Research Article

TU Delft OPEN Publishing

Beyond technical barriers: enhancing onboard safety through human-machine interaction management in ammonia-powered ships

Rustam Abubakirov [1,*], Ming Yang [1]

[1] Faculty of Technology, Policy and Management, Delft University of Technology, The Netherlands

*Corresponding author: R.Abubakirov@tudelft.nl

Abstract: As the maritime industry advances towards decarbonization, ammonia is emerging as a promising alternative fuel. However, its use introduces significant safety risks to operating personnel arising from tasks inside ship compartments, such as engine or fuel preparation rooms. Given the acute toxicity of ammonia and the effects of space confinement, reducing the personnel risks to conventional levels through technical mitigation alone poses a considerable challenge. The reliance on mitigation of leak consequences, as emphasized in current regulations for ammonia, raises ethical concerns as well. The present work seeks to explore a broader perspective on onboard safety by examining both the direct and indirect factors influencing personnel risk during interactions with hazardous processes. By analyzing the role of human-machine interactions (HMI) in ship operations, the study offers insights into how HMI management can significantly reduce accident probabilities. Our discussion underscores HMI management as a pivotal strategy for mitigating ammonia-related risks, a contrast to the approaches used for conventional, non-toxic marine fuels. This paper proposes a framework for implementing an effective HMI management strategy, highlighting the benefits and complexities involved.

One sentence summary: This study highlights the need for risk reduction in toxic spaces, explains why increasing ventilation and/or adding more detectors is not an effective solution, and proposes an alternative strategy.

Keywords: marine operations, ammonia, human-machine interaction, machinery spaces, toxic risk

Publishing history: Submitted: 14 February 2025; Revised: 22 May 2025; Accepted: 28 May 2025; Published: 10 June 2025

Cite as: Abubakirov, R., & Yang, M. (2025) Beyond technical barriers: enhancing onboard safety through human-machine interaction management in ammonia-powered ships. *Journal of Progress in Safety & Security*, *1,* https://doi.org/10.59490/pss.1.2025.8032

ISSN: 3050-4570
Vol. 1, 2025
DOI: 10.59490/pss.1.2025.8032

1 Introduction

As the maritime industry witnesses a growing number of projects utilizing ammonia as fuel, so the regulatory framework for its safe use becomes more articulated. By mid-2024, the framework already includes dedicated rulesets from most classification societies, e.g., DNV (2023), Bureau Veritas (2022), and American Bureau of Shipping (2023), considered in the present study. Additionally, the rules from the International Maritime Organization (IMO) are expected shortly (IMO, 2023). Referring to the principle of Alternative Design, the published rulesets explicitly require ammonia systems to demonstrate an equivalent level of safety as existing natural gas applications under the IGF Code (IMO, 2016a). From a formal process safety perspective, this requirement sets the risk acceptance criterion for the new technology.

The hazards inside ship compartments with potential sources of ammonia release are specifically highlighted in the regulations. These compartments include tank connection spaces, fuel preparation rooms (FPRs), machinery spaces, or engine rooms (ERs), with equipment located there containing significant inventories of ammonia to result in a major accident. Acknowledging the hazard, the regulations prescribe a series of safety barriers, most of which have already been long and successfully applied for liquified natural gas (LNG) under the IGF Code or preceding regulatory provisions (IMO, 2009, 2016a, 2016b). The principles behind the old and new measures can be summarized as follows:

- **Segregation and double containment.** All ammonia supply equipment must be located in dedicated compartments like FPR or ER, with double piping applied elsewhere. These compartments are to be gastight and designed to withstand pressure build-up in case of an ammonia release. Suction-type ventilation must be provided with the outlet leading to a safe discharge location.

- **Rapid leak detection and isolation.** Detection of leaked ammonia in the air must be automatic and quick. At least two gas detectors set at 25 – 30 ppm for alarms and 150 – 350 ppm for activation of emergency shut-down (ESD) systems are to be placed in each of the rooms, with precise setpoints varying depending on the specific document (American Bureau of Shipping, 2023; DNV, 2023). Voting principles to avoid false alarms are prescribed within the rulesets as well. ESD valves apply as for standard chemical processes.

- **Mitigation of local consequences.** In addition to normal ventilation, the rulesets require emergency, or catastrophe, ventilation to be installed and activated by the detection of ammonia in the air. While the normal ventilation for an individual room is at least 30 air changes per hour, the emergency rate implies an increase to 45 air changes per hour as a minimum (American Bureau of Shipping, 2023; DNV, 2023). Water screens shall be installed at the entrance to prevent ammonia dispersion to adjacent spaces.

The listed measures comprise a substantial set of technical barriers to be fitted onboard; nevertheless, very little has been publicly discussed on the effectiveness of those in ensuring the required safety level. Among available publications, Pomonis et al. (2022) and Yadav & Jeong (2022) addressed ammonia leak effects in engine rooms using computational fluid dynamics (CFD). Both works agree on the reduced flammability risks, while indicating elevated toxicity risks within the current requirements. The study by Lloyd's Register Maritime Decarbonisation Hub (LR MDH) and Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS) (2023) explores the subject further by applying a formal quantitative risk assessment (QRA) methodology. The work concludes the individual risks posed by ammonia fuel systems to engineering rating as being tolerable, although failing to directly address the aforementioned acceptance criterion by providing a specific interpretation of it:

For a new, novel, or alternative design, there is a requirement in the relevant Code [IGF] that the 'safety level' (i.e., risk) is equivalent to an established design. It is important to recognize that 'equivalent' does not necessarily mean 'equal'. Generally, 'equal' means things are the same, whereas 'equivalent' means things are similar. (LR MDH and MMMCZCS, 2023, p.53)

The present study aims to answer the following two questions:

1. Are the prescribed measures sufficient to ensure the risk level inside the ship compartments is equivalent (i.e., equal) to that of natural gas alternatives?

