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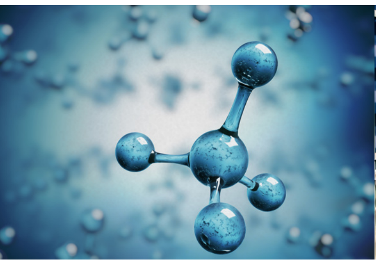

A pre-study carried out within the Swedish Transport Administration's industry program Sustainable Shipping, operated by Lighthouse
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SWEDISH MARITIME COMPETENCE CENTRE

HÅLLBAR SJÖFART

Safety of ammonia on board

Pre-study of ammonia as a new fuel in shipping, from a safety perspective.

Authors
Anna Karlsson, Oskar Grönlund, Julia Burgén, Joanne Ellis, Chen Huang, Tobias Olsson, Stina Andersson
RISE Research Institutes of Sweden AB

In cooperation with
A reference group including representatives from Bureau Veritas, Swedish Transport Agency, Port of Gothenburg, IUMI, Cefor, Afry, Wärtsilä and BlueTack.

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Summary

The Safety of Ammonia on board (SAMM) project has been built on current knowledge about ammonia safety and aimed to increase the understanding of barriers for using ammonia as a fuel for shipping. The project has also contributed to identifying future areas where more research is needed.

The pre-study was divided into two steps to increase the understanding of safety barriers for using ammonia as a fuel within the shipping sector. First, a background study was carried out to check previous and ongoing experiences with ammonia in shipping and in other sectors. This included literature, interviews and a study visit at the Port of Gothenburg. Second, a physical workshop was performed with competences covering ship operation, port operation, emergency response, insurance, rules and regulations. The workshop was divided into three activities: creation of timeline, prioritization (by voting) of barriers to overcome, and detailing of top voted activities.

SAMM was carried out together with a reference group and a group of researchers from RISE, covering a wide spectrum of the area with alternative fuels, shipping, regulations, and human factors. The project was mainly carried out during 2023 and finalized in April 2024.

From the interviews conducted during this project, all interviewees mentioned training and knowledge as the most important aspects to safely implement ammonia as a ship fuel. The needs for training and education exist for all stakeholders, from seafarers aboard the ammonia fuelled ship, to bunkering personnel, to emergency responders.

The workshop results in this study are in line with the reference literature. The main result from the workshop was a list of prioritized tasks that have to be taken care of to enable bunkering of ammonia in the Port of Gothenburg. The participants voted on the safety activities they had posted on the road map, and the highest voted activities were the following, without internal prioritization:

- Creation of an international bunkering standard
- Bunker station equipment and layout on board
- Risk assessment (including HAZIDs and HAZOPs)
- Public communication plan
- Personnel competence, experience and training (including emergency response plans)
- Sharing of accident/incident knowledge

Sammanfattning

Förstudien Säker ammoniak ombord (SAMM) har byggt på nuvarande kunskap om ammoniaksäkerhet och syftat till att öka förståelsen för barriärer för att använda ammoniak som bränsle för sjöfarten. Projektet har också bidragit till att identifiera framtida områden där mer forskning behövs.

Förstudien var uppdelad i två steg för att öka förståelsen för säkerhetsbarriärer för att använda ammoniak som bränsle inom sjöfartssektorn. Först utfördes en bakgrundsstudie för att gå igenom tidigare och pågående erfarenheter av ammoniak inom sjöfarten och inom andra sektorer. Denna del innefattade litteratur, intervjuer och ett studiebesök i Energihamnen, Göteborg. Därefter genomfördes en fysisk workshop under en dag, där deltagarna hade kompetens inom fartygsdrift, hamnverksamhet, beredskap, försäkringar, regler och föreskrifter, förutom forskning som projektgruppen bidrog med. Workshopen var uppdelad i tre aktiviteter: skapande av tidslinje, prioritering (genom omröstning) av listade barriärer på tidslinjen och detaljering av utvalda listade barriärer.

SAMM genomfördes tillsammans med en referensgrupp och en grupp forskare från RISE, som täckte ett brett spektrum av området med alternativa bränslen, sjöfart, regelverk och människa-teknik-organisation faktorer. Projektet pågick från februari 2023 till april 2024.

I de intervjuer som genomfördes under detta projekt nämnde alla intervjupersoner utbildning och kunskap som de viktigaste aspekterna att övervinna för att säkert kunna implementera ammoniak som fartygsbränsle. Behov av utbildning och träning finns bland alla aktörer, från sjöfolk ombord på det ammoniakdrivna fartyget, till bunkringspersonal till räddningspersonal.

Workshopresultaten i denna studie är i linje med referenslitteraturen. Följande säkerhetsrelaterade aktiviteter kom högst upp på listan av barriärer för att nå bunkring av ammoniak i Göteborgs Hamn (utan intern prioritering):

- Skapande av internationell bunkringsstandard
- Bunkerstationsutrustning och layout ombord
- Riskbedömning (inklusive HAZID och HAZOP)
- Offentlig kommunikationsplan
- Personalens kompetens, erfarenhet och utbildning (inklusive beredskapsplaner)
- Dela kunskap om olyckor/tillbud

List of abbreviations

ABS	American Bureau of Shipping
AEGL	Acute Exposure Guideline Levels
AiP	Approval in principle
CSB	US Chemical Safety and Hazard Investigation Board
ERS	Emergency Response Service
ESD	Emergency shut down
GHG	Greenhouse gas
IAPH	International Association of Ports and Harbours
IDLH	Immediately dangerous to life or health
IGC Code	International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk
IMCA	International Marine Contractors Association
ISGOTT	International Safety Guide for Oil Tankers and Terminals
GISIS	Global Integrated Shipping Information System
LNG	Liquified natural gas
LPG	Liquified petroleum gas
LSIR	Location-specific individual risk
OCIMF	Oil Companies International Marine Forum
OSHA	Occupational Safety and Health Administration
PPE	Personal protective equipment
SIGTTO	Society of International Gas Tanker and Terminal Operators
SIMOPS	Simultaneous operations
SOLAS	Convention for Safety of Life at Sea
STEL	Short-term exposure limit

Contents

1 Introduction

The shipping industry is a source of greenhouse gas (GHG) emissions. Currently, a large portion of the international shipping is using heavy fuel oil (IMO, 2020). According to a greenhouse gas study by International Maritime Organisation (IMO) from 2020, the GHG emissions from the shipping industry increased by 9.6% from 2012 to 2018 (IMO, 2020). IMO wants to reduce GHG emissions from international shipping and progress towards reaching net-zero GHG emissions from international shipping close to 2050 and reduce carbon dioxide (CO2) emissions by 40% by 2030 compared to 2008 (IMO, 2018) (IMO, 2023). To reduce emissions from the shipping industry, alternative fuels which are low-carbon or zero-carbon are needed (IMO, 2018). Alternative marine fuels and propulsion methods such as hydrogen, methanol and batteries are on the rise and there are already ships powered by these in our waters today, e.g. Sea Change (hydrogen), Takaroa Sun and Stena Germanica (methanol) and Aurora (batteries). Ammonia is also discussed as an alternative fuel which can be used to reduce the GHG emission from the shipping industry. There are currently (April 2024) no in-service ships using ammonia as fuel.

Ammonia, NH3, is naturally carbon free and "green ammonia" (ammonia produced using sustainable energy sources) is an option to reduce CO2 emissions for ships. There are however several challenges to be solved when discussing ammonia as a maritime fuel. Many alternative fuels have similar challenges with regulatory gaps, technological readiness levels, and a lack of infrastructure for the fuel.

1.1 Project objective and goals

This pre-study "Safety of ammonia on board" aimed to make an inventory of technical and operational safety barriers against introducing ammonia on board. The objective was to elaborate how safety can be applied with a focus on increasing the knowledge and research on human-technology interactions.

In the short term, gaps and barriers were identified for safe introduction of ammonia on ships. In the long term, this pre-study can lead to future follow-up studies which will contribute to the safe use of ammonia on ships by addressing the identified challenges.

1.2 Ammonia projects within the shipping sector

Ammonia as a potential fuel has been studied in several projects in the past. A selection of such projects is briefly described below.

"Hydrogen, ammonia and battery-electric propulsion for future shipping" (Brynolf, o.a., 2023) was a Lighthouse study led by Chalmers, with RISE as partner, where ammonia is one of the options considered for two case study designs. Part of RISE's work was to develop conceptual designs and investigate associated safety considerations. The project was completed in 2023.

The German study "Ammonia as a marine fuel" (Cames, Wissner, & Sutter, 2021) has studied the potential risks of ammonia as a marine fuel, whether the challenges with ammonia are sufficiently considered, and whether this affects ammonia's suitability as a future marine fuel. This study concludes that robust guidelines are needed for safety aspects.

The Lighthouse pre-study "The potential of ammonia as fuel for shipping" (Hansson, Fridell, & Brynolf, 2020) was completed in 2020 and had the overall goal of assessing the potential of ammonia as a marine fuel. This study notes that "appropriate chemically resistant protective clothing and other safety measures for those handling the fuel will be needed." Further, the study notes the importance of public acceptance for the introduction of ammonia as fuel within shipping. The listed key concerns are the potential exposure to humans and environment and the study proposes future research on the feasibility to apply ammonia as a marine fuel, including fuel systems, bunkering, and safety routines. SAMM continued this work by mapping of safety issues, focusing on safety aspects and how ammonia can be introduced on board. In addition, SAMM includes bunkering.

European Maritime Safety Agency (EMSA) financed the study "Potential of ammonia as fuel in shipping" (European Maritime Safety Agency, 2022) which identified operational aspects such as firefighting procedures, and new training requirements as areas where more knowledge and further studies are needed.

A recently published report by Lloyd's Register (Eriksen, Dunlop, McCafferty, & Garner, 2023) focusing on operations and maintenance activities of the crew gives a good overview of human factors issues related to ammonia. The report covers bunkering, on board fuel handling and maintenance. A wide variety of factors were identified, including:

- Occupational health hazards: Skin exposure, inhalation, personal protective equipment (PPE).
- Ergonomics: for PPE, design of surveillance systems and alarms, layouts, passages, and safe havens for example.
- Roles, responsibilities, and competence: new specialist roles on board, new competences in handling, maintenance, rules & regulations etc.
- Processes & procedures: The need for job safety analyses, permit systems, lock-out tags, new emergency procedures, new maintenance procedures etc.
- Process safety hazards: Relevant personnel will for example need to understand the consequence of potentially interacting with, replacing or repairing systems, equipment or components.
- Management of change: The challenges of realizing a large set of safety measures in a systematic way, and with sufficient quality.

