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Establishment of the Basis for Safety Evaluation and Risk Assessment of Ships Using Ammonia as Fuel

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Ammonia fuel presents a greater potential for the formation of a toxic atmosphere than an explosive atmosphere, distinguishing it from conventional and other alternative fuels. Pioneers shall obtain acceptance from the Administration by demonstrating that the design of ships using ammonia as fuel can achieve an equivalent level of safety to ships using conventional fuels. However, a basis for defining release scenarios and evaluating whether safety criteria can be met through safeguards for those scenarios has yet to be established. This poses challenges in decision-making not only for those involved in ship design but also for those responsible for conducting safety evaluation and risk assessment, and for granting approval based on the evaluation. A basis was originally prepared for an ammonia-fuelled gas carrier project and refined through this paper, providing technical justification to ensure that safety functions are appropriately designed to meet safety criteria within a specific context. The basis categorizes the operational situations into normal operation, accidental situation, and emergency and focuses on minimizing the probability of crews being exposed to the toxic atmosphere in each situation.

Keywords: Ammonia Fuel, Toxicity Risk, Release Scenarios, Safety Criteria, Safety Evaluation, Risk Assessment.

1. Introduction

Ammonia has emerged as one of zero-carbon fuels in accordance with the net-zero framework of the International Maritime Organization (IMO). Unlike conventional and other alternative fuels, the potential for forming a toxic atmosphere is greater than that of an explosive atmosphere when using ammonia as fuel. The IMO (2022) classifies ammonia as a toxic gas, though non-flammable, indicating it is expected to pose a higher risk of toxicity than of fire or explosion, especially when compared to other fuels categorized as flammable liquids or gases. Kim et al. (2020) emphasized the extreme toxicity of ammonia fuel and its risks to human health, while Moon et al. (2023) investigated eight ammonia carrier accidents from 1983 to 2021, resulting in 9 fatalities and 15 injuries. These studies suggest that using ammonia as fuel requires an integrated evaluation and quantitative risk assessment focusing on ammonia toxicity.

The IMO has maintained the principle that the safety level of ships using alternative fuels shall remain equivalent to that of ships using conventional fuels, and this principle is also applied to ammonia fuel with consideration of its toxicity. Accordingly, shipowners are responsible for demonstrating that ammonia-fuelled ships can achieve an equivalent safety level through risk assessment. However, the absence of an agreed basis defining which safety criteria should be satisfied, through which safety functions, and against which release scenarios makes this demonstration challenging. This paper proposes a basis which categorizes operational situations into three situations: normal operation, accidental situation, and emergency. It supports the evaluation of whether the safety functions are properly designed to meet specific criteria for each situation. From a risk perspective, it focuses on reducing the probability of exposure to toxic atmospheres.

Chapter 2 describes the methodology for developing the basis in two stages: concept and detailed development. Chapter 3 reviews and summarizes the IMO requirements provided for flammable fuels and ammonia as fuel. Chapters 4 and 5 elaborate on the contents of the concept development and detailed development of the basis, respectively. Chapter 6 concludes with an overview of the developed basis and its implications for ensuring safety when using ammonia as fuel.

2. Methodology

This study begins by reviewing IMO regulations and guidelines which outline the functional requirements for the safe design, construction, and operation of ships using ammonia as fuel. It also examines the international standards referenced by the IMO. It compares and analyses the strategies and solutions that regulators provide to achieve the safety goal. The study first developed the main concept, which represented the strategy to achieve the final goal and provided justifications for it. It then specified the safety measures that corresponded to the solutions. Each safety measure is presented along with the sub-goal that it aims to achieve within a specific context, specifying the requirements for the safety measure, explaining how they address particular release scenarios, and meeting the safety criteria.

The Goal Structured Notation (GSN) is employed in this study as a graphical argument notation designed to effectively present logical structures and safety cases (ACWG 2021). Fig. 1 illustrates the methodology and demonstrates how GSN connects the goal, strategies, and solutions. An agreed safety goal to minimize probability and consequence from any release of fuel is already provided by the IMO regulations and guidelines. The strategy, sub-goals, and solutions are developed to achieve the final safety goal, providing their respective contexts and justifications.

