Safety risk management of ammonia fuelled ships

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1. Introduction

Ammonia is deemed to be a promising fuel to reduce carbon emissions from shipping as well as a viable alternative solution as a global hydrogen carrier. Several initiatives are ongoing to demonstrate the use of ammonia in fuel cells and internal combustion engines for use on offshore vessels. While the interest in ammonia increases, so do the concerns regarding its safety. Ammonia is toxic to humans and to marine life, and, at certain concentrations, when mixed with air, could ignite resulting in explosions. Although safely transported as a chemical and fertilizer for decades, ammonia has always been stored in dedicated carriers and handled by highly skilled personnel, crews and operators. The potential large-scale implementation of ammonia as a fuel in the maritime environment and its handling by different users introduces emerging risks and a potential need for further guidance. This work presents a bibliographic approach for the definition of accidental scenarios for safety risk management of ammonia fuelled offshore vessels and ammonia carriers. A screening of historical accidental events potentially resulting in ammonia released to sea is performed to identify key safety risk management aspects.

2. Methods

This analysis was conducted as a bibliographic literature review of past accidents involving refrigerated liquid ammonia. Both storage and transfer operations were considered as well as different industrial domains, such as fertilizer industry, process industry and food industry, including also fishing vessels which use ammonia as a refrigerant. The study focuses on storage conditions and operations that can provide valuable insight into the use of ammonia as ship fuel.

3. Results and discussion

Ammonia as a ship fuel is likely to be stored on board as refrigerated liquid, slightly pressurized above atmospheric pressure. Compared to ammonia as cargo, guidelines and procedures for the use of ammonia as a fuel are still under development (IMO, 2024; DNV, 2024). Furthermore, the operational experience with ammonia as ship fuel is limited and not established (ABS, 2024). Mitigation measures are therefore of foremost importance. Compared to Liquefied Natural Gas (LNG), for which the requirements are set by the IGF code, when ammonia is used as ship fuel, a comprehensive risk assessment is required. Therefore, the definition of risk assessment scenarios for the quantitative analysis of risk for ammonia as ship fuel is of outmost importance.

Three incident tiers can be considered to define the safety risk management and emergency preparedness strategy for ammonia releases *at sea* (GCMD, 2024):

1. First tier incidents: releases from connection and flanges, contained on board. These are releases that are contained within a specific area;
2. Second tier incidents: medium and large releases of ammonia, potentially spreading beyond operational area and activating the emergency release system that might cause overboard spillage; and
3. Third tier incidents: catastrophic releases resulting in overboard leaks, including hose rupture.

From this categorization as well as from the analysis of the reported ammonia accidents from different databases sources (such as the analyses presented by Gant et al. 2024, Bucelli et al., 2025), two key considerations are to be made.

Firstly, the operational conditions and the release scenario should be considered, and especially the rate, duration and location. Secondly, the potential impact and effects of the ammonia release should be assessed. Ammonia is toxic to human and its dispersion can result in clouds within dangerous thresholds in the atmosphere. Dispersion studies should be carried out to identify mitigation measures for different stakeholders.

Different ammonia storage conditions on the ship can also play a significant role in the fate of ammonia upon release. Releases from deck-mounted tanks and hull-located tanks have some differences that need to be considered (see Masia et al., 2024). These two cases may require different containment and integrity management.

For the case of ammonia onboard ships as marine fuel, safety assessments should consider dispersion of ammonia, both in terms of toxic and flammable hazards (including the potential for confined explosions in some areas). Also, releases of ammonia onto the deck, onto the sea, and below the sea (e.g., from a ship collision). These can potentially impact both human health and the environment. From the investigation by Bucelli et al. (2024), based on the ARIA database, 10% of documented incidents resulted in environmental impact including effects on vegetation, water contamination, and aquatic species. This is of concern when *directly* using and transferring ammonia over water.

It should also be noted that fires and explosions are less frequent outcomes of ammonia releases (Bucelli et al., 2025), but could represent a risk when the ammonia gas is indoors and confined and exposed to ignition sources (e.g., hot surfaces), as is potentially the case in engine rooms for maritime applications.

The lesson learnt from the analysed incidents and accidents involving refrigerated liquid ammonia that can be relevant in the context of using it as ship fuel can be summarised as:

| **Key safety aspect** | **Description** |
| --- | --- |
| Material selection | Materials used in presence of ammonia should be compatible and suitable. Their compatibility should be considered for both new-built and retrofits. |
| Equipment integrity | In addition to standard equipment integrity issues, the potential for stress corrosion cracking and corrosion under insulation should be addressed when handling ammonia, with suitable procedures for inspection and maintenance to reduce the potential for loss of integrity. Cold spill protection may also need to be considered in some areas. |
| Maintenance | Maintenance errors and component failures are one of the drivers for ammonia accidents and incidents. Protocols, procedures and training for maintenance and inspection should reduce the risk and the potential exposure to ammonia gas. |
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| Gas detection systems | Suitable gas detection systems for ammonia should be in place. The gas detection system can be a part of the leakage detection system, together with low temperature measurements and other operational monitoring parameters (such as temperature and pressure on lines and storage vessels). The ammonia gas detection system should provide quick and reliable detection of ammonia releases, issue warnings and *automatically* initiate safety actions (such as emergency shut down and automatic isolation of leakages to reduce their consequences). (Green Shipping Program, 2023). |
| Ammonia tank location onboard | The location of the tank on board is proven to be critical for different tier release scenarios. Hull-located tanks are less prone to catastrophic release scenarios upon collision. |
| Personal Protection Equipment (PPE) | Different PPE should be planned for operations, maintenance and emergency response, based on the type and amount of potential exposure to ammonia. Consideration should be given to toxic inhalation protection, thermal protection (cold spills and fire) and protection from corrosive burns. |
| Effect distances | Understanding the potential extent of ammonia effect distances can support the development of dedicated handling procedures and emergency response. Consideration should be given to whether the ammonia release will impact trained and equipped operators or third parties and members of the public. Several stakeholders may be involved in the case of refuelling operations at ports. Risk analysis and quantification can support the identification of access-controlled zones.  Tools that can dynamically estimate the ammonia effect distances could support the evacuation and mitigation procedures in case of large ammonia releases, considering also the wind direction and speed. |
| Emergency preparedness | Emergency response to ammonia releases at sea requires modification of the conventional chemical spill emergency response plans (ERPs), mostly related to its toxicity. |
| Environmental damage | The environmental effects of ammonia on the marine life should be understood and handled accordingly. Ammonia can be a threat to fish, vegetation and marine life. |
| Regulation and certification | The ongoing development of regulations and certification requirements should support the safe introduction of ammonia as an alternative marine fuel for decarbonization. There are many stakeholders involved in this process: ship designers, operators, port authorities, regulators and certification bodies. Collaboration is key to successful implementation. |

Table 1. Key safety aspects in implementing ammonia as ship fuel.

4. Conclusions

This study presents a series of key factors for the safety risk management of ammonia used onboard ships as *decarbonised* fuel. The study is based on a literature reviews and findings from incident investigations. A total of nine factors were identified as being important safety considerations. These included maintenance and emergency response procedures, as well as operational procedures for carrying out critical operations, such as, bunkering. Some of these topics, notably effect distances, are the subject of ongoing research projects.

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