A few areas mentioned that require further research are:

- Emergency response organization and methods.
- Situation assessment and grounds for emergency response decisions.
- Engine control room (ECR) installations maintaining or improving systems usability.
- Challenges of reaching satisfying safety solutions in retrofit projects.
- Learning from management of change in liquified natural gas (LNG) projects.
- Effects for personnel off the ship, e.g., those working with bunkering or in the port.

Valera-Medina et al (2018) conclude that ammonia is an attractive candidate to act as the facilitator for sustainable energy (Valera-Medina, Xiao, Owen-Jones, David, & Bowen, 2018).

Although operational aspects are highlighted as an important aspect to consider when introducing ammonia as fuel in several ammonia studies (European Maritime Safety Agency, 2022) (Hansson, Fridell, & Brynolf, 2020), there was not much found regarding the perspectives of the crew, bunkering and response organizations, such as salvage and rescue services. However, during the course of this project, the Global Centre for Maritime Decarbonisation (GCMD) published a report on safety and operational guidelines for ammonia bunkering in Singapore (Global Centre for Maritime Decarbonisation (GCMD), 2023) which has perspectives of operation, emergency and bunkering included.

1.3 Shipbuilders and engine manufacturers investing in ammonia as marine fuel

The International Energy Agency considers ammonia to be the target fuel for ocean going vessels to achieve net zero emissions in 2050 (IEA, 2021). Ship builders and engine manufacturers are in the process of commercialising different types of vessels around the globe to be fuelled by ammonia.

In June 2020, the Finnish marine engine manufacturer Wärtsilä in cooperation with Knutsen OAS Shipping AS and Repsol performed the world's first long-term, full-scale, testing of ammonia as fuel in a marine four-stroke combustion engine. The testing was commenced in Sustainable Energy Catapult Centre's testing facilities at Stord, Norway (Wärtsilä, 2020). Classification society DNV also granted Approval in Principle[1] (AiP) to Wärtsilä's Ammonia Release Mitigation System (WARMS); a technology that mitigates leaks in engines that run on ammonia, reducing emissions to less than 30 ppm (Wärtsilä, 2020). In the same year, Lloyd's Register announced their AiP to South Korea's Daewoo Shipbuilding & Marine Engineering and MAN Energy Solutions for its ammonia-fuelled 23,000 TEU ultra-large containership design. Although the final approval is still pending, the vessel is expected to be commercialized by 2025 (Lloyd's Register, 2020). In September 2022, the classification society American Bureau of Shipping (ABS) granted AiP to South Korean shipbuilders Hyundai Heavy industries and Hyundai Mipo Dockyard for the concept design of two ammonia-fuelled liquefied petroleum gas (LPG) carriers (ABS, 2023). In June 2023, Swiss marine power company WinGD and Mitsubishi Shipbuilding announced their progress in taking on ammonia as fuel in shipping and is aiming to deliver the first vessels by 2027. Mitsubishi is moving to the final stages of verification testing of their Ammonia Fuel Supply System (AFSS) for large-scale, low-speed, two stroke marine engines (WIN GD, 2023).

While the industry marches forward and commercialised vessels are expected as early as 2025, there are constraints as to the speed at which solar and wind farms, ammonia plants, transportation and distribution infrastructure can be deployed, risking limiting the availability of green ammonia. For international shipping it would require the development of new bunkering facilities, or adapting existing ones, to accommodate ammonia (European Maritime Safety Agency, 2022). But the adaptation for the increased demand of green ammonia at sea has already begun. H2Carrier is developing a floating

[1] An Approval in Principle (AiP) is generally granted by classification societies as an approval of a preliminary design – from the class. It is the foundation a final design can be developed from where final approval may be granted.

production unit for green ammonia and in March 2023, H2Carrier and Trelleborg Gas Transfer signed a memorandum of understanding to cooperate on ship-to-ship ammonia transfer solutions (Atchison, 2023).

With this rapid march towards ammonia driven vessels, the need for a safe implementation is very relevant. The SAMM pre-study addresses the overall goal of making shipping more sustainable by investigating the safety conditions for ships to use ammonia as an energy source. Human element issues are an important part of introducing new fuel on board. Achieving sustainable shipping also requires knowledge and research on human-technology interactions. To this end, the pre-study considered work processes and the mindset of users involved in the handling of ammonia.

2 Method

This pre-study used the following two approaches to increase the understanding of safety barriers for using ammonia as a fuel within the shipping sector.

1. A background study to examine previous and ongoing experiences with ammonia in shipping and in other sectors.
2. A workshop with competences covering ammonia stakeholders to find and explore interfaces and barriers of using ammonia as a ship fuel from a safety perspective.

The pre-study was carried out together with a reference group and a group of researchers covering a wide spectrum of the area with alternative fuels, shipping, regulations, and human factors.

The two applied approaches are described below.

2.1 Literature and background study

This work aimed at collecting knowledge and experience of ammonia from different perspectives. The perspectives were mainly crew handling and the situation on board, emergency, rules and regulations as well as port and bunkering operations, see Figure 1.

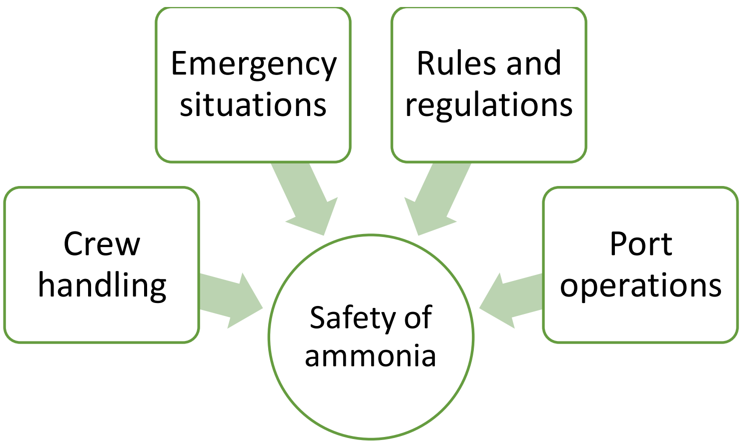

Figure 1. Perspectives included in the literature and background study.

A desktop study was carried out considering relevant regulations, guidelines, ongoing ammonia projects within the shipping sector, and relevant safety literature relating to operational use of ammonia. The literature and ongoing projects were searched for in various Internet search engines. Regulations and guidelines were gathered through the project group's and reference group's experience. The desktop study scratched on the surface of ammonia related knowledge and information.

The collected information was deepened through a site visit at the Energy Port operation in Port of Gothenburg and interviews were held to cover the perspectives of port operations, crew handling and emergency situations. The port visit was carried out 11 September 2023 and included meeting with a Risk and Safety Engineer and the Head of Business Area Energy Operation.

Four interviews were conducted. The interviews were conducted with rescue service and salvage personnel, coast guard personnel, chemical port representatives and a previous navigation officer on a gas carrier. Interviews were held digitally, and a preparatory question list was sent out to participants beforehand together with a consent form to each participant. The length of the interviews was approximately one hour. The selection of interviewees was made with the aim to represent perspectives from emergency personnel and from crew or other persons handling ammonia or chemicals. Notes were taken during the interview. After the interview, the notes were sent to the interviewee for referral. Any comments from the interviewee were then corrected in the notes so that the interview results agreed with the interviewee before it was used in the report. The results from interviews are not presented in their entirety but in appropriate parts of this report.

2.2 Safety aspects of bunkering ammonia

The work to outline safety aspects of bunkering ammonia was centred around a workshop with industry stakeholders. It was held in Gothenburg, Sweden, in January 2024 and 16 people participated. The representation of participants' area of expertise was distributed accordingly (including workshop facilitators):

- Research, 4 participants (RISE project members)
- Ship operation, 2 participants
- Ship installation supply, 2 participants
- Port, 2 participants
- Authority/class, 2 participants
- Risk expertise, 2 participants
- Insurance, 1 participant
- Rescue, 1 participant

The stakeholder workshop was intended to establish the following:

a) A timeline describing the road map from today until an ammonia fuelled vessel can safely be bunkered with ammonia in the Port of Gothenburg, focused on safety aspects.
b) Prioritization of future research and development areas.
c) Description of areas for future research and development.

2.2.1 Creation of timeline: from today to bunkering of ammonia

The first part of the workshop focused on the creation of a timeline containing activities that the industry must implement in order to enable ammonia bunkering in the Port of Gothenburg. The intention of the geographical limitation was to make the discussions more concrete and help the participants to identify necessary activities. All participants were instructed to write safety-critical activities which were then added to the timeline – relating to each other instead of in relation to specific dates. Similar activities were grouped together. This session lasted for about two hours and encouraged discussions among participants.

2.2.2 Prioritization

Once the group had completed the timeline of safety-critical activities, each stakeholder was given five votes to distribute among the identified activities. The votes were to be used to identify where the stakeholder found the biggest barriers to overcome, or a major need for future research. The voting was not limited to one vote per activity, meaning that it was possible to put more than one vote on the same activity. Participants representing the same organization were only given a total number of five votes to distribute together.

2.2.3 Detailing descriptions of highest rated areas

The six activities on the timeline with the most votes were further detailed in smaller groups. The grouping was done based on participants' own interests. The group was sitting together to write down answer and comments to the following headings:

- General description of the activity.
- Knowledge gaps and other barriers that prevent completion of the activity.
- Tasks or further studies needed to fill the knowledge gaps and overcome barriers.
- Collaborations and actors necessary to complete the activity/tasks.
- Additional aspects to consider.

The result of this part is reported for each prioritized activity, in section 4.3.

3 Literature and background study

This chapter presents the results from desk top studies, site visits and interviews.

3.1 The basics of ammonia

At normal temperature and pressure, ammonia is a colourless gas with a strong, sharp, irritating odour (odour threshold 5 ppm). It occurs naturally in water, soil, and air but at very low concentrations. Ammonia is often used as fertilizer in agriculture, and as a refrigerant agent in various industries such as on fishing vessels (Agency for Toxic Substances and Disease Registry, 2004; US EPA (United States Environmental Protection Agency), 2001). In addition, ammonia is used to produce plastics, explosives, textiles, insecticides, dyes, and other chemicals.

