Mærsk Mc-Kinney Møller Center
for Zero Carbon Shipping

Recommendations for Design and Operation of Ammonia-Fueled Vessels Based on Multi-disciplinary Risk Analysis

Executive summary

The implementation of alternatives to conventional fossil-based fuels is key to decarbonization of the global shipping industry. Ammonia is currently one of the frontrunners among alternative shipping fuels, as it can be combusted with almost no carbon dioxide emissions. However, using ammonia as a shipping fuel involves safety hazards: primarily toxicity, but also onboard fires and explosions. Therefore, it is crucial to understand these risks and the safeguards that can be implemented to reduce them to tolerable levels.

To this end, we have pioneered an innovative multi-disciplinary approach to assess and address the onboard safety risks to a ship's crew of ammonia as a shipping fuel. Our project is a collaboration between the Lloyd's Register Maritime Decarbonisation Hub (MDH) and the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS), with contributions from other partners. This report outlines the results of this project.

The first main section of this report summarizes the results of an iterative quantitative risk assessment (QRA) analysis applied to three reference designs for ammonia-fueled vessels. QRA is a powerful data-driven method that allows users to assess risk in a quantitative and granular manner. Importantly, QRA can be used to quantitatively estimate the effectiveness of risk mitigations by adding different modifications to the QRA model and observing their impact on the risk calculation. In our project, we used this capability of QRA to characterize risk levels across different vessel types, place these in the context of existing risk criteria, and identify design and operational measures that would reduce risk to crew to a tolerable level.

Based on our analysis, we highlight several recommendations and findings for the design and operation of ammonia-fueled vessels. We divided these into three groups: high-priority recommendations relating to measures that contribute significantly to reduction of risk to crew; findings that demonstrate the importance of existing good practice, guidelines, or rules; and other recommendations.

High-priority recommendations:

- Lower storage temperature reduces the safety risk from ammonia fuel.
- Divide the fuel preparation room into two or more separate spaces containing different groups of equipment that could leak ammonia.
- Access to and length of time spent in spaces containing ammonia equipment should be minimized, monitored, and controlled.
- Ventilation outlets from spaces containing ammonia equipment should be placed in a safe location adequately separated from areas accessed by crew, in order to avoid accidental release of toxic concentrations of ammonia affecting personnel.
- Multiple sensors of different types to detect ammonia leaks should be installed.

Findings:

- Secondary containment mechanisms, such as double-walled piping, used for ammonia-related equipment outside of already-restricted areas have been proven to significantly reduce risk.
- Ventilated gas-tight enclosures installed around any gas valve units in engine rooms also reduce risk.
- Ventilation of spaces containing ammonia equipment provides mitigation of toxic effects for many smaller, but not all, potential ammonia leaks. This mitigation is particularly efficient for smaller leaks. Consideration of additional precautions is required for personnel entering these spaces.
- Ventilation of spaces containing ammonia equipment reduces the risk of ammonia concentrations reaching a flammable level. Although ammonia is much less flammable than some other fuels, the flammability hazard should not be ignored.
- Ammonia leak alarms should be installed both in controlled areas (for example, the fuel preparation room) and near potential leak sources.
- The fuel system should be subject to rapid and reliable manual and automated shutdown in the event of an ammonia leak.

Other recommendations:

- Depending on storage conditions and ammonia tank location, shutdown of the ventilation for crew accommodation should be made possible in the event of an ammonia leak.
- A distinctive, vessel-wide audible toxicity alarm for ammonia leaks should be implemented.

To complement this quantitative analysis, the second main section of this report summarizes insights from an analysis of human factors considerations, such as training and work practices, that will be impacted by a transition to ammonia fuel use. Through a series of collaborative workshops, we identified relevant human factors considerations based on the three reference designs used for QRA and rated their impact as low, medium, or high. This report explains and discusses ways to address the highest-impact human factors considerations based on our analysis. These factors relate to the following areas:

- Competence and training: specific training and upskilling will be needed to prepare crew for operation and maintenance on ammonia-fueled vessels.
- Process and procedures: safe work practices and standard procedures need to be updated and should be implemented through systematic change management programs.
- Occupational health hazards: effective occupational health safeguards, such as personal protective equipment (PPE), need to be developed and implemented .
- Process safety hazards: appropriate safety management procedures for emergency response and other events need to be developed.

Taken together, we conclude that the risks to crew of using ammonia as an alternative maritime fuel can be kept to a tolerable level, provided that the maritime industry can:

- Ensure suitable and sufficient technical barriers and administrative safeguards are implemented to protect the crew against various ammonia risks;
- Address human factors considerations, such as those outlined above; and
- Build upon existing maritime industry experience with gas as fuels and cargo and carry over learnings from other industries with considerable experience in safely handling, transferring, and storing ammonia.

The recommendations and results from this report can and should be used to further inform specific regulations, guidelines, and best practices that will allow ammonia-fueled vessels to be acceptably safe for the crew.

Contents

Acknowledgements

The findings of this report are built on extensive cross-sector collaboration between organizations in the maritime industry and beyond. Initially, the project team comprised the MDH, the MMMCZCS, A. P. Moller - Maersk (Maersk), Mitsubishi Heavy Industries (MHI), NYK Line (NYK), TotalEnergies, and MAN Energy Solutions (MAN ES). The American Bureau of Shipping (ABS), BP, Cargill, CF Industries, Stolt Tankers, and V.Group were subsequently added to the team.

Drawing on resources available across these organizations, experts in risk assessment, maritime safety, human factors, ship design, ship operation, engine design, and ammonia production contributed their knowledge to the project.

Opinions found in this report do not necessarily represent those of each partner.

Detailed acknowledgements:

Project managers: Claus Rud Hansen (Maersk*) and Andrew Franks (MDH).

Assisting project manager: Martin Eriksen (MMMCZCS)

Project steering committee: Claus Winter Graugaard (MMMCZCS), Sebastien Roche (TotalEnergies), Benny Hilstrom (Maersk), Tomoo Kuzu (MHI), and Masafumi Okajima (NYK).

Preparation of reference designs: Peter Nerenst (MAN ES*), Claus Rud Hansen (Maersk*), Viviane Philippe (TotalEnergies*), Robert Bridges (TotalEnergies*), Jun Kato (NYK*), Takashi Unseki (MHI), Hiroyuki Yanagisawa (MHI*), Koichi Matsushita (MHI*), Daisuke Yamada (MHI), Jun Ito (NYK*), Koichi Sato (MHI*), and Shinichi Iwamoto (NYK*).

Quantitative risk assessment: Andrew Franks (MDH), Samie Parkar (MDH), and Paul Davies (LR).

Risk reduction workshops: Andrew Franks (MDH), Samie Parkar (MDH), Matt Dunlop (V.Group*), Toby Garner (LR), Ilie Juravle (Cargill*), Joshua Padeti (ABS), Shinichi Iwamoto (NYK*), Koichi Sato (MHI*), Jun Kato (NYK*), Takashi Mishima (NYK), Koichi Matsushita (MHI*), Takashi Unseki (MHI), Andrew McNally (BP), Mike Parker (BP), Peter Nerenst (MAN ES*), Pierre Domine (Stolt Tankers), Viviane Philippe (TotalEnergies*), and Claus Rud Hansen (Maersk*).

Human factors study: Matt Dunlop (V.Group*), Denise McCafferty (LR), Toby Garner (LR), and Martin Eriksen (MMMCZCS).

Review of HAZID studies and accident experience: Andrew Franks (MDH), Claus Rud Hansen (Maersk*), Joshua Padeti (ABS), Giorgio Guadagna (Stolt Tankers*), Pierre Domine (Stolt Tankers), Matt Dunlop (V.Group*), Andrew McNally (BP), Hiroyuki Yanagisawa (MHI*), Denis McCafferty (LR), Jun Ito (NYK*), Shinichi Iwamoto (NYK*), Ilie Juravle (Cargill*), Peter Nerenst (MAN ES*), Robert Bridges (TotalEnergies*), and Koichi Matsushita (MHI*).

Finite Element Analysis: Yong Chen and Bo Wang (ABS).

Computerized Fluid Dynamics Analysis: Zhongfu Ge (ABS).

Dispersion from vent masts and ventilation exhausts: Koichi Matsushita (MHI*), Marwan Elnesr and Samie Parkar (MDH).

(*): Seconded to MMMCZCS.

1.

Introduction: Ammonia is a potential solution to shipping's decarbonization, but new risks must be addressed

As efforts intensify to limit global temperature rise to 1.5°C in line with the Paris Agreement,[1] governments and regulators are setting increasingly ambitious greenhouse gas (GHG) reduction targets. Accordingly, the maritime industry is moving forward with short-, medium- and long-term measures to achieve year-on-year emissions reductions. Long-term solutions require alternative fuels with zero GHG emissions across the whole fuel supply chain, from resource and production through to distribution and consumption.

No single alternative fuel is likely to fulfil the needs of the entire maritime industry. This is due to many factors, including feedstock supply, technology limitations, price competitiveness, stakeholder acceptance, and the requirements of different vessel types and operating profiles. Several alternative fuels are under consideration, including methane, hydrogen, methanol, biofuels, and ammonia.[2,3] Each fuel has different characteristics and advantages but also different hurdles, including safety hazards that must be overcome before widespread adoption.

Importantly, ammonia offers the potential for zero-carbon propulsion, as its combustion does not produce carbon dioxide (CO_2). In practice, pilot fuel is required to achieve ammonia combustion, resulting in some CO_2 emissions. Furthermore, emissions of the potent greenhouse gas nitrous oxide (N_2O) from ammonia-powered vessels would need to be managed, and the energy used for ammonia production must also be zero-carbon to avoid upstream CO_2 emissions. The well-to-wake GHG emissions of green ammonia (i.e., ammonia produced using renewable electricity) have been estimated to be 97% lower than those of low-sulfur fuel oil (LSFO).[4]

As such, ammonia's potential for near-zero carbon emissions has attracted considerable interest from the shipping industry. A recent survey of shipping sector stakeholders by Lloyd's List and Lloyd's Register (LR) identified ammonia as one of the top three fuels with potential for zero carbon shipping by 2050.[5] Analysis by the MMMCZCS also indicates that ammonia could play a notable role in shipping's green transition, representing up to half of the industry's fuel needs in 2050.[6]

1 The Paris Agreement, UNFCCC, 2015.
2 Maritime Decarbonization Strategy 2022, Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022.
3 Zero Carbon Fuel Monitor, Lloyd's Register Maritime Decarbonisation Hub, 2023.
4 Maritime Decarbonization Strategy 2022, Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022.
5 Regulation is key to shipping's green push, Lloyd's List survey finds, Lloyd's List, 2021.
6 Industry Transition Strategy 2021, Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022.

However, ammonia is hazardous to both humans and the environment.[7] Ammonia is toxic, and leaks resulting in air concentrations as low as 2,700 parts per million (0.27%) can cause fatalities after 10 minutes' exposure.[8] Ammonia is also flammable, but much less flammable than other fuels such as natural gas or hydrogen. While the shipping industry is already experienced in designing vessels powered by hazardous fuels such as heavy fuel oil and liquified natural gas (LNG), ammonia's physical properties differ considerably from these established fuels. The industry also has experience in handling ammonia, as it is currently carried onboard ships as cargo. However, using ammonia as a fuel comes with many additional considerations, including bunkering, fuel preparation, piping, and ventilation, which lead to increased risks of leaks and exposure compared with carriage as cargo. As a result, safety, including crew safety, is a key hurdle for the use of ammonia as a fuel in the maritime industry.

The risks to crew of ammonia as a fuel should be assessed in the context of the current risks to seafarers. The main hazard associated with traditional oil-based fuels is fires in the engine room. A 2011 study on fire safety in engine rooms reported 73 such fires over a 13-year period in a fleet of 6,000 merchant vessels. Around 60% of these fires arose from the fuel oil or diesel oil part of the system.[9] Seafarers are also exposed to numerous other hazards, including container fires, collisions, and non-fuel fires. A 2014 study of fatalities in the British merchant fleet records 49 seafarer fatalities in marine accidents over the period 2003 – 2012.[10] The causes of death included vessel capsize, asphyxiation in enclosed spaces, falls overboard and onboard, and being struck by ropes and other objects. Although a more recent study is available,[11] it provides less detail on the causes of fatalities and which crew groups were affected (see Appendix 1).

Hence, introduction of ammonia as a shipping fuel without implementation of appropriate controls would increase the level of hazard in an already hazardous environment, leading to two fundamental questions:

- What are the risks to crew in using ammonia as a shipping fuel?
- What safety measures can be implemented to reduce these risks?

The industry must reach a consensus on these questions to develop safety concepts and enable the use of ammonia as a marine fuel.

7 Ammonia at sea: Studying the potential impact of ammonia as a shipping fuel on marine ecosystems, Environmental Defense Fund, Lloyd's Register and Ricardo, 2022.

8 Table 2 -1, Acute Exposure Guideline Levels for Selected Airborne Chemicals: Volume 6. National Research Council (US) Committee on Acute Exposure Guideline Levels, 2008.