2. What other practicable risk control options exist in the present case?

This work is organized as follows: Chapter 2 tests the acceptance criterion under question #1 and discusses potential seafarer well-being issues associated with the proposed mitigation strategies if applied alone. Chapter 3 proposes a theoretical framework for an alternative, yet also complementary, risk control strategy by applying human-machine interaction management. Chapter 4 further develops the concept by specifying practicable measures within the framework, demonstrated in the case of an ammonia engine room.

2 (Un)mitigating toxic release consequences

2.1 Dispersion of gases inside a ventilated room

After the initiation of a leak, expansion, and the loss of initial momentum, the fuel gases will disperse in highly turbulent conditions induced by forced ventilation and a significant level of obstruction in the FPR / ER. Ammonia, if originally gaseous, as for port injection engines, will disperse in the compartments as gas, i.e., without condensation and reaction with atmospheric water (Haddock & Williams, 1979). The same is always true for natural gas. Considering this, the model assuming a complete mixing of the gas within compartment volume have been adopted as a simple and popular proxy for the consequences inside (Lautkaski, 1997; Mastellone et al., 2003; Montoya et al., 2009). Thus, for a room of volume V, a gas influx rate Q_g, and a ventilation rate v from the surroundings, the time-dependence of average gas concentration across the space, C, can be described as follows:

$$V\frac{dC}{dt} = Q_g - vC \tag{1}$$

which yields the following solution for concentration, accounting for the gas source isolation at t_{iso}:

$$C(t) = \begin{cases} \frac{Q_g}{v}\left(1 - exp\left(-\frac{vt}{V}\right)\right), & t \leq t_{iso} \\ C(t_{iso})\, exp\left(-\frac{v(t - t_{iso})}{V}\right), & t > t_{iso} \end{cases} \tag{2}$$

2.2 Dispersion of gases inside a ventilated room

There are effectively two mechanisms the proposed mitigation measures can influence the risk inside the compartments: (1) through the minimization of leak detection and isolation times, t_{iso}, resulting in the lower amount of gas being released and (2) through the increase of ventilation rates, v, leading to the gas dilution. Conceptually, this influence pathway is presented in Figure 1. There, the state of a random variable F, which indicates a fatality event with two possible outcomes, true or false $\{f, \bar{f}\}$, is influenced by the state of a leakage, L, and any other random factors affecting the integrity of supply equipment, which are beyond our control. Acting on the barrier systems, collectively taken as **B**, such that $\mathbf{B} = [t_{iso}, v]$, is intended to minimize the probability of fatality in a room, $F = f$, should a leak happen. Note that changing the FPR / engine room volumes or any other barriers listed in Chapter 1 may also affect ammonia dispersion and the risk, yet such manipulations are not deemed practically implementable within the ship design.

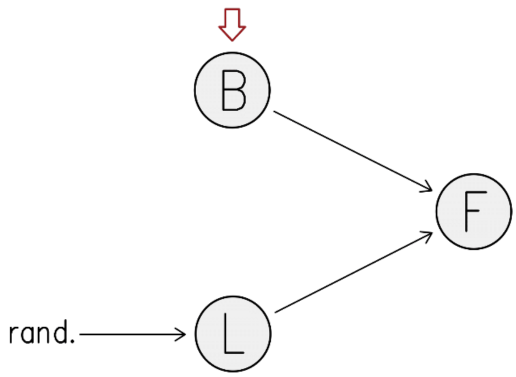


Figure 1. Directed graph model of a fatality event, $F = f$, inside an engine or fuel preparation room as the result of a gas leak, $L = l$. Manipulation of the barriers' performance, B, influences the probability of the fatal event.

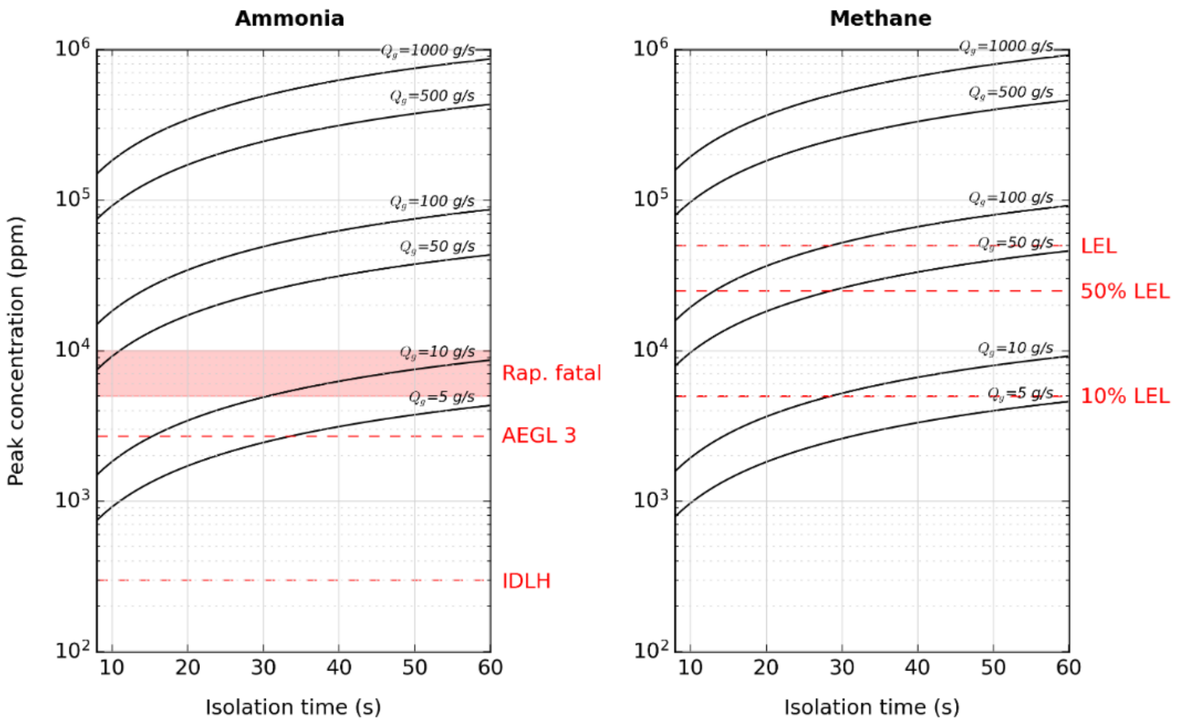
To evaluate the effectiveness of the barriers, consider an example control volume with dimensions 6x4 meters and a height of 3 meters, corresponding to an FPR or a smaller engine compartment. Figure 2 illustrates dependencies of analytical peak concentrations of a dispersed gas under standard conditions, i.e., maximum $C(t)$ over a 10-min exposure period, versus barrier performance parameters for several leak rates. Key toxic exposure levels for ammonia and flammability levels for methane have been included to indicate the potential consequences of gas dispersion. The abbreviations used in Figure 2 are as follows: AEGL 3 – Acute Exposure Guideline Level 3, corresponding to a fatality within 10-min exposure, as defined by the National Research Council