According to Valera-Medina et al. (2018), the major risk with ammonia is toxicity, whereas the secondary risk is fire and explosion. Corrosivity is another main risk to consider (MSB, 2023).

Regarding toxicity, the US National Institute of Occupational Safety and Health's (NIOSH) standards permits, in a 40-hour work week with 8-hour workdays, a maximum time-weighted average (TWA) exposure to anhydrous ammonia (pure ammonia) of 25 ppm (Centers for Disease Control and Prevention, u.d.).

Ammonia is commonly stored in liquid form at atmospheric pressure and -33°C, at industrial scale. This is also considered the safest way to store and bunker ammonia on board (Duong, o.a., 2023). In its pure vapor form at ambient conditions, ammonia is lighter than air. Behaviour of an ammonia leakage will result in gas phase ammonia or liquid ammonia, depending on the storage conditions.

Ammonia solubility in water is dependent on the water temperature. When dissolved, ammonia reacts with water and produces ammonium hydroxide (NH4OH), which is corrosive and can damage cells in the body (MSB, 2023).

3.2 Safety issues with ammonia

Ammonia gas is both flammable and toxic, however the ignition energy required to ignite a flammable mixture of ammonia is significantly higher than for other flammable gases. Anhydrous ammonia has lower and upper flammability limits of 15 and 28 vol-%, respectively, while the lowest temperature required for ammonia to ignite without an ignition source (auto-ignition temperature) is 630℃ (MSB, 2023). This can be compared to traditional diesel fuel which is flammable in the range of 0.6 to 7 vol-% and has an auto-ignition temperature of 220 ℃ (MSB, 2024).

Toxic doses are described as a combination of concentration and exposure duration. When it comes to accidental releases and exposure to 3rd party, it is common to refer to Acute Exposure Guideline Levels (AEGL). AEGL have been developed for rescue services to dimension preparedness and to take measures during emergency interventions. The levels are chosen to protect the elderly and children, as well as other sensitive individuals (National Research Council, 2007). These levels and other threshold values are listed in the Table 1. Values are taken from the MSB RIB, a decision support for Swedish rescue services that provides support all the way from planning future interventions to making the right decision when the accident occurs.

Table 1 Threshold values for ammonia (MSB, 2023)

Consequence/ threshold* (ppm)	**10 min**	**30 min**	**1 h**	**4 h**	**8 h**
Life-threatening conditions or death.	2 700	1 600	1 100	550	390
Irreversible, serious and long-term health effects or a reduced ability to escape from the exposure.	220	220	160	110	110
Experience of discomfort, irritation or certain effects that do not cause symptoms. Transient.	30	30	30	30	30

** Concentration in air*

The table shows above the AEGL thresholds, and if such were not available the Emergency Response Planning Guidelines levels (ERPG). If neither AEGL nor ERPG were available, Temporary Emergency Exposure Limits (TEEL) are listed (MSB, 2023).

It can be emphasized that there is a margin between the level at which ammonia is detected by smell to levels where it can cause discomfort to the body. The odour from ammonia can be scented at concentrations of as low as 5 ppm, which is far below the concentration of immediate danger to life. The smell of ammonia was therefore raised as a positive aspect of ammonia in interviews with firefighters in this study. However, MSB (2023) states that the sense of smell can be dulled by other substance, while at 50 ppm, there is generally no doubt that ammonia is present. The sense of smell as a pre-toxicity indicator must hence be used with caution (MSB, 2023).

In terms of personnel and 3rd party/passengers on board a vessel, several safety concerns need to be addressed (not limited to these concerns):

- Work environment risks to personnel on board, e.g., corrosive ammonia on skin, in eyes, risk of breathing toxic gas, fires; and
- Risks related to passengers on board, e.g., risk of breathing toxic gas, fires.

Examples of safety tasks to consider may include (but are not limited to) the following:

- Type and amount of ammonia used,
- Minimizing the amount of ammonia that can leak at one instance by reducing amounts stored or segregating the amounts through several closed systems/tanks),
- Detection and emergency shutdown means, in the event of a leakage, to minimize amounts released. It is important with early detection, which requires high reliability and coverage of the gas detection system,
- Alarm and announcement to personnel and passengers in the event of a leakage,
- Performing risk assessments and ensuring emergency preparedness plans for personnel,
- Safety equipment in terms of PPE and breathing apparatus, and
- Need for ATEX[2] classification zones around ammonia handling to reduce and mitigate risks of fire/explosion.

3.3 Safety experience from other industries

Although ammonia is a toxic substance to humans, experience accumulated during a century in agriculture has made the handling of ammonia a mature technology (Valera-Medina, Xiao, Owen-Jones, David, & Bowen, 2018). For example, the US Occupational Safety and Health Administration (OSHA) has published an informative material about Agricultural Chemical Safety which considers safe use of ammonia (Occupational Safety and Health Administration, U.S. Department of Labor, 2018). In this material, recommendations regarding PPE when working with anhydrous ammonia for agricultural are presented. The PPE should include eye protection, respiratory protection,

[2] ATEX is an abbreviation for atmospheres explosibles and is two directives from the European Committee for Standardization that covers the minimum safety requirements for workplaces and products used in explosive atmospheres.

gloves, clothing, and head covering. It is worth noting that water is the key to anhydrous ammonia safety. OSHA specifically emphasizes the importance of carrying a small "squirt" bottle of water in your shirt pocket for washing off any ammonia that may come into contact with eyes or skin.

In addition to the agriculture area, ammonia has been widely used as a refrigerant in many industrial facilities. Recognized and generally accepted good engineering practices, including laws, standards, guidelines, safety data sheets, are available in the refrigeration industry. For instance, the US Environmental Protection Agency (EPA) has released a report summarizing prevention and response actions for anhydrous ammonia refrigeration (U.S. Environmental Protection Agency, 2015). Chemical incidents are required to be reported to the EPA and up to 96% of the incidents reported by industry from 2004 – 2014 were assessed to be possible to prevent by organisational measures. Examples of organisational measures are operator training, improved procedures, and better communication of lessons learned (U.S. Environmental Protection Agency, 2015).

An investigation of ammonia accident data was presented at the IMO Maritime Safety Committee meeting in 2021 (MSC 104/15/30) (IMO MSC, 2021). Two national databases have been searched:

- The High Pressure Gas Safety Institute of Japan (KHK) database of casualties involving high pressure gases: During the period 1965 to 2019, a total of 16 832 accidents were reported. The total number involving ammonia was 787. Of these, 764 involved exclusively ammonia, and the remaining incidents involved release of another gas in addition to ammonia. Of the 764 accidents involving only ammonia, 130 resulted in fatality or injury, and the 17 fatal incidents resulted in a total of 20 fatalities (IMO MSC, 2021).
- Occupational Safety and Health Administration (OSHA) of the Department of Labor of the United States. A search in the web-based accident database for the period 1 January 1984 to 30 June 2021 for the key words "anhydrous ammonia" returned 75 accidents. Fourteen of these accidents had fatality as a consequence. In total 15 fatalities were recorded for the 14 accidents (IMO MSC, 2021)

The worst known industrial accident involving ammonia, in terms of fatalities, occurred in Dakar, Senegal in 1992 (Dharmavaram, 2023). The accident involved the catastrophic rupture of a portable tank, resulting in the release of 22 tons of anhydrous ammonia and causing 129 fatalities and 1 150 injuries (Dharmavaram, 2023). Overfilling was noted to be the main cause of the accident. Main learnings highlighted in a recent article about the accident (Dharmavaram, 2023) include the importance of ensuring that the hazards of pressurized anhydrous ammonia are understood, and that fail-safe equipment is properly designed and utilized in the production, transportation, and handling of ammonia.

Studying and understanding accidents which have already happened is a good way of avoiding similar accidents. The US Chemical Safety and Hazard Investigation Board (CSB) continuously releases high quality chemical incidents reports and easy-to-understand YouTube videos for spreading the knowledge. Three incidents involving ammonia which have been investigated by CSB are discussed in the following subsections.

3.3.1 Hydraulic shock in industrial refrigeration systems

CSB has released an investigation report and a YouTube video regarding an anhydrous ammonia release incident in industrial refrigeration systems (U.S. Chemical Safety and Hazard Investigation Board, 2015). Millard Refrigerated Services in Theodore, Alabama, USA, was a maritime export facility that exported frozen meat that operated a refrigeration system with more than 64 tons of ammonia, in five product storage freezers and three blast freezers. The Millard facility and its refrigeration system had a power loss that lasted for more than seven hours the afternoon before the incident on August 23, 2010. The refrigeration system operator manually ignored an alert in the system after the system restored power in an effort to identify equipment problems. This caused an interruption in the defrost cycle of a blast freezer evaporator, which was running. The hot gas collapsed as it quickly condensed to a liquid due to the manual bypass of the scheduled defrost cycle, which allowed low-temperature liquid and hot gas to mix in the same pipe. Accordingly, the refrigeration system at the Millard's site experienced a hydraulic shock event just before 9 in the morning the next day, which caused a catastrophic pipe system breakdown and the leakage of 14.5 tons of anhydrous ammonia. A hydraulic shock is a fast localized increase in pressure that can happen in piping or equipment when the flow rate of a liquid changes quickly. One Millard employee suffered injuries after briefly losing consciousness due to ammonia exposure. Over 800 contractors were working at a Deepwater Horizon oil disaster clean-up site, about 400 meters downwind of the ammonia cloud. Downwind of the release, 153 people reported ammonia exposures, including one Millard employee, 9 ship crew members and 143 offsite contractors. A total of 32 workers were hospitalized with 4 placed in intensive care. The release also contaminated 3 600 tons poultry and packaging material.

The CSB summarized lessons learned from this incident. First, CSB recommended not to use a single set of control valves to control multiple evaporators especially for large capacity vessel with more than 20 tons ammonia. Second, to avoid hydraulic shock, the defrost control system should be programmed to avoid the coexistence of hot gas and cold liquid in the system. Third, never allow manual interruption of evaporators in defrost unless trained and authorized personnel. Fourth, especially after power outages, ensure pump-out times are long enough to remove enough residual liquid refrigerant in the evaporator coil before introducing hot gas. Fifth, instead of attempting to disconnect leaking equipment while the refrigeration system is running, in the event of an ammonia discharge that cannot be quickly isolated, turn on the emergency shut-down switch to de-energize pumps, compressors, and valves.

