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Accident scenarios for safety risk management of ammonia fuelled ships

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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 explode if ignited. Although safely transported as a chemical and fertilizer for decades, ammonia has been stored in dedicated carriers. Transfer and handling operations have been performed in this time by highly trained and specialized crews and operators. The potential large-scale implementation of ammonia in the maritime environment and its handling by different users introduce emerging risks and a potential for stricter requirements. 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 is performed and a statistical analysis of the causes and consequences of the relevant events is provided to support a tailored and effective risk management.

Keywords: Ammonia, accidents, maritime safety.

1. Introduction

The International Maritime Organization (IMO) has defined in the 2023 IMO GHG Strategy an ambitious framework to reduce carbon intensity of international shipping by 40% by 2030 (Brinks and Hektor 2020)(International Maritime Organization 2023). The 2023 IMO GHG Strategy also includes a plan for the uptake of zero or near-zero greenhouse gas (GHG) emission technologies, fuels and energy sources. These must represent at least 5% of the energy used by international shipping by 2030, striving for 10%(International Maritime Organization 2023).

Anhydrous ammonia is often considered as an alternative to replace conventional maritime fuels with the aim of meeting the decarbonization targets set for global shipping. Currently, it is already stored and used as a refrigerant on board shipping vessels. Compared to other alternative fuels, such as hydrogen, ammonia has a higher calorific value per unit volume and therefore it is easier to store, use and handle on board ships. Efforts are ongoing to demonstrate its cost-effective use as a fuel in internal combustion engines for ship propulsion (f.e. AMAZE project) or offshore power generation. Research is also focused on its use as a hydrogen carrier.

Either as a fuel or as an energy carrier, ammonia is stored, used and handled on the waterways or in their proximity. For the use as a refrigerant, when used as shipping fuel ammonia is stored as refrigerated liquid (-33°C) and pressurized. However, unlike when used as a refrigerant, the amount of ammonia stored on board as ship fuel is larger and could lead to more serious effects in the event of an accident but it is kept at atmospheric conditions. This is deemed to be the safest storage condition (DNV GL 2021). Moreover, in maritime applications, emerging risks could be introduced due to the novelty of the application and increased amount and operations in the sector.

While used as a fertilizer for decades, accidents leading to severe injuries and fatalities have been reported (S.D. and French Ministry of Ecology 2014). Besides being toxic for humans and potentially flammable, ammonia has also severe effects on marine life: concentrations above 1700 mg/L represent a threat for fish and marine organisms. Therefore, increasing the percentage of the fleet storing and using ammonia on the waterways can pose a risk from an environmental perspective that should be considered.

This paper presents the investigation of liquid ammonia related accidents in a specific database. The goal of this analysis is to assess the causes that led to ammonia accidents in the past decades, from 1950s to nowadays, to provide a basis for the development of a specific risk management framework of ammonia used as a shipping fuel. Both the effects of ammonia releases to humans and the environment are considered in the database investigation.

2. Methodology

2.1. *Database description*

Data on past accidents involving ammonia releases were obtained from the ARIA (Analyse, Recherche et Information sur les Accidents) database (S.D. and French Ministry of Ecology 2014). The database, which is one of the main European sources on technological accidents, is administrated by the French Ministry and collects around 50,000 accidents, mainly occurred in France, that threatened the public safety and the environment. Since 1992, information from inspections of classified installation, fire and rescue services and other government services were collected to build the database. In there, the events are presented in two ways. For some accidents, a detailed report with the most relevant information, including the description of the accident location, the course of events, the consequences, the causes and circumstances and the actions taken after the event is provided. However, in most cases, only a summary of the accident is available.

2.2. *Past accidents selection*

The scope of the present work is to collect data on past accidents involving liquid ammonia. Thus, the keywords "liquid" and "NH_3" were combined with the logical "AND" operator to extract the accidents of interest in the database. These keywords were selected to ensure that both the accidents with an available English translation and those documented solely in French version were included in the search (since "liquide NH3" in French is captured by the chosen keywords). A total of 92 accidents compliant with the chosen criteria were found. A further screening was performed to eliminate the events in which the liquid ammonia was not used as a process fluid (i.e., ammonia produced by an unexpected reaction). Following this, 10 accidents were excluded, leaving 82 relevant events for further analysis. The information retrieved and systematically organized is summarized in Table 1.

Table 1. Classification of the information retrieved from the past accidents collected from the database. ID = Identification number.

Information	Numerical entry	Text entry
ID	X	
Year	X	
Country		X
Injuries	X	
Type of injury		X
Fatalities	X	
Economic losses	X	X
Causes		X
Scenario		X
Asset damage		X

The following definitions are considered in this analysis:

- Asset damage: damage to targets nearby the accident location (i.e., equipment in the accident facility, roads, external installations, etc.).
- Scenario: final event generated from the accident, including fires, explosions, and toxic dispersions.

