonia is highly corrosive and can cause chemical corrosion resulting in structural damage.

The main materials corroded include copper, brass and zinc alloys forming green/blue corrosion. Therefore, in order to reduce the risk of corrosion when using ammonia fuel, it is necessary to avoid the use of these materials in the manufacture of storage tanks, engines and various fuel systems.

In terms of structural damage, ammonia can cause stress corrosion cracking (SCC), a phenomenon that can occur in metals exposed to a combination of stress and corrosive environments. This produces cracks by destabilising the protective oxide layer without causing general corrosion under certain circumstances. In the process of failure, general external signs such as surface corrosion or reduction in thickness are not seen. In other words, when a structure or part is damaged due to SCC, the damage occurs suddenly without any warning signal, resulting in a large structural and economic loss due to an accident that cannot be prepared in advance.

Table 2
Effects on humans for different exposure durations and concentrations.

Risk level	Exposure duration (in min)			Effect on humans
	10	20	30	
AEGL-1	30 ppm	30 ppm	30 ppm	Discomfort, irritation, or asymptomatic numb effect
AEGL-2	220 ppm	220 ppm	160 ppm	Irreversible or other serious and long-lasting adverse health effects or impaired ability to escape
AEGL-3	2700 ppm	1600 ppm	1100 ppm	Life-threatening health effects or death

Therefore, if not handled properly, SCC can occur, which can lead to vessel rupture and pose a serious threat. This is due to two factors: the stress condition applied to the part or structure and the corrosive atmosphere condition, so each damage condition can be identified, and its occurrence can be suppressed during prevention. In terms of stress, cracks can be caused by both internal and external factors. The internal factor refers to the residual stress formed during product processing or the residual thermal stress generated during the welding/heat treatment process. The external factor refers to stresses that occur during periodic use, such as operating pressure or external load.

Corrosive atmosphere conditions encompass a spectrum of environmental factors that elicit corrosion processes. These factors notably encompass chlorides, moisture, and various other chemical agents recognized for their corrosive nature. These conditions are often categorized into two main types: wet and dry corrosive atmospheres. A wet corrosive atmosphere denotes an environment saturated with moisture content, frequently observed in locales like coastal regions or areas characterized by substantial rainfall. Conversely, a dry corrosive atmosphere pertains to an arid setting, yet harbouring corrosive agents, commonly encountered in industrial complexes or regions subjected to acid rain.

The corrosive atmospheric conditions hinge on the interplay of multiple parameters, including the concentration of corrosive agents, ambient temperature, and humidity levels. The escalation in these variables corresponds to an augmented severity of the corrosive atmosphere. Specifically, heightened concentrations of corrosive agents, elevated temperatures, and increased humidity collectively contribute to the exacerbation of corrosive atmospheric effects.

Typically, anhydrous ammonia can cause stress corrosion cracking in containments and systems made of carbon-manganese steel or nickel steel. Therefore, in ships to which the ammonia system is applied, the use of those materials is strictly prohibited, and the welding area requires stress relief heat treatment after work.

2.3. Accident statistics

2.3.1. Onshore ammonia accident statistics

In order to evaluate the risk of ammonia-fuelled ships, it would be ideal to analyze the existing cases of the same type of ship (ammonia-fuelled ship) accidents and therefore, the target ship should be evaluated based on this. However, as mentioned before, it is true that not only there is no ammonia fuelled ships being actually built, but also it is rare that it has been even used as a fuel in the automobile industry. Therefore, there is insufficient accident data that can be used to evaluate the safety of the target ship. Thus, it can be used as data to indirectly evaluate the potential risk of ammonia fuelled ships by expanding the scope of analysis to onshore ammonia production/consumption plants and gaining experience by analysing what accidents have occurred in the industry related to ammonia.

There have been countless reports of accidents on land related to ammonia since it is widely used in the fertiliser and food industry. According to the Canadian government report, between 2007 and 2017 in British Columbia, western Canada, there were a total of 59 ammonia leak incidents recorded, 14 of which resulted in casualties. Fig. 1 shows the number of accidents sorted by year related to ammonia facilities in the area. In general, the accident trend is increasing year by year, indicating that ammonia accident is no more of a temporary problem in the past, but is still an ongoing problem (Technical Safety BC, 2007).

Table 3 shows the total number of ammonia accident cases that occurred in British Columbia classified into three major groups (excluding unidentified cases), along with their corresponding sub-

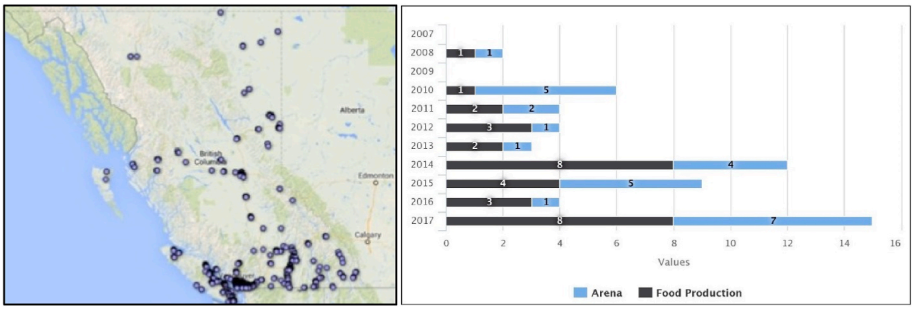

Fig. 1. *Ammonia industrial facilities (left) and leakage accident statistics (right) in British Columbia* (Technical Safety BC, 2007).

Table 3
The main causes of accidents in ammonia facilities in British Columbia.

Cause of accident	Number of cases	Accident failures
Equipment damage	15	Component failure/wear
	4	System control failure or monitoring
	1	Breakdown of worker tools
	2	Incorrect use of component
Operating problem	9	Lack or inadequate preventive maintenance programs and procedures
	5	Improper operating procedures
	4	Operating environment (e.g., higher than expected operating temperature, humidity, excessive vibration)
	2	Operator error/lack of training
	1	Failure to restrict access to areas surrounding maintenance work
Installation	3	System component compatibility issues
	1	Missing isolation such as valves when installing new components
	1	Missing component
	1	Improper installation/alignment of components
	1	Inadequate protective equipment for components
Unidentified	4	Not recorded

category ‘contents’. Among them, it shows that the accidents due to the operating problem were quite high while the accidents due to component failure/wear in the equipment damage group occur most frequently.

These findings indirectly confirm that the ship’s ammonia fuel system can also be sufficiently exposed to risks due to mechanical problems such as failure/wearing of parts or improper operating procedures.

Furthermore, the US Department of Labor offers an Occupational Safety and Health Administration (OSHA) database (United States Department of Labor, 2023) encompassing instances of ammonia leakage accidents reported since 1984. Accordingly, there have been a total of 306 reported incidents during storage and handling of ammonia. Among these cases, 58 have resulted in fatalities, while a significant portion of these incidents involves injuries like chemical burns and respiratory issues.

A representative serious accident case is reported at the Texas plant of Yara, the world’s leading ammonia manufacturer and trader. In 2013, an accident occurred in which 15 people died due to a fire caused by ammonia leakage at a fertiliser plant. The accident destroyed the factory and injured more than 100 people. In the wake of this accident, an investigation into the accident history of the fertiliser plant revealed a total of 939 related accidents occurring between 1996 and 2011. That is, an average of 1 or more accidents occurred per week. The Texas accident record warns that ammonia leaks occur frequently during the installation, storage and handling phases.

2.3.2. Offshore ammonia accident statistics

Insights on ammonia-fuelled ships can be gained from accidents involving ships carrying ammonia as cargo, particularly during bunkering, storage, and transportation, due to the lack of experience in this area. Table 4 lists all 12 worldwide accidents obtained from the IHS Seaweb database recorded for the period 1978–2021, with most of them

Table 4
Worldwide offshore accident statistics of ships carrying ammonia.

No.	Year	Ship type	Accident type	Severity	Fatalities	Cause of ammonia leakage
1	1978	LPG Tanker	Hull/Machinery Damage	Non Serious	0	Vessel adrift and ammonia leak in a storm
2	1981	Crude/Oil Products Tanker	Hull/Machinery Damage	Non Serious	0	Ammonia leak in refrigeration system after the pipe was damaged whilst discharging
3	1982	Fishing Vessel	Hull/Machinery Damage	Serious	14	Leakage of ammonia from one of the cargoes of containers situated close to the ship’s accommodation block
4	1982	Fish Factory Ship	Fire/Explosion	Serious	0	Rupture of a refrigerant pipe
5	1983	LPG Tanker	Hull/Machinery Damage	Serious	46	Explosion in engine room following rupture of ammonia storage tank
6	1996	LPG Tanker	Hull/Machinery Damage	Serious	1	A valve was accidently mis-operated during tank cleaning preparations
7	1999	LPG Tanker	Hull/Machinery Damage	Non Serious	0	Leakage of ammonia from loading arm
8	2005	Container Ship (Fully Cellular)	Hull/Machinery Damage	Non Serious	0	A net filled with fish hit a pipeline near the ceiling and ammonia gas leaked, whilst discharging at the port
9	2007	Fishing Vessel	Hull/Machinery Damage	Serious	6	Hose burst whilst discharging anhydrous ammonia
10	2014	Chemical/Products Tanker	Collisions	Serious	0	Caught fire whilst undergoing repairs by welders torch and some canisters of ammonia exploded
11	2014	Fishing Vessel	Hull/Machinery Damage	Serious	38	Ammonia liquid dripped from valves while loading, subsequently experienced extensive failures of heating coils in the wing tanks
12	2021	LPG Tanker	Fatality/Injury	Serious	4	Ammonia leakage causes unknown

being classified as serious accidents (approximately 66%) and involving LPG tankers. There were no reports of environmental pollution or major harm to the ship structure. However, in the majority of cases, there were fatalities, with the most severe incident being an explosion in the engine room of an LPG tanker caused by a rupture in the ammonia storage tank, which led to 46 casualties. This indicates the need for caution when handling ammonia at all stages of its operations, as ammonia transport is expected to increase in the future, combined with a lack of effective regulation, operational experience, training, and potential corruption at sea.

In conclusion, although ammonia has been typically transported as a ship's cargo or used as a refrigerant in a refrigeration plant, the fact that it has not been utilized yet as a ship fuel is a major concern due to sufficiently high safety implications and risks related to bunkering, storage, supply and use of ammonia on board ships, and the impact is not small enough to be treated as negligible.

Ammonia is projected to be classified as useable energy in about three to four years. Therefore, securing the safety of the use of it as a ship fuel is seen as a very urgent matter. Above all, unlike other general alternative fuels, ammonia has a more serious risk of toxicity and corrosion than the risk of fire and explosion (DNV GL, 2020; MSC, 2015). Therefore, based on these fuel characteristics, a more accurate and reliable risk assessment must be performed in order to secure the safety of the ship and eliminate loss or injury of human life.

3. Current regulations, rules, standards, and guidelines

3.1. International regulations

Currently, there are several international regulations ensuring the safety of ammonia transport on ships, such as the '*International Code for the Construction and Equipment of Ships Carrying Dangerous Chemicals in Bulk (IBC Code)*' (IMO, 2004) (for aqueous ammonia) and the '*International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code)*' (MSC, 2014) (for anhydrous ammonia). However, for the use of ammonia as a fuel in shipping, the only relevant regulation is the IGF code (MSC, 2015), which was adopted in 2017, which provides general requirements for Low-Flashpoint fuels (in Part A) and specific requirements for natural gas (in PartA-1). Recently in 2020, IMO approved the '*Interim Guidelines for the Safety of Ships Using Methyl/Ethyl Alcohol as Fuel*' (MSC.1/Circ.1621) (IMO, 2020). Moreover, the IMO correspondence group is in the process of developing specific regulations for ammonia and at present, the following documents presented and listed in Table 5 are available.

3.2. ISO standards

The ISO has established a range of standards related to ammonia, which cover topics such as the installation and design of storage tanks, as well as the measurement of the concentration of liquefied gases. To determine the most pertinent standards for ensuring the safety of ammonia storage and operation aboard marine vessels, a filtering process was conducted using keywords such as "ammonia," "storage for liquefied gas," and "ship technologies." As a result, the most relevant ISO standards were identified and Table A presents a summary of how these documents can be applied to ensure the secure and efficient storage and use of ammonia on board marine vessels.

These standards serve as a robust foundation, offering a roadmap to mitigate risks associated with the use of ammonia as ship fuel. Moreover, the integration of ISO standards with the forefront of ammonia propulsion exemplifies a dedicated effort towards sustainability within the maritime realm.