9 Charchalis A and Czyz S (2011). Journal of KONES Powertrain and Transport, Vol. 18, No.2, 49-56.

10 Fatal accidents and injuries among merchant seafarers worldwide; S. E. Roberts, D. Nielsen, A. Kotłowski and B. Jaremin; Occupational Medicine, 2014.

11 European Maritime Safety Agency (2022). Annual Overview of Marine Casualties and Incidents 2022. Ares (2022) 8241169 – 29/11/2022.

This report summarizes a novel multi-disciplinary project to address the safety challenges of ammonia fuel. It presents the results of a quantitative risk assessment study carried out in partnership between the MDH and the MMMCZCS. A collaborative team of over 15 experts drawn from the participating organizations contributed to this project over a two-year period.

We begin this report with a brief overview of the methodology used to evaluate and reduce the risks of using ammonia as a fuel and present the findings of the study in the context of existing risks and published risk guidelines. We summarize the key sources of risk to crew and provide practical guidance to reduce this risk on ammonia-fueled vessels, including advice on vessel design and layout. Furthermore, we provide an overview of key human factors considerations that must be addressed to enable safe use of ammonia as a marine fuel, including competence and training needs across segments, changes to work practices and procedures, and knowledge and guidance on occupational health and process safety hazards.

2.

Quantitative risk assessment (QRA) provides an innovative approach to evaluate and reduce risk in ship design

2.1 Quantitative risk assessment can enable safer design

Before new technologies are introduced, the risks must be fully understood and reduced to be “as low as reasonably practicable” (ALARP). The shipping industry typically uses qualitative risk assessment methods, such as hazard identification (HAZID) studies, as part of the process of assessing and certifying the design of new ships, onboard systems, and components ahead of any manufacturing. These risk assessments typically determine risk by estimating 1) how likely an undesired event is, and 2) how severe the consequences of the event could be. These estimates are made based on the subjective judgement of experts in the field, often working in teams through workshops. Risk likelihood and consequences are typically rated using categories such as low, medium, and high.

Qualitative studies of engineered systems provide useful insights but have known limitations (although there are other applications, such as human factors, where a qualitative approach is often preferable). Specifically, in the engineering context, the subjective nature of qualitative studies can introduce inconsistencies, the lack of precision can reduce the understanding of risk, they may be too coarse to show changes in risk level following risk mitigation, and comparison of different risks is difficult. Together, these factors limit our ability to fully understand risks using a qualitative approach. This challenge increases further as systems become more complex, making prediction of outcomes more difficult. When applied to a ship, qualitative studies cannot define the total risk to the crew and tend to be quite insensitive to all but the largest design changes. What do we do when we want to compare the total risk to a vessel’s crew with published criteria or similar technologies, or when we want to test the effectiveness of different risk mitigation measures?

Quantitative risk assessment (QRA) is an analytical tool that has been widely used to assess risk in other industries, including oil and gas and onshore chemicals,[12,13] but has seen only limited use in the maritime sector to date. Compared to qualitative approaches, QRA provides a more objective and granular understanding of risk, enabling the use of numerical risk criteria and benchmarks. However, QRA is time-consuming and requires both specialist expertise and a large volume of input data. In addition, the outputs of QRA can be sensitive to the assumptions made during the assessment. An overview of QRA methodology is shown in Figure 1.

12 Spouge, J, A Guide to Quantitative Risk Assessment for Offshore Installations (1999).
13 *Center for Chemical Process Safety, Guidelines for Chemical Process Quantitative Risk Analysis. 2nd ed (1999).*

When applied to a vessel design before construction, QRA allows us to identify, assess and reduce risks to the crew, thereby improving safety without the costs of physical manufacture and testing. QRA provides decision-makers in shipping with the information required to choose between fuel options and designs. It can also provide the insights needed to develop rules and guidelines for vessel certification and to test the effectiveness of proposed mitigations: for example, the International Maritime Organization (IMO) Formal Safety Assessment (FSA) guidelines for shipping include a form of QRA.[14]

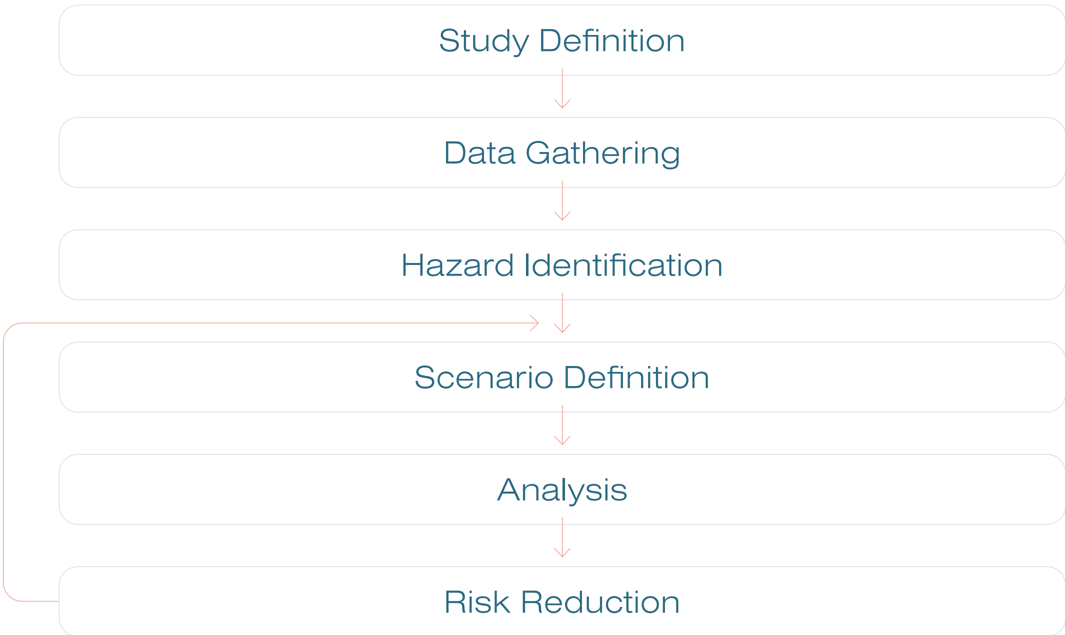


Figure 1: Overview of quantitative risk assessment (QRA) methodology.

14 *IMO, Revised Guidelines for Formal Safety Assessment (FSA) for Use in the IMO Rule-Making Process. MSC-MEPC.2/Circ.12/Rev 2 (2018).*

2.1.1 Study definition and scope

This project is the first part of an ongoing study of ammonia safety in the maritime industry. Our objectives were to:

- Provide an estimate of the risk of fatality to crew members working on board ammonia-fueled cargo ships
- Determine the acceptability of these risks in relation to established criteria
- Propose measures to reduce the risks where needed

While planning our work, we were aware of other completed and planned safety studies, several of which focused on ammonia bunkering and the accompanying risk to third parties.[15,16,17,18] However, we identified an absence of similar studies addressing ammonia fuel and crew safety, which we consider an important area worthy of detailed attention. Therefore, we decided to focus the scope of our project on onboard risks to the crew.

Hence, this study covers the ammonia systems on board, starting at the bunkering manifold. It also addresses fuel storage, preparation, and supply to the main engine, auxiliary engines, boilers, and other consumers. The study does not cover risk to shore personnel, personnel on adjacent vessels, or other third parties.

The ammonia systems on the engine, boilers, auxiliary engines, and other integrated units themselves are not included in the QRA modelling. This is because the design of these items is still evolving, and final details are not yet available. However, these items are addressed in a review of HAZID studies and accident experience described in Appendix 2. In addition, such equipment is subject to a separate and rigorous approval process.

2.1.2 Preliminary data gathering

Data gathering forms the groundwork for risk assessment. In addition to creating reference ship designs, this step included definition of fuel and safety systems, crew distribution, and vessel operating modes.

In this project, we considered three ammonia-fueled vessel reference designs: a container ship, tanker, and bulk carrier, each with a different storage system (fully refrigerated, semi-refrigerated, and fully pressurized, respectively). In fully refrigerated storage, ammonia is cooled to its boiling point and kept at pressures close to atmospheric. In fully pressurized storage, ammonia is compressed until it becomes a liquid at ambient temperature and then kept under these conditions. Semi-refrigerated refers to a combination of refrigeration and pressurization.

15 DNV (2021). External safety study – bunkering of alternative marine fuel for seagoing vessels. Report No. 10288905-1, Rev. 0; Document No.: 11J5ON0R-1.
16 European Project for Smart Green Ports – MAGPIE. https://www.magpie-ports.eu/.
17 Global Centre for Maritime Decarbonisation – Ammonia Bunkering Safety Study. https://www.gcformd.org/press-release-ammonia-bunkering-safety-study-award.
18 Yara Clean Ammonia, Pilbara Ports Authority and Lloyd's Register – Feasibility Studies into Using Ammonia to Refuel Ships. https://www.yara.com/news-and-media/news/archive/news-2022/lloyds-register-to-investigate-pilbara-potential-for-ammonia-as-a-clean-shipping-fuel/.

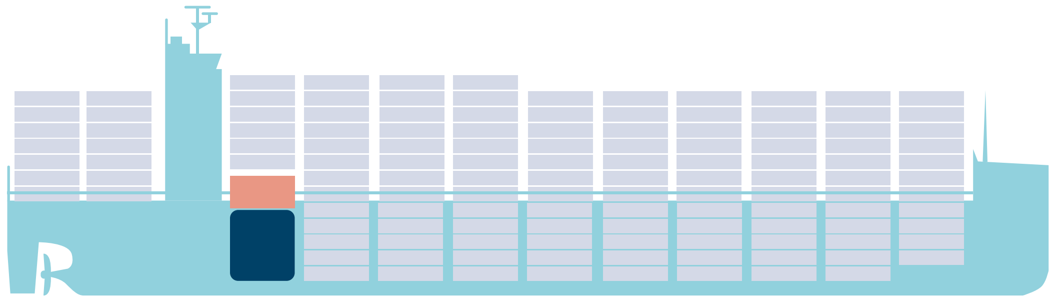


Figure 2: Simplified schematic of container ship reference design (fully refrigerated).

FPR (fuel preparation room)
Fuel storage tank

Figure 3: Simplified schematic of tanker reference design (semi-refrigerated).

FPR (fuel preparation room)
Fuel storage tank

Figure 4: Simplified schematic of bulk carrier reference design (fully pressurized).

FPR (fuel preparation room)
Fuel storage tank

2.1.3 Hazard identification

Given the scope of our project on the safety of ammonia as a marine fuel, we considered the following specific hazard events in our analysis:

- Fuel system leaks leading to toxic exposure, fire, or explosion (in the case of ammonia)
- Fires (in the case of low-sulfur fuel oil (LSFO) and marine gas oil (MGO))

2.1.4 Analysis

Leaks arise from fuel system components such as pipes, filters, pumps, valves, and flanges. We used data on leak rates for these components from other industries[19,20] to estimate the likelihood of ammonia leaks for each ship design. Consequence analysis was mainly carried out using DNV Process Hazard Analysis Software Tool (PHAST), an industry-standard process hazard software. Recognizing that PHAST has limitations when modelling leaks in enclosed spaces, this analysis was supplemented by computerized fluid dynamics (CFD) studies of leaks in a vessel engine room conducted by ABS. An example of the CFD output is shown in Figure 5.

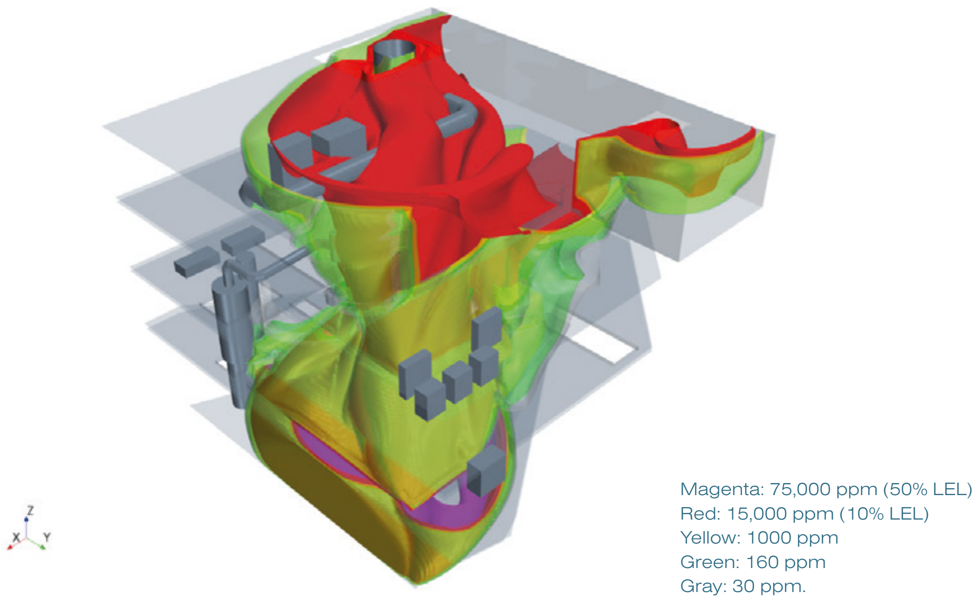


Figure 5: CFD simulation of 0.23 kg/second leak of ammonia for 300 seconds into an engine room ventilated at 30 air changes per hour, against the ventilation air flow.