3. Results and discussion

In Figure 1, the 82 accidents selected from the database are grouped by year of occurrence, and their distribution over the 68-year period is shown. As expected, most of the accidents (71) reported in the database occurred in France; among the others, 4 were in Germany, 3 in America, 1 in China, 1 in Lithuania, 1 in Senegal, and 1 in Switzerland. Clearly, the total number of accidents has increased in the last four decades, growing of around eight times in the period 2000-2014.

Overall, 57 of the occurred accidents (70%) did not result in any injuries and/or fatalities. Injuries were registered for 25 events (31%) while fatalities occurred in 4 cases (5%). Regarding the type of injury, burns caused by contact with cryogenic jets of liquid ammonia, as well as intoxication or other respiratory issues (e.g., asthma, breathing difficulties), were reported. When present, the number of injured subjects and deaths was typically less than 10; in just one case, that was an explosion of ammonia tank occurred in Senegal in 1992, the highest value of more than 1,000 injuries and 129 victims was registered.

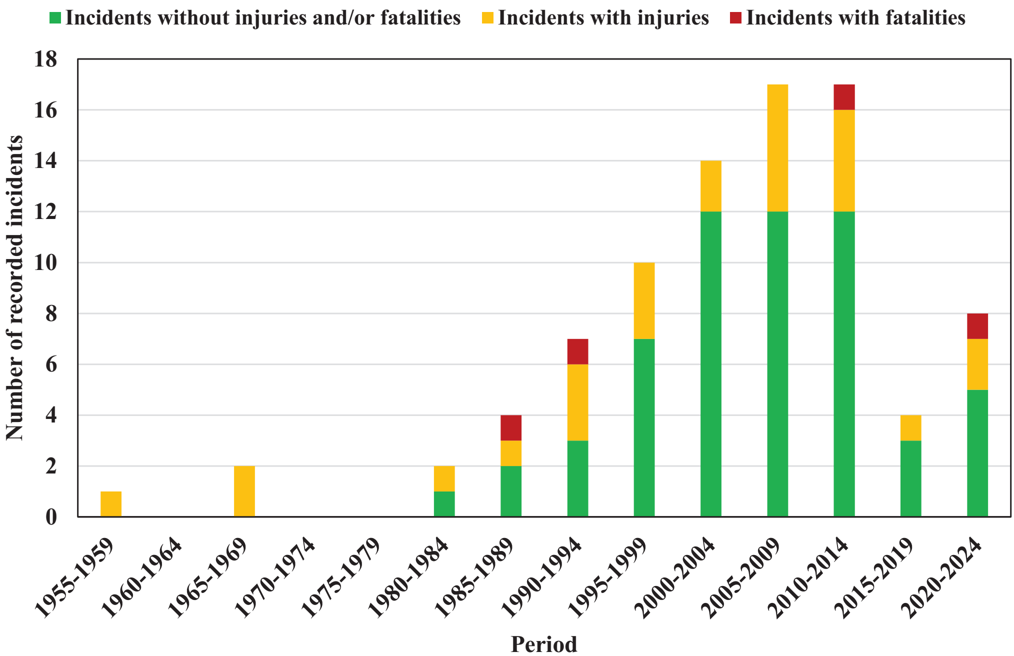

Figure 1. Distribution over time of the accidents selected from the ARIA database.

Data about the economic losses were scarcely available, not allowing a quantitative analysis. Regarding ammonia utilization in the documented accidents, ammonia was primarily used for refrigeration and fertilizer production.

With respect to the causes of the accidents, a qualitative classification was performed based on the available information.

Five categories of causes were considered, following the definitions provided in (Casson Moreno and Cozzani 2015):

- Maintenance errors: actions and operations performed or not performed (i.e., lack of maintenance) during maintenance that cause the accident.
- Operational errors: actions and operations performed during normal working time of the system.
- Equipment failure: failure of a set of components.
- Component failure: failure of a single component.
- Design errors: errors in the design phase of the system (e.g., incorrect sizing of a component).

Incidents occurring during start-up and shutdown procedures were classified as being caused by maintenance errors, as these phases fall outside the normal working conditions of the systems. Similarly, events attributed to errors during repair, drainage, or isolation of a plant section were also considered consequences of maintenance errors.

The results are summarized in Table 2, where the type of cause "multiple causes" was added to include the events triggered by a combination of the abovementioned categories of causes.

The results indicate that maintenance errors were the main cause of accidents, followed by the failure of single components in the system. Among the causes of maintenance-related errors, insufficient knowledge of operations and inadequate procedures were identified as critical factors. Regarding operational errors, most were caused by improper manual interventions in equipment items (e.g., valves) within the plants. Finally, for what concerns the "multiple causes" category, combinations of component failure and/or design and operational errors and the combination of design and operation errors were found.