3.3.2 Heat exchanger rupture and ammonia release

The tire and rubber firm Goodyear in Houston, Texas, USA, cools the synthetic rubber-making chemicals in a heat exchanger using pressurized anhydrous ammonia (U.S. Chemical Safety and Hazard, 2011). In the morning of 10 June 2008, during a maintenance, a worker closed an isolation valve which can be used to release ammonia in case of too high pressure in the heat exchanger. However, the closed valve was not reopened after the maintenance. The next morning, 11 June, another worker closed another valve which was also connected to the heat exchanger. The worker intended to clean the piping system using a steam line. The steam line flowed into the heat exchange tubes and heated the liquid ammonia. Since all the valves for venting purpose were closed, this led to rupture of the heat exchanger shell due to pressure rise.

The catastrophic rupture threw debris that struck and killed an employee passing through the area. In addition, ammonia was discharged, exposing five nearby workers to the toxin. One more employee was injured while leaving the area. Three key lessons learned were summarized by the CSB. First, companies should practice their emergency response strategies facility-wide by conducting worker headcount drills. Second, the safe operation of a process plant depends on maintenance and operations staff communicating plant conditions. Third, when there is a possibility that a pressure vessel installed in a process system could be over-pressurized by any pressure source, continual over-pressure protection must be provided.

3.3.3 Ammonia release after natural gas explosion

A significant natural gas explosion on 9 June 2009 severely destroyed the ConAgra Slim Jim meat processing plant in Garner, North Carolina, USA (U.S. Chemical Safety and Hazard Investigation Board, 2009). When a significant portion of the building collapsed, three workers were crushed to death. A total of 71 people, including three firefighters, were hospitalized because of anhydrous ammonia release from the plant's refrigeration system. Four more individuals sustained severe burn injuries. A total of 9 000 m^2 of the vegetation were damaged, and about 8.1 tons of ammonia were leaked into the atmosphere.

The natural gas explosion was caused by the installation of a new gas pipeline. Following the company’s normal practice, the new gas piping was purged with natural gas directly into the room with the gas-fired equipment. The accumulation of natural gas inside the building reached the lower explosive limit. At the same time, the building had several unclassified electrical devices, which served as multiple ignition sources for natural gas.

The CSB concluded several key lessons learned. For example, directly vent purged gases wherever possible to a secure outside area far from people and potential fire sources. Never rely solely on smell to identify fuel gas emissions. Always keep an eye on the gas concentration while performing purging.

3.4 Marine casualty events involving ammonia

Several accident and incident events related to use or carriage of ammonia on board ships have been documented. A search for marine casualties where ammonia was involved was carried out using both IHS Markit’s Sea-Web database casualty module and IMO’s Global Integrated Shipping Information System (GISIS) marine casualties and incidents module. Both databases were searched using the keyword “ammonia” in the incident description field. One additional incident was found in a recent news article. This involved an ammonia leak on the fishing vessel *Albacora Cuatro* that resulted in the deaths of two crew members (Karapetyan, 2022). Casualty events found through the database and literature search are summarized in Table 2.

Table 2 Ship incidents and accidents involving release of ammonia – 1982 to 2023

Ship Type	Incident Year	Description	Consequences (human)
Fish processing vessel	2023	Ammonia leak from refrigeration system while vessel was at sea	1 crew fatality
Fishing vessel	2022	Ammonia leak while the vessel was at anchor	2 crew fatalities
LPG tanker	2021	Inhalation of ammonia by crew members while vessel was at sea	1 crew fatality; 3 serious injuries
Fishing vessel	2020	Ammonia leak from a ruptured refrigerant line occurred while workers were cleaning the fish hold	2 fatalities
Fishing vessel	2014	Ammonia leak, due to damage in refrigerant pipe sustained while unloading fish cargo	6 fatalities; 32 injuries
Fishing vessel	2008	Large ammonia leak occurred while repairs were being made to the refrigerant system while the vessel was berthed	6 fatalities; 4 injuries
Fishing vessel	2007	Rupture of ammonia tank resulting in explosion in engine room, while vessel was berthed	5 crew fatalities; 16 injuries (one subsequent death); 4 local firefighters injured
Container ship	2005	Leak from an ammonia container close to ship accommodation block while the vessel was underway	No injuries; crew were moved to a safe location
LPG tanker	1999	Cloud of ammonia released while vessel was anchored two kilometers off Gibraltar. Cause was identified as error when opening valves during tank cleaning	No injuries reported
LPG tanker	1996	Leakage of ammonia from a loading arm while at quay	1 fatality
LPG Tanker	1983	Ammonia released when hose burst during discharge operation at the quay	6 fatalities; approximately 40 injured
Fish factory vessel	1982	Ammonia cannisters exploded as a result of fire on board the vessel initiated by welding activities during repairs at quayside	No injuries or fatalities
Fishing vessel	1982	Ammonia pipe ruptured when hit by cargo net during unloading operations	7 fatalities (stevedores); 7 injuries (stevedores)

Four of the incidents involved LPG tankers carrying ammonia as cargo, one involved a container ship, and the other involved fishing industry vessels where ammonia is used in the refrigeration system. Ten of the thirteen incidents resulted in at least one fatality. Two of the four incidents involving LPG tankers occurred during loading and unloading operations. The most recent incident involving an LPG tanker, the ammonia leak on board the *Hamburg DW* that resulted in the death of one crew member and three serious fatalities, occurred while the vessel was anchored offshore Malaysia (TheMaritimeExecutive, 2021). Under-reporting of maritime accidents to vessel accident databases has been reported previously (Hassel, 2011) and the same thing was found in this investigation. For example, the fishing vessel accident in 2022, in Table 2, was not in the databases searched but was found in news articles. In addition, two incidents were described during the interviews in this project that were not found in the databases that were searched in this study.

Ammonia has not yet been used as a fuel for vessels, so it is difficult to draw direct conclusions from the incidents found in accident databases. Future ammonia bunkering operations, however, could be considered a similar operation to loading ammonia as cargo on an LPG vessel, although likely with lower transfer rates and volumes. Using ammonia as a fuel for the vessel means that ammonia will be in different phases and spaces compared to transporting ammonia. Other types of equipment may be used when using it for propulsion compared to when transporting ammonia as cargo in a closed tank system or using it in a closed refrigeration system. For example, fuel pumps, piping system, valves, fuel consumer (internal combustion engine or fuel cell), etc. using ammonia are areas where risk of release needs to be carefully considered.

3.5 Bunkering of ammonia in port

How to safely bunker ammonia is going to be a key factor in introducing ammonia on board as a marine fuel. According to The Port of Gothenburg, bunkering is often carried out simultaneously as loading/unloading ship cargo in port, meaning close to land and civilization. A leakage during bunkering at port could therefore induce harm to not only ship crew but also for port personnel and nearby citizens.

Refrigerated (-33°C) liquified ammonia at atmospheric pressure is considered the safest way to store ammonia on board (Kay Leng Ng, Ming, Siu See Lam, & Yang, 2023). Liquified refrigerated ammonia does not flash evaporate during leakage. Instead, low-temperature ammonia is heavier than air and it forms a low-temperature pool that will evaporate slowly. (Duong, o.a., 2023) (Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping; Seaspan, 2023). However, spilled liquid ammonia on a sea surface will spread into a pool across the surface to party evaporate, partly dissolve in the seawater. The dissolution of ammonia is an exothermic process that generates a large amount of heat that can drive up the pool vaporisation rate, resulting in more turbulent mixing of ammonia vapour with the atmosphere, forming a dense ammonia cloud that spreads with the wind (Kay Leng Ng, Ming, Siu See Lam, & Yang, 2023).

Ammonia can spread far distances downwind. In the report *A bunkering safety study* (DNV, 2021), dispersion models of leaked ammonia during bunkering were simulated for the average metrological conditions in the port of Amsterdam. For refrigerated ammonia, the simulated distances varied between 155 m and 2 624 m, depending on probability, bunkering flow rate and the consequence criteria. The lower distances were in the risk contour of 10^{-5} (once every 100 000 year), bunkering flow rate of 400 m^3/h and with LSIR[3] criterion "fatal harm for individuals who stay within the distance for 24 hours a

[3] Location specific individual risk (LSIR) – the frequency per year at which an individual, who stays unprotected for 24 hours per day and 365 days per year at a specific location, is expected to sustain fatal harm.

day and 365 days per year (LSIR)". The distance of 2 624 m was found in the risk contour 10^{-6} (once every 1 000 000 year), with a bunkering flow rate of 1 000 m^3/h and the criterion "people are insufficiently protected to harm indoors" according to Netherlands Environmental and Planning Act 2022 (not necessarily fatal consequences). In all cases the time to emergency shut down or isolation of the leak was set to 120 seconds (DNV, 2021).

The mentioned distance of 2 624 matches the Swedish Civil Contingencies Agency's action plan towards Swedish Rescue Service in case of a leakage of liquified ammonia. The action plan states that in case of a large leak of ammonia, safety zones for unprotected individuals should be deployed 600 m downwind if the wind speed is 5 m/s and above, or 3 100 m radius for wind speeds less than 2 m/s (Enheten för beslutsstöd, 2016). It is important to add that the distances in the action plan are created to fit a wide range of locations and incidents and may be considered conservative. Additionally, no mitigation measures are considered for the above-mentioned distances. It is stated in the action plan that the safety distances should only be used in urgent situations when there is a lack of time and information, and that customized calculations and assessments should be carried out as soon as possible. Although the probability of larger accidents is low, an accident in port can have large consequences to nearby citizens and it will be of great importance to establish regulations, guidelines, and training programs to mitigate these risks.

The IGF Code Interim Guidelines for Ammonia-Fuelled vessels states: "Safe and suitable fuel supply, storage and bunkering arrangements should be made, capable of receiving and containing the fuel in the required state without leakage" (IMO, 2023). Like other fuels, such as LNG and methanol, bunkering guidelines for ammonia will need to be developed. These will likely take the form of an ISO Standard - for example for LNG there is a "Specification for bunkering of liquefied natural gas fuelled vessels" and there is draft standard for methanol. There will likely be guidelines developed for ammonia eventually. Emergency response plans with involvement of ship owners, port operators, bunker barge operators and responders will also be required to limit the consequences in case of large ammonia leakages near cities. Other risks such as economic losses due to port shut down or harm to marine ecosystems in case of major accidents will also need to be considered when introducing ammonia-fuelled and ammonia bunkering vessels in port. Although conventional fuels also cause harm to marine ecosystems if spilled, ammonia's specific risks to the marine environment will need to be considered.