(2008), IDLH – immediately dangerous to life and health limit, as per Ludwig et al. (1994), LEL – lower explosive limit (Green & Southard, 2019). The probability of fatality for toxic substances depends on exposure duration; nevertheless, ammonia concentrations above 5,000 – 10,000 ppm are widely reported as rapidly fatal due to airway obstruction and further medical complications (Roney et al., 2004).

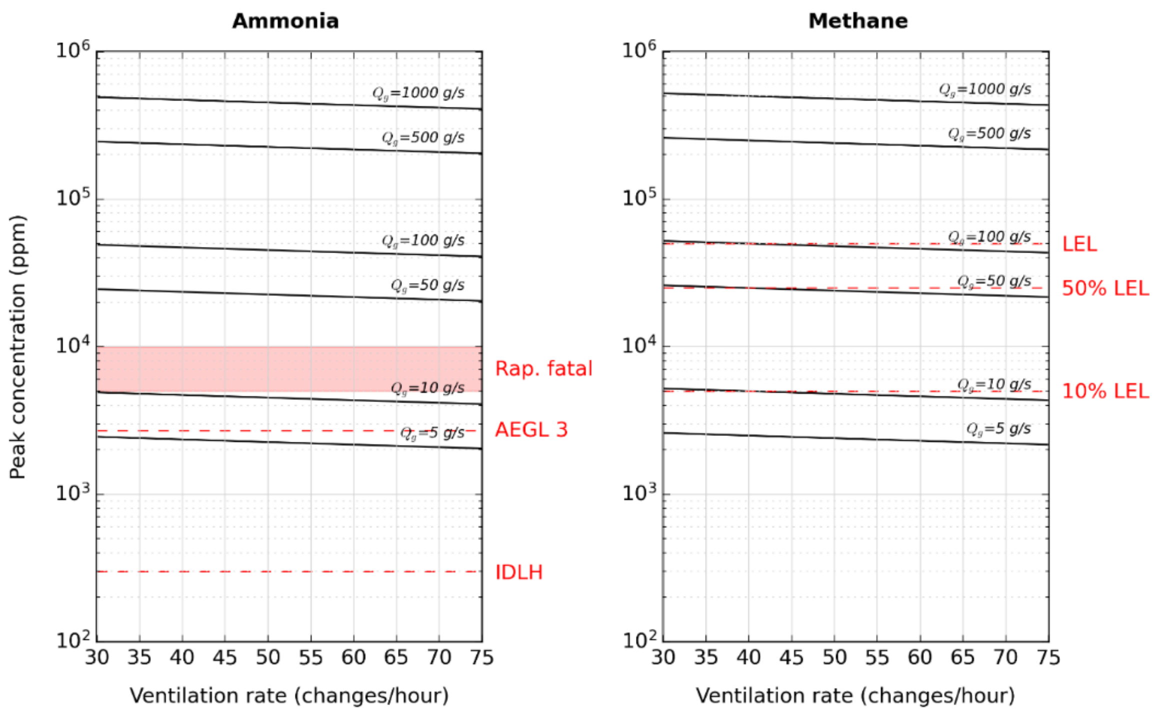
The following observations can be made based on Figure 2:

- As long as technologies enabling reliable $t_{iso} \ll 10$ s are not applied, the sensitivity of release consequences on leak isolation times and ventilation rates within the practicable limits is minimal. This does not imply that the barriers are altogether redundant, yet further marginal increases in their performance, e.g., in ventilation – from 30 to 45 changes – or in isolation – anywhere above 30 s, do not sensibly affect the consequences.
- The consequences for a given ammonia leak are naturally more severe than for an equal leak of methane. Although comparisons of toxic and flammable events are non-trivial, the authors cannot foresee conditions when the opposite will be true. Given that significant differences in leak frequencies between ammonia and gas-powered machinery are not expected as the same engine and systems designs are used, this will lead to the risks of ammonia use being higher than those of gas-fueled applications if other mitigation is not applied (MAN Energy Solutions, 2020; Wärtsilä, 2020, 2023).

Thus, addressing question #1 on the role of prescribed measures, these are unlikely to be sufficient to make ammonia risks equal to the established reference under the IGF Code. The effectiveness of the listed measures was shown to be minimal, while there are no practical reasons to believe that the risks with ammonia are lower than those of existing natural gas alternatives without any different actions.