For instance, ISO 7103:1982 (ISO, 1982) serves as a global standard outlining the apparatus and methodologies employed in procuring representative samples of industrial liquefied anhydrous ammonia from various containers like barrels, cylinders, and tanks. In addition, this standard provides guidelines for handling liquefied anhydrous ammonia, which is a highly caustic and hazardous substance with a boiling point of −33.3 °C under standard atmospheric pressure. In a related context, the document PGS 12:2014 (PGS, 2014) delineates the proper procedures for storing and managing ammonia. Due to its toxicity, corrosiveness, and potential for asphyxiation, the document underscores the critical importance of ensuring secure storage and handling to avert accidents.

To ensure safe storage and disposal of ammonia, it is imperative that storage areas are well-ventilated and equipped with leak detection systems. Employees tasked with ammonia-related tasks must adopt appropriate personal protective gear, including respirators, safety goggles, and gloves.

3.3. EU legislation

The Seveso Directives are the primary EU legislation addressing the prevention, preparedness and response to major accidents involving dangerous substances that occur on land. Seveso directives were established in the aftermath of an explosion in the chemical factory located in the Italian town of Seveso and the residents were exposed to high levels of dioxin, which is known as a human carcinogen and potent endocrine disruptor. A Seveso establishment engages in the handling, production, use, or storage of hazardous materials (i.e. refineries, petrochemical

Table 5
Summary of various international regulations on using ammonia as a marine fuel.

Reference No.	Document title	Summary
MSC 104/15/9 (IMO, 2021)	Development of non-mandatory guidelines for the safety of ships using ammonia as fuel	Proposes a new output to develop non-mandatory guidelines for the safety of newly built ships using ammonia as a fuel
MSC 104/15/10 (IMO, 2021a)	Hazard identification of ships using ammonia as a fuel	Provides the results of hazard identification of ships using ammonia as a fuel
MSC 104/15/30 (IMO, 2021b)	Necessity of deliberations on operational safety measures and fire safety measures	Points out the necessity of careful deliberations on operational safety measures and fire safety measures for ammonia-fuelled ships
CCC 7/3/9 (IMO, 2021c)	Report from the correspondence group and proposal for developing guidelines for the use of ammonia and hydrogen as a fuel	Provide comments on the progress made in the report from the correspondence group on the development of technical provisions for the safety of ships using low-flashpoint fuels and propose to include the development of two separate guidelines for the safety of ships using ammonia and hydrogen as fuel in the work plan of the CCC Sub-Committee
CCC 7/INF.8 (IMO, 2020)	Forecasting the alternative marine fuel: ammonia	Introduces the outline of the outlook of ammonia as green ship fuel
CCC 8/13/1 (IMO, 2022a)	Development of guidelines for the safety of ships using ammonia as fuel	Provides information on possible issues to be considered for developing guidelines for the safety of ships using ammonia as fuel and proposes the way forward
CCC 8/13/2 (IMO, 2022)	Comments on document CCC 8/13	Proposes a review of the environmental effect which will be considered in future discussions
CCC 8/13 (IMO, 2022b)	Report of the Correspondence Group (safety information for the use of ammonia)	Provides the report of Correspondence Group on the development of technical provisions for the safety of ships using low-flashpoint fuels, regarding the collection of the safety information for the use of ammonia.

sites, oil depots or explosives depots). The first Seveso Directive (82/501/EEC) (EEC Directive, 1982) was adopted in 1985 and introduced a set of preventive measures and notifications in order to reduce the risk of hazardous activities, followed by the Seveso II Directive (96/82/EC) (EU Directive, 1997), which considers lessons learned from later accidents such as Bhopal, Toulouse and Enschede. The latest Seveso III Directive (2012/18/EU) (EU Directives, 2012) was enacted in 2012, in light of modifications made to Union legislation regarding the classification of chemicals and expanded rights for citizens to access information and justice. As the Seveso directives are mainly applicable to land-based facilities, this has not been considered in the following comparative gap analysis of rules and guidelines concerning ammonia-fuelled ships.

3.4. Class rules and guidelines

Major classification societies have developed their own rules and guidelines for ammonia-fuelled ships in 2021 and 2022. The following list of classification societies and their documents were used in the gap analysis.

- LR (2021) – '*Rules and Regulations for the Classification of Ships using Gases or other Low-flashpoint Fuels*' (LR, 2021)
- ABS (2021) - '*Requirements for Ammonia Fuelled Vessels*' (ABS, 2021a)
- ABS (2021) – '*Guide for Ammonia Fuelled Vessels*' (ABS, 2021b)
- ABS (2022) – '*Rules for Building and Classing Marine Vessels (MVR) - Part 5C, Specific Vessel Types (Chapters 7–18)*' (ABS, 2022)
- BV (2022) - '*Ammonia-Fuelled Ships*' (BV, 2022)
- DNV AS (2021) - '*Part 6 additional class notations - Chapter 2 Propulsion, power generation and auxiliary systems*' (DNV AS, 2021)
- KR (2021) - '*Guidelines for Ships Using Ammonia as Fuels*' (KR, 2021)
- NK (2021) – '*Guidelines for Ships Using Alternative Fuels*' (ClassNK, 2021)
- RINA (2021) – '*Amendments to the "Rules for the Classification of Ships"*' (RINA, 2021)

Although most directives are broadly consistent with the IGF code, there are currently no international standards applicable to ammonia-fuelled ships. Therefore, the following sub-sections provide a detailed understanding of the safety requirements and guidelines that ammonia-fuelled ships must comply with by comparing the differences between classification guidelines and the IGF code.

4. Regulatory gap analysis in the safe design of ammonia-fuelled ship

Fig. 2 provides a summary of different safety design regulations considered in the study. It also shows how regulations from various organizations are considered in the design of ammonia-fuelled ships, such as ventilation, materials, fire safety, fuel containment and supply systems. The following sections discuss in detail the gap analysis of each design element and Tables 9–16 summarise and compare key outcomes from this study.

4.1. Ship design and arrangement

4.1.1. Machinery space

In the machinery space protected by an emergency shutoff, a single failure can cause a potential ammonia leakage in the machinery space. In other words, in order to satisfy a safe machinery space under all conditions, a gas-free machinery space needs to be applied, rather than a machinery space protected by an emergency shutdown ensuring that a single failure will not lead to the release of fuel gas into the machinery space. ABS specifically requires that machinery spaces containing ammonia should be supplied with remote monitoring arrangements in accordance with ACC,[1] ACCU[2] and ABCU[3] requirements.

4.1.2. Fuel preparation room

The fuel preparation room is generally regarded as a highly hazardous area because it is an area where equipment and systems for supplying ammonia fuel are installed. To reduce possible ammonia leak damage in the fuel preparation room, the fuel preparation room should be located in an open area (IGF code 5.8) (MSC, 2015), or located in a dedicated, unmanned space that is separated from other areas by gastight bulkheads and decks. These rooms must contain only the essential equipment for fuel preparation and supply, along with necessary safety equipment.

Further, ABS and BV have reported that the room must be designed to withstand a potential maximum pressure build-up or vacuum pressure, during leakages or the activation of safety systems. In addition, as per ABS and DNV (except for KR and NK) guidelines, a minimum of two widely separated means of escape are to be provided for these spaces and a water screen system shall be installed at the entrance of the fuel preparation room above access doors in order to provide a means of escaping ammonia from the fuel preparation room. The water screen system should be capable of being manually operated from a safe location outside of the area in case of a leak, as well as automatically operated within the room. This action prevents the diffusion of ammonia into a non-hazardous area due to a single damage leak in the fuel preparation room. Also, the water screen system should be able to operate manually in a safe place outside the area in case of leakage, as well as to operate automatically inside the room.

4.1.3. Bilge systems

An independent bilge system needs to be installed in the fuel preparation room. ABS recommends that the draining system should be able to remove at least 125% of the capacity of the water screen system, but there are no specific guidelines for water screen systems in KR and NK reports. Instead, NK added a directive that the bilge system must be able to operate outside the fuel preparation room.

In addition, independent bilge holding tanks or drain tanks must be provided for the discharge from the bilge system to avoid direct discharge into seawater on the grounds that anhydrous ammonia is extremely harmful to aquatic life. KR added a guideline that the bilge well should be as small as possible.

4.1.4. Drip trays

Drip trays shall be fitted where leakage may occur which can cause damage to the ship structure. It should be made of suitable material having sufficient capacity and be equipped with a drain valve so that rainwater can be drained to the side of the ship and thermally insulated from the ship's structure so that the surrounding hull or deck is not exposed to unacceptable cooling, in case of leakage of liquid fuel.

ABS requires where liquid piping is dismantled regularly, or where liquid leakage may be anticipated, such as at shore connections or pump seals, protection for the hull beneath be provided. Further, drip trays located below the tank connections and other sources of vapours from the tanks shall be at least 3 m from inlets, air intakes and openings to accommodation, service, cargo or machinery spaces and control stations. Finally, Type C LNG storage tanks should meet the safety principle and arrangement of "tank connection space" ABS rules and may be permitted to be installed on an open deck without a drip tray.

According to NK guidelines, the hull should be provided with a manually emptied drip tray in case of a leak of fewer than 10 L and the storage tank should be equipped with a water level indicator and alarm

[1] Automatic Centralized Control.
[2] Automatic Centralized Control Unmanned.
[3] Automatic Bridge Centralized Control Unmanned.

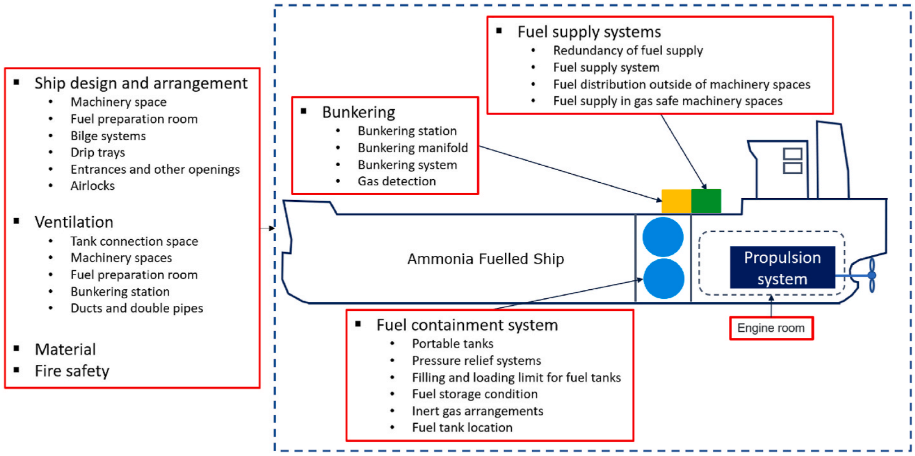

Fig. 2. The different safety regulations identified for an ammonia-fuelled ship.

system.

4.1.5. Entrances and other openings in enclosed spaces

In any case, direct access from the gas safety area to the gas hazardous area is not permitted in principle, but if access is necessary for operational reasons, an appropriate air lock must be installed. In particular, if there is no direct access from the open deck to the tank connection space, a bolted cover should be installed.

ABS and NK provided an opening size limit to ensure sufficient space to allow a person wearing a breathing apparatus to use any ladder and also to move off injured persons. Accordingly, the minimum transparent opening must be at least 600 mm × 600 mm for horizontal openings and 600 mm × 800 mm at a height of not more than 600 mm from the floor plate for vertical openings. In case access is not direct from the open deck, a bolted hatch will be arranged and classified as a hazardous Zone 2.

4.1.6. Airlocks

An airlock is an area enclosed by a gastight bulkhead provided with two reliable gastight doors. These doors should be spaced apart from each other by more than 1.5 m but less than 2.5 m with a self-closing door having a sill not less than 300 mm in height.

Summarising the above discussions, Table 9 provides the results of the gap analysis for different safety regulations of ship design and general arrangements.

4.2. Fuel containment system

4.2.1. General regulations

In general, the fuel containment system shall be designed so that leakage from the tank or its connections does not pose a hazard to the ship, occupants or the environment, and any anticipated potential hazards shall be avoided.

Regarding the design life of a fuel storage tank, except for DNV (i.e. 25 years), other classification societies stipulate that it should not be less than the design life of a ship or 20 years, whichever is longer.

Further, as per IGF code (MSC, 2015) (6.3.2) and ABS (ABS, 2022) (5C-13-6/3.2), the maximum allowable working pressure (MAWP) of the ammonia fuel containment tank shall not exceed 90% of the maximum allowable relief valve setting (MARVS), but KR provides an additional guideline that the maximum vapour pressure of a fuel tank installed on an open deck should be set in accordance with the maximum temperature that can rise due to solar radiation. The bulkhead material of the tank connection space shall be designed to withstand the maximum pressure rise even during the maximum ammonia leakage.