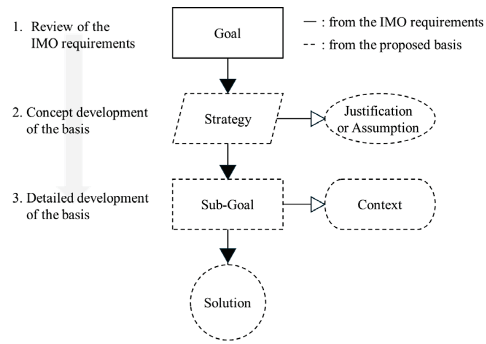

Fig. 1. Methodology for developing the basis

3. Review of The IMO Requirements

The IMO Convention and Codes for ships using flammable fuels, including conventional fuels, gases, and low-flashpoint fuels are reviewed first, followed by a review of the IMO guidelines specific to ships using ammonia as fuel.

3.1. *The IMO Convention and Codes and IEC Standards for flammable fuels*

Ships using ammonia as fuel have to ensure the equivalent level of safety as those using conventional fuels (IMO 2024b). Therefore, the IMO requirements for conventional flammable fuels, The International Convention for the Safety of Life at Sea (SOLAS) (IMO 2024a), The International Code for the Construction and Equipment of Ships carrying Dangerous Chemicals in Bulk (IBC Code) (IMO 2020), and The International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code) (IMO 2016a) are reviewed. In addition, The International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF Code) (IMO 2016b) is reviewed to understand IMO's approaches for gases and low-flashpoint fuels. To minimize risks related to fuel releases, the IMO Convention and Codes adopted the concept of Hazardous Area Classification (HAC) and partially referenced the International Electrotechnical Commission (IEC) Standards. Therefore, IEC Standards are also reviewed, particularly IEC 60079-10-1 (IEC

2020) introducing concept of hazardous areas and IEC 60092-502 (IEC 1999) focusing on its application to ships.

The IMO requires the prevention of explosive atmosphere formation through appropriate ventilation for hazardous areas. An explosive atmosphere is defined as a flammable condition where fuel and air are mixed (IEC 2020), with the fuel concentration between the Lower Flammability Limit (LFL) and the Upper Flammability Limit (UFL). To prevent this, the ventilation ensures that fuel concentration remains below the LFL. The concept of Air Change rate per Hour (ACH) is introduced, representing the ventilation capacity required to replace the air in a given space with fresh air within a specific timeframe. This ventilation with a capacity of 10–30 ACH maintains fuel concentrations below a critical level, typically around 10–30% of the LFL, distinguishing non-hazardous areas from hazardous areas. If the critical concentration is exceeded, gas detection systems shall initiate an alarm, alerting the crew for intervention work. For flammable gases or low-flashpoint liquids, the IGC Code and IGF Code require safety functions that automatically stop gas fuel supply upon gas detection of 40–60% LFL, limiting the formation of explosive atmosphere. Hazardous areas are prescriptively defined by the IMO, requiring explosion-proof electrical apparatus to prevent an explosive atmosphere from leading to an explosion. Emergency procedures mandate the use of safety equipment to minimize harm during fire or explosion incidents, while periodic emergency exercises ensure preparedness.

For non-hazardous or safe areas, the IMO requires maintaining a safety distance to avoid the potentials of gas ingress from hazardous areas depending on the sizes of releases. This includes careful consideration of the arrangement of air intakes and openings of safe areas. However, even with the provision of safety distances, the IGC Code mandates the application of closing devices on air intakes if gas ingress occurs

The IMO specifies the detailed functional requirements for safety measures that shall be placed on ships using flammable fuels. However, these requirements alone cannot clearly define the specific situations in which these measures are required or the specific goals they aim to achieve. For instance, it is difficult to understand under what situations the ventilation system requirements are necessary and what specific goals they are intended to meet. Additionally, it is difficult to know how these requirements, in conjunction with other safety measures, contribute to reducing the risks associated with flammable fuel releases. A deep understanding of the HAC concept from the IEC Standards, as referenced in the IMO regulations, is essential to fully understand these aspects.

3.2. *The IMO guidelines for ammonia fuel*

The IMO, through the 10th Sub-Committee on Carriage of Cargoes and Containers (CCC), finalized the draft of interim guidelines for the safe use of ammonia as fuel on ships other than gas carriers (IMO 2024b). To minimize risks related to ammonia releases, the draft introduced the concept of Toxic Area Classification. While a draft for interim guidelines for gas carriers was circulated at the 10th session of the CCC, it was returned with comments (IMO 2024c). Given the uncertainties for future amendments, which may lead to confusion, the review of the draft for gas carriers is not included.