(a) Peak concentrations vs isolation time at v = 30 changes/hour



(b) Peak concentrations vs ventilation rate at t_{iso}= 30 s

Figure 2. Relationship of analytical peak gas concentrations following a release into a 72 m^3 room and the corresponding consequences versus the performance of mitigative barriers. Complete mixing model is assumed.

2.3 The human behind the numbers

Certainly, the employed complete mixing model is limited in many aspects, yet the value of more sophisticated toxic consequence models and for the present risk management appears to be low as well. Consider that natural gas and any other hydrocarbon fuel used in the maritime are not acutely toxic, so the life- and health-threatening consequences associated with them altogether depend on ignition. This is drastically different for ammonia, where consequences are caused by the absorption of the gas and its reaction with body tissues. Above 5 ppm in the air, this is distinguishable by odor, while at 110 – 380 ppm, the reaction leads to severe irritation of the eyes and upper respiratory system. Short-term exposure below AEGL 3 and the fatality thresholds, while not death, still causes serious health effects impacting long-term well-being (Makarovsky et al., 2008; Roney et al., 2004). Reports of traumatic experiences of workers following ammonia leak accidents are distressing (Tolan & Chapman, 2023). In this light, the potential conservativeness of consequence models can be justified. Otherwise, relying on the safety measures that solely aim to bring "very high" concentrations to "high" while still damaging health and well-being might be ethically faulted. Another consideration is that the engineering ratings, wipers, and others exposed to the new hazard in ship machinery spaces are typically one of the lowest-paid crew and are driven to seaman careers by challenging labor situation in their home countries (Deloitte, 2011). Decarbonization should not lie a burden of the most vulnerable ones.

3 Reducing risk through HMI management

In light of the challenges in reducing release consequences and likelihoods, one can add that in order to have an accident affecting a person's life and health, the person must be present at the accident location first. And given that the rulesets unequivocally require the placement of the fuel systems into dedicated compartments, such as ER or FPR, a person's entering and interaction with hazardous machinery inside become a necessary condition for the accident of interest (American Bureau of Shipping, 2023; Bureau Veritas, 2022; DNV, 2023).

Figure 3 illustrates this causal logic. A fatality by intoxication there, $F = f$, must be preceded by an ammonia leak, $L = l$, and the crew's presence in a compartment for any task / interaction, $I = i_1, i_2, \dots\ i_j$. There must be a link from I to L, as an interaction with the machinery itself can be the cause of a leak, e.g., in maintenance. A pertinent question would be why I, with far less random influence than L, cannot be the objective for control. After all, entry into an engine room is always intentional.

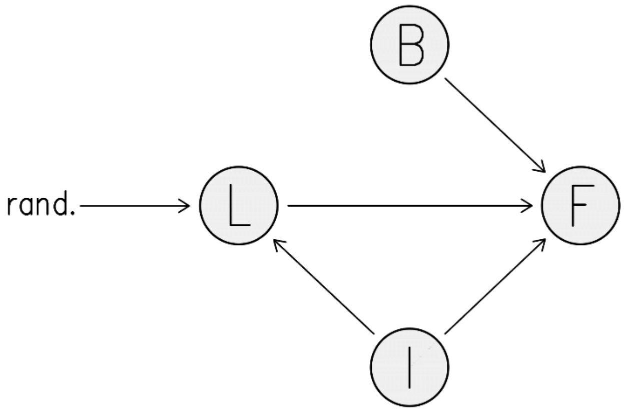


Figure 3. Directed graph model of a fatal intoxication event, $F = f$, inside an engine or fuel preparation room, which is influenced by the outcomes of L, I and **B**.

Note that with ammonia, the strength of the introduced necessary condition of becomes ever more profound than for other marine fuels. Firstly, this is because of the rather poor flammability of ammonia, making fires and explosions unlikely to escalate by domino beyond the original compartment where a leak has happened. Secondly, the consequences of toxic gas leaks are primarily dangerous to humans, and provided a well-designed vent system, their acute effects are limited to a room where it happens. Both these factors will lead to a separation of exposure zones such that, for an individual not being present within the boundaries of a hazardous compartment, e.g., outside an engine room, the probability / risk of fatality due to an ammonia leak, $p(f, l)$, will tend to zero.

To utilize this feature, it is worth considering the risk of fatality, $p(f, l)$, in conjunction with I because the former will sensibly vary depending on the type of interaction. By taking $\{i_1, i_2, \dots, i_{n-1}\}$ to represent a set of applicable HMIs inside a compartment (e.g., inspection, testing, and maintenance) and i_n to be reserved for non-interaction (the crew is outside a hazardous compartment) such that $\sum_{j=1}^{n} p_j = 1$, the fatality risk over a period Δt for any individual onboard can be seen as the marginal probability of $p(f, l, i_j)$ over the values of I:

$$p(f, l) = \sum_{j=1}^{n} p(f, l, i_j) = \sum_{j=1}^{n} p(f \mid l, i_j) \cdot p(l \mid i_j) \cdot p(i_j) \tag{3}$$

The main reason for making interactions explicit and accounting for them is that, following the logic above, $p(f \mid l, i_{j\neq n}) \gg p(f \mid l, i_{j=n})$, and the decision whether to eventually expose someone to ammonia risks, $i_{j\neq n}$, or not, $i_{j=n}$, is totally within an operator's control. This differs significantly from other variables. The idea is not to further reduce the toxic exposure severity, $p(f, \mathbf{b} \mid l)$, by changing the barriers' performance $\mathbf{b}$. Further improvements in this direction are limited, leaving $p(f, \mathbf{b} \mid l)$ a weak function of $\mathbf{b}$, and thus reducing the useful scope to $p(f \mid l)$. Instead, the focus is on reorganizing the interactions to $\{i'_1, i'_2, \dots, i'_{n-1}\}$ such that either exposure, $p(i'_{j\neq n})$, the associated probabilities $p(f \mid l, i'_{j\neq n})$ and $p(l \mid i'_{j\neq n})$, or both are lower. Analogously, the new objective is not emphasizing lowering $p(l)$, or equipment leak likelihood, including by a "*human error*", but to give the crew less opportunity to be present in the hazardous spaces and interact with equipment, potentially making the "*error*". Such a strategy will require shifting the primary control objective from technical barriers to human interactions, which will be a core variable to manipulate.