Collision with another vessel was identified as a potential cause of an ammonia leak, particularly when the fuel tank is below the deck, as with the container ship reference design in Figure 2. Therefore, ABS also conducted finite element computer simulations of the reference container ship being struck by a much larger 19,000-TEU vessel, finding that leaks due to collisions between these two vessels in open water would be extremely unlikely. Further details of both the CFD and finite element analyses are included in Appendix 2.

19 International Association of Oil & Gas Producers (2019). Risk Assessment Data Directory – Process Release Frequencies. Report 434-01 September 2019.

20 Health & Safety Executive (2017). Failure Rate and Event Data for use within Risk Assessments. Planning Case Assessment Guide Chapter 6K.

A QRA model developed by LR was subsequently used to combine likelihood and consequence results into a calculation of risk. The main numerical risk output discussed in this report is individual risk per annum (IRPA). This is the risk of fatality per year for an individual with defined characteristics. In our case, the individual is a member of a specified crew group. The IRPA figures were calculated for each of the different crew groups on a vessel (bridge team, deck officers, deck ratings, support crew, engineering officers, engineering ratings, and cadets).

2.1.5 Risk reduction

We then conducted an iterative QRA process, which can be summarized as follows:

- Using the QRA results, scrutinize the breakdown in risk to determine the main contributors
- Propose design or operational modifications that aim to reduce the risk, targeting these contributors
- Implement the proposed mitigations in the QRA model
- Re-run the model and observe the change in results

This process was repeated multiple times during the project. In total, the model was run in excess of 50 times across the three reference designs. In addition, over 20 runs were performed to test the model's sensitivity to different inputs and assumptions.

The principles used in the application of risk criteria and ALARP are explained further in Appendix 1. The risk criteria framework and target set for the project are illustrated in Figure 6. The overall risk criteria framework is that published by the UK Health & Safety Executive[21] and referenced by the International Maritime Organization (IMO). The risk target for the project (purple dashed line in Figure 6) was based on a published guideline from the IMO.[22]

21 HSE (2001), Reducing Risks, Protecting People – HSE's decision-making process. C100.
22 IMO (2018), Revised Guidelines for Formal Safety Assessment (FSA) for Use in the IMO Rule-Making Process. MSC-MEPC.2/Circ.12/Rev 2, Appendix 5.

Figure 6: IRPA criteria framework and project target.

A fuller description of the QRA process for this study was presented at the Royal Institute of Naval Architects (RINA) conference 'Scaling Decarbonisation Solutions – Reducing Emissions 2030' in November 2022.[23]

Overall, we applied a variety of methods to investigate various aspects of ammonia safety. The results of some analyses, including modelling of vessel impact and gas dispersion scenarios, were used to improve or complement the main QRA. These additional studies are described in greater detail in Appendix 2, and we expect that some will be the subject of separate detailed publications in due course.

23 Quantitative Risk Assessment of Ammonia Fuelled Vessels, AP Franks, C Graugaard, RINA Scaling Decarbonisation Solutions: Reducing Emissions by 2030, 2022.

2.2 Crew risk can be substantially reduced through stepwise mitigation

2.2.1 Successive application of targeted measures can drive down risk to crew

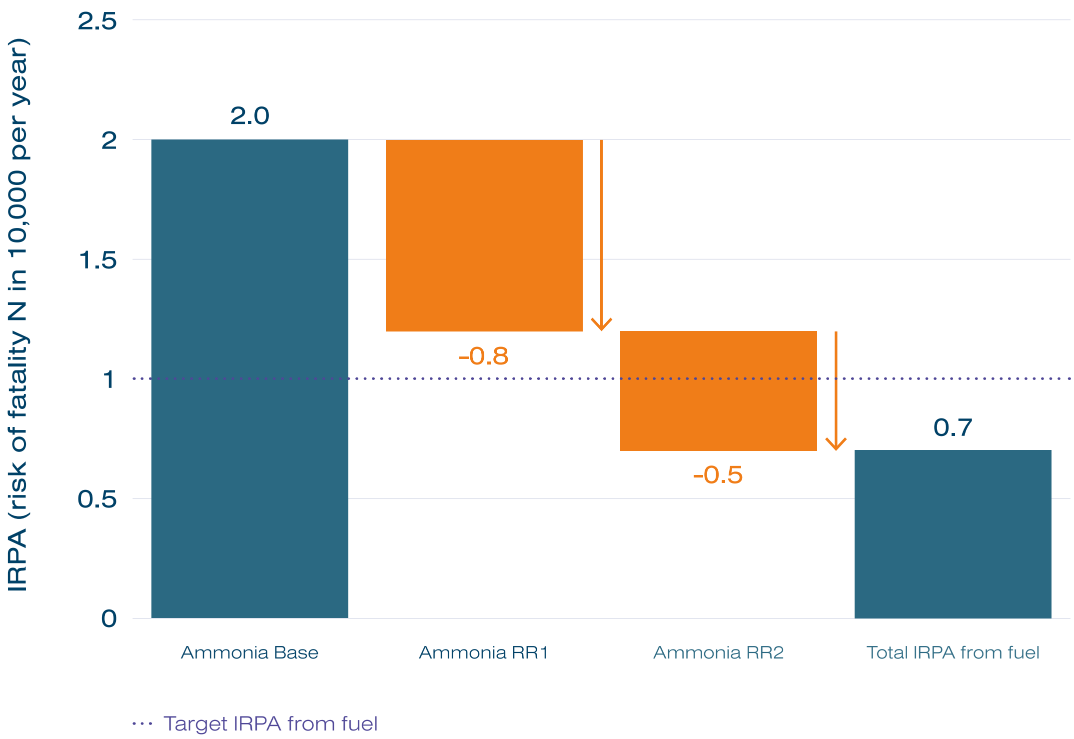
One of the most powerful uses of QRA is to test the effectiveness of proposed risk mitigations in driving risk downwards. In this project, we applied an iterative QRA process as described in the previous section to explore the best approaches to reduce risk to the crew on board ammonia-powered vessels.

This section summarizes key QRA results and illustrates how the analysis has been used to reduce risk. The results presented here are those for the engineering ratings, as this crew group was consistently found to have the highest IRPA from ammonia.

Appendix 1 provides a detailed description of the IRPA criteria and target value adopted for the study. For the purposes of this section, it is sufficient to note that an IRPA of 1 in 10,000 risk of fatality per year (represented by the purple dashed line) was set for the project target for crew IRPA from fuel hazards.

The graphs below show a series of columns. In each case, the first column (working from left to right) shows the initial QRA result for ammonia as a fuel (together with the pilot fuel), which we term the ammonia base case. The remaining columns show the change in risk following the application of risk mitigation measures and other design changes (orange), followed by the final total IRPA value from ammonia as fuel after application of these changes (blue right-most column).

Container ship/fully refrigerated storage

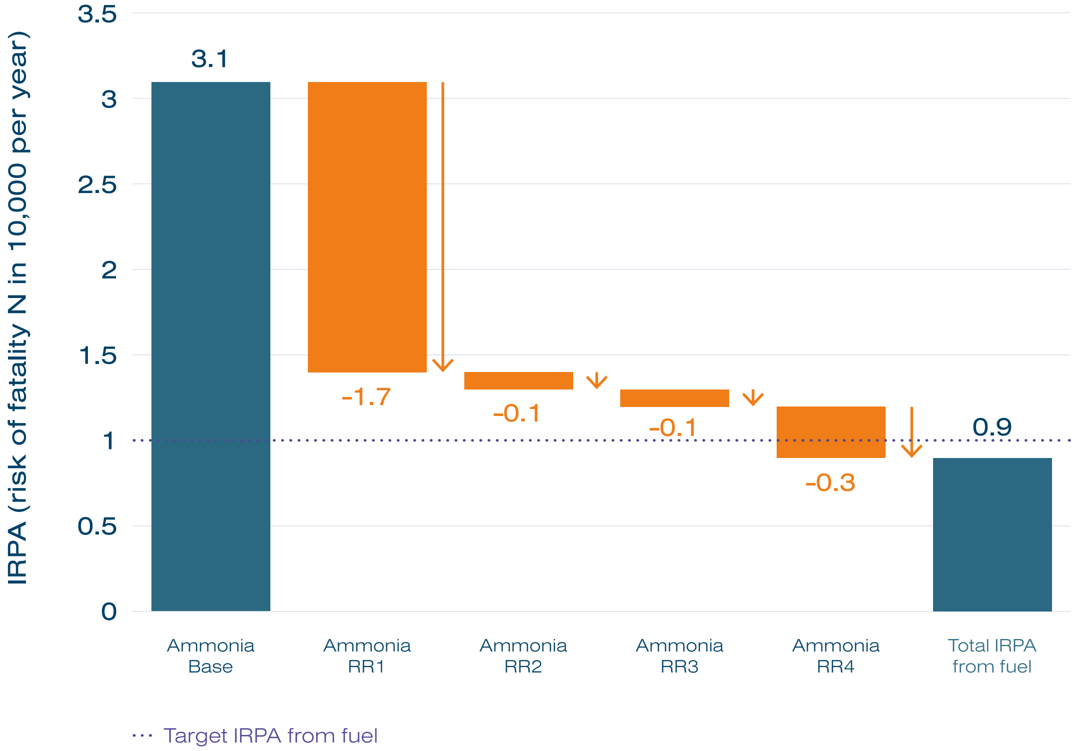


Key

Label	Description	Comment
Ammonia Base	First iteration of QRA results for this design.	
Ammonia RR1	Risk Reduction 1: Single fuel preparation room (FPR) divided into three separate spaces.	40% reduction in ammonia risk relative to base case
Ammonia RR2	Risk Reduction 2: Increasing ventilation rates in FPRs and re-liquefaction room from 30 to 45 air changes per hour, together with modifications to the fuel system design.	Further 25% reduction in ammonia risk relative to base case

Figure 7: Changes in total IRPA for engineering ratings on a container ship with fully refrigerated ammonia fuel storage.

Semi-Refrigerated Storage / Tanker

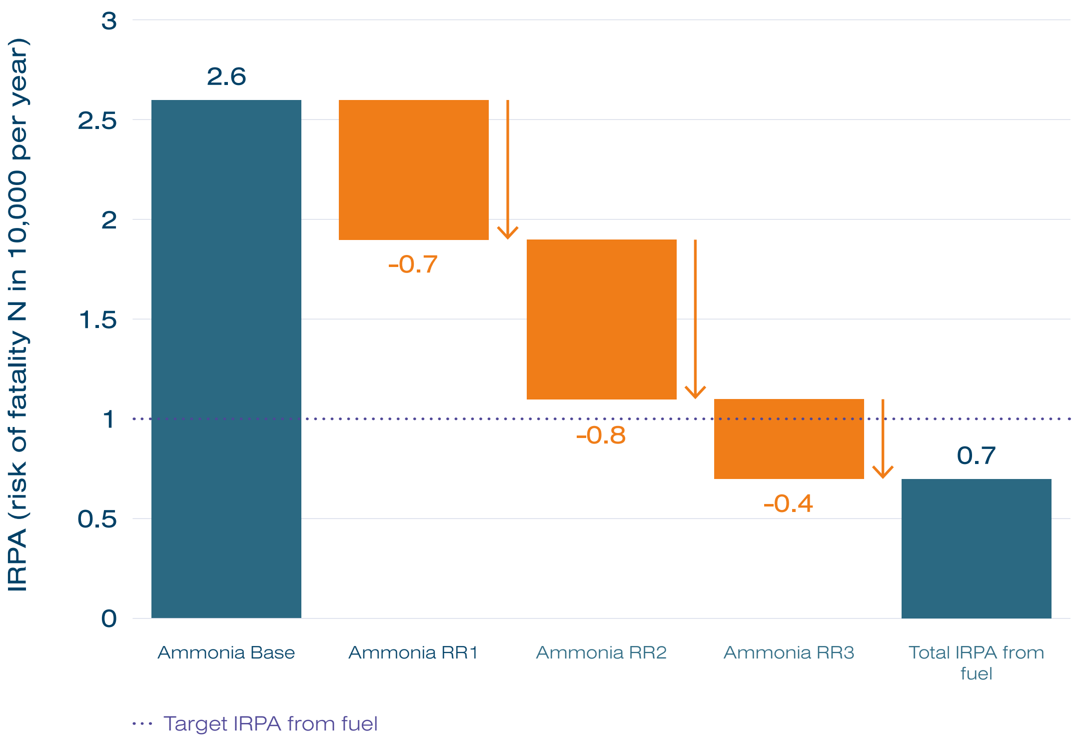


Key

Label	Description	Comment
Ammonia Base	First iteration of QRA results for this design.	
Ammonia RR1	Risk Reduction 1: Single fuel preparation room (FPR) divided into three separate spaces.	56% reduction in ammonia risk relative to base case
Ammonia RR2	Risk Reduction 2: Increasing ventilation rates in FPRs and re-liquefaction room from 30 to 45 air changes per hour, together with modifications to the fuel system design.	Further 5% reduction in ammonia risk relative to base case
Ammonia RR3	Risk Reduction 3: Shut-off of the ventilation in the accommodation (as opposed to switching to recycle) upon gas detection in the ventilation intake.	Further 3% reduction in ammonia risk relative to base case
Ammonia RR4	Risk Reduction 4: Further subdivision of the FPR to provide a separate room for duplex filters.	Further 9% reduction in ammonia risk relative to base case

Figure 8: Changes in total IRPA for engineering ratings on a tanker with semi-refrigerated ammonia fuel storage.