Additionally, ABS requires the fuel containment system to be thermally insulated so that the surrounding hull is not exposed to unacceptable cooling in case of leakage of the gas. Also, fuel storage tank types must be provided with a secondary barrier according to the following table (Table 6).

Table 6
Fuel tank types and their secondary barrier requirements.

No.	Basic tank type	Secondary barrier
1	Membrane	Complete secondary barrier
2	Type A	Complete secondary barrier
3	Type B	Partial secondary barrier
4	Type C	No secondary barrier

4.2.2. Portable tanks

All portable fuel tanks are to be located in dedicated spaces and fixed to the deck while connected to the ship. ABS (ABS, 2022) (5C-13-6/5.11) recommends that decks and structures under or near the portable tank connection hose must be protected from potential leaks by providing adequate drip trays and spray shields.

4.2.3. Pressure relief systems

At least two pressure relief valves (PRVs) should be installed in the liquefied gas fuel tank in case of malfunction or leakage. In addition, a pressure relief device should be installed in the space enclosed between the barriers. However, the standard procedures provided for installing pressure relief valves are slightly different among each classification.

ABS requires that fuel tank PRV vents be located at least *B* (breadth) or 25 m, whichever is shorter, from the nearest air intake, exhaust or opening to accommodation, service and control stations. However, the KR (KR, 2021) (Ch. 6, 702. 8) recommends vent locations be at least 15 m apart in the horizontal direction and shall be arranged at a height of at least 4 m above the open deck. When a device to reduce ammonia emission is additionally installed and the length of the ship is less than 90 m, KR accepts a small value of at least 6 m in the horizontal direction, and gas dispersion analysis should be performed if necessary. Unlike KR, ABS did not specify specific distances, and smaller distances may be accepted based on justification through gas dispersion analysis.

In addition, ABS sets a safe distance of 25 m to life-saving equipment, muster stations and escape routes unless justified by gas dispersion analysis.

4.2.4. Filling and loading limit for fuel tanks

The fuel storage tank should not be filled with more than 98% of the total tank volume when the fuel reaches the reference temperature, i.e. the temperature corresponding to the vapour pressure of the fuel in a fuel tank at the set pressure of the pressure relief valves (PRVs). A loading limit curve for the actual fuel loading reference temperature should also be drawn up.

As per IGF code (MSC, 2015) (6.8.2), in case the temperature of the tank contents will not rise in the event of an external fire due to adequate insulation or tank location, the loading limit may be increased, but never above 95% of the calculated reference temperature.

4.2.5. Fuel storage condition

Except for liquefied gas fuel tanks that are designed to withstand the maximum gauge vapour pressure of fuel at the upper limit of the ambient design temperature, the pressure and temperature of liquefied gas fuel tanks are maintained within the design range by methods prescribed by IGF code, namely reliquefaction of vapours, thermal oxidation of vapours, pressure accumulation; or liquefied gas fuel cooling.

The selected method should be able to maintain the tank pressure below the tank set pressure for 15 days, assuming that the tank is full at the normal operating pressure and the vessel is in idle condition, that is, only the onboard power is produced.

In addition, the discharge of fuel vapour to the atmosphere for pressure control of the tank is not permitted except in emergencies.

The interbarrier and fuel storage spaces in liquefied gas fuel containment systems must be filled with dry inert gas or dry air to prevent dangerous situations, and these spaces must be equipped with a vapour detection system for quick leak detection. The inert gas or dry air must be maintained for at least 30 days, with the exception of partial secondary barriers which may only require dry air if the vessel is equipped with a stored charge of inert gas or an inert gas generation system. The liquefied gas fuel tanks must also be surrounded by dry air to prevent condensation and icing.

4.2.6. Inert gas arrangements

To ensure that the backflow of fuel vapour into the inert gas system is prevented, the inert gas supply line must be equipped with a double block and bleed arrangement, consisting of two shutoff valves with a venting valve positioned in between and a closable non-return valve that connects to the fuel system. If the connections to the fuel piping systems are not permanent, two non-return valves may be utilized as an alternative. The arrangement should facilitate the isolation of each space undergoing inerting, and the necessary controls and pressure-regulating valves must be provided. Additionally, for insulation spaces that receive a continual supply of inert gas as part of a leak detection system, monitoring systems must be established to track the amount of gas being supplied to individual spaces.

The equipment must be capable of generating an inert gas with an oxygen content not exceeding 5%. A continuous oxygen content meter reading must be equipped with an inert gas supply. Also, an alarm is set to an oxygen content of up to 5% by volume. ABS added that this device must have an automatic means of venting inert gas with an oxygen content greater than 5%, to the atmosphere during start-up and abnormal operation.

Table 10 summarises and compares different fuel containment system safety requirements provided by classification rules and the IGF code.

4.2.7. Fuel tank location

IGF code provides specific guidelines for the location of LNG tanks based on the purpose of protecting the LNG tanks from external damage such as collision and grounding by maintaining a minimum distance between the LNG tank and the hull. The safety distance is determined by the hazard level of the liquid stored in the tank, expressed as 1G, 2G and 3G types. Type 1G is considered to be the most dangerous cargo, while Type 3G is considered the least dangerous cargo. The IGF code placed the LNG as fuel into the Type 1G category, meaning that the LNG-fuelled tanks should meet the strict Type 1G requirements.

According to IGF code (MSC, 2015) (5.3.3.3), for independent tanks, the protection distance must be measured to the outer wall of the tank (the primary barrier of the tank containment system), and for membrane tanks, the protection distance must be measured to the bulkhead around the tank insulation. The following Fig. 3 shows the independent tank case with Table 7 describing the safety requirements for 4 different tank locations.

As an alternative, the probabilistic approach to the distance of the LNG tank can be more flexibly deployed without reducing the safety aspect. In this respect, IGF code (MSC, 2015) (5.3.4) alone introduced the probabilistic approach to determine the safety distance using the concept of damage stability analysis in accordance with SOLAS II-1. Accordingly, the transverse distance from the ship side can be calculated using Eq. (1),

$$f_{CN} = f_l \times f_t \times f_v \tag{1}$$

where,

Table 7
Safety distance requirement descriptions for different storage tank locations.

No.	Tank location	Safety requirements
1	Transverse distance from ship side	$B/5$ m or 11.5 m, whichever is less as summer load water line
2	Distance from side shell	0.8–2 m
3	Longitudinal location	Abaft the collision bulkhead
4	Vertical distance from the bottom shell	$B/15$ m or 2.0 m, whichever is less

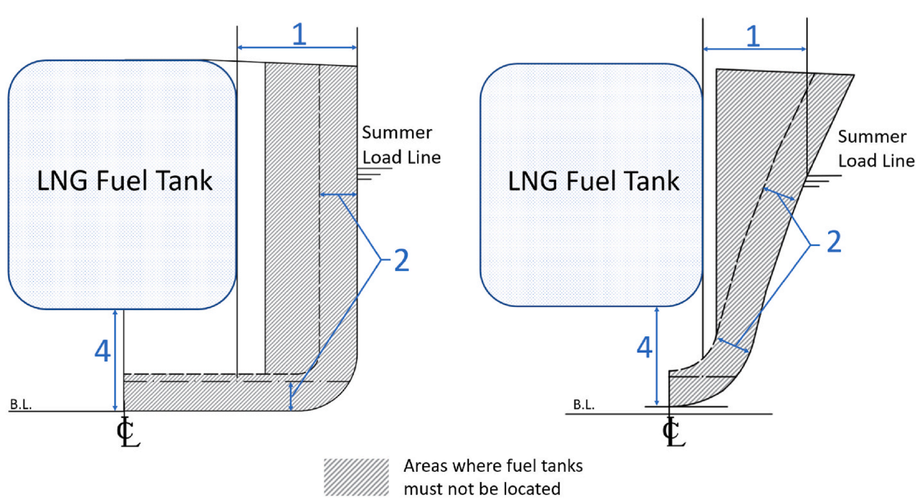

Fig. 3. *Safe distance regulations for LNG tank storage locations (commonly applied to ammonia storage tanks)* (Ha et al., 2022).

f_{CN} is the parameter to be included in a simplified assessment of the probability of hitting the tank in a collision (f_{CN} shall be less than 0.02 for passenger ships and 0.04 for cargo ships),

f_l is the longitudinal penetration factor,

f_t is the transverse (inboard penetration) factor,

and f_v is the vertical penetration factor.

Table 11 summarises and compares the guidelines for establishing the safety distance stated in the IGF code and other class rules.

4.3. Material

To minimize the risk of stress corrosion cracking in containment structures and in process systems made of sensitive materials such as carbon-manganese and nickel steel, the following regulatory measures must be taken:

- According to the IGF code (MSC, 2015) (7.4.1), when carbon-manganese steel is used, the specified minimum yield stress should not exceed 410 N/mm^2. As per ABS (ABS, 2022) (5C-8–17/12.2), cargo tanks, pressure vessels and cargo piping systems should be made of fine-grained steel with a specified minimum yield stress of 355 N/mm^2 or less and an actual yield stress of 440 N/mm^2 or less. If not, take operational measures such as stress relief heat treatment, keeping the temperature close to the boiling point during transportation, or containing water 0.1% or more by mass.
- Carbon-manganese steel with yield stress above the standard value is subjected to stress relief heat treatment after welding.
- The tensile and yield properties of the electrode must be greater than those of the tank or piping material at the smallest actual value.
- Do not use nickel steel with a nickel content exceeding 5% or carbon-manganese steel with a yield stress higher than the standard value without heat treatment.
- Nickel steel exceeding 5% nickel content can be used if the transport temperature does not exceed −20 °C.
- It is recommended to keep the dissolved oxygen content of less than 2.5 ppm by mass.
- Mercury, cadmium, copper, zinc or alloys of these substances are not normally used in fuel tanks and related pipelines, valves, fittings and other equipment in direct contact with ammonia liquid or vapour
- It is not recommended to use components made of rubber or plastic materials that may deteriorate when exposed to ammonia.

Similar measures regarding structural material regulations can be found in all class rules. In addition, ABS identified the risk of pressure surges in pipelines and recommends piping systems be designed to withstand gas pressure surges and use materials such as aluminium and austenitic stainless steel.

Table 12 provides the summary and comparison of different materials specified by class societies and the IGF code.

4.4. Bunkering

4.4.1. Bunkering station

The bunker station should be placed on an open deck to allow proper ventilation. Stations that are enclosed or partially enclosed will require extra consideration during risk assessment. Piping and connections should be positioned in a way that prevents fuel pipe damage, which could result in an uncontrolled gas release. There should be a plan in place to handle any fuel spills safely. Adequate means should be provided to release pressure and remove liquid from pump suctions and bunker lines, which should be discharged into the fuel tanks or another suitable location. The hull or deck structures should not be affected by excessive cooling in the event of a fuel leak. Hoses used for fuel transfer should be compatible with the fuel and suitable for the fuel temperature and have a bursting pressure of at least five times the maximum pressure during bunkering. Hoses that are subjected to tank pressure or discharge pressure from pumps or vapour compressors should be designed to handle a bursting pressure of not less than five times the maximum pressure they will be subjected to during bunkering.

Furthermore, ABS mandates the placement of drip trays under bunkering connections to guard against low temperatures affecting the hull structure. If there is a potential for accidental LNG spillage during bunkering operations to cause damage to the hull structure, additional protective measures, such as a low-pressure water curtain, must be installed under the bunker station to ensure the hull steel and ship's side structure are adequately safeguarded.

4.4.2. Bunkering manifold

The bunkering manifold valve must be located at least 10 m away from any non-hazardous area openings and air intakes.

The design of the bunkering manifold should be able to handle external loads during bunkering operations. The connections at the bunkering station must be of a dry-disconnect type, equipped with extra safety dry break-away couplings or self-sealing quick-release couplings, which must be standard.

ABS also requires that arrangements be made for installing an emergency release system. This system should prevent damage and spark generation, minimize the release of LNG when activated, and have measures to prevent accidental operation. It should also be of the fail-release type, and the responsibility for these features may fall on the bunker supplier (bunkering vessel, truck, or shore side facility). Additionally, filters/strainers must be installed to prevent the transfer of foreign objects.

4.4.3. Bunkering system

For fuel bunkering, provisions shall be made for purging the lines with inert gas. The bunkering setup should be structured in such a way that no gas escapes into the atmosphere during the filling of the storage tanks. Every bunkering line should have a stop valve that can be manually operated and a shutdown valve that can be remotely operated, either in series or combined as one. The remote valve should be accessible from the control location for bunker operations or another secure location. ABS specifies that the remote valve should be fail-closed, meaning it will close if power is lost, be manually closable locally and display the valve's current position.