The IMO requires a ventilation capacity of 30 ACH for toxic spaces, the same as that for hazardous areas. If the gas detection system detects concentrations exceeding 25 ppm, an alarm is initiated to prompt the crew to conduct intervention. If appropriate intervention is not conducted, leading to an increase in concentrations, the detection of concentrations 220 ppm by two or more gas detectors automatically stops the ammonia fuel supply. To reduce the probability of exposure to toxic gases, safe havens capable of accommodating all crew members should be provided appropriately, so that crew in toxic spaces or toxic areas can escape from the toxic atmosphere and stay in the safe havens. However, specific requirements regarding the number, location, capacity, and survivability of safe havens are not provided. Appropriate Personnel Protective Equipment (PPE) for escape and emergency response shall be provided appropriately. Details of risks mitigated by safety measures and emergency procedures shall be addressed and accepted by the Administration (IMO 2024b).

The IMO focuses on maintaining safety distances to air intakes and openings of safe areas to prevent the ingress of toxic gases. The IMO and the IEC have previously distinguished hazardous areas from safety distances. However, the draft defines toxic areas as safety distances, which should be noted as it may cause potential confusion. These toxic areas have been defined prescriptively like the IGC Code. Additionally, to prevent the toxic gas leakage from toxic spaces, water screens should be installed at the entrances. Emergency preparedness should be ensured through a response plan with provision of proper safety equipment.

Similarly, while the IMO specifies detailed functional requirements for safety functions, it does not define specific situations or goals. Unlike flammable fuels, there are no applicable international standards for reference, making it even more challenging to determine how these requirements contribute to achieving the final safety goal. As previously mentioned, ships using ammonia as fuel are required to conduct safety evaluations and risk assessments to demonstrate equivalent safety. For instance, an evaluation shall be provided to assess whether the required ventilation capacity of 30 ACH for toxic spaces ensures equivalent safety, followed by final approval from the Administration. However, the absence of clearly defined context and criteria makes it difficult to conduct consistent evaluations and complicates the approval process.

4. Concept Development

The main concept of the basis is developed and proposed, categorizing operational conditions into normal operation, accidental situation, and emergency, requiring effective safety measures to be provided for each situation. Unlike the IMO requirements, which do not explicitly describe operational situations but instead provide functional requirements for safety measures according to the area classifications in separate chapters, the IEC Standards provide functional requirements against specific release grades depending on the operational situations. The IEC Standards outline requirements specified to prevent explosions caused by continuous releases and the primary grade releases that may occur during normal operation. They also address the secondary grade releases, which may result from failures, indicating that the system is out of normal operation. However, events like rare malfunctions, typically resulting from a chain of events, or catastrophic releases are beyond the scope of the IEC Standards.

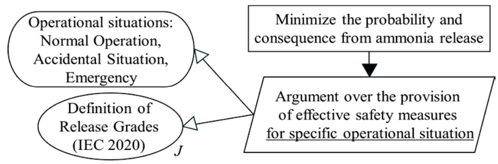

Fig. 2. Strategy to ensure safety for ships using ammonia as fuel

The basis proposes considering three operational situations: normal operation, accidental situation, and emergency, as shown in Fig. 2, based on the IEC Standards. Normal operation refers to a "situation when the equipment is operating within its designed parameters," as explicitly defined in the IEC 60079-10-1 (2020). It includes routine maintenance that does not involve unexpected releases beyond those occurring during normal operation. An accidental situation is defined as one involving a release caused by the failure of a sealing element, which requires repair or shutdown. The definition of emergency is a situation involving catastrophic releases or releases caused by a rare malfunction. The basis adopts a strategy to provide effective safety measures for specific operational situations to achieve the safety goal.

5. Detailed Development

Following the concept of the basis, safety criteria for each operational situation are defined, and safety measures to achieve these criteria are identified and proposed. The safety criteria to be achieved for each operational situation are explicitly represented as sub-goals, while the release scenarios considered in the operational situations are defined as the context. The process of demonstrating that the safety criteria can be satisfied through the safety measures is presented as sub-strategy with its justification, corresponding to a method for safety evaluation.