Pressurized Storage / Bulk Carrier



Key

Label	Description	Comment
Ammonia Base	First iteration of QRA results for this design (fully pressurized storage).	
Ammonia RR1	Risk Reduction 1: Switch to semi-refrigerated storage and extensive redesign of fuel system.	26% reduction in ammonia risk relative to base case
Ammonia RR2	Risk Reduction 2: Addition of a scrubber on the ventilation intake to the accommodation, which operates on gas detection in the ventilation intake.	Further 29% reduction in ammonia risk relative to base case
Ammonia RR3	Risk Reduction 3: Further refinement of fuel system design (changes in fuel flow rates and pipe diameters).	Further 17% reduction in ammonia risk relative to base case

Note: In the case of the bulk carrier, a sub-divided FPR was implemented at the outset.

Figure 9: Changes in total IRPA for engineering ratings on a bulk carrier with fully pressurized and semi-refrigerated ammonia fuel storage.

Conclusion: risks from fuel

The project IRPA target for fuel hazards was achieved for all three vessel designs.

2.2.2 Risks can be kept within tolerable limits

As well as showing that the project IRPA target for fuel hazards is met, it is also necessary to verify that the total IRPA from all hazards is below the 'Unacceptable' boundary (as shown in Figure 6).

For all vessels and fuel system designs assessed, the introduction of ammonia as fuel increases the total risk to the crew. However, the application of risk mitigation measures can minimize this increase and keep the total risk within tolerable limits. Figure 10 shows the total IRPA for engineering ratings following the application of risk mitigation measures for each of the three vessel types. This total IRPA is broken down into contributions from fuel (ammonia and pilot fuel) and other hazards. Appendix 1 covers our definition of tolerable risk limits and how they are applied in the current study.

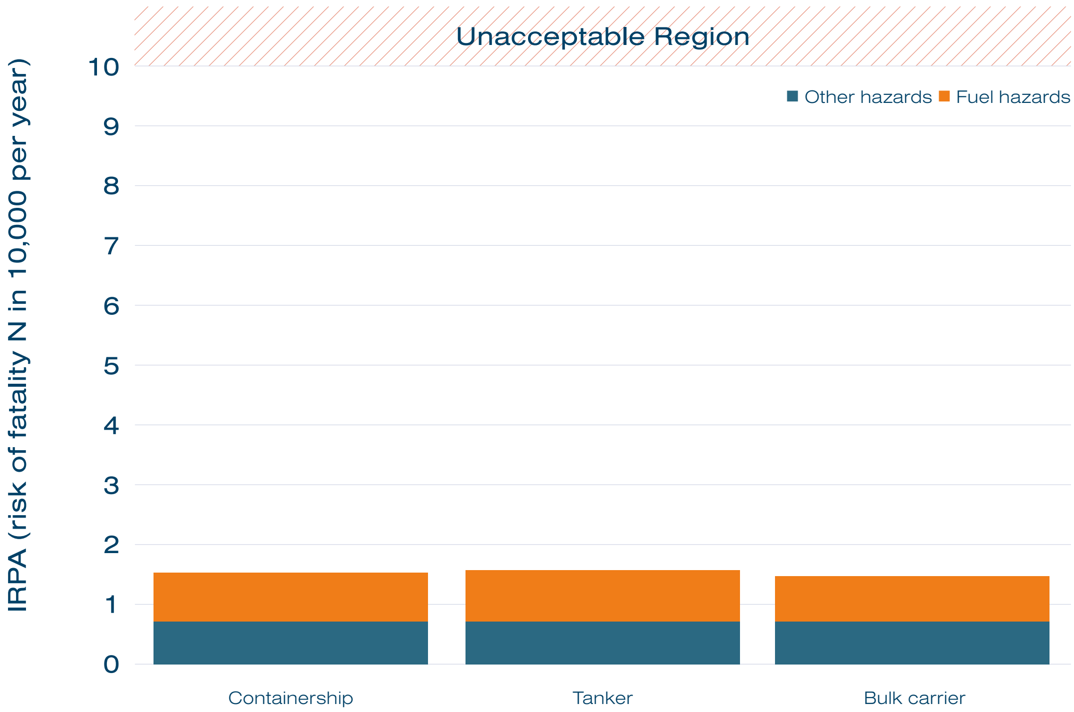


Figure 10: Comparison of total IRPA on board ammonia-fueled reference vessels with risk criteria.

There were some risk mitigation measures (such as the separate duplex filter room modeled for the tanker) which could, in principle, be applied to the other vessel designs also. However, time did not allow all of the possible combinations of measures to be studied for all three designs.

In addition, innovative risk reduction measures outside the scope of the current study could reduce the safety risk still further. For example, our results showed that the amount of time spent in rooms where ammonia equipment is present, such as the fuel preparation room (FPR), has a significant effect on the IRPA of the engineering team. Therefore, using remote monitoring or automated technology to reduce the need for crew to enter these spaces would have a major safety benefit. This is an example of an area that we may investigate in future projects.

2.3 New vessel designs and additional equipment are needed

2.3.1 User-centered design will be a key principle

Moving from fuel oil only to dual-fuel engines using both ammonia and fuel oil will require not only new equipment and systems, but also new procedures, work processes, and maintenance regimes. Application of specific user-centered ergonomic design would benefit the operability and maintainability of new ammonia-related systems, equipment, components, and spaces. These include specific critical work areas such as the engine control room (to accommodate novel technology) and the ease with which crew can perform maintenance and access certain areas such as the FPR. The application of human factors design criteria and principles could reduce potential crew exposure to ammonia through ensuring usability, efficiency, and safety. Human factors considerations are discussed in greater detail in the next section of this report.

2.3.2 Lower storage temperature reduces the safety risk from ammonia fuel

The safety impacts of an ammonia leak differ depending on the ammonia's storage pressure and temperature. When stored in a non-pressurized condition at -33°C, a leak of ammonia will form a pool that will evaporate as it heats up. This evaporation is relatively slow compared to a pressurized and warm condition, where the leaked ammonia evaporates immediately when the pressure is released. This means that the ammonia from a leak in warm and pressurized containment enters the gas cloud more rapidly, leading to a bigger cloud.

This principle is illustrated in Figure 11, which shows the IRPA from ammonia for engineering ratings for each of the vessel designs. In this case, the FPR is sub-divided but no additional mitigation measures have been implemented (although further risk reduction efforts subsequently brought all three designs to very similar IRPA values). Direct comparison between the vessels is difficult due to other differences in design, but storage of ammonia as a fully refrigerated liquid has the lowest IRPA, followed by the semi-refrigerated options, with fully pressurized liquified gas being the riskiest storage type. In particular, the change from fully pressurized to semi-refrigerated storage on the bulk carrier (where other aspects of the design are similar) resulted in a 26% reduction in IRPA.

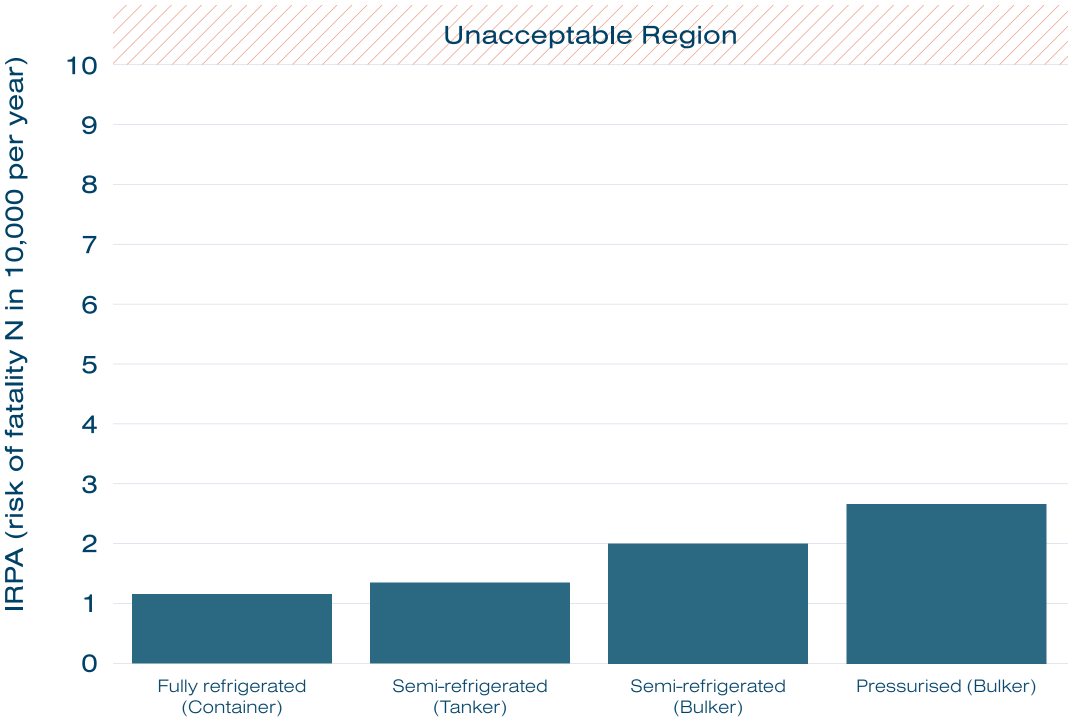


Figure 11: IRPA from ammonia for engineering ratings by type of fuel storage.

Therefore, from a safety perspective, we recommend that ammonia fuel should be stored at as low a temperature as possible. The higher the storage temperature, the more mitigation measures need to be implemented to bring the safety risk from ammonia leaks to a tolerable level.

2.3.3 Secondary containment is an important risk mitigator

Use of secondary containment for pipes outside controlled spaces reduces risk

IRPA is significantly reduced when a secondary barrier is applied around pipes that contain ammonia. For example, double-walled pipe is a pipe within a pipe, which provides a second containment barrier. The space between the pipes can be purged with another gas such as nitrogen or dry air and can be monitored for leaks from the inner pipe.

The risk levels for the reference vessels reported in our study assume that all pipes are double-walled, except for those at the bunker station, pipes on open deck, and pipes in the FPR and tank connection space. Piping without secondary containment (but with impact protection) is currently permitted on open deck under the International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF Code) for LNG.[24]

24 IGF Code – International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels – Part A-1 – Specific requirements for Ships using Natural Gas as Fuel – Section 5.3 – Regulations – General.

As the FPR and tank connection space are separated from other machinery spaces, the structure around these spaces is considered a secondary barrier. Access to these areas must therefore be restricted and controlled.

The value of double-walled piping in reducing risk is illustrated by a sensitivity study in which we modelled liquid ammonia pipe in the container ship engine room as single-walled instead of double-walled. In this study, the IRPA for engineering ratings from ammonia was more than four times higher when using single-walled pipe compared to double-walled, as illustrated in Figure 12.

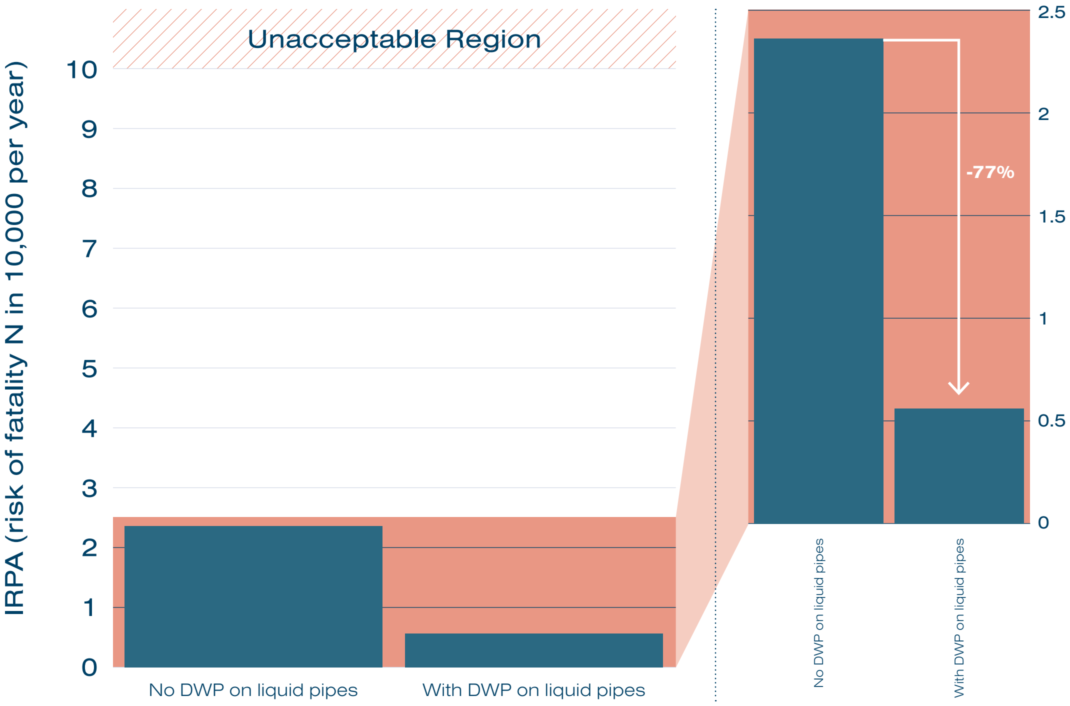


Figure 12: IRPA from ammonia for engineering ratings with and without double-walled pipe (DWP) on liquid lines in the container ship engine room. Left: IRPA results shown in relation to unacceptable region; right: magnified view to show scale of change in IRPA.