Facilities should be available for draining any remaining fuel from the bunkering pipes after operations are complete. Bunkering lines should be equipped for the inerting and freeing of gas. Unless otherwise approved, the bunkering pipes should be free of gas when not in use for bunkering. In the event that bunkering lines have cross-overs, suitable measures should be in place to prevent fuel from being transferred unintentionally to the unused side of the ship. A ship-shore link (SSL) or a similar mechanism should be installed for automatic and manual emergency shutdown (ESD) communication with the bunkering source. ABS notes that the ESD system must be functional during bunker operations to ensure a safe shutdown in case of an emergency during bunker delivery. If pressure surge considerations do not call for a higher value, the default time between the trigger of the alarm and the full closure of the remote valve should be adjusted based on calculations. DNV requires that the time from the trigger of the alarm to a full closure of the shutdown valve should not exceed 5 s, unless pressure surge considerations make a longer closing time necessary. The closing time should also be sufficient to prevent overfilling of the tank when automatic shutdown is triggered by high tank levels.

4.4.4. Gas detection

All fuel bunker pipes and their surrounding areas, including bunker stations and ventilation ducts or double wall piping systems, must be equipped with permanent gas detectors or leak detection systems capable of detecting flammability and toxicity.

Table 13 provides a summary and comparison of different bunkering safety regulations between class rules and the IGF code.

4.5. Fuel supply systems

4.5.1. Functional requirements

The method of preventing fuel leakage during the fuel supply process differs in classification society. For example, ABS requires that fuel supply systems must be engineered so as to avoid any release of fuel fumes during normal operation, including when the engine is idle, whereas KR prevents unintended phase change from occurring by considering the vapour pressure at the fuel operating temperature and is designed so that liquid fuel is not released into the atmosphere.

4.5.2. Redundancy of fuel supply

The setup of the propulsion and power generation system, as well as the fuel delivery mechanism, must be structured to avoid an unacceptable reduction in power in the event of a fuel supply malfunction.

The propulsion unit and the power generation unit together with the fuel supply system must be arranged so that an unacceptable loss of power due to a fuel supply failure occurs.

In order to prevent power loss, KR guides that the fuel must be stored in two or more tanks in a single fuel system, and each tank is installed in a separate compartment to prevent power loss.

According to ABS, the arrangement of the propulsion, support systems, and fuel supply must be such that it enables continued propulsion and manoeuvrability, along with maintaining power for critical services, even in the event of an emergency fuel shutdown. In this scenario, the residual power must provide a minimum speed of 7 knots or half the design speed, whichever is lower. The implementation of dual-fuel engines, which feature independent conventional fuel oil and ammonia fuel systems, is considered to meet the requirement for redundancy and attain this objective (ABS (ABS, 2021a) Sec.9/4.2, ABS (ABS, 2022) 5C-13-9/3.4).

4.5.3. Fuel supply system

The fuel storage tank inlets and outlets should have valves close to the tanks, with a remote operation for valves supplying inaccessible gas and refuelling. ABS requires the tank valves to be remotely actuated, fail-close type with local manual closure, and show the current valve position. The main gas supply line to each gas consumer should have a manual stop valve and automatic master gas fuel valve in series. The valve should be located outside the machine space near the gas heating installation. The master gas fuel valve should shut off the gas supply when activated by the safety system and be operable from a safe location. Each gas consumer has a "double block and bleed" valve arrangement for safety and normal engine shutdown. The shut-off valves automatically close, and the bleed valves open, stopping the gas flow and opening ventilation. The valve used must be a fail-to-close type, and the ventilation valve must be a fail-to-open type (IGF (MSC, 2015) 9.4; ABS (ABS, 2021b) Sec.9/5; ABS (ABS, 2022) 5C-13-9/4).

4.5.4. Fuel distribution outside of machinery spaces

Gas supply lines passing through enclosed spaces within the ship, unless are of fully welded type, are to be protected by secondary sealing enclosures. The duct or double pipe system shall be mechanically ventilated under negative pressure and the number of ventilations shall be 30 times per hour.

ABS (ABS, 2022) (5C-13-9/5.3) requires the gas vent piping from the tank relief valves, bunker station relief valves and block and bleed valve to be single-walled when located on the open deck.

4.5.5. Fuel supply in gas-safe (non-hazardous) machinery spaces

ABS requires that the ventilation system must be activated whenever the fuel is present in the supply line. In addition, the corresponding master gas valve should automatically close in the event of a problem with the ventilation system.

Table 14 provides a summary and comparison of different fuel supply systems safety regulations between class rules and the IGF code.

4.6. Fire safety

In general, all areas where fuel-related equipment is installed such as pumps, compressors, heat exchangers, carburettors and pressure vessels shall be designated as category A machinery spaces for fire protection purposes.

According to ABS, the arrangement of the propulsion, support systems, and fuel supply must be such that it enables continued propulsion and manoeuvrability, along with maintaining power for critical services, even in the event of an emergency fuel shutdown. In this scenario, the residual power must provide a minimum speed of 7 knots or half the design speed, whichever is lower. The implementation of dual-fuel engines, which feature independent conventional fuel oil and ammonia fuel systems, is considered to meet the requirement for redundancy and attain this objective.

This space must comply with the provisions of SOLAS Chapter II-2 Regulation 10 and the FSS Code, and a fixed fire extinguishing system must be provided.

On the other hand, ammonia-fuelled ships focus on the risk of toxicity from the spread of ammonia itself rather than the risk of fire spread. Therefore, ABS and DNV recommend that the fuel tank bunker manifold and bunker station area exposed to the open deck must be protected by a water spray system, and the BV has additionally added regulations for inert gas. Since the inert gas contains carbon dioxide to form carbamates and the formed carbamates have the potential to contaminate ammonia, arrangements and systems such as in storage tanks, fuel preparation rooms and bunkering are required to avoid the build-up of the inert gas in the machinery space or gas fuel preparation room. Also, water-based firefighting systems are prohibited for use in liquid ammonia.

ABS and KR have provided further guidelines for protective equipment, safety equipment, and emergency equipment.

Table 15 provides a summary and comparison of different fire safety prevention and mitigation guidelines.

4.7. Ventilation

In general, all class rules considered layout and system design such as ventilation, detection and safety measures that are designed to minimize the potential for hazards to ammonia.

Although gaseous anhydrous ammonia is lighter than air, due to its hygroscopic property which absorbs moisture easily, there is a possibility that it will become heavier than air when released into the atmosphere. Because of this property, the ventilation system must take into account the potential release density of ammonia. Also, considering the toxicity of ammonia, closing devices are to be provided at all air intakes and other openings leading to accommodation, service spaces and control stations normally occupied by persons.

4.7.1. Tank connection space

As per IGF code (MSC, 2015) (13.4) requirement (also KR guidelines), the tank connection space must be provided with an effective mechanical forced ventilation system of the extraction type. A minimum of 30 ventilations per hour must be provided. Air change rates may be reduced if other suitable explosion-proof measures are installed. The equivalence of alternative installations must be demonstrated by a risk assessment.

An approved automatic fail-safe fire damper must be fitted in the ventilation trunk of the tank connection space.

4.7.2. Machinery spaces

Ventilation systems in engine rooms that use gas must be separated from all other ventilation systems. ABS requires that ventilation systems in engine rooms protected by ESD must always be operational during normal operation when there is gaseous fuel in the piping, and during clean-up prior to maintenance. Additionally, forced ventilation must be installed in ESD-protected machinery spaces so that leaked gas can be quickly evacuated without leaving any pockets of gas in corners. An analysis of gas dispersal or physical smoke testing should be performed to ensure the duct intake locations are strategically placed for the effective removal of leaked gas from the space.

Guidelines from ABS, BV, DNV, and KR require that ESD-protected machinery rooms must have ventilation with a capacity of at least 30 air changes per hour. The ventilation system must ensure good air circulation in all spaces and detect the formation of gas pockets in the room. However, arrangements can also be made to ventilate the engine room 15 times per hour under normal operating conditions, provided that the air change rate is automatically increased to 30 times per hour if gas is detected in the engine room.

ABS requires that the number and power of ventilation fans for ESD-protected machinery areas must be at least 100% of the total demand of the remaining fans in the event that one fan or group of fans with a common circuit in the main switchboard or emergency switchboard fails. However, NK requires that the minimum requirement is 50%.

4.7.3. Fuel preparation room

Besides the IGF code (MSC, 2015) (13.6) requirement, KR and DNV also recommend installing an effective negative pressure mechanical ventilation system with a ventilation capacity of at least 30 times per hour in the fuel preparation room as well as the tank connection space. The ventilation system in the fuel preparation room is to be in operation when the pump or compressor is operating. Ventilation systems for fuel preparation rooms must be in operation when fuel equipment is in use. The rooms must also have increased ventilation through a gas evacuation system that starts automatically when ammonia concentration exceeds 150 ppm. The ventilation and gas evacuation system must provide 45 air changes per hour. The controls for the gas evacuation system are to be positioned outside the room and the exhaust duct outlets must be positioned at least 10 m from air intake openings and at least 4 m above the open deck, discharging ammonia vapours away from accommodations and other enclosed areas.

4.7.4. Bunkering station

In general, bunkering stations that are not located on open decks must have proper ventilation in order to remove any fumes produced during bunkering procedures to the outside. If natural ventilation is insufficient, then mechanical ventilation must be implemented after conducting a proper risk assessment (IGF (MSC, 2015) 13.7; ABS (ABS, 2021b) Sec.13/7; ABS (ABS, 2022) 5C-13-13/7).

4.7.5. Ducts and double pipes

Ducts and double pipes containing fuel piping must also be equipped with an effective mechanical ventilation system of extraction type providing a ventilation capacity of at least 30 ventilations per hour and must always be located in an open, non-hazardous area away from sources of ignition.

The ventilation system for double piping and gas valve unit spaces in gas-safe engine rooms must be independent of all other ventilation systems.

The ventilation inlet for the double wall piping or duct must always be located in a non-hazardous area away from ignition sources.

The inlet must also be fitted with a wire mesh guard to protect it from the ingress of water. The ventilation capacity of pipe ducts or double-walled piping can be less than 30 air changes per hour if a flow rate of at least 3 m/s is guaranteed. Flow rates should be calculated for ducts in which fuel pipes and other components are installed.

Furthermore, as per KR (KR, 2021) 801. 1, Ch 13, the ventilation inlets to the double-walled pipes and ducts should be located in such a way that negative pressure is maintained in the entire space between the inner pipe and the outer ducts/pipes.

According to ABS, the vents in double-walled piping or ducts must always be ventilated when fuel is in the fuel gas supply pipeline. Enough ventilation fans with sufficient power must be installed so that if one fan, or a group of fans with a common circuit from the main or emergency switchboard, fail, the capacity of the remaining ventilation fan(s) is not to be less than 100% of the total ventilation required.

Table 16 summarises various ventilation requirements provided by the class societies and the IGF code.

5. Risk assessment on ammonia-fuelled ship

Table 8 provides a summary of risk assessment studies required as specified by the ABS, RINA and the IGF code. This includes identifying and defining the different targets, scopes, hazard categories, and risk assessment plans, such as different techniques to be used, design elements to be considered, and the involvement of experts' groups in the risk assessment. In short, the ABS and IGF codes define particular hazard categories and require a thorough risk assessment plan to be included in the risk assessment studies, whereas only RINA offers a comprehensive list of expert groups that need to participate in the risk and safety assessment studies.

5.1. Risks identified from the previous qualitative assessments

Eighteen pieces of literature have been collated and reviewed with a focus on identifying key hazards and their associated risks, the key challenges faced & gaps identified and different kinds of risk assessment techniques applied. A summary of these details is listed in Table B.

In most cases, qualitative risk assessment studies have been conducted for the introduction of new systems, and appropriate qualitative risk assessment techniques have been selected according to each situation and purpose of the study.

First, HAZID has been used in a way that it is performed based on the initial concept design and the risk assessment results are reflected in the concept design. When LNG fuel was first introduced into the shipping sector, HAZID was originally used to conduct an initial risk assessment, and HAZID techniques were used to evaluate hazards for the initial concept design of ships using new alternative fuels such as LNG dual fuel, methanol, and ammonia.

In the HAZID study for alternate fuelled ships, the evaluation was conducted mainly focusing on the bunkering station, fuel tank and fuel supply system. The main hazards identified are leakage or accidents during bunkering, leakage from fuel tanks and fuel supply systems, fire/explosion and control system failure. Several HAZOP studies have been conducted on ships using LNG as fuel. In these studies, HAZOP was performed based on guide words such as no/not, more, less, part of, reverse, other than, early, late, before, and after. Hazards such as leakage in the LNG tank, fuel supply problems due to control failure, LNG vapour generation, high temperature, high pressure, and valve problems during bunkering were identified.