5.1. *Normal operation*

There shall be no intentional release of toxic gases into the atmosphere during normal operation. The basis considers fugitive emissions from sealing elements in flanges, valves, and machinery. Fugitive emissions from sealing elements has an extremely small release rate on the order of 10^{-7} to 10^{-5} kg/s (U.S. EPA 1995), but the release is continuous, and the amount of releases is determined by the maintenance strategy, as shown in Fig. 3. Considering the continuous characteristics of the release, the 8-hour Time Weighted Average (TWA) value of 50 ppm, specified by Occupational Safety and Health Administration (OSHA) for a standard work schedule of 8 hours per day and 40 hours per week, is selected as the safety criterion for addressing chronic effects (OSHA 2025). The 10-hour TWA value of 25 ppm can be used instead of 50 ppm as recommended by National Institute for Occupational Safety and Health (NIOSH) for the 40-hour workweek. Safety criteria, which should be selected with caution due to their significant impact on determining ventilation capacity, can be selected by considering the working hours of the crew.

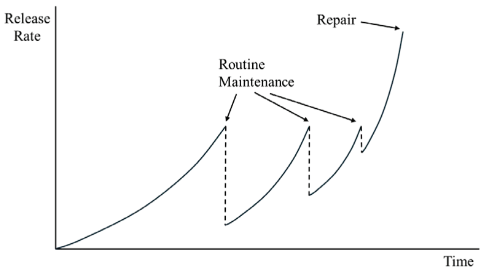

Fig. 3. Typical release profile of fugitive emissions. Adapted from BOHS (1984, 3)

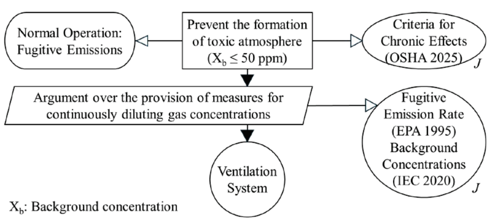

Fig. 4. Provision of ventilation system to prevent toxic atmosphere for toxic spaces during normal operation

For toxic spaces, the basis requires an appropriate ventilation system to maintain gas concentrations within the space below 50 ppm during normal operation as shown in Fig. 4. Once the arrangement of ammonia fuel handling systems within a specific area is determined, the sealing elements corresponding to sources of release can be identified. Although the fugitive emission rate from sealing elements varies over time depending on the maintenance strategy, the U.S. Environmental Protection Agency (U.S. EPA) provides a methodology for estimating averaged mass flow rates along with supporting data (U.S. EPA 1995). The IEC offers a methodology for estimating concentrations in a steady state within a given area based on release rates, determining the ventilation capacity required to dilute (IEC 2020, see eq. (1)). The safety factor can take values from 1 to 5 and is qualitatively selected based on the level of congestion. While this approach can be used as a design methodology, it serves as a safety evaluation method to assess whether the capacity requirement of 30 ACH from the IMO remains applicable, or a higher capacity is required.

$$X_{\mathrm{b}}\ (vol/vol) = \frac{Factor \times Q_{\mathrm{gas}}\ (m^3/s)}{Q_{ventilation}\ (m^3/s)} \tag{1}$$

For safe areas, the basis requires safety distances from the sources of release. Although safety distances for flammable gases can account for accidental releases, they may not be feasible for ammonia fuel, which requires a distance exceeding 70 meters (Nam et al. 2024). Accordingly, additional safety measures shall be considered to ensure equivalent safety such as closing devices on air intakes of safe areas. The basis proposes securing safety distances from fugitive emissions occurring during normal operation, referencing the IEC methodology for estimating hazardous distances according to release rates (IEC 2020) as shown in Fig. 5. Once the fugitive emission rate is estimated, distances to 50 ppm can be determined with the pre-defined curve. Nam et al. (2024) provide toxic distance curves for a diffusive release and a two-phase jet release of ammonia, both extending up to 50 ppm.