Risk can be reduced by gas-tight enclosures around gas valve units in engine rooms

Another effective risk mitigation measure can be to install ventilated, gas-tight enclosures around gas valve units (GVUs) on the inlets to gas-fueled auxiliary engines and on valves and instruments on the inlets to other gas-fed equipment, such as supply to boilers or selective catalytic reduction (SCR) units.

We investigated this measure using another sensitivity study that compared the IRPA from ammonia for the engineering ratings with and without secondary containment on the GVUs in the tanker engine room. With secondary containment, the IRPA from ammonia for the engineering ratings is 8% lower, as illustrated in Figure 13.

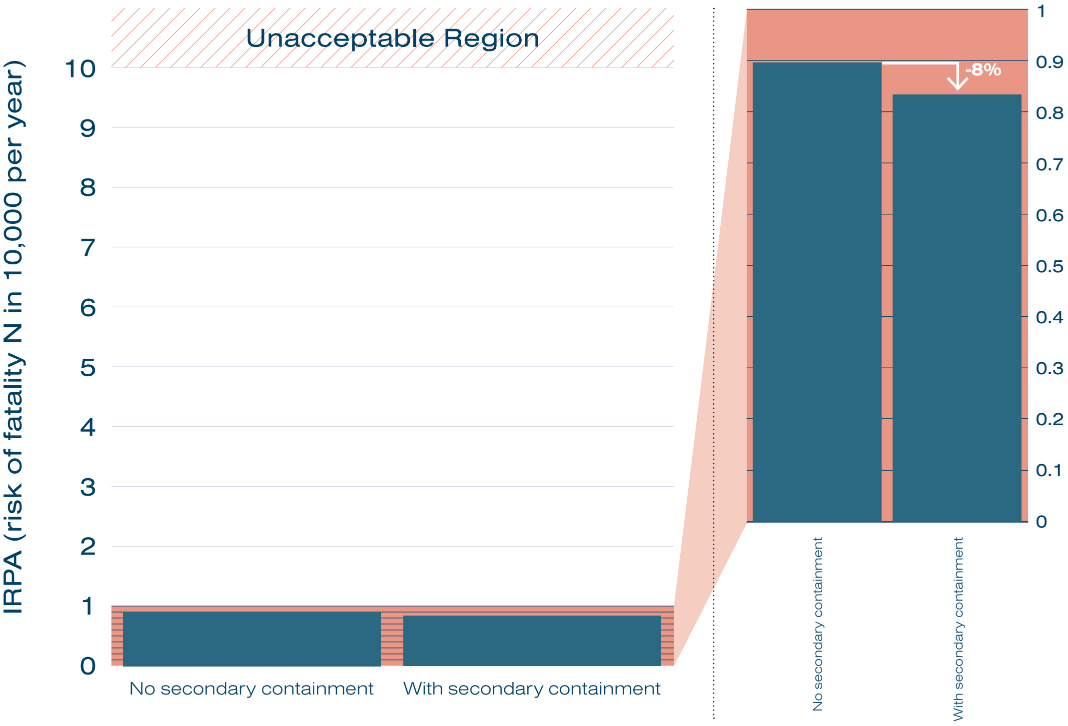


Figure 13: IRPA from ammonia for engineering ratings with and without secondary containment on GVUs in the tanker engine room. Left: IRPA results shown in relation to unacceptable region; right: magnified view to show scale of change in IRPA.

2.3.4 Control of ventilation is a key risk mitigator

Ventilation is important in spaces where ammonia equipment is located

A high ventilation rate of 45 air changes per hour can help reduce the concentration of ammonia in a given space in the event of a leak.[25] We have found that:

- Ventilation is only partly effective at preventing ammonia concentrations from reaching levels that may be fatally toxic. Even at short exposure times, the concentration threshold for ammonia toxicity is much lower than the threshold for flammability. This means that, in addition to ventilation, other precautions will need to be considered for personnel entering these spaces.

- Ventilation is more effective at preventing ammonia concentrations from reaching a flammable level. Although the flammability of ammonia should not be ignored, it is considerably less flammable than other fuels such as natural gas or hydrogen.

- Room size also has an effect on IRPA, with larger rooms being better than smaller rooms since the ammonia concentration in case of a leak will be more diluted. However, the room size must be substantially increased for this effect to be noticeable.

25 https://ww2.eagle.org/content/dam/eagle/rules-and-guides/current/other/325-requirements-for-ammonia-fueled-vessels/325-ammonia-fueled-vessels-reqts-july22.pdf, ABS class requirements 2022.

Consider measures to limit ventilation in the accommodation

Most time on board is spent in the crew accommodation, and this space should be protected from ammonia ingress as far as possible. In the event of an ammonia leak on deck (e.g., during bunkering), one option is that detection of ammonia close to the leak source or in the ventilation intake triggers both an auto-stop function for all accommodation fans and an auto-shut concept for all accommodation air inlet dampers.

Alternative or additional measures could include the use of scrubber systems or chemical filters on the ventilation intakes, although such technology would need to be proven fit for maritime application. Scrubbers work by bringing the contaminated air in contact with a substance (usually in liquid form) that dissolves or reacts with the ammonia, removing it from the air. Including a measure of this type reduced the IRPA from ammonia for the engineering ratings by 29% in our QRA, as shown in Figure 9 (RR2).

We further recommend establishing an emergency response procedure in case of ammonia detection at the accommodation's air inlet. The procedure should consider how long the crew can remain 'shut in' in the accommodation, bearing in mind crew numbers, oxygen and humidity levels, and the potential for ammonia ingress, albeit at a much lower rate than under normal ventilation conditions. It may also be necessary to consider how the crew can safely evacuate the accommodation while ammonia is still present outside (e.g., if the gas-tightness of the accommodation is impaired). This is likely to require the provision of suitable PPE, including respiratory protection. Enhancements to work practices and procedures are further outlined within our human factors study.

2.3.5 Focused attention should be paid to key spaces

Limit the number of leak sources in a single space

When a crew member enters a space, they are exposed to any of the ammonia leak sources in that space. This means that the amount of ammonia-containing equipment in a given space affects the IRPA for individuals who spend time in that space. The IRPA can therefore be reduced by dividing this equipment between two or three spaces, so that a crew member entering one of these spaces is only exposed to the equipment in that space rather than to all the equipment at once.

Our approach in this project was to split fuel preparation equipment and re-liquefaction equipment (where present) across up to three separate, albeit smaller, spaces. One space contains the fuel supply system for the main engine, another space the fuel supply system for the auxiliary engines and auxiliary boiler, and a third room the re-liquefaction units. The effectiveness of this measure can be seen in Figures 7 and 8, where this measure reduced the IRPA from ammonia to the engineering ratings by 40% and 56%, respectively. This benefit far outweighs any risk increase from reducing the volume of the rooms.

Minimize entry to the extent practicable and control access to restricted spaces

A crew member's IRPA is strongly dependent on their time spent in spaces containing ammonia equipment, especially when secondary containment measures are not applied to the equipment. Such locations – such as the FPR(s), re-liquefaction room, and tank connection space (TCS) – should be treated as restricted areas. Minimizing, monitoring, and controlling access to and length of time spent in these areas should be considered. We also recommend consideration of the following specific safety measures for these restricted areas:

- Requiring individuals entering these areas to wear appropriate personal protective equipment (PPE) and carry personal gas detectors
- Managing entry to the restricted space as part of the onboard control of safe work practices
- Registering the presence of personnel in the room, who it is, and when the room is left unattended again every time a restricted space is entered
- Giving a clear visual and audible warning at the room entrance on detection of ammonia in the restricted space, stating that ammonia is present above the acceptable threshold

Our study has assumed that maintenance of ammonia-containing equipment will be subject to strict procedural control and, wherever possible, will be performed when the equipment has been purged of ammonia and isolated. However, it may still be necessary to enter rooms containing ammonia equipment for short periods (around 8-9 minutes per day on average) when equipment is 'live', in order to conduct inspections. This time was determined by careful consideration of what would be required by experts in the team with operational experience on chemical tankers and gas carriers.

We conducted a sensitivity study that demonstrates the importance of controlling the time spent in these restricted spaces. The study considered the effect of increasing the time spent in these spaces on a container ship by 50%, from 8 minutes to 12 minutes per day. As Figure 14 indicates, this results in a 25% increase in IRPA from ammonia for the engineering ratings. Therefore, any additional control measures that reduce the need for personnel to physically enter these spaces for routine inspections, such as remote monitoring or CCTV, would help to reduce risk.

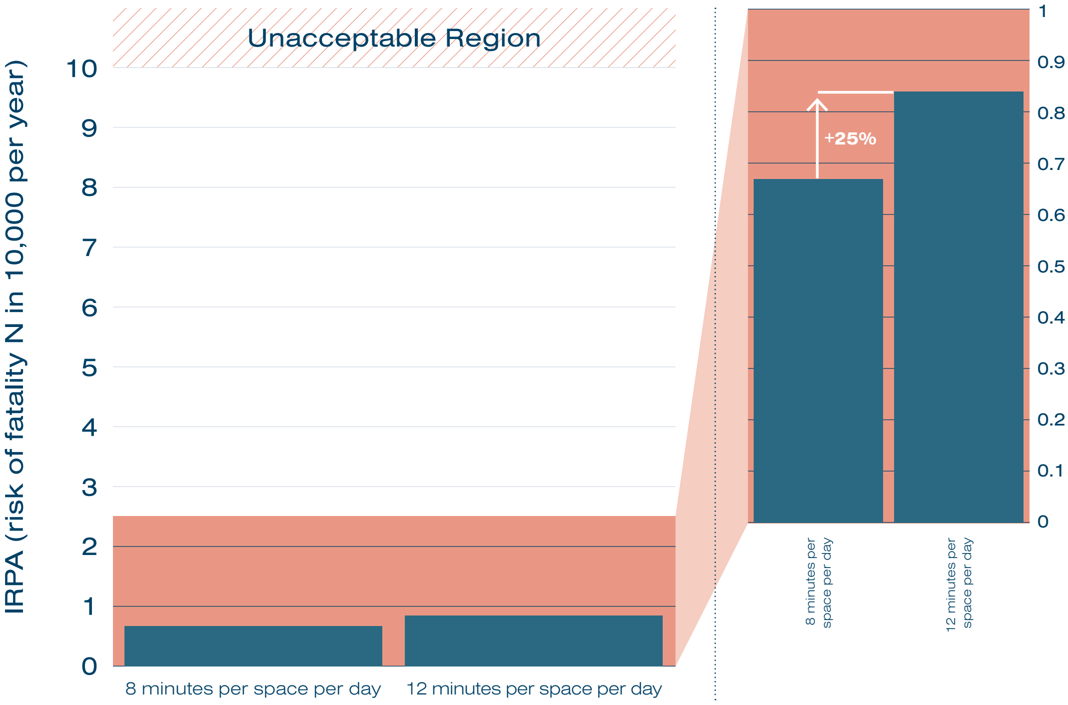


Figure 14: Change in IRPA from ammonia for engineering ratings by time spent in high-risk spaces. Left: IRPA results shown in relation to unacceptable region; right: magnified view to show scale of change in IRPA.

Additionally, it is important to ensure that leaks in one space cannot find a path to other areas. Integrity of high-risk spaces needs to be maintained: for example, doors should be self-closing and seals should be inspected regularly as per maintenance regime and replaced as necessary.

During bunkering, bunker stations are also potentially hazardous locations – therefore, crew presence should be avoided or minimized during this process. For our reference vessel designs, we have proposed a semi-enclosed, ventilated design for the bunker station, with the open side towards the bunker vessel and protected with a water curtain. This should allow mitigation of small leaks. However, we are not aware of any experimental work that demonstrates the effectiveness of such a system.

A water curtain system can provide effective mitigation, provided that it is well-designed and correctly installed and maintained. However, the system's effectiveness depends on several factors, including the weather conditions and the size of the leak.[26] As with any active protection system, there is also the possibility that it may not work when required. Therefore, a water curtain should not be regarded as an impenetrable barrier.