Concerning the practical realization of HMI control, the independence of manipulated variables is crucial. For example, manipulation of barrier performance, e.g., ventilation rates, is easy to implement in design because these variables are rather standalone. Conversely, manipulation of interactions is more complex as there are many interdependencies and reasons why someone needs to attend, for example, an engine room. (From a communication with a gas-fueled ship operator, the number of distinct procedures inside it reaches 600). A significant fraction of these procedures is directly prescribed in operating manuals, e.g., regarding inspections, tests, and planned overhauls. Other interactions are emergent and can be viewed as a response to a change in another variable – equipment performance, P. For instance, no one prescribes the need for corrective maintenance a priori, as this will be required only when the performance of a technical system is deemed unsatisfactory at an uncertain point in time. Thus, the outcome of P will call for an interaction under I, the same as outcome of P being dependent on whether the human intervention has been successful before, leading to a two-way dependence between P and I.

This causal relationship has been added to the model in Figure 4, with the direct manipulation of I (Arrow 1) and the indirect – manipulation of P (Arrow 2) – both central to the new safety management strategy. Changes under Arrow 1 relate to measures directly affecting how interactions are practiced. Changes under Arrow 2 aim to modify how interactions are called.

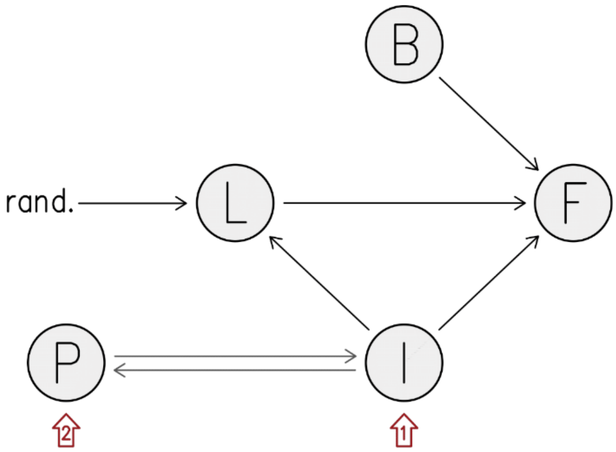


Figure 4. The proposed strategy for risk management in confined spaces through (1) direct changes to operational procedures influencing I and (2) indirect changes to the performance of the systems influencing P.

4 Case of an engine room

To demonstrate the concept, consider an ammonia-fueled engine room presented in Figure 5. Without the changes indicated in red, the room is equipped with three equal dual-fuel engines used as generators for both propulsion and energy. Ammonia is supplied to the engines from an FPR to the gas valve units (GVUs) within the room. Double piping is applied throughout. As with current dual-fuel LNG machinery, the engines are fully controlled from the bridge, plus there is a local control panel for each engine that is routinely attended during the vessel's maneuvering or mooring and which is occasionally used. All auxiliary systems (engine oil and cooling systems, starting machinery, local controls, etc.) are located in the same compartment. The primary duties of the engine department crew include the following:

1. **Engine start, monitoring, and inspection.** A gas leak test is to be performed before the start of an engine. During the operations, the engine is inspected 3 – 4 times daily for any visual / sound indications of malfunctions.
2. **Engine maintenance.** This includes both planned and corrective maintenance. To utilize the vessel efficiently, repairing the systems onboard while sailing is preferable. In this case, the remaining engines continue to work. The maintenance frequency and durations are difficult to predict, yet this can take up to several workdays in the engine room.
3. **Auxiliary systems service and maintenance.** Analogous to #1 and #2.

In total, the engine room is manned for approximately 50% of the time (Adipradhana, 2024). Although the concept assumes the use of double piping and other measures in accordance with rule requirements, the findings in Section 2 indicate that the safety risks associated with the listed crew interactions with ammonia machinery will remain higher than those of established designs. Therefore, alternative / additional design measures are proposed to mitigate the residual risks.

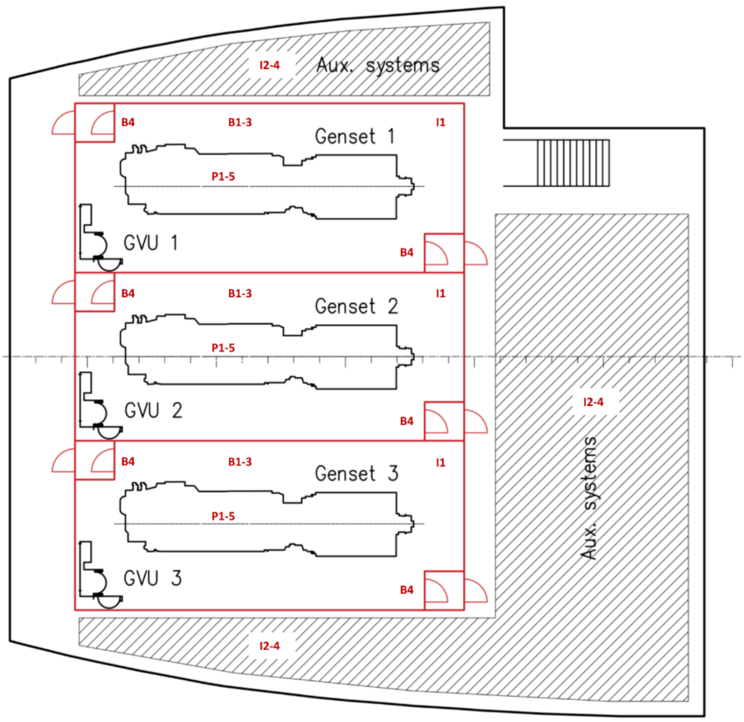


Figure 5. Layout of an ammonia engine room. The proposed changes for HMI management are indicated in red.