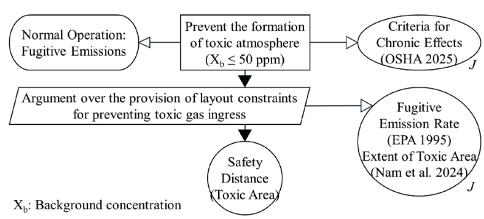

Fig. 5. Provision of safety distance to prevent toxic atmosphere for safe areas during normal operation

5.2. *Accidental situation*

Based on the definition of the accidental situation, the focus remains on scenarios involving a single failure of sealing elements. The IEC suggests using a hole size of approximately 1.8 mm or less for flanges and valves and 2.5 mm or less for pumps and compressors without considering escalation to severe failures (IEC 2020). According to the IEC, in such cases, the duration of any release shall be kept as short as possible through the operator interventions upon gas detection. Acute effects should be considered for selection of safety criterion considering the short exposure time to accidental releases. The basis adopts the Immediately Dangerous to Life or Health (IDLH) concentration value of 300 ppm for 30 minutes, as specified by the NIOSH (NIOSH 2019). This represents the criterion required for a 70-kg worker to safely escape from an area where an accidental release has occurred without irreversible injuries (Ludwig et al. 1994).

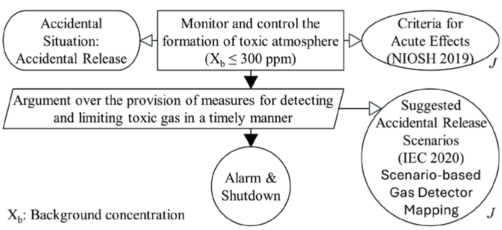

Fig. 6. Provision of detection system to control toxic atmosphere for toxic spaces in accidental situation

The basis proposes providing an alarm at 50 ppm for toxic spaces, corresponding to the normal operation criterion, and implementing shutdowns before 300 ppm. The basis proposes designing the gas detection system and evaluating the suitability of its arrangement based on the suggested accidental scenarios through traditional scenario-based detector mapping methodologies (see Fig. 6).

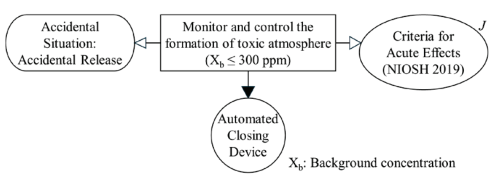

Fig. 7. Provision of closing device to control toxic atmosphere for safe areas in accidental situation

For safe areas, the basis proposes the provision of automated closing devices for air intakes, which automatically shut-off upon detecting toxic gas concentrations before exceeding 300 ppm at each air-intake with a provision of gas detection system (see Fig. 7). Additional analysis should be conducted to determine how long the crew can safely remain in the area after the air intakes are closed.

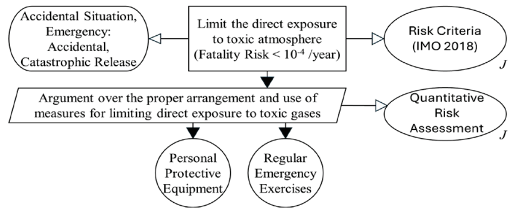

Fig. 8. Provision of personal protective equipment to limit direct exposure to toxic atmosphere

In the event of the accidental and catastrophic release, even if the gas detection system initiates a shutdown, it cannot immediately stop the release. Therefore, an atmosphere exceeding the IDLH concentration can develop in these situations. In such cases, the priority should be to minimize the probability of crew being directly exposed to this toxic atmosphere, which requires the proper use of PPE. The NIOSH recommends any appropriate escape-type respirators for this purpose (NIOSH 2019), which shall be adequately provided in toxic spaces and along escape routes. Regular drills and emergency exercises shall be conducted to ensure that the probability of direct exposure to toxic gases is managed with PPE, ensuring that individual risk remains within acceptable levels (see Fig. 8). Moon et al. (2023) has investigated that the ammonia release frequency can be estimated as 3.1×10^{-3} per year from maritime accident data and 3.1×10^{-2} per year using oil and gas release data. To meet the risk criteria of 10^{-4} per year for newbuilding vessels (IMO 2018), the probability of direct exposure should be managed from 10^{-3} to 10^{-2} when following an event tree shown in Fig. 9. Assuming a 24-hour workday, a probability of approximately 10^{-3} is required; however, considering a realistic assumption of an 8-hour workday, a probability of approximately 10^{-2} is required. Traditional human error probability methodologies can be applied to determine the appropriate interval for emergency exercises. These methodologies can also be used to verify whether the existing interval of exercises has been appropriately planned. Measures to minimize working hours in toxic spaces and areas should be considered. The development of automation and unmanned technologies can reduce toxicity risks to near-zero.