26 Mukherjee S et al (2017). Effectiveness of Water Sprays in Mitigating Toxic Releases. Process Safety Progress 37(2), 256-262.

Additional alarm mechanisms will be required

Ammonia leak alarms with visual indications should be present not only in control locations (engine control room (ECR), deck office, and bridge) but also local to potential leak sources. It should not be possible to enter a space where ammonia gas could be present and be unaware of whether ammonia is present in that space.

Audible toxicity alarms should be distinct from other alarms on board and should give warning to all personnel on board – including any who are not members of the vessel's crew, such as stevedores.

Detection of gas leaks may require a combination of sensors

Depending on their arrangement and location, a combination of gas detectors, temperature sensors, and liquid detection may be used to detect ammonia leaks. The location and number of gas detectors used in a given space should take into account the size of the room, the pattern of air flow around the room, and the likely behavior of the leaked ammonia.

Gas detection is most challenging in a large space, such as an engine room. Our CFD study (Appendix 2) showed that dispersion of leaked ammonia is highly dependent on the direction of the leak flow compared to the ventilation flow. Furthermore, a high ventilation rate may divert the flow of a gas leak away from a gas sensor, and the high airflow may dilute the gas to a level where a leak is not detected. Therefore, an array of detectors will be needed and could be of a variety of types (e.g., concentration, temperature, acoustic) to improve reliability.

The human nose is very sensitive to ammonia, but smell should not be relied upon as a leak detection method. After a period of exposure to even low concentrations of ammonia, smell sensitivity decreases, and smaller leaks may not be noticed. Requirement of personal gas detectors could help address this problem.

Low- and high-level ammonia detection limits need to be specified

Detection of both low and high levels of leaked ammonia should trigger alarms associated with a specific safety response procedure. Although the ammonia detection limits proposed by class societies are similar, they are not identical. An aligned set of values would be beneficial to the industry and would help to standardize appropriate safety procedures.

2.3.6 Rapid and reliable shutdown in the event of a leak is required

The volume of leaked gas depends on the volume of the leaking system, the time taken to detect the leak, and the time until the leak is stopped. Rapid detection combined with fast shutdown of the leaking section is key. Larger systems should be sectionalized to enable sectional shut-off and to limit the volume released in the event of leakage.

Shutdown should be automatic where possible

To achieve rapid and reliable shutdown, shutdown should also be automated where feasible. However, the option to shut down manually is still required. Voting systems, such as 'two out of three' voting on the output of a set of gas detectors, can help reduce the number of spurious shutdowns.

2.3.7 Care is needed in the design and positioning of ventilation exhausts

Forced ventilation of a space containing ammonia equipment, such as the FPR, carries any leaking ammonia in that space out through the ventilation exhaust. For the largest leaks, this process could generate potentially lethal toxic concentrations of ammonia at deck level unless the exhaust is positioned with care. We carried out gas dispersion modelling using PHAST to study this effect. We found that, depending on the weather conditions, such concentrations can be experienced tens of meters downwind of the space containing the ammonia leak. While leaks of this scale are comparatively unlikely, the risk still needs to be mitigated. If spaces containing ammonia equipment are located at deck level, this mitigation can be achieved by directing the exhaust vertically upwards through the roof of the space and up a vent pipe, so that the toxic cloud is lifted off the deck. Figure 15 gives a simplified illustration of the toxic cloud from an exhaust on the roof of the tanker FPR; Figure 16 shows the same scenario, but with the exhaust channeled through a three-meter vent pipe on top of the FPR.

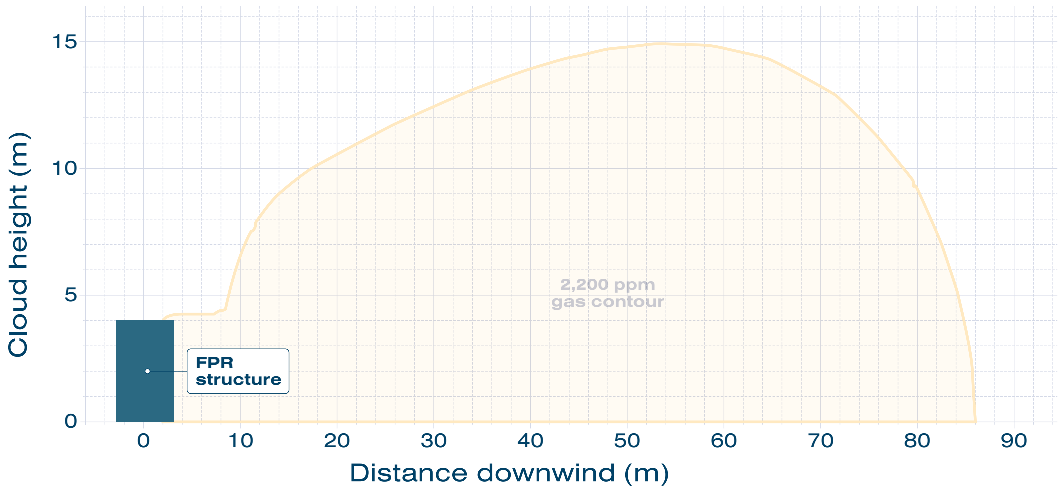


Figure 15: Side view of ammonia cloud 2,200ppm contour from a 2kg/second leak into a FPR on deck ventilated at 45 air changes per hour in low wind (1.5 meters/second) conditions. Exhaust is directly through the building roof (e.g., via a mushroom vent).

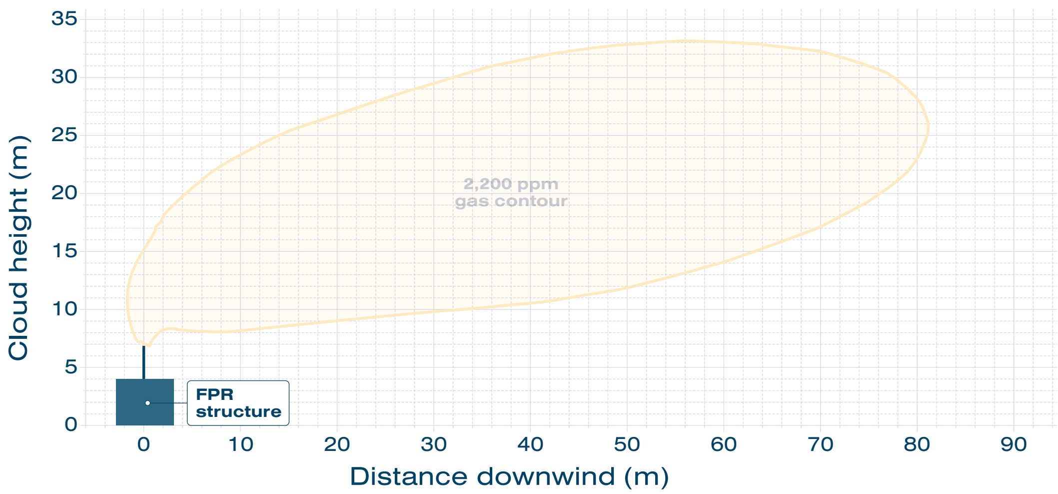


Figure 16: The same case as in Figure 15, but now released via a three-meter stack (chimney) on the roof of the FPR.

2.4 Summary of quantitative risk assessment

Through application of iterative QRA and risk mitigation measures, the risks to the crew from ammonia fuel hazards have been reduced to below the project target. When hazards from other sources are included, the total risks have been shown to be well below the 'unacceptable' level. The outputs of these analyses have been used to derive a number of useful insights and recommendations for the design of ammonia-fueled vessels.

3.

Human factors considerations must be addressed

3.1 Introduction to human factors analysis and key findings

As ammonia is a novel fuel for the maritime industry, it is critical to identify and understand the various ammonia risks associated with human factors. Human factors is a concept that is commonly applied in the design and management of work systems across high-hazard sectors such as the maritime, oil and gas, nuclear, and aviation industries. Human factors is defined as "the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data, and methods to design in order to optimize human well-being and overall system performance."[27]

In this section, we supplement the QRA by applying a human factors perspective to the use of ammonia as a fuel in the shipping industry. In this way, we can help the industry to identify and implement appropriate operational and design safeguards to reduce ammonia risk to tolerable levels.

MMMCZCS and LR's human factors advisory department jointly conducted a range of human factors workshops as part of this project. Insights and guidance regarding the principal human factors considerations related to the use of ammonia as fuel were developed through workshops. The workshops considered the three project reference designs for container, tanker, and bulk carrier vessels. The following activities were conducted:

- **Early human factors analysis (EHFA):** identification of human factors safety challenges associated with industry preparedness for using ammonia fuel, used to establish further risk assessment approaches
- **Risk reduction workshops:** participation in safety workshops to explore human factors considerations and challenge assumptions of risk associated with various design risk nodes
- **Safety critical task analysis (SCTA):** application of a qualitative risk assessment method method used to assess human error opportunities contributing to process safety for various scenarios
- **Working environment health risk assessment (WEHRA):** assessment of conceptual vessel designs to address the health and safety of persons for bunkering, maintenance, and fuel preparation activities
- **Competency needs analysis:** identification of key areas for upskilling based on a high-level concept of new operations

27 International Ergonomics Association: https://iea.cc/about/what-is-ergonomics/

The results of our human factors analysis are summarized in Table 1, which provides an overview of human factors considerations regarding ammonia fuel use and rates their impact level as low, medium, or high. Our results highlight the need for companies and the maritime industry to apply human factors engineering principles when designing and managing ammonia-fueled vessels.

As a supplement to the overall human factors considerations shown in Table 1, we developed an overview of the anticipated human factors impact on a range of specific operational-phase processes such as bunkering, fuel storage and transfers, and general maintenance. These are illustrated in Appendix 3.

Table 1: Human factors considerations for ammonia-fueled vessels.

Stages	Description	Impact	Ammonia-fueled vessels are anticipated to impact the following areas:
Ergonomic design	Workspace arrangements and human-machine interface	Medium	• Deck and bunker stations • Local engine and tank spaces (e.g., FPR, TCS) • Systems process command, control, and remote monitoring
Roles and responsibilities	Organizational structure and assigned roles	Low	• Changes to organizational structure with new accountabilities • Updated responsibilities related to risk assessment, safe work practices, and emergency response • Contractor interfaces, tasks, and actions
Competence and training	Technical and non-technical skills, knowledge, understanding and application	High	• New technical skills for specific operations and maintenance • General ammonia risk awareness across crew • Emergency response • Increased importance of non-technical skills
Resourcing and personnel	Workload distribution and number of personnel	Low	• Maintaining the structural integrity of fuel machinery and spaces through safe systems of working • Tasks associated with overseeing process control • Preparedness for onboard emergencies
Process and procedures	Documented processes and work practices	High	• New ammonia-specific policies, procedures, and processes • Updates to operational and maintenance work practices, procedures, and plans • Increased requirements for managing safety risks and employment of formal safe work practices • Review and, where necessary, change of emergency response processes

Stages	Description	Impact	Ammonia-fueled vessels are anticipated to impact the following areas:
Occupational health hazards	Exposure to toxicity, fire, noise, musculoskeletal risks, trips and falls, etc.	High	• Mechanical (energy of components of a mechanical system e.g., crushing, motion, falling) • Thermal • Materials / substance exposure (e.g., toxicity) • Fatigue
Process safety hazards	Human involvement in the contribution, exacerbation, and recovery of a major accident	High	• Changes to and management of ammonia system parameters such as those associated with tanks and the system including level, temperature, and pressure • New skills related to ammonia leak detection, isolation, and repair • New explosivity and flammability atmospheric conditions • Corrosivity potential • Updates to gas and chemical management • New supply and maintenance precautions with metals and materials
Management of change	Organizational, operational, and technical changes that must be managed to achieve final ammonia preparedness and the process of change itself	Medium	• Change management program to address ammonia operations and risks at company level • Modified approaches to vessel operations and maintenance • Increased awareness of when vessel management of change processes may be required • Potential changes to planning and communications involving entities outside the vessel and company

Impact	Criteria Description
Low	Small changes to seafarer tasks where vessel design/operational practices addressed through industry practiced guidance and requirements.
Medium	Changes to seafarer tasks through additional complexity, time-consuming nature, and/or increased reliance on human reliability. Vessel design/ operational practices addressed through further application of human factors principles.
High	Significant changes to seafarer tasks through additional complexity, time-consuming nature, and/or increased reliance on human reliability. Specific human factors studies required to address implications and involvement of human actions in accidents.

In the following sections, we provide a synopsis of key human factors considerations that we expect to have the greatest impact during transition from conventional to ammonia fuel. These factors relate to the areas of competence and training, process and procedures, occupational health hazards, and process safety hazards.