Table 1 lists the introduced changes mapped in Figure 5 for facilitation. The changes have been classified into three, as per the proposed HMI management framework, covering the practical observations presented earlier in Adipradhana (2024). Beyond the application of technical barriers (manipulation of B), the list extends to the measures modifying the interaction of the crew with hazardous machinery, either directly (manipulating I) or indirectly (manipulating P).

The direct measures under I aim to introduce technical changes in the organization of the engine room that change crew interactions while maintaining the interaction objectives. A straightforward example will be creating a dedicated chamber around the engines (I1) and providing independent ventilation systems for each. In this manner, all other crew operations with auxiliary machinery and engines under maintenance, while not taking less time, will be limited in the exposure intensity, $p(f \mid l, i_j)$. A change in the strength of another link from $I - p(l \mid i_j)$ will also be reasonable to assume because the physical wall will affect the chances of the machinery, e.g., being rammed or impacted by a dropped object. Thus, the joint probability $p(f, l \mid i_j)$ after a single modification is lower, and similar principles apply to I2, I3, and I5. This reduction in $p(f, l \mid i_j)$ is conceptually illustrated in Figure 6, where the risk associated with each interaction category $p(f, l, i_j) = p(f, l \mid i_j) \cdot p(i_j)$ is represented by the shaded areas of the rectangles, with the total risk from ammonia machinery onboard being the cumulative sum of these areas.

The indirect measures under P address the design of ammonia machinery itself and aim to affect the frequency, complexity, and duration of interactions. For instance, maintenance of engine systems accounts for a significant portion of crew time in the ER over the long term. Designing systems to be easier to maintain (P1) and/or more reliable (P2 – 4) will reasonably reduce the need for hazardous interactions, and thus $p(i_2)$, as in Figure 6. Similarly, incorporating power redundancy (P5) can delay maintenance until more qualified service is available onshore. Although prioritizing system performance for safety might appear unconventional, addressing primarily engine and technology providers, it can serve as a valuable tool for risk reduction for maritime designers. Since the risk $p(f, l, i_j) = p(f, l \mid i_j) \cdot p(i_j)$ does not discriminate which factor to reduce, advocating for such improvements can drive the technology market towards developing more autonomous and thus safer solutions.

Table 1. List of risk mitigation measures for the engine room classified by the primary manipulated variable under the HMI management framework

Manipulating B	**Manipulating *I* (1)**	**Manipulating *P* (2)**
1. Gas leak detection 2. Leak isolation, blowdown, line inerting 3. Ventilation (incl. emergency capacity) 4. Water curtains around engines	1. Dedicated space within ER for each ammonia engine. The engine spaces are to be equipped with independent ventilation. 2. Valves and instrumentation for auxiliary engine systems (except ammonia inlet / return valves) located outside the engine space. 3. Allocating engine local control panels outside engine space 4. Reducing visual routine inspections by CCTV, noise, vibration sensors in engine space. Providing engine visibility from outside. 5. Dedicated permit to entry procedures; reduced / no paperwork filling inside the engine space.	1. Higher maintainability and standardization of engine systems 2. Higher durability & reliability of engine components (transmitters, actuators, injectors, turbochargers, etc.) 3. Integrated engine diagnostics systems (reducing corrective maintenance needs) 4. Superior lubrication oil properties 5. Power redundancy and/or diesel back-up in case of ammonia engine shutdown