In the FMEA method, which identifies and takes action on risks caused by failure modes of each component, risks caused by failures of pumps, valves, strainers, etc. in the fuel supply line, loss of fuel supply due to failures of heating devices, and hazards of tank overfill or pressure/temperature control failure due to sensor failure and power source failure were identified.

The hazards already identified can be reviewed, selected, and similarly incorporated into risk assessments for vessels powered by ammonia. For instance (Trivyza et al., 2021), highlights the crucial assessment of safety and dependability inherent in ammonia-fuelled fuel cell systems, encompassing critical evaluations encompassing operational, safety, and dependability facets (de Vries, 2019). delves into apprehensions regarding the potential impacts of ammonia usage on humans and the environment, stressing the necessity for thorough risk evaluation and thorough data gathering. Similarly (EMSA, 2022), underscores the intricacies of securely implementing ammonia in marine contexts, underscoring the significance of implementing robust operational procedures, comprehensive training, and a sophisticated

Table 8
Summary of risk assessment studies considered in the IGF code and classification rules.

	ABS	RINA	IGF code
Targets	Persons on board, environment, and ship (structural strength and integrity)		
Scope	Physical layout, operation and maintenance, following any reasonably foreseeable failure		
Hazard categories	Loss of function, component damage, fire, explosion, toxicity and electric shock	Not described in the rules	Loss of function, component damage, fire, explosion and electric shock
Risk assessment plans to be submitted	- Description of the proposed function - Quantitative or qualitative risk assessment method (s) - Scope and objectives of the assessment - Subject matter experts/participants/risk analysts, including their background and area of expertise - Proposed risk acceptance criteria or risk matrix - Risk control and management measures	Not described in the rules	- Dip tray (5.10.5) - Airlock (5.12.3) - Fuel containment system (6.4.1.1) - Structural analysis for accidental - scenarios (6.4.15.4.7.2) - Bunkering (8.3.1.1) - Ventilation for tank connection space (13.4.1) - Gas detection (13.7) - Gas detection to accommodation/machinery space (15.8.1.10) - Structural failure (Annex 4.4) - Accidental scenario for fuel tanks (Annex 6.8)
Experts' groups	Not described in the rules	- Class, owner, builder or designer, and consultants having the necessary knowledge and experience in safety, design and/or operation as necessary for the specific evaluation at hand. - Marine surveyors, ship operators, safety engineers, equipment manufacturers, human factors experts, naval architects and marine engineers, according to the problem under the scope	Nil
References	i) IACS Recommendation No.146 (Required by the IGF Code) (IACS, 2016) ii) ABS Guidance Notes on Risk Assessment Applications for the Marine and Offshore Industries for further guidance on risk assessment (ABS, 2020)	i) IACS Recommendation No.146 (Required by the IGF Code) (IACS, 2016) ii) Guidance on risk analysis techniques can be found in the "RINA Guide on Risk Analysis".	

approach to identifying potential hazards. This approach partially mitigates the limitations of qualitative risk assessments, which often rely on expert intuition, facilitating a more detailed and inclusive risk assessment process.

5.2. Risks identified from the previous quantitative assessments

Regarding quantitative analysis, a series of articles, conference papers and reports have been collected and reviewed. Table C lists and summarises the key hazard/risk, main challenges addressed & gaps identified and adopted risk assessment methods of these studies.

Unlike qualitative risk assessment, which can be subjective, quantitative risk assessment has the advantage of being able to derive objective and quantified results and provide an acceptable level of risk. Due to these advantages, according to Table C, quantitative risk assessments have been conducted in various fields such as oil storage facilities (tank storage, engine room, bunkering, and ventilation system), ammonia rail transportation (cargo system), and ship security accidents. Among these, the key risks that have been actively studied recently are studies on ammonia toxicity leaks from storage tanks or bunkering, but there are still insufficient risk assessment guidelines or studies related to this.

Delving further into this extensive analysis, a prominent focus is directed toward the emerging discourse encompassing the utilization of ammonia fuel in maritime settings. Particularly noteworthy is the evident trajectory of exploration regarding the implications of ammonia toxicity, especially in relation to leaks originating from storage tanks or bunkering operations (Namboothiri and Soman, 2018; Fan et al., 2022). However, a careful examination also brings to light a noticeable gap, highlighting the scarcity of comprehensive frameworks for risk assessment or studies tailored specifically to address this aspect.

A compelling revelation stemming from this scholarly panorama pertains to the significant stress placed on the necessity of mitigating risks associated with ammonia toxicity. Scholars have underscored that among the broad spectrum of risks linked to ammonia, its toxic attributes exert a more profound influence than considerations of flammability or corrosiveness. It is worth noting, though, that the specific findings gleaned from each meticulous study predominantly apply to individual instances, thus impeding their smooth applicability to diverse scenarios.

In addition, studies to date highlight that risk mitigation measures must focus on toxicity, as toxicity contributes more to overall ammonia risk than flammability or corrosiveness. However, the specific results of each study are limited to individual case studies, making it difficult to apply the same to other cases.

On the other hand, the methodology mainly used for quantitative risk assessment was fault tree analysis (FTA) or Bayesian networks (BN) used for frequency analysis. Studies that mainly adopt BN have used it because of the advantages of BN as an efficient model for performing probability calculations and a flexible model for performing causal diagnosis.

For consequence analysis, computational fluid dynamics (CFD) was mainly used, and depending on the research purpose and scope, there are studies that develop and apply various modelling techniques or methodologies such as quantitative probabilistic seismic risk assessment

Table 9
Ship design and arrangement comparison between different classification rules and the IGF code.

	IGF	LR	ABS	BV	DNV	KR	NK	RINA
Machinery Space arrangements	Gas-safe machinery space ESD machinery space		Only gas-safe machinery space					
Location and protection of fuel piping	The fuel pipe is located 800 mm or more from the side of the ship Do not pass directly through accommodation, service areas, electrical installation rooms or control stations Fuel pipes passing through ro-ro spaces, special category spaces and the upper open deck are to be protected from mechanical damage							
Ammonia vapour detection level	–		25 ppm	30 ppm		25 ppm	25 ppm	50 ppm
Location of fuel preparation room	On an open deck		Outside other machinery spaces of category A	In a dedicated space	On an open deck			
Prevention of ammonia leakage	–		Must be gastight to other areas of the vessel	–	Must be gastight to other areas of the vessel	–	Must be gastight to other areas of the vessel	–
Materials for the fuel preparation room	–		–	–	Must have a design temperature that can withstand cooling as much as possible	–	Must have a design temperature that can withstand cooling as much as possible	–
Fuel preparation room entrance height	–		–	–	Must not be lower than 300 mm.	–	–	–
Installation of a water screen system or water mist system	–		Considered (water screen system)	Considered (water mist system)	Considered (water screen system)	–	–	–
Bilge system	An independent bilge system has to be installed in the fuel preparation room Emissions from the fuel preparation bilge system are either sent to a separate storage tank or disposed of onshore after further treatment				–	An independent bilge system has to be installed in the fuel preparation room Emissions from the fuel preparation bilge system are either sent to a separate storage tank or disposed of onshore after further treatment		
Draining system	–		The draining system has to be sized to remove not less than 125% of the capacity of the water screen system	There shall be no risk of water accumulating in the area where the water mist system is installed	–	The draining system should be able to operate outside the fuel preparation room	Bilge wells should be as small as possible	–
Drip trays	Drip trays are to be installed in locations where leaks that may damage the hull structure are likely to occur It must be made of suitable material, have sufficient capacity, and be equipped with a drain valve							
	–		At shore connections or pump seals, protection for the hull beneath is to be provided The drip tray located below the tank connection must be at least 3 m from entrances, air inlets, and openings to accommodation spaces, service spaces, cargo spaces, machinery spaces and control stations.	–	–	It should be able to detect leaks and shut off fuel	–	A drip tray that can be emptied manually should be installed in case of a leak of fewer than 10 L
Airlocks	Airlocks are an area enclosed by a gas-tight bulkhead with two reliable gas-tight doors installed, and these doors are spaced apart from each other by 1.5 m or more and 2.5 m or less							

(QpsRA) or fire-explosion-poisoning quantitative probability model (FEPQPM).

Besides traditional methods that analyze failures and deviations, certain latest risk assessment techniques could be potentially applied to ammonia-fuelled ships such as FRAM (Functional Resonance Analysis Method), LOPA (Layers of Protection Analysis), etc. For instance, FRAM focuses on understanding complex systems and their interactions and explores how everyday variations in tasks and conditions can lead to unexpected outcomes. It is important to note that while FRAM provides valuable insights, it might not replace traditional risk assessment techniques entirely. Combining FRAM with techniques like HAZID, FMECA, or event tree analysis can provide a comprehensive understanding of risks associated with ammonia-fuelled ships. Also, given that FRAM requires a deep understanding of the system and its interactions, it might require the involvement of subject matter experts and a thorough analysis to be effective.

In conclusion, it was found that various methodologies for frequency analysis and consequence analysis can be selectively applied or, if necessary, various modelling techniques or methodologies can be developed and applied. However, looking at the studies conducted so far, it can be confirmed that, in addition to the importance of quantitative risk assessment studies such as the risk due to the toxicity of ammonia, related studies are still lacking and have limitations that are difficult to apply to other cases because they are focused only on individual cases.

Table 10
Fuel containment system comparison between classification rules and the IGF code.

	IGF	LR	ABS	BV	DNV	KR	NK	RINA
MARVS	–					1.0 MPa or more	–	Up to 2.0 MPa
MAWP	Shall not exceed 90% of the MARVS							
General	–		The surrounding hull is thermally insulated so that it is not exposed to cooling	–	–	The maximum temperature that can be raised by solar radiation must also be considered	–	–
PRV	All fuel storage tanks shall be provided with a pressure relief system appropriate to the design of the fuel containment system and the fuel being carried. Liquefied gas fuel tanks shall be fitted with a minimum of 2 PRVs allowing for disconnection of one PRV in case of malfunction or leakage							
Distance from the outlet of the PRV to the air intakes and outlets leading to accommodation, service and control spaces and other non-hazardous spaces.	At least 10 m apart.		At least *B* or 25 m, whichever is shorter. For vessels less than 90 m, smaller distances may be permitted.	–	–	At least 15 m apart in the horizontal direction and at least 4 m above the open deck at a vertical height	–	–
The fuel storage tank design life	It shall not be less than the design life of the ship or 20 years, whichever is greater				It shall not be less than the design life of the ship or 25 years, whichever is greater	It shall not be less than the design life of the ship or 20 years, whichever is greater		
Means of maintaining the pressure and temperature of the liquefied gas fuel tank	(1) Reliquefaction of vapours (2) Thermal oxidation of vapours (3) Pressure accumulation (4) Liquefied gas fuel cooling				(1) Reliquefaction (2) Thermal oxidation of vapours (3) Pressure accumulation (4) Energy consumption by the ship	(1) Reliquefaction of vapours (2) Thermal oxidation of vapours (3) Pressure accumulation (4) Liquefied gas fuel cooling		
Fuel storage condition - Duration to keep tank pressure below the set pressure of the relief valve	For 15 days			For 21 days	For 15 days			
Allowing fuel vapour evacuation for tank pressure control	Not acceptable except in emergencies							

Table 11
Fuel tank location according to classification rules and the IGF code.

	IGF	LR	ABS	NK	RINA	KR	BV	DNV
Location of the fuel tank	Location of the fuel tank in accordance with IGF code.						Specific guidelines of the IGF code cannot be found, but the LNG tanks need to be located in such a way that they should be protected from external damage.	

5.3. Risk management regulations

Risk management regulations can help ensure the safe operation of ammonia-fuelled ships. These regulations provide a structured approach to identify, assess, and manage risks associated with the use of ammonia as a marine fuel. The following provides a brief overview of three important risk management regulations: ISO 31000 (International Standards), ISO 31010 (ISO, 2019), and IMO Formal Safety Assessment (FSA) (IMO, 2018).

ISO 31000 provides principles and guidelines for effective risk management. For ammonia-fuelled ships, the following steps can be taken:

a. Risk identification: Identify the potential hazards and risks associated with ammonia-fuelled ships, including ammonia handling, storage, transfer, and utilization.
b. Risk assessment: Assess the likelihood and potential consequences of each identified risk. This could involve conducting quantitative or qualitative risk assessments.
c. Risk mitigation: Develop and implement strategies to mitigate identified risks. This might include adopting safety systems, training crew members, using safety equipment, and establishing emergency response plans.
d. Risk monitoring and review: Continuously monitor and review the effectiveness of risk mitigation measures. Regularly update risk assessments based on new information or experiences.