3.2 Many roles will require new skills and knowledge, driving a need for upskilling and training

A safe and just transition to net zero emissions by 2050 must safeguard the shipping industry's ability to ensure that the skills and competencies of the future workforce match what is required to successfully switch to alternative fuels within the designated timeline. A recent analysis suggests that to align with the Paris 1.5°C emissions reduction trajectory, an estimated 450,000 seafarers will require essential training or re- and upskilling by 2030, and 800,000 will require training by the mid-2030s.[28]

As part of this transition, the novelty of ammonia fuel and associated new systems and equipment will present new technical and system complexity. New and modified technical skills will be required for those directly involved in managing the transfer or handling of ammonia. All personnel will need to be aware of ammonia's properties and hazards, and relevant officers will need to increase their knowledge of relevant regulations and any special requirements, such as those for interfacing with flag administrations, contractors, and port personnel. There will also be further need for enhanced non-technical skills for all crew, such as maintaining situational awareness and recognizing potential hazards that will affect decision-making, communication, and leadership. These skills are especially important to prepare crew for potential high-risk operations, including emergencies.

We expect that the impact of competency updates needed for ammonia fuels will differ based on vessel type and on previous experience with low-flashpoint gases and with use of computerized systems or automation. Regulations currently require personnel on tanker vessels to undertake additional training and certification, and the same is true for crews interfacing with low-flashpoint gases. As a result, additional training or upskilling will likely be less for gas-tanker personnel, particularly those who have experience with gas fuel or cargo, compared to crew on bulk or container vessels. Shoreside company personnel, such as fleet or ship managers, superintendents, and support functions, will also need to be cognizant of any specific requirements and changes needed to accommodate ammonia bunkering, carriage, fuel operations, maintenance, and emergency response support.

The Standards of Training, Certification & Watchkeeping for Seafarers (STCW) Code will be developed together with the IGF Code to provide enhanced or additional rules for training. The onus will then be placed upon the operating companies to establish the competencies necessary and demonstrate that crew have appropriate training and certification for ammonia fuel use.

We recommend that further training needs analysis should be undertaken for seafarers across segments to identify key competency requirements for operations and maintenance. Specific attention should be paid not only to developing the technical competencies of those personnel who undertake safety-critical tasks (e.g., engineering team), but also to the non-technical competencies of all crew members in sharing and motivating others to communicate hazard-related information.

28 'Mapping a Just Transition for the Global Maritime Workforce,' The Just Transition Task Force (UNGC), 2022.

3.3 There will be numerous changes to, and increased reliance upon, functional work practices and procedures

Ammonia fuel and its associated systems present numerous changes to work practices, procedures, and plans. On board ammonia-fueled vessels, there will be a more frequent need to use risk management practices such as risk assessments, permits, confined space, lock-out tag-out, and toolbox talks. Applying these measures will require operators to review how procedures and work practices are adhered to and incorporated in competence and training development.

Ammonia fuel and associated systems use will require change and adaptation across the industry for safe decision-making. The move from engines using fuel oil to dual-fuel engines using both ammonia and fuel oil results in not just new equipment and automated systems, but also new procedures, work processes, and maintenance regimes. The aggregation of these changes will present different challenges depending on the industry sector's maturity, experience, and current methods of working.

Companies operating ammonia-fueled vessels should implement a change management program that systematically addresses changes needed throughout the organization as well as at the ship level. A mature approach to safety practices incorporating good leadership, communication, learning, crew engagement, and work practice adherence will be key to successfully maintaining a high level of safety.

We recommend that further guidance should be produced to assist companies in determining which operations would benefit from explicit procedures, based on operational complexity, crew experience, and task frequency. This is particularly important for procedures that relate to safety-critical operations and maintenance tasks where reliable human behavior is a critical control.

3.4 Ammonia-fueled vessels will introduce new occupational health hazards

Providing safeguards for occupational health and safety hazards is a necessity for any industrial workplace. Ammonia can cause a range of occupational health effects based on the nature, duration, and level of ammonia exposure; storage method; and combination with other chemicals.

We have identified a range of occupational health hazards considerations, which can serve as a basis for further assessment of appropriate safeguards to control and manage effects from:

- Material and substance hazards e.g., acute and chronic toxicity
- Thermal hazards e.g., hot and cold surfaces, cold stress
- Mechanical hazards e.g., energy of components of a mechanical system, crushing, motion, falling

Additionally, it is important to anticipate potential side effects of some safeguards on task performance and timing. For example, donning additional PPE such as respirators for maintenance tasks may physically encumber the crew.

The introduction of ammonia-fueled vessels may also change how the vessel interfaces with other organizations, such as ports, vendors, contractors, and other ships. Appropriate safeguards must be in place during these interactions to protect all involved in case of events such as leaks.

We recommend that further guidance on specific PPE requirements be developed to define recommended PPE and other occupational safeguards for various expected operating and maintenance scenarios.

3.5 Managing process safety hazards requires continued improvement in standards

Managing high standards of safety will require companies to further develop their standards of planning, emergency preparedness, and maintenance as guided by the ISM Code. The sustainable operation of shipping companies relies fundamentally on how well the operational risks are understood and the degree of commitment to continuously seeking and implementing appropriate safeguards to reduce the risk.

Most process hazards related to ammonia fuel revolve around control of storage and handling pressures and temperatures to prevent loss of containment and reduce effects of unwanted consequences of any leaks or spills. Such consequences include accelerated corrosion, displacement of oxygen, fire, and explosions. Effective and reliable safeguards, including engineering and administrative controls, must be present in the work environment to prevent or, if necessary, reduce the potential impact of such consequences. Adoption of analytical tools will be required for the identification and assessment of ammonia releases and for evaluation of resulting impacts that may extend beyond the boundaries of the ship.

Delivering effective and continuous assurance of safety performance requires the development of a thorough safety management system to document and assign responsibility for the completion of critical activities relating to planning and control of work, maintenance of safeguards, and emergency preparedness. To ensure the competency and preparedness of crew, contractors, and external emergency agencies, the shipping industry as a whole and individual companies will need to tailor existing (or develop new) safety and emergency arrangements. These arrangements should be guided by the IMO's International Safety Management (ISM) Code and should address all reasonably foreseeable unwanted events involving ammonia-fueled shipping operations, including the necessary steps to avoid or address negative outcomes.

Risks associated with ammonia storage and handling are well understood and effectively managed in related industries today. However, we emphasize that the success of ammonia-fueled vessel operations will rely on all personnel supporting ammonia operations, both shipboard and shoreside, having an appropriate understanding of potential ammonia process hazards and the means to reduce or eliminate their impacts. In addition, safety management processes and procedures must outline necessary steps to avoid or address negative outcomes such as ammonia exposures, releases, leaks, or spills.

4.

Conclusion: Use of appropriate risk mitigations can bring the safety risks of ammonia fuel to within tolerable limits

We conclude that the risks to crew of using ammonia as an alternative maritime fuel can be kept within tolerable limits, provided that the maritime industry can:

- Ensure suitable and sufficient technical barriers and administrative safeguards are implemented to protect the crew against various ammonia risks;
- Address human factors considerations, such as those outlined above; and
- Build upon existing maritime industry experience with gas as fuels and cargo and carry over learnings from other industries with considerable experience in safely handling, transferring, and storing ammonia.

Our analysis highlighted the importance of several key design and operational factors that can improve safety on board ammonia-fueled vessels. These include the choice of ammonia fuel storage system, secondary containment mechanisms, ventilation, division of risk of ammonia exposure across multiple areas, tightly controlling access to and time spent in high-risk spaces, appropriate sensors and alarms for ammonia leaks, rapid and reliable shutdown of fuel systems, and positioning of ventilation exhausts.

If we are to reach consensus on the safe implementation of ammonia as an alternative fuel, the industry will also need further detail on the high-impact human factors areas identified in this report. Future work towards this goal includes mapping of competence and training requirements across segments, specification of necessary changes to work practices and procedures, increasing understanding of occupational health hazards, and conveyance of process safety hazards knowledge and guidance. The introduction of ammonia fuel will be accompanied by various technical innovations including automation, new maintenance regimes, and modernization of process control. As part of this process, the industry as a whole and seafarers in particular will encounter challenges that require further attention to human factors themes.

It is critical that the recommendations identified in this study are further investigated and developed into tangible guidance and actions for the industry. Detailed guidance addressing the technical, engineering, and human factors aspects of these requirements is needed to help the industry move forward with the implementation of low-carbon fuel alternatives.

Abbreviations

Abbreviation	Definition
ABS	American Bureau of Shipping
ALARP	As Low as Reasonably Practicable
CCTV	Closed-Circuit Television
CFD	Computerized Fluid Dynamics
CO_2	Carbon Dioxide
ECR	Engine Control Room
EHFA	Early Human Factors Analysis
EMSA	European Maritime Safety Agency
EU	European Union
FAR	Fatal Accident Rate
FPR	Fuel Preparation Room
FSA	Formal Safety Assessment
GHG	Greenhouse Gas
GVU	Gas Valve Unit
HAZID	Hazard Identification
HSE	Health & Safety Executive
IGF (Code)	International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels
IMO	International Maritime Organization
IRPA	Individual Risk per Annum
ISM (Code)	International Safety Management Code
LEL	Lower Explosive Limit
LNG	Liquified Natural Gas
LPG	Liquified Petroleum Gas
LR	Lloyd's Register
LSFO	Low-Sulfur Fuel Oil
MDH	LR Maritime Decarbonisation Hub
MGO	Marine Gas Oil
MMMCZCS	Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping
N_2O	Nitrous Oxide
PPE	Personal Protective Equipment
QRA	Quantitative Risk Assessment

Abbreviation	Definition
RINA	Royal Institute of Naval Architects
SCR	Selective Catalytic Reduction
SCTA	Safety Critical Task Analysis
STCW	Standards of Training, Certification & Watchkeeping for Seafarers
STS	Ship-to-Ship
TCS	Tank Connection Space
TEMPSC	Totally Enclosed Motor-Propelled Survival Craft
TEU	Twenty-foot (container) Equivalent Units
WEHRA	Working Environment Health Risk Assessment

Appendix 1: Application of risk criteria and targets for QRA

Measures of risk

The risk criteria discussed in this report relate to the individual risk of fatality per annum (or IRPA) for members of a ship's crew.

In studies of occurrences of fatalities in worker groups, a slightly different risk metric is used – the Fatal Accident Rate (FAR), which is the number of fatalities per 100,000 worker years.

It is relatively easy to convert FAR numbers to IRPA values and vice versa (e.g., a FAR of 14.5 equates to an IRPA of 1.45 in 10,000). To avoid confusion, the discussion below only uses IRPA – any FAR values have been converted.

The HSE tolerability of risk framework

Perhaps the best known and one of the most widely adopted set of risk criteria are found in the UK Health and Safety Executive (HSE) tolerability of risk framework.[29]

The HSE divides levels of risk into three bands or regions:

- A high 'unacceptable' region, in which the risks are so high that they are unacceptable whatever the level of benefits associated with the activity. Activities producing risks falling into this region must be ruled out or modified so that the risks fall into one of the lower regions.
- An intermediate 'tolerable' region, where the risk is tolerable if the level of risk has been properly assessed and the results used to determine control measures. The level of risk remaining after control measures have been applied (the residual risk) is not regarded as unduly high if the risks are kept as low as reasonably practicable (ALARP).
- A very low 'broadly acceptable' region, where the risks are generally accepted as insignificant and adequately controlled.

Risk can be regarded as ALARP when the cost (i.e., to use the legal terminology, the 'sacrifice' in terms of money, time, or trouble) of any further measure to reduce the risk would be very high ('grossly disproportionate') compared to the risk reduction benefit that would be gained.

The framework is illustrated in Figure 17.

29 HSE (2001), Reducing Risks, Protecting People – HSE's decision-making process. C100.

Figure 17: HSE tolerability of risk framework.

The HSE has established numerical values for the IRPA values at the boundaries, as shown in Figure 16. It should be noted, however, that the HSE framework does not propose boundary values for new facilities or activities.

Risk criteria for seafarers

Relevant IMO guidelines[30] present a discussion of risk criteria and cite the UK HSE framework as an example. The following points are made:

"The lower and upper bound risk acceptance criteria … are provided for illustrative purposes only. The specific values selected as appropriate should be explicitly defined in FSA studies." (Appendix 5, para. 5.1.6)

"It is important to understand that the above risk acceptance criteria always refer to the total risk to the individual and/or group of persons. Total risk means the sum of all risks, e.g. that a person on board a ship is exposed to." (Appendix 5, para 5.3.2)

30 IMO (2018), Revised Guidelines for Formal Safety Assessment (FSA) for Use in the IMO Rule-Making Process. MSC-MEPC.2/Circ.12/Rev 2, Appendix 5.

The document also introduces a target IRPA value of 1 in 10,000 risk of fatality per year as a *"target value for new ships"* (Appendix 5, Table 1). A note to the table states:

"While it is recommended that the maximum tolerable criteria for Individual Risk as listed should apply to all ships, it is proposed, in accordance with MSC 72/16, that for comprehensive FSA studies for new ships a more demanding target is appropriate."

Figure 18 shows this target value in the context of the HSE tolerability of risk framework.