3.6 Regulations and guidelines of ammonia as a marine fuel

Previous studies have concluded that there is an absence of harmonised international rules regarding using ammonia as a marine fuel (European Maritime Safety Agency, 2022, s. 4). To address this gap, IMO has work underway to develop guidelines for the safety of ships using ammonia as fuel. Interim Guidelines for the Safety of Ships Using Ammonia Fuels were presented in the report of the Correspondence Group on Development of Technical Provisions for Safety of Ships using Alternative Fuel, at IMO Sub-Committee on Carriage of Cargoes and Containers (CCC) session held in September 2023 (IMO CCC, 2023a). The guidelines have been closely aligned with the International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels (IGF Code). The guidelines for ammonia are expected to be finalised in 2024. The purpose of the guidelines is to provide an international standard for ships using ammonia as fuel. The guidelines are similar to those developed for other alternative fuels.

Classification societies have published rules and guidelines on ammonia. Table 3 presents an overview of such guidelines.

Table 3. Rules and guidelines from Classification Societies on the topic of ammonia as marine fuel

Classification Society	Document Title	Year Published	Brief Description
American Bureau of Shipping	Ammonia as Marine Fuel (ABS Sustainability White Paper)	2020	Provides information regarding the use of ammonia as a marine fuel in both the near term and long term
DNV	Ammonia as a Marine Fuel, White Paper	2020	Examination of the potential use of ammonia in shipping and other industries, and considerations with respect to adoption of ammonia as a marine fuel.
DNV, Norwegian Maritime Authority	Ammonia as a Marine Fuel Safety Handbook	2021	Handbook developed within the Green Shipping Programme, with the intent of providing guidance on safety aspects as part of the design of ammonia-fuelled ships.
DNV	Pt.6 Ch.2 Sec.14 Class Notation, Gas fuelled ammonia	2021, 2023 update	Detail the "criteria for the arrangement and installation of machinery for propulsion and auxiliary purposes, using ammonia as fuel". Bunkering and crew training not specifically covered in this section.
RINA	"Rules for the Classification of Ships" requirements for Class Notation "NH3 Fuelled"	2021	The rules follow the IGF Code pattern of establishing goals and functional requirements. They consider ammonia's toxicity, and describe general preventive measures to be confirmed by an extensive risk assessment on vessel specific arrangements (RINA, 2021)
Class NK (Japan)	Guidelines for the Safety of Ships Using Ammonia as Fuel	2021	The guidelines specify the requirements for the safety of ships using ammonia as fuel. In 2023 Class NK issued approval in principle for an ammonia fuel supply system for a tanker and a container vessel.
Korean Register	Guidelines for Ships Using Ammonia as Fuel	2021	The guidelines put forth functional requirements for all appliances and arrangements of ships using ammonia as fuel. Korean register granted approval in principle for an ammonia bunkering vessel.
Bureau Veritas	NR671 Ammonia-Fuelled Ships – Tentative Rules	2022	This Rule Note covers "the arrangement, installation, control and monitoring of machinery, equipment and systems using ammonia to minimize the risk to the ship, crew, passengers and the environment".
American Bureau of Shipping	Requirements for Ammonia Fueled Vessels	2023	Guidance for the design, construction, and survey of ammonia fueled vessels, with a focus on systems and arrangements for use of ammonia for propulsion and auxiliary systems. Originally published in 2021 as a "Guide for Ammonia Fueled Vessels".
Lloyd's Register	Recommendations for Design and Operation of Ammonia-Fuelled Vessels based on Multi-disciplinary Risk Analysis	2023	Describes results of an iterative quantitative risk assessment applied to three reference designs of ammonia-fuelled vessels. Additionally, an assessment of human factors considerations was carried out.

The table indicate that there is an interest in ammonia as ship fuel, since all the larger classification societies has published something on ammonia in the last four years.

LPG-carriers, governed by the International Code for the Construction and Equipment of Ships Carrying Liquified Gases in Bulk (IGC Code) may be an early adopter of ammonia as a ship fuel, at least the ones that are already carrying it as a cargo. It should however be noted that under current regulations, the use of cargoes identified as toxic products shall not be permitted as fuels (Chapter 16, regulation 16.9), hence an adaptation in the IGC Code is required to use ammonia as a fuel on these types of ships. A proposal to modify the code to exempt "ammonia, anhydrous" from the list of toxic cargoes that cannot be used as fuel was put forward at IMO's CCC 9 in September 2023 and will be further developed (CCC, 2023b).

The interim guidelines developed for ammonia follow the generic guidelines for developing IMO goal-based standards as described in MSC.1/Circ.1394/Rev2. The interim guideline specifies goals and functional requirements that provide the basis for design, construction, and operation of ships using ammonia as fuel. An additional functional requirement proposed to be added to the interim guidelines, specific to ammonia, states that "measures to minimize the health hazards associated with the toxicity of ammonia should be provided". Discussions at CCC 9 in September 2023 stated that the interim guidelines should cover refrigerated and semi-refrigerated storage of ammonia, and pressurized ammonia should be handled in the alternative design process. The draft interim guidelines currently state that there should be no venting of ammonia under normal operations. Additionally, machinery spaces should be required to be gas-safe, with emergency shut down (ESD) concepts to be covered in an alternative design process. Further work on the interim guidelines will take place in 2024.

The lack of established international regulations, the need to perform an alternative design, and the lack of existing applications and operational experience constitute barriers for ship owners to invest in alternative fuels such as ammonia. Until such guidelines are developed further into established regulations and codes, the approval of ammonia as a fuel would need to be made through an "alternative design" approach. It is the same for other alternative fuels, such as hydrogen (Bach, o.a., 2022).

Alternative design analysis of fire safety shall be performed according to SOLAS Chapter II-2, Regulation 17. It means that the design and arrangements must meet the fire safety objectives and functional requirements of SOLAS Chapter II-2 and achieve the same degree of fire safety as if prescriptive requirements were met. The assessment is ship unique and if the assumptions, and operational restrictions that were stipulated in the analysis are changed, it shall be carried out under the changed condition and shall be approved again by the Administration.

3.7 Technology

So far there are no vessels using ammonia as fuel, but a lot of initiatives and investments are put into this field. When it comes to the design of ships fuelled by ammonia, Seaspan and MMMCZC has published a report introducing a principal concept design for a 15,000 TEU ammonia driven container vessel (Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping; Seaspan, 2023). The concept is a dual fuel main engine and diesel generator, using ammonia and low-sulfur fuel oil (LSFO). A section view with the distribution of storage tanks is shown in a screenshot from the report in Figure 2.

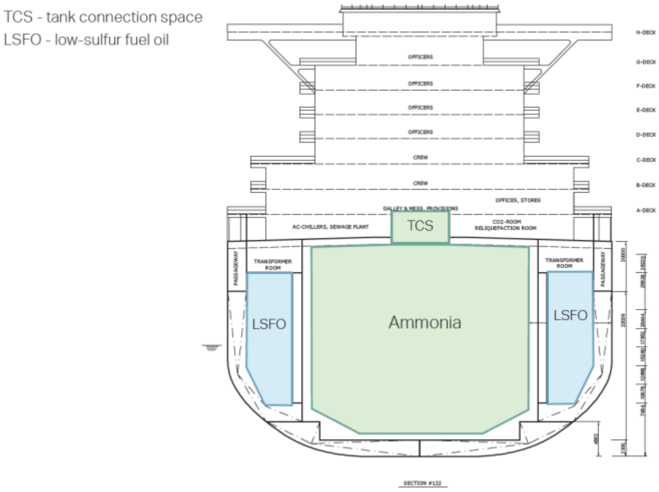

Figure 2. Ammonia and storage tank arrangement (Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping; Seaspan, 2023)

Another ship type using ammonia was found in document MSC 104/15/10 submitted to MSC by Japan. Figure 3 shows a screenshot of a schematic drawing for a bulk carrier (MSC 104/15/10, 2021).

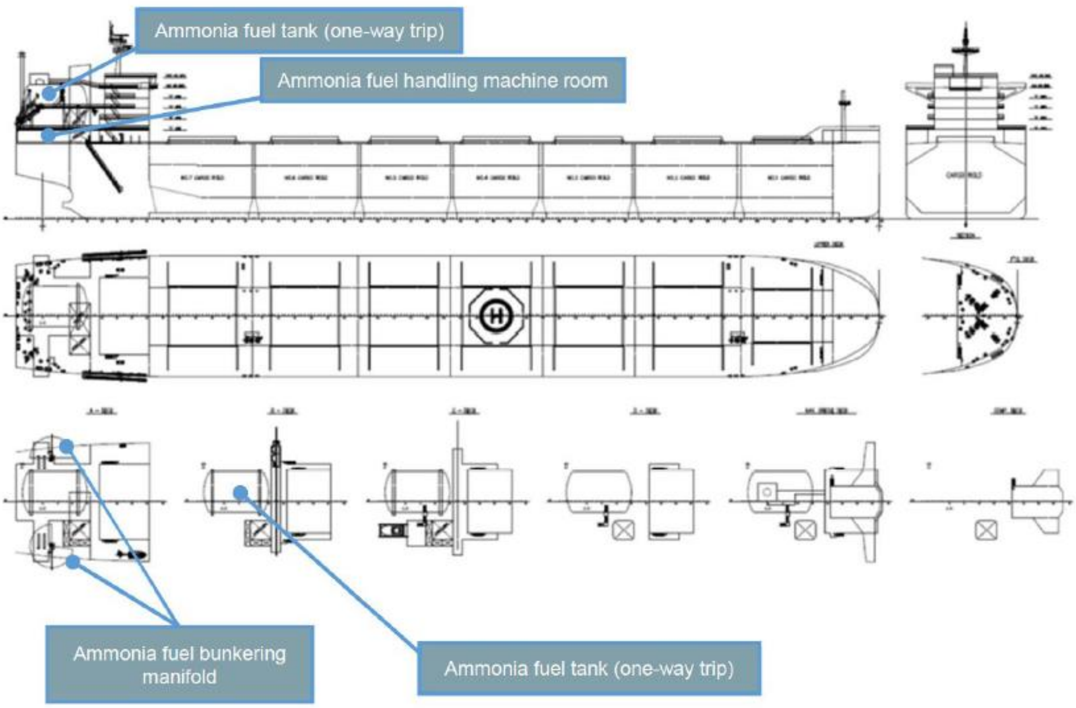

Figure 3. General arrangements of the ammonia-fuelled ship (MSC 104/15/10, 2021).