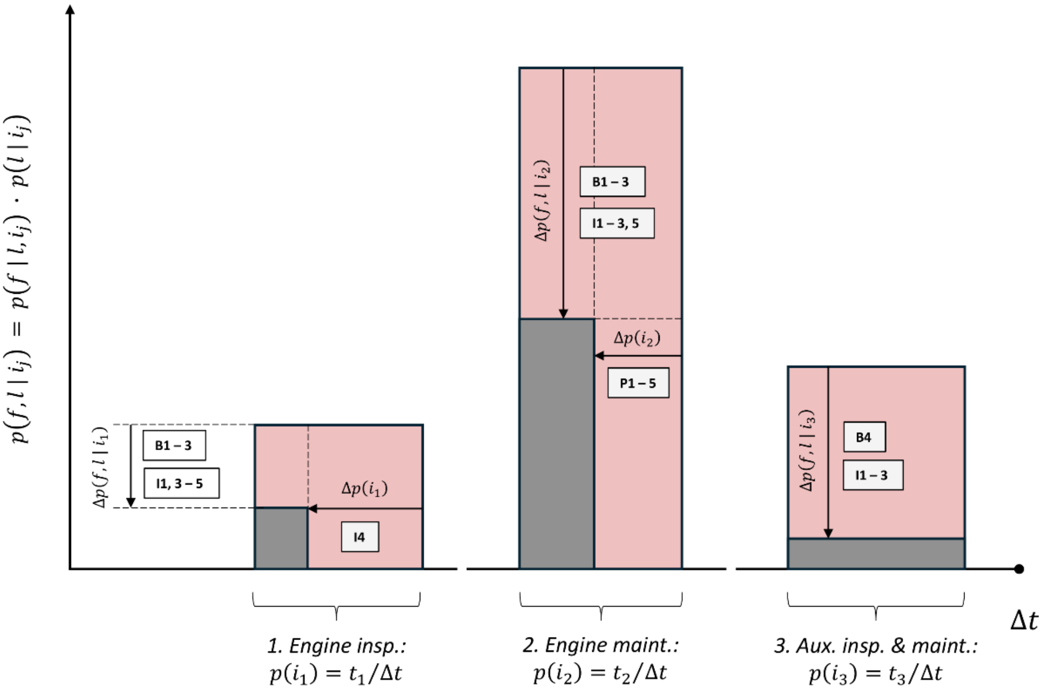


Figure 6. Schematic illustration of risk components and the applicability of mitigative measures in Table 1. The area of rectangles, as $p(f, l \mid i_j) \cdot p(i_j)$ product, represents the risk by interaction groups. The goal is to reduce $p(f, l)$, or cumulative area representing the total risk.

There are several considerations and challenges to add to the proposed HMI management approach. First, while the measures mitigate ammonia toxicity risks, it is crucial to ensure the power system's proper functionality and performance to maintain the safety of the entire vessel. For example, while substituting in-person visual inspections with CCTV may reduce ammonia risk, this also can increase the likelihood of critical degradation going unnoticed. To avoid such downsides, an extensive risk analysis accounting for local conditions should be applied. This study provides a framework to enable and estimate the risk reduction but, for the same reason, abstains from quantification of the generic case used, acknowledging these possible side effects of measures' implementation.

Second, HMI solutions will be highly case-specific, depending on the vessel type, room configuration, and, eventually, the operator's own preferences. For instance, a single engine space may be more effective than the segmented one, as in Figure 5, once the sub-spaces become small in volume. The effectiveness of this and other measures will largely depend on the quality of the risk analysis, e.g., gas dispersion studies, and the consideration of these specifics. Such variability of results makes it challenging to reflect HMI measures in prescriptive rules, thus shifting safety decision-making from classification societies more toward ship operators and builders. To manage this division responsibly, at least before the best practices are codified, it may be more effective to focus plan approval efforts not on compliance with technical requirements set by any relevant authority but on the scope and quality of the risk assessments provided. Valuable lessons can be drawn from the offshore petroleum industry in this regard (Barua et al., 2016; Dagg et al., 2011).

5 Conclusions

This paper analyzes the onboard safety of ammonia-fueled vessels, focusing on two main issues: (1) the sufficiency of technical barriers in mitigating ammonia safety risks and (2) alternative safety management strategies.

Firstly, the application of technical barriers in compartments with a potential of ammonia leak, as prescribed in the current rulesets, was found insufficient to yield the safety risks equivalent to that of natural gas alternatives. While these barriers effectively address ammonia flammability hazards, the low toxic threshold limits of ammonia present challenges that exceed the practical capabilities of these barriers. Given that ammonia technologies are greatly based on established engine & system designs and thus have similar leak frequencies, higher safety risks of ammonia applications are expected. Moreover, reliance on these barriers in areas where crew members are routinely present can negatively impact workplace conditions and crew well-being.

To address these challenges, a risk control strategy based on the HMI management concept has been proposed and demonstrated through a case study of an ammonia engine room. The case involved creating a secondary enclosure for the engine, relocating auxiliary and control systems to minimize exposure intensity, as well as enhancing the reliability and autonomy of the systems to minimize interaction frequency. These measures significantly expand the scope of available risk control options beyond the technical barriers, thus offering a naval architect more opportunities for toxic risk reduction. Certainly, some of the proposed changes, like increasing engines' maintainability or reliability, are not traditional in safety discourse, yet if there are any other business-motivated reasons to do so, safety may rightfully appear as an extra argument in favor. The proposed HMI framework illustrates how safety and these measures are related.

CRediT authorship contribution statement

Rustam Abubakirov: Writing – original draft, Investigation, Methodology, Formal analysis, Conceptualization. **Ming Yang:** Writing – review & editing, Supervision, Funding acquisition.

Funding or Grant

This publication is supported by the AmmoniaDrive project (project 14267) which is financed by the Netherlands Organisation for Scientific Research (NWO).

Use of AI

During the preparation of this work, the authors used OpenAI's GPT-4 model in order to improve logical coherence of the text. After using this tool, the authors reviewed, edited, and made the content their own, and validated the outcome as needed, and took full responsibility for the content of the publication.

Acknowledgement

An earlier version of this paper was presented at the Mary Kay O'Connor Safety & Risk Conference on October 22, 2024, in College Station, Texas. The authors are thankful to Devano Yehezkiel Adipradhana for invaluable support in developing the case study.

Declaration of competing interests

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

References

Adipradhana, D. Y. (2024). *Incorporating Socio-Technical Perspective on Ammonia-Powered Ship Safety Risk Management with a Focus on the Engine Room*. https://resolver.tudelft.nl/uuid:df90f54c-d781-4e1b-871f-5737f5ae243c

American Bureau of Shipping. (2023). *Requirements for Ammonia Fueled Vessels* (Sep. 2023). American Bureau of Shipping. https://ww2.eagle.org/en/rules-and-resources/rules-and-guides-v2.html

Barua, S., Gao, X., & Mannan, M. S. (2016). Comparison of prescriptive and performance-based regulatory regimes in the USA and the UK. *Journal of Loss Prevention in the Process Industries*, *44*, 764–769. https://doi.org/10.1016/j.jlp.2016.10.009

Bureau Veritas. (2022). *NR671 Ammonia-fuelled Ships - Tentative Rules* (July 2022). Bureau Veritas. https://marine-offshore.bureauveritas.com/nr671-ammonia-fuelled-ships-tentative-rules