ISO 31010 complements ISO 31000 by providing detailed guidance on various risk assessment techniques. ISO 31010 provides guidance on various risk assessment techniques. For ammonia-fuelled ships, these techniques can be used to perform more detailed risk assessments, including:

a. HAZID: Systematically identify potential hazards associated with ammonia use on ships.
b. HAZOP: Examine how variations in ship operations or conditions may lead to potential hazards.
c. FMECA (Failure Modes, Effects, and Criticality Analysis): Identify potential failures of critical components in the ammonia system and evaluate their consequences.
d. Event tree analysis (ETA) and fault tree analysis (FTA): Analyze potential sequences of events or failures that may lead to hazardous situations.
e. ISO 31010 helps organizations tailor their risk assessment approaches to suit their specific needs and improve the overall risk management process.

IMO's FSA is a structured framework for evaluating the safety and environmental performance of ships and proposing measures to improve safety associated with ship design, operations, and other aspects related to maritime transportation. For ammonia-fuelled ships, the FSA process can be applied to:

Table 12
Material comparison between classification rules and IGF code.

	IGF	LR	ABS	BV	DNV	KR	NK	RINA
Guidelines for the use of copper and zinc materials	–		Copper and zinc or alloys of these materials shall not be used in ammonia fuel systems					-
Guidelines for the use of rubber or plastics	–		Do not use components made of rubber or plastic materials that are susceptible to deterioration when exposed to ammonia	Gaskets and seals must be made of rubber and polymers compatible with ammonia such as PTFE (Polytetrafluoroethylene)	–	Rubber, plastic, vinyl or aluminium alloy must be approved by KR	–	-
Guidelines for the use of materials capable of forming explosive compounds	–		Materials such as mercury must not be used	–	–	Materials such as silver, gold, mercury and thallium must not be used	Materials such as mercury must not be used	-
Requirements for stress corrosion cracking (0)	–		Since anhydrous ammonia can cause stress corrosion cracking in containers or manufacturing equipment made of carbon-manganese steel or nickel steel, measures should be taken to minimize them as below (1) and (2).					-
Requirements for using carbon manganese steel (1)	Specified minimum yield stress not to exceed 410 N/mm^2		(a) Specified minimum yield stress not to exceed 410 N/mm^2 (b) Cargo tanks, piping, etc., shall be post-weld stress relief heat treated; or (c) Carriage temperature shall be maintained preferably at a temperature close to the product's boiling point of −33 °C but in no case at a temperature above −20 °C; or (d) The ammonia shall contain not less than 0.1% w/w water.					Specified minimum yield stress not to exceed 410 N/mm^2
Heat treatment for carbon-manganese steels with higher yield properties (2)	–		If carbon-manganese steels with higher yield properties are used other than those specified in (1), the completed cargo tanks, piping, etc., are to be given a post-weld stress relief heat treatment.					-
Heat treatment for process pressure vessels	–		Process pressure vessels and piping of the condensate part of the refrigeration system are to be given a post-weld stress relief heat treatment when made of materials mentioned in (0).					-
Mechanical properties of the welding consumables	–		The tensile and yield properties of the welding consumables are to exceed those of the tank or piping material by the smallest practical amount.					-
Unsuitable materials to use	–		Nickel steel containing more than 5% nickel and carbon-manganese steel, not complying with the requirements of (1) and (2), are particularly susceptible to ammonia stress corrosion cracking and are not to be used in containment and piping systems for the carriage of this product.					-
Requirements for using nickel steel containing not more than 5% nickel	–		Nickel steel containing not more than 5% nickel may be used, provided the carriage temperature complies with the requirements specified in (1) (c).					-
Dissolved oxygen content	–		To minimize the risk of ammonia stress corrosion cracking, it is advisable to keep the dissolved oxygen content below 2.5 ppm w/w.					-

Table 13
Bunkering safety regulations comparison between different classification rules and IGF code.

	IGF	LR	ABS	BV	DNV	KR	NK	RINA
Prevention of gas release	Bunkering systems are to be designed to prevent venting under all normal operating conditions including idle periods							
Location of bunkering system	Open deck with sufficient natural ventilation							
Bunkering manifold valve position	–		At least 10 m away from the non-hazardous area openings and air intakes	–	–	At least 10 m away from the non-hazardous area openings and air intakes (if the gas detector is installed in the air intake or non-hazardous area, it could be 4.5 m away)	–	-
Measures to prevent the spread of ammonia	–		An ammonia detection system and leak detection system are to be arranged	An ammonia detection system and water mist system are to be arranged	–	A water spray system is to be arranged		Means must be provided to manage the vapours generated during bunkering

a. Identify hazards related to the use of ammonia as a fuel on ships.
b. Assess the potential risks associated with these hazards.
c. Evaluate the effectiveness of existing safety measures and propose additional measures, if necessary.
d. Consider the impact of ammonia-fuelled ships on the environment and propose measures to reduce environmental risks.

FSA helps maritime stakeholders make informed decisions about safety improvements and regulatory measures, contributing to a safer and more secure maritime industry. By integrating these risk management regulations into the design, construction, operation, and maintenance of ammonia-fuelled ships, it is possible to enhance safety and minimize the potential risks associated with using ammonia as a marine fuel. The regulations provide a systematic approach to identifying and addressing risks, enabling stakeholders to make informed decisions and promote safe practices in the shipping industry.

Table 14
Fuel supply systems comparison between different classification rules and IGF code.

	IGF	LR	ABS	BV	DNV	KR	NK	RINA
Redundancy of fuel supply	The fuel supply system needs to be arranged in a way that prevents a significant decrease in power output.							
Dependability assessment	–	For single-fuel installations, a system dependability assessment is to be undertaken	–	–				
Fuel storage and remaining power	–		Sufficient for at least 7 knots or half of the design speed, whichever is lesser	–	–	–	–	–
Safety function of the fuel supply system installation	- Require valves with automatic shut-off and remote operation. - Require the main gas supply line to have manually and automatically operated valves.							
Fuel distribution outside of machinery space	When fuel pipes pass through confined spaces on the vessel, they must be protected by secondary enclosures such as ventilation ducts or double-walled piping systems, mechanically low-pressure vented with 30 ventilations per hour, and with gas detection.							
Fuel supply in gas-safe machinery spaces	It must be enclosed in a double pipe or duct. The double pipe/duct must either be a double wall piping system or installed within a ventilated duct with mechanical under-pressure ventilation.							

Table 15
Fire safety prevention measures comparison between each classification rule and the IGF code.

	IGF	LR	ABS	BV	DNV	KR	NK	RINA
Water spray systems	- A water spray system is to be installed to cover the exposed part of the fuel storage tank and fuel piping on the open deck except where double walled. - A spray rate of 10 $l/min/m^2$ for the largest horizontal projection plane and 4 $l/min/m^2$ for the vertical plane - Stop valves shall be installed at intervals not exceeding 40 m, or the system shall be divided into two or more independently operated parts - The capacity of the water spray system should be sufficient to supply the required amount of water to the areas where the greatest water pressure is required - If the water spray system is not part of the main fire extinguishing system, it should be connected to the fire main of the ship through a stop valve - The nozzle of the water spray should be approved full bore type							
Additional details for water spray systems	–		The water spray system must be positioned to cover all exposed fuel piping, including bunkering	Inert gases containing carbon dioxide are not permitted	–	Protective safety and emergency equipment shall be provided	–	–
Fire-extinguishing system in fuel preparation rooms	A fixed fire detection and fire alarm system shall be provided							
Dry chemical powder fire-extinguishing systems	- The dry chemical powder fire extinguishing system to be installed in the bunkering station has a capacity of at least 3.5 kg/s and can be discharged for at least 45 s. - One portable powder fire extinguisher with a capacity of at least 5 kg must be located near the bunkering station							

Table 16
Ventilation requirements comparison between each classification rule and the IGF code.

	IGF	LR	ABS	BV	DNV	KR	NK	RINA
Hygroscopicity of gaseous anhydrous ammonia	Not considered		Considered	Not considered	Considered	Considered	Not considered	Not considered
Required ventilation system capacity	–		At least 30 air changes per hour, and at least 45 air changes per hour considering a large amount of ammonia leak	At least 30 air changes per hour	At least 30 air changes per hour, and at least 45 air changes per hour considering a large amount of ammonia leak	At least 45 air changes per hour	–	–
Ventilation capacity of the tank connection system	At least 30 air changes per hour							
Ventilation capacity of fuel preparation room	At least 30 air changes per hour							
The number and power of ventilation fans in fuel preparation rooms	Not to be more than 50% of the total required.		Not to be less than 100% of the total required.	More than 50% of the total required.	–	More than 50% of the total required.		Not to be more than 50% of the total required.
Bunkering station	Bunkering stations which are not located on the open deck shall be adequately ventilated to evacuate the vapours released during bunkering operations.				–	Bunkering stations which are not located on the open deck shall be adequately ventilated to evacuate the vapours released during bunkering operations.		
Ventilation capacity of ducts and double pipes	At least 30 air changes per hour				Below 30 air changes per hour if a flow velocity of a minimum of 3 m/s is ensured			At least 30 air changes per hour
The number and power of ventilation fans in ducts and double pipes	–		Not to be less than 100% of the total required	–	–	–	Not to be less than 50% of the total required	–

6. Conclusions and future developments

Although ammonia has a low carbon footprint and is being considered a green fuel for ships, there are no officially agreed safety guidelines for its use as a ship fuel. This article extensively reviews regulations, standards, rules and guidelines related to using ammonia as a potential alternative fuel for shipping. It discusses the general characteristics of ammonia and identifies potential hazards associated with its use as a marine fuel. It also examines existing and upcoming international regulations addressing the safety of ammonia storage, handling, and operation on ships.

The study considers various classification rules, ISO standards, and safety guidelines and performs gap analysis for the ship design and arrangement for ammonia storage tanks, engine rooms, ventilation, bunkering systems, and fuel gas supply systems to minimize ammonia leakage, thereby avoiding toxicity impact on humans, and structural damage due to fire and explosion or corrosion.

In addition, this study reviews and discusses various qualitative and quantitative risk assessment methods in accordance with different hazard types and their significance to ammonia-fuelled ships. The conclusions, recommendations, and areas where ammonia safety guidelines may need further improvements are outlined below:

1. In general, all classification societies adhere to the IGF code rules and regulations. For instance, machinery spaces containing ammonia must be free of gas and remotely monitored. Independent bilge systems must be installed, and drip trays must be installed where leaks may occur. Direct access to gas hazardous areas is not allowed, and airlocks must be installed. Fuel containment systems must be designed to prevent ammonia leaks from tanks or their connections. The bunkering station should be installed on an open deck with adequate ventilation, and appropriate measures must be in place to deal with fuel spills. Bunkering manifold valves should be located away from non-hazardous areas and require dry disconnect connections with additional safety features. Permanent gas detectors or leak detection systems should be installed on all fuel bunker pipes and their surrounding areas. The settings of propulsion and power generation systems should be configured to prevent unacceptable loss of power due to fuel supply malfunctions.
2. Due to the high toxicity of ammonia which is different from low flash point fuels such as LNG, to which the existing IGF code is applied, it was found that different classification societies have slightly different tolerances for ammonia, and there are varying choices and requirements for preventing ammonia leaks. For instance, the IGF code does not cover the acceptable limits for ammonia leakage, which differ across various classification societies. ABS and KR mandate a maximum of 25 ppm, whereas BV permits 30 ppm, and RINA allows up to 50 ppm. Although the fuel preparation room's location is consistent with the IGF code and most classifications, ABS requires that it be situated outside the machinery space, whereas BV requires it to be installed in a designated area. The lifespan of a fuel storage tank typically does not exceed 20 years, but DNV permits up to 25 years. The distance from the PRV outlet to the air intake and outlet leading to accommodation, service, and control spaces, as well as other non-hazardous areas, varies significantly across IGF codes and classifications. The IGF code specifies a minimum distance of 10 m, whereas KR mandates a minimum of 15 m, and ABS requires either *B* or 25 m. Other classifications do not have specific guidelines. Similarly, bunkering safety regulations also vary. ABS and KR require the bunkering manifold valve position to be at least 10 m apart, while the IGF code and other classifications do not specify this. The hygroscopicity of gaseous anhydrous ammonia is accounted for in ABS, DNV, and KR, but not in the IGF code or other classifications. Moreover, the ventilation system capacity required varies across classification societies, concerning the number and power of ventilation fans in the fuel preparation room and ducts and double pipes. Nonetheless, it is evident that the regulations put in place are aimed at promoting safety and minimizing the risk of loss of life.
3. It is imperative to reevaluate current safety measures for prevention and mitigation, considering the high toxicity of ammonia and even a minor release can result in fatality. Enhanced, efficient designs and operational approaches should be pursued, along with the creation of advanced techniques for detecting and monitoring ammonia leaks. This is of particular importance, especially when considering large passenger ships. Primarily, the detrimental toxic effects of ammonia on humans and the environment should be taken into account when developing safety guidelines for its use as a marine fuel, with the additional regulations taking into account the ship's structural damage due to corrosion and fire/explosion in the event of ammonia leakage accidents.
4. Ammonia is not flammable at normal room temperature, but can ignite at high temperatures or when exposed to an ignition source. Further research is necessary to better comprehend the various conditions under which ammonia can be ignited, and to develop effective fire prevention and suppression systems for ships utilizing ammonia fuel. This may also involve structural integrity analysis for the ammonia tank storage systems.
5. It is recommended to identify and use materials that are resistant to ammonia-induced corrosion during the design and construction of ships as the corrosive properties of ammonia can cause stress corrosion cracking.
6. In addition to its significant toxicity, ammonia stands apart from other fuels and toxic substances due to two key characteristics: firstly, its vapour is denser than air, and secondly, its remarkable solubility in water. These distinctions necessitate supplementary risk mitigation strategies, such as the implementation of unique sprinkler systems linked to gas detection setups. Furthermore, the positioning of individuals in elevated compartments and the establishment of entirely distinct ventilation system prerequisites may also be warranted.
7. The relevant hazards identified through qualitative risk assessment can be examined and utilized for the risk assessment of ammonia-fuelled ships, which helps to address the limitations of relying on expert experience in qualitative risk assessment and allows for a more comprehensive and detailed risk assessment.
8. There are still limitations in applying the results of quantitative risk assessment to individual case studies and there is a need for further development of risk assessment guidelines and methodologies, although it has the advantage of providing objective and quantified results. As such, a need for further safety regulations considering risk assessment studies dedicated to ammonia-fuelled ships, including numerical simulations such as toxic dispersion analysis of ammonia under varying environmental conditions, is necessary for each type of ship and different hazardous zones to select the best possible risk control options for establishing the prevention and mitigation plans of ammonia leaks on ships.