Representatives from emergency organisations who were interviewed in the present study mentioned that it is important for them to be informed in an early phase of the development, since they should gain knowledge and be able to assist in case of emergency. The design needs to consider where safety critical functions are located so that they are accessible. Already today, the land-based rescue service has knowledge about chemical accidents; some individuals have a standard knowledge, and some have more education and training.

All interviewees mentioned education and knowledge as the most important aspect to safely implement ammonia as a new ship fuel. The education is needed for all who can be involved in the process, from crew on board the ammonia fuelled ship, to harbour and bunkering personnel, to emergency responders.

The four interviews showed that there is existing knowledge about ammonia, but there is a need to transfer and apply this to the process of introducing ammonia powered ships. Work methods may need to be added or changed in the organization. It was also pointed out that crews on ships carrying ammonia have a higher level of safety training than those on, e.g., general cargo ships, and the crew on a gas carrier are on their toes for a chemical release and will act almost instinctively.

In August 2023, Lloyds Register and Maersk McKinney Moeller Centre for Zero Carbon Shipping published a report with a high focus on human factors. The report gives a good overview of human factor issues related to ammonia. The report covers bunkering, on board fuel handling and maintenance. A wide variety of factors are presented, including:

- Occupational health hazards: Skin exposure, inhalation etc.
- Ergonomics (e.g., for PPE, design of surveillance systems and alarms, layouts, passages, and safe havens).
- Roles, responsibilities, and competence: New specialist roles on board, new competences in handling, maintenance, rules & regulations etc.
- Processes & procedures: The need for extended job safety analyses, permit systems, lock-out tags, new emergency procedures, new maintenance procedures etc.
- Process safety hazards: E.g., leak detection & repair, explosivity & flammability, corrosivity.
- Management of change: The challenges of realizing this wide set of safety measures in a systematic way, and with enough quality.

4 Workshop - Safety aspects of bunkering ammonia

The workshop was divided into three activities: creation of timeline, prioritization of barriers to overcome to enable bunkering of ammonia in Port of Gothenburg and detailing the top priority barriers.

4.1 Creation of a timeline

Participants were invited to write down activities or tasks needed to realize bunkering of ammonia – using the Port of Gothenburg as a case. Some explanatory comments that were made around the table about some of the activities posted were as follows:

- Dispersion analysis was noted by many participants to be an activity required relatively early in the project.
- A key activity is to obtain risk-based approval of the vessel.

- Clear bunkering procedures/instructions need to be developed.
- Standards and acceptance procedures need to be in place. It was considered that there is not a universally accepted limit for what is acceptable regarding modelling of dispersion and for exposure limits. For a vessel operator, it is important that if their ship meets all SOLAS requirements then they expect that they should be able to enter any port. It was noted that ports around the world, however, do have different requirements, even though they are working together in IAPH (International Association of Ports and Harbours).
- Emergency response plans (ERP) must be developed – encompassing everything (on board the ship, port, emergency services and first response agencies, and any potentially affected adjacent areas). Leak management is one detail here but there are many more aspects that should be included. Conducting a scenario selection workshop where worst case scenarios are identified will allow all to prepare and assess suitable responses.
- Emergency response – noted that for Port of Gothenburg, the Swedish Rescue Services is responsible for incidents while at quay, while other actors are responsible at sea. In Swedish territory, The Swedish Maritime Administration is the responsible authority for maritime rescue services. This borderline, and handling of this, needs to be defined during hazid/bunker operation.
- Cooperation within the shipping cluster is important to ensure consistency among different ports, to ensure that the interface between the ship risk assessment and the port-based risk assessment aligns and covers all potential scenarios and risks.
- Safe equipment and safe connections suitable for ammonia and the marine environment are needed.
- Ship construction: information on this is important for emergency response organizations. They need to know where ammonia tanks and bunkering stations on board are when responding to incidents.
- Permits required for ammonia bunkering and handling at the Port of Gothenburg: including the Environmental Code, SEVESO (necessary if storage facilities are to be built for ammonia).
- Bunkering procedure development: truck-to-ship; ship-to-ship; and land storage-to-ship all need to be considered as they have different risks, but they will come at different stages. Land storage will likely be the last one to be used. Additionally, ship-to-ship bunkering may take place at anchorage or at quayside. There are different risks for each of these as well – at anchorage there could be risk of collisions at speed while at quayside the potential consequences and exposed population will be larger. Ship-to-ship will likely be easier for simultaneous operations (SIMOPS).
- For truck transport, ammonia is pressurized – not refrigerated. Ammonia liquefied at pressure needs about 10 bar. It cannot be bunkered to a cold tank. Liquid ammonia is preferred for ship fuel due to the higher density. Ship to ship bunkering of refrigerated ammonia (-33°C at ambient pressure) is possible.
- Supply management of ammonia is needed.

- Public communication plan was noted to be important by all parties for acceptance of bunkering activities in the main port areas. The ship operator expects that this should be done by the authorities or the port. In Sweden, public consultation is required for this type of activity. It was noted that when LNG was first bunkered there was a lot of public concern but now there have been about 3 000 bunkering instances carried out in the port of Stockholm and everything goes very well. It was considered important to have results of the port risk assessment available for the public consultation.
- Training plans need to be developed and it will be difficult to have "standardized" layouts and procedures. It is important to note that vessels are "prototypes" as generally each ship is unique and built 3 or 4 at a time. Vessels cannot be compared to cars and airplanes which are mass produced. Human surveillance and intervention will be required more for a ship because of this. For crew on an ammonia-fueled vessel, the IMO's STCW Code (The Seafarers' Training, Certification and Watchkeeping Code) sets out mandatory minimum requirements for both basic and advanced training. Model training code material has yet to be developed for ammonia, however. Bunker barge operators training will be mandatory for vessels that are covered by the IGC Code. Similarly, personnel based at the port such as terminal personnel, pilots, local rescue services, etc. will need training appropriate to their roles.
- Single failure should not result in a leakage (requirement for low-flashpoint fuel alternative designs).
- Risk assessment for the vessel approval should be detailed for specific areas and concerns that are new for ammonia – currently HAZID can be done at a fairly high (overview) level for LNG and battery ships. There have been many LNG approvals and the HAZIDs are often very similar to what has been done before – they are required according to the regulation but have become quite "routine". More detailed assessments should be done for ammonia vessels.

The timeline, containing safety critical activities that must be solved through industry collaboration or research, is presented in its entirety in Appendix A – Bunkering of ammonia timeline.

4.2 Prioritizing

The six barriers (or groups of barriers) on the timeline that received the most votes during the workshop were:

- ❖ Creation of an international bunkering standard.
- ❖ Bunker station equipment and layout on board.
- ❖ Risk assessment.
- ❖ Public communication plan.
- ❖ Personnel competence, experience and training.
- ❖ Sharing of accident/incident knowledge.

This means that these are the activities that the group judged to be the largest barriers to overcome to enable ammonia bunkering. Naturally, this is not an exhaustive list of the activities that must be addressed going forward to enable ammonia bunkering. The prioritizing is without internal order. Further details of these activities were written down by smaller working groups and are reported in the section 4.3.

4.3 Detailing descriptions of highest rated activities

The six top-rated activities are further detailed below. Method of how this detailing was done is found in section 2.2. Due to time limitation of the workshop, the group was mostly writing down bullet point or shorter sentences.

4.3.1 Creation of an international bunkering standard

An international bunkering standard needs to be created, and to establish a draft of such a standard would be the first step.

Knowledge gaps and other barriers that prevent completion of this activity:	- To understand ammonia release characteristics, associated consequences, and emergency response required. For example, o What is considered a "small" spill and what is considered a "large" spill? o How fast do we need to close the valves to not reach a large spill? o What safety systems and equipment need to be available? - Vapour return needs more knowledge, not used to this during bunkering today with conventional fuel oil. - Gas detection on both vessel and in port further to be understood and implemented. - Handling of ammonia water, required to be contained at some ports by a dedicated system. - Look into IGC Code and what is noted about the ammonia leakage in cargo transfer procedure. - Discussion on emergency shut down (ESD) link, communication so both sides (vessel and bunker barge) can stop the bunkering.
What tasks or further studies are needed to fill the knowledge gaps and overcome barriers?	- Use the existing standards (e.g. port standards, methanol and LNG bunkering standards) and see what would need to be different with ammonia due to its different properties. - Learn from gas carriers and their safety routines etc. - Define credible scenarios and simulate consequences for different weather conditions.
Collaborations and actors necessary to complete this activity/tasks?	- Chemical ports, and other ports with ammonia experience. - Port, vessel, authority, chemical experience and perhaps bunker operators. Rescue Service in a second round. - The Oil Companies International Marine Forum (OCIMF). - The Society of International Gas Tanker and Terminal Operators (SIGTTO). - International Safety Guide for Oil Tankers and Terminals (ISGOTT).

Additional aspects to consider:	- For example, consequences for different weather conditions and emergency operations.

4.3.2 Bunker station equipment and on board layout

Layout and equipment for bunker stations on board vessels are needed, including safety barriers.

Knowledge gaps and other barriers that prevent completion of this activity:	- How large spill can a bunker station/space take care of? - Dimensioned for the worst credible leak scenario during ammonia bunkering. - For emergency response planning it is important to understand the ship layout and have a layout of the ship, to understand what the preferred option is to enter an ammonia powered ship. Check the possibility to have the most common ship layouts available to emergency responders. - Overcome the initial challenge by training emergency responders to ask what fuel is on board the vessel involved in the accident. - Vapour return needs more knowledge, not used to this during bunkering today with conventional fuel oil. - Bunkering system on ammonia fuelled vessel will have to be purged to remove ammonia. The hose must be empty, the ammonia must go back to the ship or the tank. Couplings shall be leak-free. How to make this layout in practice. Depends on Ship-to-Ship bunkering or Truck-to-Ship bunkering. - Load and bunker at the same time (simultaneous operations) desired.
What tasks or further studies are needed to fill the knowledge gaps and overcome barriers?	- Person in charge - awareness education. Emergency responders cannot know all ship types and it must be known what fuel the vessel is powered by.
Collaborations and actors necessary to complete this activity/tasks?	- Bunker experts (bunker operator), buying a service and they are experts in bunkering (therefore we do not see that mockup of on board bunkering station is not necessarily needed). Sufficient time and well-chosen location with regards to safety aspects the first times of bunkering. Time for double check and so on.
Additional aspects to consider:	- Crew must be trained to respond to an incident. - A small leakage scenario can also be interesting to consider, so small that when emergency responders arrive the spill has already dispersed.