Table 2. Causes of the accidents.

Type of cause	Accidents (%)
Component failure	29
Design error	6
Equipment failure	6
Maintenance error	33
Operational error	17
Multiple causes	*5*
Unknown	4

Figure 2 depicts the classification of accident scenarios associated with ammonia releases, based on the reference accidents considered in the analysis. The total number of recorded scenarios is 92, exceeding the 82 accidental events identified in the databases. This is because some accidents involved multiple scenarios, such as toxic dispersion from atmospheric releases and environmental damage caused by ammonia-contaminated water discharges.

Regarding the accident location, 45 events (49%) occurred indoors, within buildings or enclosed. The remaining 47 accident scenarios (51%) occurred in external areas, such as open industrial sites or storage facilities.

Dispersion of toxic gas was identified as the most frequent scenario, accounting for 77% of the recorded events. These events involved the release of ammonia into the atmosphere, followed by its dispersion in the form of vapour or aerosol.

Environmental damage was identified as the second most frequent scenario, occurring in 9 out of 92 documented events. These accidents were characterised by significant impacts on ecosystems, including vegetation loss, water contamination, and the mortality of aquatic species such as fish and amphibians.

Ultimately, fires and explosions accounted only for 4% of the documented events. Notably, ammonia vapour ignition was observed in just two out of 92 events, corresponding to a 2% probability of ignition. This suggests that ammonia ignition is unlikely unless high-energy ignition sources, such as electrical or mechanical sparks or extremely hot surfaces, are present. However, these sources may pose a significant concern onboard ships, particularly with the adoption of emerging technologies such as solid oxide fuel cells (SOFCs) for fuel use, which require ammonia processing at substantially high temperatures (Zanobetti et al. 2023). Another concern regarding the potential ignition of accidental ammonia vapour cloud is related to the relative potential confinement of the vapours on board (for example, in the engine room). Techniques for ventilation and vapour extraction could help in mitigating this risk.

Finally, since the accidents mainly resulted in toxic dispersion, asset damages were recorded in just three cases.

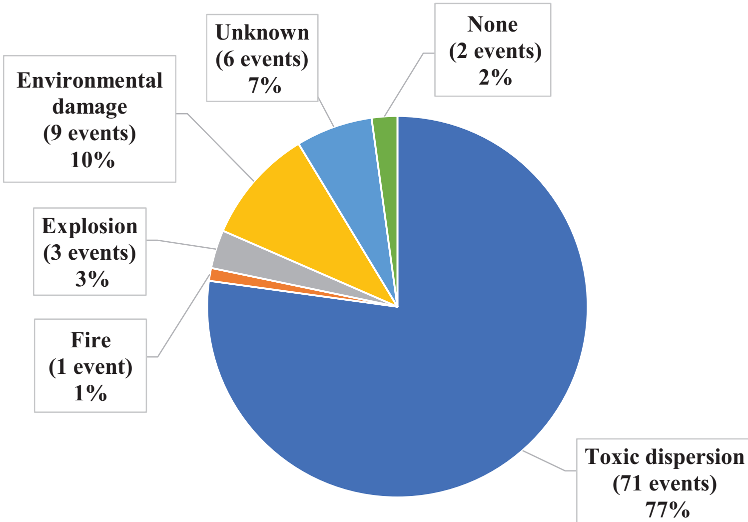

Figure 2. Classification of accident scenarios associated with ammonia releases (based on 92 documented accidents occurring between 1955 and 2024).

4. Conclusions

This study highlights some of the safety challenges associated with adopting ammonia as a marine fuel. An analysis of historical accidents identified toxic dispersion as the most frequent scenario, accounting for 77% of events, suggesting the importance of effective containment measures and advanced monitoring systems to ensure safe operations onboard ships.

Environmental damage, accounting for 10% of documented incidents, included impacts such as vegetation loss, water contamination, and aquatic species mortality.

Fires and explosions, while less frequent, present significant risks in maritime applications, particularly on ships employing fuel cells, where high-temperature ammonia processing introduces hot surfaces as potential ignition sources.

Additionally, maintenance errors and component failures emerged as key contributors to ammonia-related accidents, further highlighting the need for tailored safety protocols. The findings of this study provide a valuable basis for developing comprehensive risk mitigation measures, ensuring the safe integration of ammonia-based ship fuel systems. By addressing these safety challenges, the maritime industry can leverage ammonia as a key decarbonisation solution, enabling its large-scale and sustainable deployment while safeguarding human health, marine ecosystems, and operational infrastructure.

Suitable maintenance and operational programs can support the implementation of ammonia as a ship-fuel and prevent the loss of containment scenarios that can potentially result in exposure to toxic clouds.

Finally, regulations and certification procedures can also contribute to the safe implementation of ammonia on ships.

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