The future development of ship design risks for ammonia-fuelled ships involves addressing various challenges and considerations as the maritime industry explores this alternative fuel option. Following are some key areas of focus:

1. Materials compatibility and corrosion resistance: Developing and selecting materials that are compatible with ammonia to prevent corrosion and ensure the integrity of ship components and systems.
2. Fuel storage and handling systems: Designing safe and efficient storage and handling systems for ammonia fuel to minimize leakage risks and ensure proper containment.
3. Bunkering infrastructure: Establishing bunkering infrastructure that can safely and efficiently transfer ammonia fuel to ships

while minimizing the risks associated with handling and transportation.
4. Safety systems and protocols: Implementing robust safety systems, protocols, and emergency response plans specific to ammonia-fuelled ships to mitigate risks associated with fuelling, storage, and onboard handling.
5. Ventilation and exhaust systems: Designing effective ventilation and exhaust systems to manage ammonia emissions and prevent buildup within ship compartments.
6. Training and certification: Developing training programs and certification standards for ship crews and maintenance personnel to ensure they are proficient in handling ammonia-fuelled ships safely.
7. Regulatory compliance: Staying abreast of and adhering to evolving regulations and guidelines related to ammonia as a marine fuel, which may require modifications to ship design and operational procedures.
8. Risk assessment and simulation: Utilizing advanced risk assessment tools and simulation techniques to model potential risks and scenarios, allowing for design adjustments and safety enhancements. This includes use of a dynamic risk assessment approach with real-time monitoring and adjustments of risk mitigation strategies based on new operational factors and advanced safety instrumented systems.
9. Environmental impact mitigation: Exploring technologies and strategies to reduce the environmental impact of ammonia emissions, such as emissions control systems and exhaust gas treatment.
10. Collaboration and knowledge sharing: Encouraging collaboration among shipbuilders, designers, regulators, and industry stakeholders to share knowledge, best practices, and lessons learned in designing and operating ammonia-fuelled ships.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgements

The work presented in this paper has been carried out within the UKRI HORIZON-CL5-2021-D5-01 NH_3CRAFT project, co-funded by the European Commission (Project Number: 101056831 (HE), 10105683 (IUK)). The authors would like to express sincere gratitude to all the partners in the project including designers, class societies, industries, and academia for their critical review and constructive feedback during the course of this study. The views and opinions presented in this paper are those of the authors alone.

Appendix

Table A
A summary of the techniques examined in ISO standards and their applicability to ammonia-fuelled ships.

No.	Document title and issuing	Source (No, URL, DOI, ISO, …)	Note: (Summary or brief explanation)	Relevancy to ammonia-fuelled ship
1	Storage and handling of anhydrous ammonia by the Occupational Safety and Health Administration (OSHA) of the United States (United States Department of Labor, 2017)	29 CFR § 1910.111	(Related MSC 104/15/9) (IMO, 2021)	A regional version of the IMO document
2	Liquefied anhydrous ammonia for industrial use – Sampling – Taking a laboratory sample By ISO (ISO, 1982)	ISO 7103:1982	(Related MSC 104/15/9) (IMO, 2021)	Sampling technique and requirements not relevant
3	Safety assessment of ammonia as a transport fuel By Riso (Jan Duijm et al., 2005)	Roskilde Denmark February 2005	1. Safety of operation of the ammonia-powered vehicle under normal and accident (collision) conditions, 2. Safety of transport of ammonia to the refuelling stations 3. Safety of the activities at the refuelling station (unloading and refuelling).	Safety operation, transportation and bunkering of ammonia
4	Ammonia – storage and handling (PGS, 2014)	PGS 12:2014 nl (nen.nl)	With regards to bunkering operations	With regards to bunkering operations
5	Ammonia as refrigerant (PGS, 2009)	PGS 13:2009 versie 0.1 (2–2009) nl (nen.nl)	Gas detection requirements	Gas detection requirements
6	Testing of copper alloys, stress corrosion cracking test in ammonia: testing of tubes, rods and profiles (European Standards, 1976)	DIN 50916, part 1	International conformity with TS ISO 6957 (1998-11-03).	Materials test for ammonia
7	Testing of copper alloys, stress corrosion cracking test in ammonia: testing of components (European Standards, 1985)	DIN 50916, part 2	1. Copper alloys stress conditions check under wet ammonia vapour which can lead to stress corrosion cracking 2. For comparison of the stress corrosion cracking susceptibility of different copper alloys in components and to test the influence of protective methods.	Materials test for ammonia
8	Refrigerating systems and heat pumps – Safety and environmental requirements – Part 1: Basic requirements, definitions, classification and selection criteria; German version EN 378-1:2016 + A1:2020 (European Standards, 2021a)	DIN EN 378-1, 2020-12	The classification and selection criteria applicable to refrigerating systems	Specify details about ammonia as a refrigerant
9	Refrigerating systems and heat pumps – Safety and environmental requirements – Part 2: Design,	DIN EN 378-2, 2018-04	1. Design, construction and installation of refrigerating systems including piping, components and materials	Specify details about ammonia as a refrigerant

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Table A (*continued*)

No.	Document title and issuing	Source (No, URL, DOI, ISO, …)	Note: (Summary or brief explanation)	Relevancy to ammonia-fuelled ship
	construction, testing, marking and documentation (European Standards, 2018)		2. Requirements for testing, commissioning, marking and documentation	
10	Refrigerating systems and heat pumps – Safety and environmental requirements – Part 3: Installation site and personal protection; German version EN 378-3:2016 + A1:2020 (European Standards, 2020a)	DIN EN 378-3, 2020-12	1. Applicable to the installation site 2. Requirements on the site for safety, which may be needed because of, but not directly connected with, the refrigerating system and its ancillary components	Specify details about ammonia as a refrigerant
11	Refrigerating systems and heat pumps –Safety and environmental requirements – Part 4: Operation, maintenance, repair and recovery; German version EN 378-4:2016 + A1:2019 (European Standards, 2019a)	DIN EN 378-4, 2019-12	1. This standard applies to new refrigerating systems, extensions or modifications of already existing systems, and existing stationary systems being transferred to and operated on another site. 2. This standard also applies in the case of the conversion of a system to another refrigerant type, in which case conformity to the relevant clauses of parts 1 to 4 of the standard shall be assessed. 3. To minimize risks of injury to persons and damage to property and the environment resulting from improper handling of the refrigerants or from contaminants leading to system breakdown and resultant emission of the refrigerant.	Specify details about ammonia as a refrigerant
12	Rubber and thermoplastics hoses and hose assemblies for liquid or gaseous chemicals – Specification; German version EN 12115:2021 (European Standards, 2021b)	DIN EN 12115, 2021-04	Specifies requirements for hoses	Hose requirements for ammonia
13	Pressure equipment for refrigerating systems and heat pumps–Part 1:Vessels–General requirements; German version EN 14276-1:2020 (European Standards, 2020b)	DIN EN 14276-1, 2020-11	1. Provides requirements for material, design, manufacturing, testing and documentation for stationary pressure vessels intended for use in refrigerating systems and heat pumps. 2. This document applies to vessels, including welded or brazed attachments up to and including the nozzle flanges, screwed, welded or brazed connectors, or to the edge to be welded or brazed at the first circumferential joint connecting piping or other elements. 3. This document applies to both mechanical loading conditions and thermal conditions. 4. This document applies to pressure vessels where the main pressure-bearing parts are manufactured from metallic ductile materials.	Specify details about ammonia as a refrigerant
14	Pressure equipment for refrigerating systems and heat pumps – Part 2: Piping – General requirements; German version EN 14276-2:2020 (European Standards, 2020c)	DIN EN 14276-2, 2020-11	1. Applies to the selection, application and installation of safety accessories intended to protect the piping during the various phases of the refrigeration cycle. 2. Piping, including welded or brazed attachments up to and including the flanges, screwed, welded or brazed connectors, or to the edge to be welded or brazed at the first circumferential joint connecting piping or other elements.	Hose requirements for ammonia
15	Rubber and thermoplastics hoses and hose assemblies for liquid or gaseous chemicals – Specification; German version EN 12115:2021 (European Standards, 2021c)	DIN EN 12115:2021–04	Specifies requirements for hoses	Hose requirements for ammonia
16	Explosive atmospheres – Part 0: Equipment – General requirements (IEC 60079-0:2017); German version EN IEC 60079-0:2018 (European Standards, 2019b)	DIN EN IEC 60079-0:2019-09	Specifies the general requirements for construction, testing and marking of electrical equipment and Ex Components intended for use in explosive atmospheres.	Requirement of components and equipment under ammonia explosive atmosphere
17	Explosive atmospheres - Part 10-1: Classification of areas - Explosive gas atmospheres (IEC 60079-10-1:2020 + COR1:2021); German version EN IEC 60079-10-1:2021 (European Standards, 2022)	DIN EN IEC 60079-10-1:2022-02	IEC 60079 is concerned with the classification of areas where flammable gas or vapour hazards may arise and may then be used as a basis to support the proper selection and installation of equipment for use in hazardous areas.	Requirement of components and equipment in hazardous areas
18	Gas cylinders –Compatibility of cylinder and valve materials with gas contents–Part 1: Metallic materials (ISO 11114-1:2020); German version EN ISO 11114-1:2020 (European Standards, 2020d)	DIN EN ISO 11114-1:2020	1. Provides requirements for the selection of safe combinations of the metallic cylinder and valve materials and cylinder gas content. 2. The compatibility data given is related to single gases and gas mixtures. 3. Seamless metallic, welded metallic and composite gas cylinders and their valves, used to contain compressed, liquefied and dissolved gases, are considered.	Requirement of ammonia cylinder and valve material
19	Ships and marine technology–Identification colours for the content of piping systems (ISO 14726:2008) English translation of DIN ISO 14726:2010–10 (DIN ISO, 2010)	DIN ISO 14726:2010–10	1. Specifies main and additional colours for identifying piping systems in accordance with the content or function on board ships and marine structures.	Pipe color code

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Table A (*continued*)