4.3.3 Risk assessment

To perform risk assessments of ship and port, related to bunkering it is needed to identify, evaluate and mitigate relevant risks. The objective would be to identify, evaluate and mitigate risks related to loss of life, the environment and assets. It would be necessary to include crew, employees and visitors in the port area, as well as 3rd party.

Knowledge gaps and other barriers that prevent completion of this activity:	- Harbor, crew and general public need general information. - Consistency of dispersion modelling is a barrier. There are different dispersion models used and the quality of input data may also vary, so it can be difficult to interpret results and apply them consistently. There is a need for more knowledge about the models used e.g., with regard to threshold limits.
What tasks or further studies are needed to fill the knowledge gaps and overcome barriers?	- Ensure that risk assessments are carried out, and information is shared, specific to ships and ports. - Include relevant stakeholders in port, shipowners, engineering/consultants etc. - Check different transferring operations. - Gain experience/info from companies that transport ammonia as cargo.
Collaborations and actors necessary to complete this activity/tasks?	- See above
Additional aspects to consider:	- To ensure knowledge sharing, confidentiality issues must be solved.

4.3.4 Public communication plan

A communication plan for public perception/acceptance needs to be developed and executed.

Knowledge gaps and other barriers that prevent completion of this activity:	- There is a lot of knowledge regarding ammonia in other industries, but how ammonia is to be handled as fuel is a whole different story. There is a lack of experience within the business.
What tasks or further studies are needed to fill the knowledge gaps and overcome barriers?	- Even though tankers and ships with dangerous chemical as fuel are exempt from the SEVESO law, the port would benefit from using the requirements and work methods in SEVESO as guidelines regarding communication to the public and conducting contingency plans together with city authorities and rescue service. The upper level of SEVESO with more strict requirements is 200 tons of ammonia. Representatives from DFDS mentioned that their concept design in the fall of 2023 has a tank volume of 1 800 m3 which is approximately 1 200 tons ammonia.

	- After the risk assessment, the port should identify which groups are affected in the worst-case scenario. - Prepare questions and answers in as simple a way as possible so that all people can absorb the information. - Communication with authorities after the analysis is required. - Develop methods to provide early warnings to industries and people within the port cluster in case of a major leak. One method is through text messages.
Collaborations and actors necessary to complete this activity/tasks?	- The port should have public hearings to involve the citizens and share information. - Go out with information through various channels. Today's channels are newspapers (within shipping), the ports website and press releases. More channels to share information are desired.

4.3.5 Personnel competence, experience and training

Technical solutions are worth little without competent and experienced individuals: crews, port personnel, management, suppliers.

Knowledge gaps and other barriers that prevent completion of this activity:	- There is currently a lack of practical experience regarding ammonia bunkering. - What should competence-based training be based on? - How to gain the knowledge and experience from other industries, like the LPG tanker segment?
What tasks or further studies are needed to fill the knowledge gaps and overcome barriers?	- Management of change: map out training needs, training intended to avoid complacency. - Competence transfer: gather training routines from other industries and transfer to shipping context.
Collaborations and actors necessary to complete this activity/tasks?	- Collaborations with other industries (incl rescue service, rail, agriculture, cooling/ventilation) could improve competence within the shipping industry.
Additional aspects to consider:	- For an engine room crew there might be a complacency issue to start working with ammonia. For example, use of zones and PPE. - Training also includes training collaboration between stakeholders.

4.3.6 Sharing of accident/incident knowledge

Creation of a system for sharing incident/accident data on an industry basis. The ISM regime ensures that, within the shipping company, procedures will be in place for handling near misses, incidents and accidents but sharing is missing.

Knowledge gaps and other barriers that prevent completion of this activity:	- Simple and effective system reporting tools are not available today. E.g. through using a phone. - No incentive to do so (and no feedback). - Lack of trust between industry stakeholders. - Under-developed professional safety culture.
What tasks or further studies are needed to fill the knowledge gaps and overcome barriers?	- Feedback and follow-up on incident input is needed. - Appointing an organization in charge of an industry wide reporting system. - Is it possible to create an agreement on incident data sharing? Compare with airlines.
Collaborations and actors necessary to complete this activity/tasks?	- Include ship, port authorities, class, insurance, flag states, suppliers, port actors, emergency response. - Investigate if the IMCA model for dynamic position (DP) event and incident reporting could be used: https://www.imca-int.com/dp-events-and-incidents/
Additional aspects to consider:	- What are the incident statistics for bunkering today? Survey of bunkering activities. *Green bunkering concept* involved all bunker shipowners. - It might not be possible to be anonymous in the beginning (few accidents).

5 Discussion

Ammonia has been used and handled for many years in different industries (fishery, agriculture, refrigeration, etc.) and there is long-term experience from transporting it at sea. Many studies, including this one, mention that learning from previous experience is a good way to minimize risks and overcome barriers. It can for example provide a better background for risk assessments and improve the design of ships and bunker stations. Information sharing regarding use and transportation of ammonia at sea, however, was not found to be widespread and more should be done in this area. The shipping industry is moving forward to adopt new fuels, and ammonia experts need to be part of this transition to avoid both too high and/or too low requirements being established for the use of ammonia as a marine fuel.

According to EPA, up to 96% of the incidents reported by industry from 2004 to 2014 were assessed to be possible to prevent by organisational measures, such as training, improved procedures, and better communication of lessons learned (U.S. Environmental Protection Agency, 2015). Open sharing of information related to safety would benefit the process of introducing ammonia as a marine fuel, and it was brought up in the workshop that such systems could be inspired by the aviation industry. The offshore industry also has a well-developed safety culture and could serve as a model. Furthermore, International Marine Contractors Association (IMCA) has a system for quickly reporting incidents. Under-reporting of maritime accidents to vessel accident databases has been reported previously (Hassel, 2011) and the same thing was found in this investigation. It can be concluded that a change is needed, and that the introduction of new fuels accelerates the need for change. Safety shall not be competitive.

Since ammonia has not yet been used as a fuel on board vessels, it is difficult to draw direct conclusions from the incidents found in marine accident databases which include ammonia as cargo or refrigerant agent. When introducing ammonia as a fuel in shipping, much can be learned from gas carriers and their safety culture, their routines, training etc. The use of ammonia as a fuel, however, brings different types of risks and potential release scenarios from fuel transfer systems and fuel consumers, and these need additional consideration. Crew training and safe manning was lifted as important topics in this project. Manning is influenced by flag state, and shipping is driven by economic issues. Having lower crew costs may not be compatible with safe manning, which was noted as a problem during the workshop in this project.

For the emergency response organization, they may need to expand their response capabilities and staff training to be able to respond to incidents involving new ship fuels such as ammonia. The Swedish Coast Guard has one ship classified for “chemical response” and this can be hours away from a possible ammonia accident. Irrespective of how the emergency response should be organized and what resources are needed, it is important for emergency response organisations to be informed and involved at an early phase of the introduction of a new fuel. Since they must gain knowledge and be able to assist in case of emergency, they also need to understand the background, the design and the safety considerations.

An Emergency Response Service (ERS) system which is mandatory for tankers may be something to consider for all ammonia-fueled vessels. ERS provides shore-based service with access to ship information to be able to assess various options in the event of an emergency; this includes the availability of ship drawings ready to be shared.

A standard approach to how the bunkering station layout on a ship is designed would be helpful for training and emergency response. It could be useful to create a mock-up and have standardized equipment. One of the early adopters may perhaps set the trend for this.

6 Conclusion

Ammonia has not yet been used as a fuel on board vessels and hence no bunkering of ammonia as a ship fuel has been conducted. Many initiatives are ongoing and vessel operators hope to see their first ammonia driven vessel perform bunkering operation in the coming five years.

The results from the workshop in this study are in line with the reference literature. For example, the Lighthouse pre-study “The potential of ammonia as fuel for shipping” (Hansson, Fridell, & Brynolf, 2020) was completed in 2020 and noted that “appropriate chemically resistant protective clothing and other safety measures for those handling the fuel will be needed.”. PPE is considered a necessary part of the safety concept and will be required for ammonia fuelled vessels in the future. Training and education were top voted during this workshop and were also further detailed as future areas where more research is needed. Technical solutions are worth little without competent and experienced individuals: crew, port personnel, management, suppliers, rescue service, etc.

Further, the study by Hansson et al. (2020) noted the importance of public acceptance for the introduction of ammonia as a marine fuel. The public perception was discussed during the workshop in the current study and a public communication plan was one of the top voted activities.

From the interviews conducted it can be concluded that all interviewees mentioned training and knowledge as the most important parts to safely implement ammonia as a new ship fuel. The needs of training and education apply to all stakeholders, from seafarers on board ammonia fuelled ships, to bunkering personnel and emergency responders. The similar need for the many stakeholders makes it event that cooperation is key in the transition to reducing greenhouse gases.