Dagg, J., Holroyd, P., Lemphers, N., Lucas, R., & Thibault, B. (2011). *Comparing the offshore drilling regulatory regimes of the Canadian Arctic, the US, the UK, Greenland and Norway*. Pembina Institute Drayton Valley, Alberta. https://www.pembina.org/reports/comparing-offshore-oil-and-gas-regulations.pdf

Deloitte. (2011). *Challenge to the industry - Securing skilled crews in today's marketplace*. https://www2.deloitte.com/content/dam/Deloitte/global/Documents/dttl-er-challengeindustry-08072013.pdf

DNV. (2023). *Rules for Classification: Ships - Part 6 Additional class notations, Chapter 2 Propulsion, power generation and auxiliary systems* (Jul. 2023). DNV AS. dnv.com

Green, D. W., & Southard, M. Z. (2019). *Perry's chemical engineers' handbook*. McGraw-Hill Education. https://www.mheducation.com/highered/mhp/product/perry-s-chemical-engineers-handbook-9th-edition.html

Haddock, S. R., & Williams, R. J. (1979). The density of an ammonia cloud in the early stages of atmospheric dispersion. *Journal of Chemical Technology and Biotechnology*, *29*(11), 655–672. https://doi.org/10.1002/jctb.503291102

IMO. (2009). *IMO Resolution MSC.285(86). Interim Guidelines on Safety for Natural Gas-fuelled Engine Installations in Ships. Adopted 1 June 2009.* https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/MSCResolutions/MSC.285(86).pdf

IMO. (2016a). *International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF Code)*. International Maritime Organization. https://www.imo.org/en/ourwork/safety/pages/igf-code.aspx

IMO. (2016b). *The International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code)*. International Maritime Organization. https://www.imo.org/en/OurWork/Environment/Pages/IGCCode.aspx

IMO. (2023). *Sub-Committee on Carriage of Cargoes and Containers (CCC 9), 9th session, 20-29 September 2023*. International Maritime Organization. https://www.imo.org/en/MediaCentre/MeetingSummaries/Pages/CCC-9th-session.aspx

Lautkaski, R. (1997). *Understanding vented gas explosions*. Technical Research Centre of Finland. https://publications.vtt.fi/pdf/tiedotteet/1997/T1812.pdf

LR MDH and MMMCZCS. (2023). *Recommendations for Design and Operation of Ammonia-Fuelled Vessels Based on Multi-disciplinary Risk Analysis*. https://www.lr.org/en/knowledge/research-reports/recommendations-for-design-and-operation-of-ammonia-fuelled-vessels-based-on-multi-disciplinary-risk-analysis/

Ludwig, H. R., Cairelli, S. G., & Whalen, J. J. (1994). *Documentation for immediately dangerous to life or health concentrations (IDLHS)*. https://ntrl.ntis.gov/NTRL/dashboard/searchResults/titleDetail/PB94195047.xhtml

Makarovsky, I., Markel, G., Dushnitsky, T., & Eisenkraft, A. (2008). Ammonia--when something smells wrong. *The Israel Medical Association Journal: IMAJ*, *10*(7), 537–543. https://www.ima.org.il/MedicineIMAJ/viewarticle.aspx?year=2008&month=07&page=537

MAN Energy Solutions. (2020). *MAN B&W two-stroke engine operating on ammonia*. https://www.man-es.com/marine/strategic-expertise/future-fuels/ammonia

Mastellone, M. L., Ponte, M., & Arena, U. (2003). Design of mitigation systems for indoor and outdoor ammonia releases. *Journal of Loss Prevention in the Process Industries*, *16*(2), 93–101. https://doi.org/10.1016/S0950-4230(02)00116-X

Montoya, M. I., Planas, E., & Casal, J. (2009). A comparative analysis of mathematical models for relating indoor and outdoor toxic gas concentrations in accidental releases. *Journal of Loss Prevention in the Process Industries*, *22*(4), 381–391. https://doi.org/10.1016/j.jlp.2009.01.009

National Research Council. (2008). *Acute Exposure Guideline Levels for Selected Airborne Chemicals: Volume 6*. The National Academies Press. https://doi.org/10.17226/12018

Pomonis, T., Jeong, B., & Kuo, C. (2022). Engine room fire safety evaluation of ammonia as marine fuel. *Journal of International Maritime Safety, Environmental Affairs, and Shipping*, *6*(1), 67–90. https://doi.org/10.1080/25725084.2021.2015867

Roney, N., Llados, F., Little, S., & Knaebel, D. (2004). *Toxicological profile for ammonia*. Agency for Toxic Substances and Disease Registry. https://www.atsdr.cdc.gov/toxprofiles/tp126.pdf

Tolan, C., & Chapman, I. (2023). *Dangerous chemical leaks have injured workers at one of America's largest meat processors*. CNN. https://edition.cnn.com/2023/05/04/business/tyson-ammonia-leaks-invs/index.html

Wärtsilä. (2020). *What does an ammonia-ready vessel look like?* Wärtsilä Corporation, News 1 December 2020. https://www.wartsila.com/media/news/01-12-2020-what-does-an-ammonia-ready-vessel-look-like--2825961

Wärtsilä. (2023). *Wärtsilä 25 – The power to target net zero*. https://www.wartsila.com/marine/products/engines-and-generating-sets/dual-fuel-engines/wartsila-25

Yadav, A., & Jeong, B. (2022). Safety evaluation of using ammonia as marine fuel by analysing gas dispersion in a ship engine room using CFD. *Journal of International Maritime Safety, Environmental Affairs, and Shipping*, *6*(2–3), 99–116. https://doi.org/10.1080/25725084.2022.2083295