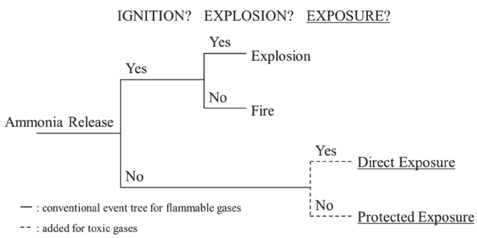

Fig. 9. Event tree for risk assessment from ammonia release. Adapted from Spouge (1999, 77)

5.3. *Emergency*

The release of fuel itself may not be considered an emergency under the grouping of emergencies outlined in the SOLAS (IMO 2024a). For toxic fuels, emergencies may arise if personnel are injured, or fatalities occur due to exposure to toxic atmospheres. In such cases, entering toxic atmospheres exceeding the IDLH concentrations is inevitable for rescuing casualties and minimizing further casualties as part of the emergency response. Provision of appropriate safety equipment is therefore essential. Emergency procedures should be prepared with an understanding of the associated risks, providing guidance on alarms, response team organization, role definitions, and appropriate safety equipment for such situations (see Fig. 10).

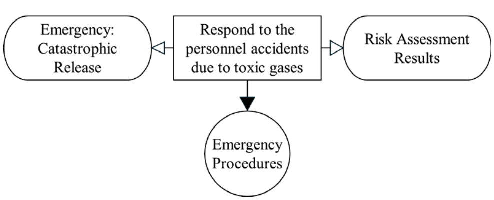

Fig. 10. Provision of emergency procedures to respond to the casualties due to toxic gases

5.4. *Overall goal structures*

Overall goal structures of the basis are given in Fig. 11 and Fig. 12. Contexts and justifications are not shown in the overall goal structures.

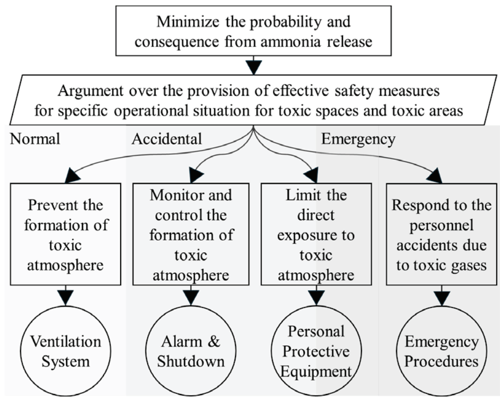

Fig. 11. Overall goal structure for toxic spaces

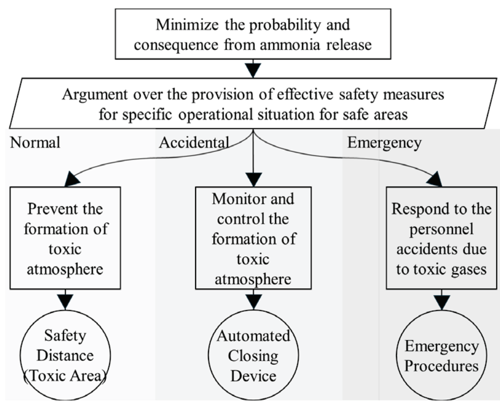

Fig. 12 Overall goal structure for safe areas

6. Concluding Remarks

This paper proposes a basis for the safety evaluation and risk assessment of ships using ammonia as fuel with the concept of categorizing operating situations into three defined categories. The safety criteria to be achieved for each operational situation have been represented as sub-goals, the release scenarios are defined as the context, and the process for demonstrating that the safety criteria can be satisfied through safety measures has been illustrated with a subordinate strategy using the GSN. This structured approach facilitates a consistent evaluation of safety design in the absence of finalized design guidelines. Risk assessment is essential for planning emergency responses, and it is recommended to manage the probability of personnel being directly exposed to toxic atmospheres by appropriately arranging the PPE and ensuring its proper use.

The basis focuses on the safety of the crew onboard, but the societal impact of ammonia releases should also be considered. To address this, it is essential to adopt appropriate safety criteria for the public, including susceptible individuals, which require further investigation.

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