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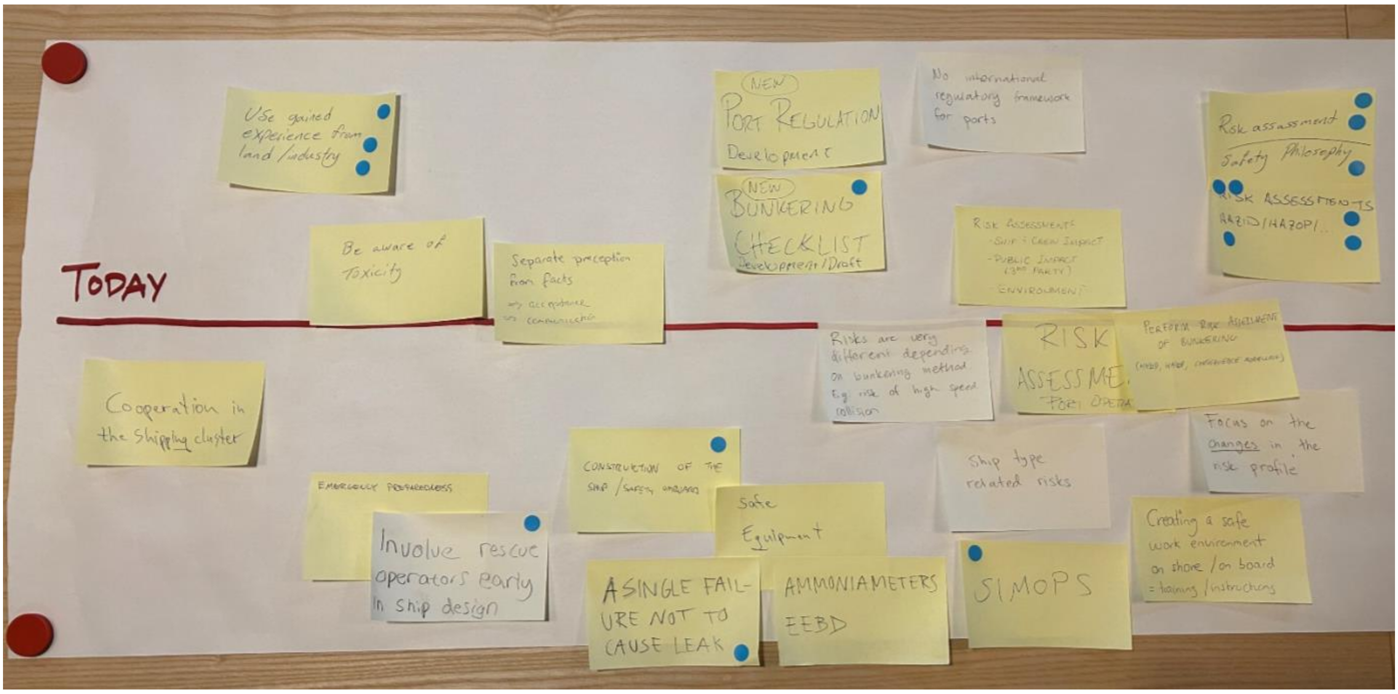
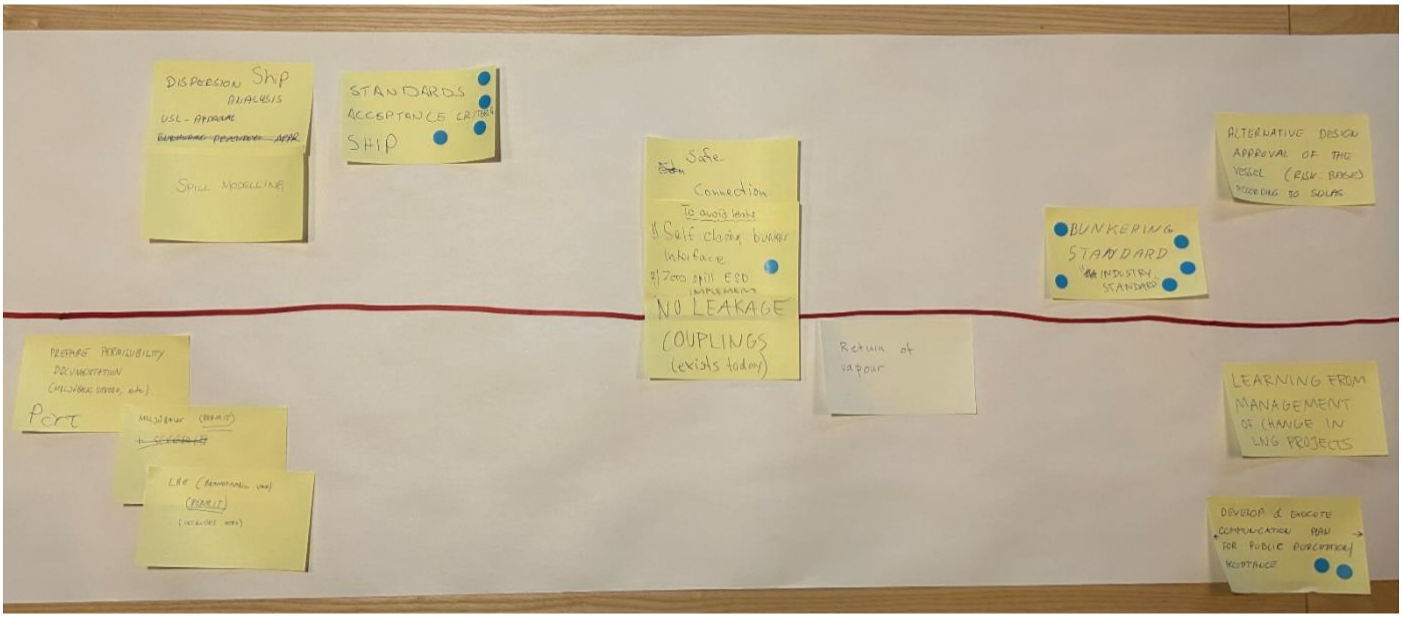
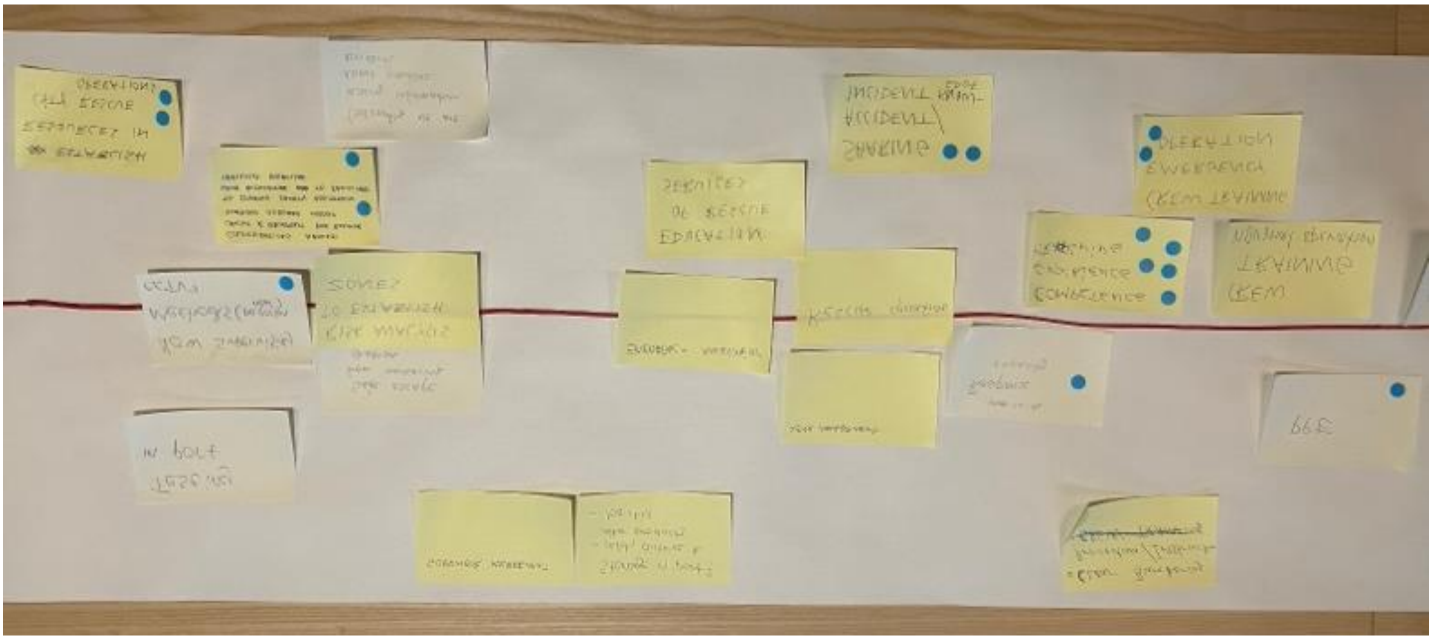
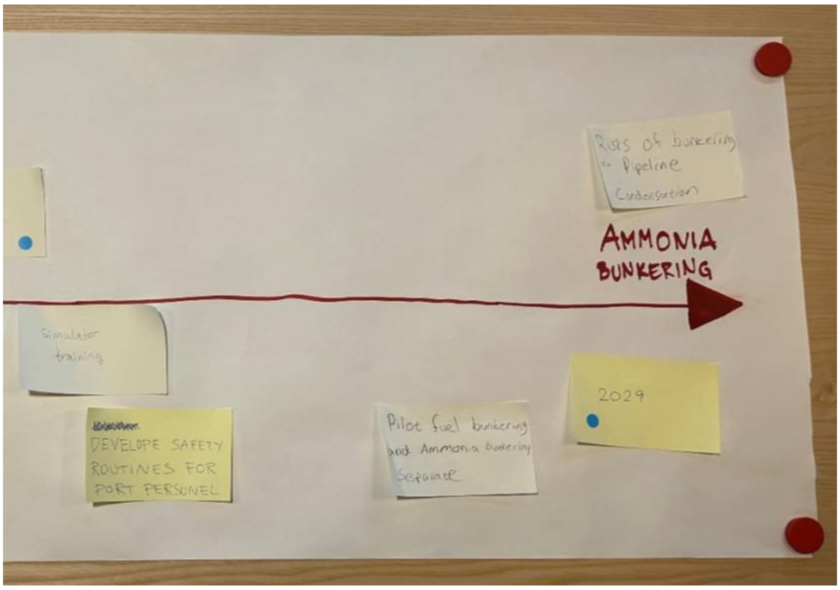
Appendix A – Bunkering of ammonia timeline








Risks of bunkering
– Pipeline
Condensation
AMMONIA
BUNKERING
Simulator
training
DEVELOPE SAFETY
ROUTINES FOR
PORT PERSONEL
Pilot fuel bunkering
and Ammonia bunkering
Separate
2029

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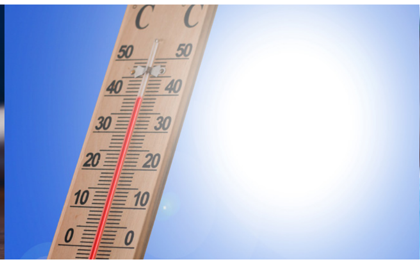

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