No.	Document title and issuing	Source (No, URL, DOI, ISO, …)	Note: (Summary or brief explanation)	Relevancy to ammonia-fuelled ship
			2. These colours can also be used for piping systems on drawings and diagrams. 3. This International Standard does not apply to piping systems for medical gases, industrial gases and cargo. 4. This International Standard can also be used for land installations.	
20	Special pressure vessels-Pressure vessels in refrigerating and heat-pumping plant (DIN, 2016)	AD 2000 HP 801Nr.14, 2017 June	Contains additional requirements for pressure vessels in refrigerating and heat pumping plants and as such has priority over other AD 2000-Merkblätter. Excluded are pressure vessels comprising exclusively parts with a clear cross-sectional area of less than 10 cm^2. AD 2000-Merkblätter HP 801 Nos. 26, 27, 34 and 37 do not apply to pressure vessels in the refrigerating plant.	Specify details about ammonia as a refrigerant
21	Special pressure vessels-Ammonia storage vessels (DIN, 2016)	AD 2000 HP 801Nr.34, 2016 May	Contains additional requirements for ammonia storage vessels and as such has priority over other AD 2000-Merkblätter. Applies to ammonia storage vessels for the storage of pressurized liquefied ammonia. This does not apply to ammonia storage vessels that are components of process plants or refrigeration plants. Process plants comprise all the necessary and reserve equipment for carrying out chemical, physical or biological procedures to prepare, produce or dispose of materials or products.	The requirement of the ammonia storage vessel
22	Health and safety executive –Safety report assessment guidance (technical aspects) (HSE, 2015)	https://www.hse.gov.uk/comah/sragtech/asscr'itcontents.htm	Risk assessment guidance with external links to accidents/incidents forms the basis of the guidance content.	Risk assessment guidance linking with database
23	Rubber hoses and hose assemblies for transferring anhydrous ammonia - Specification (ISO 5771:2008); German version EN ISO 5771:2008 (ISO, 2009)	DIN EN ISO 5771 (2009-10-00)	Specifies the minimum requirements for rubber hose used for transferring ammonia, in liquid or in gaseous form, at ambient temperatures from −40 °C to and including +55 °C. It does not include specifications for end fittings but is limited to the performance of the hose and hose assemblies.	Hose requirements for ammonia

Table B
Matrix on a qualitative risk assessment study

No.	Document title	Key risks/hazards identified	Challenges addressed & gaps identified	Risk assessment techniques employed	References
1	Risk analysis of a fuel storage terminal using HAZOP and FTA	The four fuels (petrol, diesel, methanol, and kerosene) are hazardous substances to handle (both storage and distribution)	The size and complexity of industrial chemical plants and the nature of the products they handle make it difficult to analyze and manage the associated risks.	HAZOP + FTA	Fuentes-Bargues et al. (2017)
2	A preliminary risk assessment on the development of the fuel gas supply system of a small LNG-fuelled fishing ship	Identified risks in the stage of concept design by HAZID for dual-fuel LNG engines of a fishing ship	As of now, a HAZID analysis of a fishing vessel powered by LNG has not been conducted	HAZID	Shao et al. (2022)
3	Fire, explosion and safety hazard identification (HAZID) of the entire methanol dual-fuelled system and ship	Design of the system and operation for the methanol fuelled ship	Criteria for the placement and installation of machinery for propulsion and auxiliary purposes using methanol as fuel are not yet available	HAZID	Etemad and Choi (2017a)
4	Hazard identification (HAZID) of LNG dual-fuelled ships operating between the Korean port of Busan and the Iranian port of Bandar Abbas	Identified potential hazards that can be caused and consequences of several scenarios in the step of concept design	To provide a baseline for vessels firing natural gas as a fuel, as LNG risk assessments are not yet performed to meet the requirements of the IMO Interim Guidelines and IGF Code	HAZID	Etemad and Choi (2017b)
5	SOFC ammonia fuel supply system safety assessment	Identified hazards of ammonia-fuelled fuel cell	Combination of HAZID with hazard impact simulation which is functional and model base	HAZID	Cheliotis et al. (2021)
6	Research on quantitative risk assessment of fuel leak of LNG-fuelled ship during the lock transition process	Due to the absence of historical data on accidents involving LNG-fuelled ships during lockage, this study utilized the HAZOP-LOPA technique to pinpoint the potential risk factors associated with fuel leakage during lockage	The HAZOP technique involving brainstorming sessions is used to assess systems and manage risks, while the LOPA method is a semi-quantitative approach used to identify and evaluate high-risk scenarios	HAZOP and LOPA	Xie et al. (2022)
7	Safety study of an LNG regasification plant using failure modes, effects and	Identified potential unintended incidents that may occur in the storage	A combined FMECA and HAZOP methodologies are utilized	FHIA (FMECA and HAZOP	Giardina and Morale (2015)

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Table B (*continued*)

No.	Document title	Key risks/hazards identified	Challenges addressed & gaps identified	Risk assessment techniques employed	References
	criticality analysis (FMECA) and HAZOP integrated methodology	system employed by the liquefied natural gas regasification facility		integrated analysis)	
8	Safety guidelines and a training framework for LNG storage and bunkering at ports	Pinpointed potential causes of accidents, evaluated the reaction of the plant to these incidents, and determined the final damage that may result.	The HAZOP method is utilized to identify potential hazards and develop safety measures for the operation of LNG port facilities, including the use of LNG storage equipment	HAZOP	Aneziris et al. (2021)
9	Safety and reliability analysis of an ammonia-powered fuel-cell system	The potential safety and reliability issues associated with the proposed system that runs on ammonia	Conducted a comprehensive evaluation of the safety, operability, and reliability aspects of a ship powered by an ammonia fuel cell, considering the fuel specifications and bunkering requirements	HAZID, FMECA, FTA	Trivyza et al. (2021)
10	Risk assessment for natural gas hydrate carriers: a hazard identification (HAZID) study	Pinpointed potential hazards and incidents that may occur with Natural Gas Hydrate (NGH) carriers	HAZID study is conducted to recognize potential hazards and dangers	HAZID	Kim et al. (2015)
11	The application of HAZOP analysis on risk assessment of the 10000 TEU container ships	Created a pre-control guidance system is essential for providing adequate technical and security assistance, as well as improving the overall safety of operations	The HAZOP technology is utilized	HAZOP	Zhan et al. (2009)
12	Concept design and risk assessment of nuclear propulsion ship	Ensured the safety of the novel ships that employ nuclear energy as fuel	The HAZID methodology was employed to affirm the dependability and safety	HAZID	Gil et al. (2014)
13	Hazard identification for a dynamic positioning and mooring system in arctic condition: Complementary use of hazard identification study (HAZID) and systems theoretic process analysis (STPA)	It is necessary to conduct evaluations and appraisals of potential hazards since the developing system incorporates numerous innovations in contrast to the standard DP or mooring system	The HAZID approach is implemented for the structural components of the system, such as the hull structure, mooring lines, and turret system, while STPA was employed for the control system, including the DP systems	HAZID and STPA	Joung et al. (2018)
14	Risk-based preventive maintenance planning using failure mode and effect analysis (FMEA) for marine engine systems	Suggested a technique for evaluating preventive maintenance planning by using a reliability model for the fuel oil system on a ship, with the aim of assessing potential risks	Employment of adaptable time frames for maintenance interventions	FMEA	Cicek et al. (2010)
15	Hazard analysis: Application of STPA to ship-to-ship transfer of LNG	Conventional hazard analysis tools like HAZOP or basic reliability analysis techniques like FMEA are inadequate in assessing the deficiencies of intricate systems	STPA is developed for assessing the safety of intricate systems, acting as a supplement to the traditional HAZOP technique	STPA (HAZOP)	Sultana et al. (2019)
16	Application of fuzzy failure mode effect and criticality analysis on unloading facility of LNG terminal	The acceptance of LNG facilities by society is mainly reliant on the effective execution of suitable safety regulations and programs for managing risks	Fuzzy-based FMECA methodology is utilized for an LNG unloading facility located in an LNG terminal	FMECA	George et al. (2019)
17	Safe and effective application of ammonia as a marine fuel	One specific hazard associated with ammonia is its potential impact on humans and the environment if there is exposure	Due to the limited scope of risk assessment for ammonia fuel, comprehensive data collection has not been conducted	FMECA	de Vries (2019)
18	Potential of ammonia as fuel in shipping	Ammonia is a toxic gas and necessitates a sophisticated system to implement its use in marine applications safely. Thorough training of crews and operators is necessary to ensure safe operation	The conventional HAZID approach is utilized for hazard identification, but it has its limitations in identifying more profound and complex hazards	HAZID	EMSA (2022)

Table C
Matrix on a quantitative risk assessment study

No.	Document title	Key hazards identified	Challenges addressed & gaps identified	Risk assessment techniques employed	References
1	Quantitative risk assessment for accidental release of titanium tetrachloride in a titanium sponge production plant	Storage and purification section of a titanium sponge production facility	The spilling or leaking of $TiCl_4$ storage tanks resulted in the discharge of hydrogen chloride (HCl), as well as the evolution of HCl due to a ruptured heat exchanger	FTA, consequence analysis	Roy et al. (2003)
2	Reliable risk estimation in the risk analysis of chemical industry case study: Ammonia storage pressurized spherical tank	Evaluation of individual and societal risk	There is a need for more advanced probabilistic safety analysis methods in the chemical industry. This is necessary to create better and faster procedures for estimating complex risks with accurate and realistic probability values	FTA, ETA, consequence analysis	Jelemensk et al. (2004)

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Table C (*continued*)

No.	Document title	Key hazards identified	Challenges addressed & gaps identified	Risk assessment techniques employed	References
3	Quantitative risk analysis of oil storage facilities in seismic areas	Oil storage facilities	Engineering procedures able to evaluate quantitatively the effect of seismic action are not well-established	Quantitative probabilistic seismic risk analysis (QpsRA)	Fabbrocino et al. (2005)
4	A quantitative risk analysis approach to port hydrocarbon logistics	Marine hydrocarbon terminals sited in ports	A significant gap was identified in the technical literature regarding QRA for the management of hazardous substances in ports that were published before this study	ETA, consequence analysis	Ronza et al. (2006)
5	Quantitative risk assessment for the transport of ammonia by rail	Ammonia transportation by rail in Malaysia	To conduct a risk assessment for the transportation of anhydrous liquefied ammonia by rail from the Petronas Fertilizers Kedah (PFK) plant in Gurun, Malaysia to the Chemical Company of Malaysia (CCM) fertilizer facilities in Port Klang, Malaysia.	Hazard analysis (HAZAN) technique, probabilistic and fuzzy logic technique	Che Hassan et al. (2010)
6	Consequence and risk assessment: Case study of an ammonia storage facility	Ammonia storage facility	All the failure modes which could result in the occurrence of the undesirable incident more commonly known as the "top event"	FTA, consequence analysis	Roy et al. (2011)
7	Quantitative risk assessment model of hazardous chemicals leakage and application	The emergency management of hazardous chemicals leakage	Focuses on one enterprise's storage tank at Changshou Chemical Industrial Distripark (CID) in Chongqing, China	Fire explosion poisoning quantitative probability model (FEPQPM), probability analysis methods	Si et al. (2012)
8	Risk analysis of cryogenic ammonia storage tank in Iran by fault tree method	Ammonia storage tank	To identify and evaluate the related risks of the ammonia storage tank with a capacity of 20,000 tons in the Lordegan petrochemical plant (Iran)	FTA	Nemati and Heidary (2012)
9	Quantitative risk analysis - Ship security analysis for effective risk control options	Ship security assessment (e.g., Somali-based maritime piracy)	Investigated the potential for quantifying and conducted a more comprehensive risk analysis related to ship security	ETA	Liwå et al. (2013)
10	Quantitative risk analysis of offshore drilling operations: A Bayesian approach	Blowout accidents	The rapid alteration of physical factors and the tendency of barriers to fail over time require methodologies that can account for changes and time-dependencies during the lifespan of a well	FTA, ETA, Bow-tie and BN methods	Khakzad et al. (2013)
11	Quantitative risk analysis on leakage failure of submarine oil and gas pipelines using Bayesian network	The failure probability of submarine pipeline could lead to spill accidents in oil and gas	The challenges associated with using the bow-tie method for modelling uncertainties and conditional dependencies	Bow-tie and BN methods	Li et al. (2016)
12	A quantitative individual risk assessment method in process facilities with toxic gas release hazards: a combined scenario set and CFD approach	Toxic gas release in process facilities	The approach based on worst-case scenarios may not accurately represent actual release risks and could potentially overestimate the individual risk (IR)	CASS (complete accident scenario set) and CFD	Zhang et al. (2019)
13	Consequence assessment of anhydrous ammonia release using CFD-probit analysis	Anhydrous ammonia	Consequence assessment is a critical aspect of risk assessment that is necessary for devising an effective mitigation strategy	CFD	Namboothiri and Soman (2018)
14	Quantitative risk assessment for ammonia ship-to-ship bunkering based on Bayesian network	Ammonia bunkering	There are significant uncertainties regarding the consequences of toxic gas dispersion and fire incidents, and there is a lack of sufficient risk assessment guidelines for ammonia bunkering	Bayesian network-based quantitative risk assessment framework	Fan et al. (2022)
15	Ammonia bunkering of passenger vessel – concept quantitative risk assessment	Ammonia has relatively high toxicity and low flammability. This study is specifically centred on the discharge of ammonia into the ocean while in a pressurized or refrigerated state	The study only considered the toxic hazards of ammonia and did not address the release of ammonia associated with storage tanks and equipment on case ships as well as bunkering ships and trucks	Frequency analysis, consequence analysis	DNV AS (2021)

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