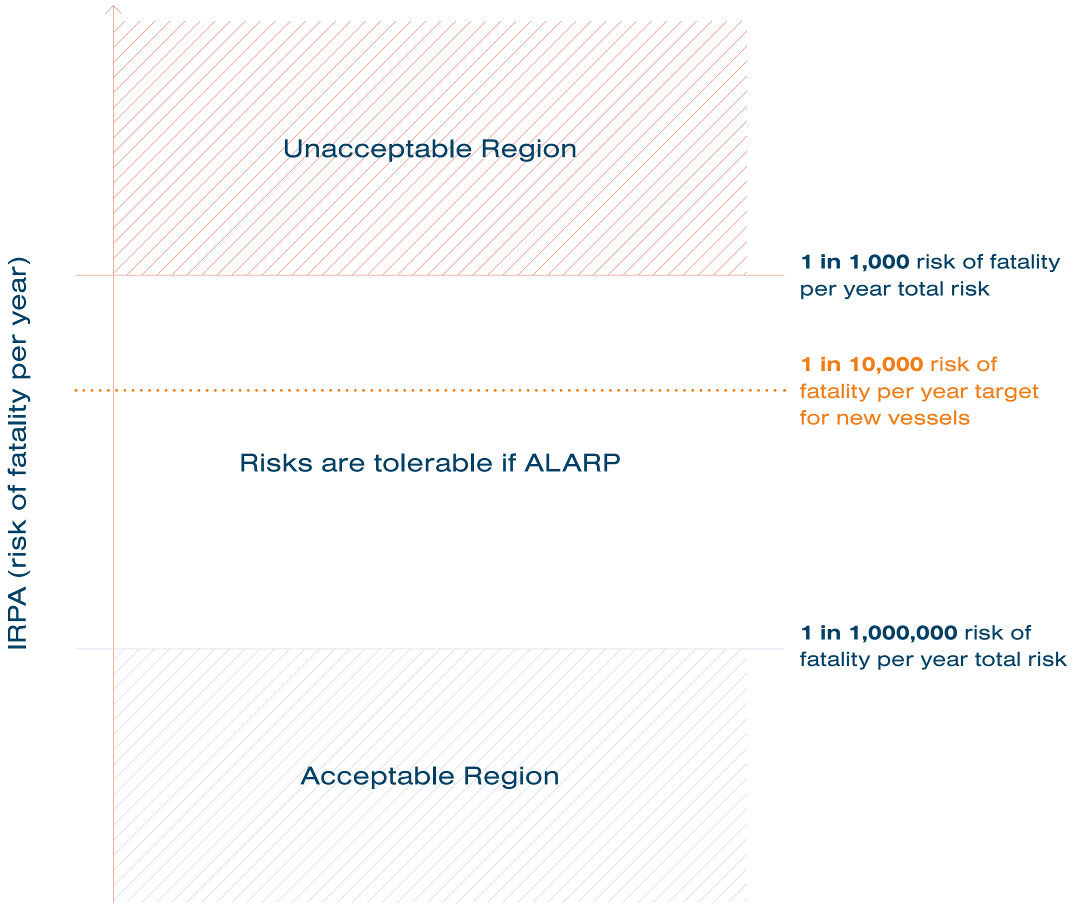


Figure 18: HSE tolerability of risk framework and IMO target value for new ships.

The QRA study presented in this report only looks at one component of the risk to the crew (risks from ammonia as a fuel). Therefore, in order to compare our findings with these criteria, it would be necessary to add the risk result produced by the QRA to the risk from all other hazards to which seafarers are exposed. These other hazards include potential serious accidents (such as collision, grounding, and accommodation fires) and occupational hazards (such as falls from height, being struck by falling or moving objects, or electric shock).

Current risks to seafarers

Some values of the risk to which seafarers are currently exposed are available in recent studies as FARs (which have been converted to IRPA values for the purposes of this discussion).

One study presents a detailed analysis of fatalities in the British merchant fleet over the period 2003-2012.[31] The paper also collates FAR data from several countries dating back to 1945. The IRPA for seafarers in British shipping for 2003-2012 is given as 1.45 in 10,000 risk of fatality per year for all accidents, averaged over all ranks and all merchant vessel types. This does not include suicides or deaths by "undetermined intent". The paper also shows that the risk varies widely across ranks, being highest amongst deck ratings, with 24 of the 49 recorded fatalities being in this group. In contrast, four fatalities were experienced amongst engineering ratings, and the lowest numbers of fatalities were amongst captains and cadets. An overall downward trend in fatal accident risk was observed when considering the historical data across several nations.

A European Maritime Safety Agency (EMSA) report presents statistics on marine casualties and incidents which involved ships flying a flag of one of the European Union (EU) member states and those which occurred within EU member states' territorial seas or internal waters.[32] The report gives an IRPA for crew for 2019 of 1.04 in 10,000 risk of fatality per year across all ranks and all vessel types (cargo, passenger, fishing, service, and other). It is not possible to break down this value by rank or by vessel type from the data presented. This analysis also observed a decreasing trend in fatality risk over time.

From the information in these sources, it is not possible to determine how much of the current fatality risk is due to fuel-related accidents. It is also not possible to determine how the risk varies between newer and older vessels.

The IRPA values for seafarers from these studies are shown in Figure 19, together with the HSE framework and the IMO target value for new ships. Note the logarithmic scale on the Y-axis of the graph.

31 Roberts S E et al. (2014), Fatal accidents and injuries among merchant seafarers worldwide. Occupational Medicine 2014; 64:259-266.

32 European Maritime Safety Agency (2022). Annual Overview of Marine Casualties and Incidents 2022. Ares (2022) 8241169 – 29/11/2022.

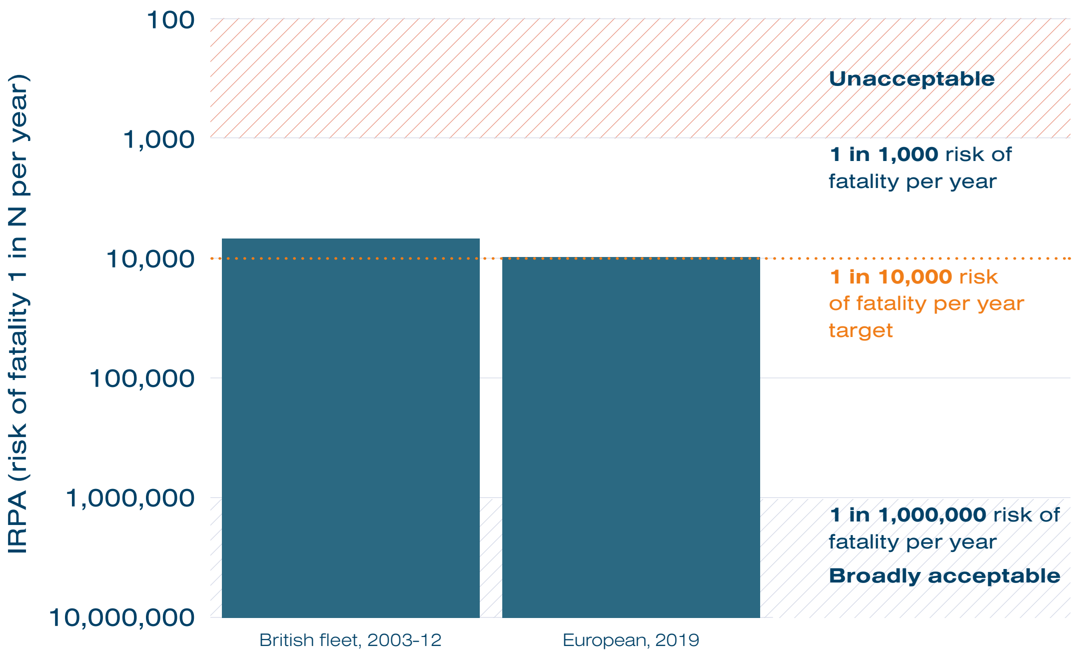


Figure 19: IRPA values for seafarers from two recent studies of fatalities in shipping, compared to HSE tolerability of risk framework and IMO target value for new ships.

It is clear from Figure 19 that recent real-world values of fatality risk to seafarers exceed the IMO target value for new ships. This presents an issue when using the target value in the context of the QRA study. Because the IRPA arising from ammonia in the QRA would need to be added to the IRPA from other hazards, the total estimated IRPA for ammonia-fueled vessels would in all likelihood always exceed the target for new ships set by the IMO. In fact, to get below the target, an alternative fuel would have to present a lower risk to the crew than current oil-based fuels, and/or there would need to be a reduction in the risk to seafarers from the other hazards to which they are exposed.

Equivalent level of safety

For a new, novel, or alternative design, there is a requirement in the relevant Codes[33] 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.

The risk of fatality from fuel oil is accepted; there are risks, but they are not so high as to be considered unacceptable. In terms of Figure 17, they probably sit in the 'tolerable if ALARP' band. For an alternative design using ammonia as fuel, it is a reasonable requirement that the risk of fatality be equivalent, but not equal, to that from fuel oil. This is because ammonia is toxic and fuel oil is not, and so ammonia fuel presents a greater a priori risk than fuel oil. However, the design may be such that the risk from ammonia is equivalent to that from fuel oil, because they both fall within the 'tolerable if ALARP' band.

33 IGF Code – International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels – Part A - General, Section 2.3.

Individual risk of fatality criteria for the project

In view of the discussion above, for the purposes of the project, the following criteria have been adopted:

The IRPA values specified in the HSE tolerability of risk framework are used to define the upper (tolerable/unacceptable) and lower (tolerable/broadly acceptable) boundaries. These are 1 in 1,000 risk of fatality per year and 1 in 1,000,000 risk of fatality per year, respectively.

A total IRPA (ammonia risk plus risk from other hazards) that exceeds the upper bound value will be considered unacceptable. The total will be calculated using the data presented by Roberts et al. Since this reference gives a slightly higher value than the EMSA report, this is a conservative approach.

A target IRPA value of 1 in 10,000 risk of fatality per year is used for the IRPA from ammonia to the crew group at highest risk (noting that the average risk across the whole crew will be lower). Where the IRPA to the crew group at highest risk exceeds the target, risk mitigation measures will be applied to reduce the value.

Appendix 2: Description and results of additional studies used to inform or supplement QRA

This appendix outlines details of specific analyses we conducted to improve or supplement our central QRA.

Review of HAZID studies and accident experience

We conducted a review of existing hazard identification (HAZID) findings and marine accident reports to capture additional leak scenarios and consider implications for the design of ammonia-fueled vessels. The range of events covered included fires and explosions (both cargo-related and non-cargo-related), dropped objects, loss of services, collisions, and groundings. The results were used to update and extend the QRA model. In addition, vessel collision was investigated in more detail using finite element analysis.

Vessel impact study

A vessel collision scenario was modeled using finite element analysis, with the reference ammonia-fueled container feeder vessel with a Type-A fuel tank in the hold (see Figure 2) being struck by a larger (19,000-TEU) container vessel. The collision we modeled was perpendicular to the side of the ammonia-fueled vessel and at the location of the ammonia tank. We wanted to determine how much speed the incoming vessel would need to not only penetrate the outer hull and inner hull, but also reach the ammonia tank. The location of the tank was determined in accordance with current requirements for ships using natural gas as fuel, applying the B/5 rule.[34]

The results showed that if the reference vessel was moored at quay (‘clamped’), the colliding vessel needed to be travelling at 0.58 knots in order to penetrate the outer hull. However, to reach the ammonia tank, the colliding vessel’s speed needed to increase by 6.5 times to 3.78 knots.

In case of the vessel being struck while at sea, the impact would be reduced due to hydrodynamic effects. In this situation, the speed of the colliding vessel required to penetrate the outer hull is 1.2 knots, but the ammonia tank will not be reached even with speeds up to 25 knots. Therefore, a major leak due to a collision between the two vessels in open water is considered extremely unlikely.

34 IGF Code – International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels – Part A-1 – Specific Requirements for Ships Using Natural Gas as Fuel, Section 5.

Collision scenarios have been included in the QRA. Based on the collisions and allisions (impacts between a moving ship and a fixed object) we have seen over the years, it is not unlikely to have a collision at a speed of 4 knots in port. It is, however, deemed unlikely that the colliding vessel will strike the moored vessel at right angles, which is the worst case. To fully understand the risk of leakage due to a collision, further impact studies should be made with varying angles of impact and draft.

Note that our analysis studied a fuel tank in the vessel's hold. We consider that a tank on deck would be less likely to be impacted by a striking ship.

Computerized fluid dynamics (CFD) dispersion study

Initially, the QRA used the results of a simple model to assess the build-up of ammonia in a room following a leak. However, the simple calculation assumes that the gas from a leak is evenly dispersed in the room where the leak occurs. Whilst this is a reasonable assumption for small rooms, there is a concern that this assumption might give non-conservative results for larger rooms such as an engine room.

Therefore, we conducted a computerized fluid dynamics (CFD) study of different leak scenarios in the main engine room of our reference vessels. Examples of the CFD output are given in Figures 20-22, for the cases where the leak is against, along, and perpendicular to the air flow in the room.

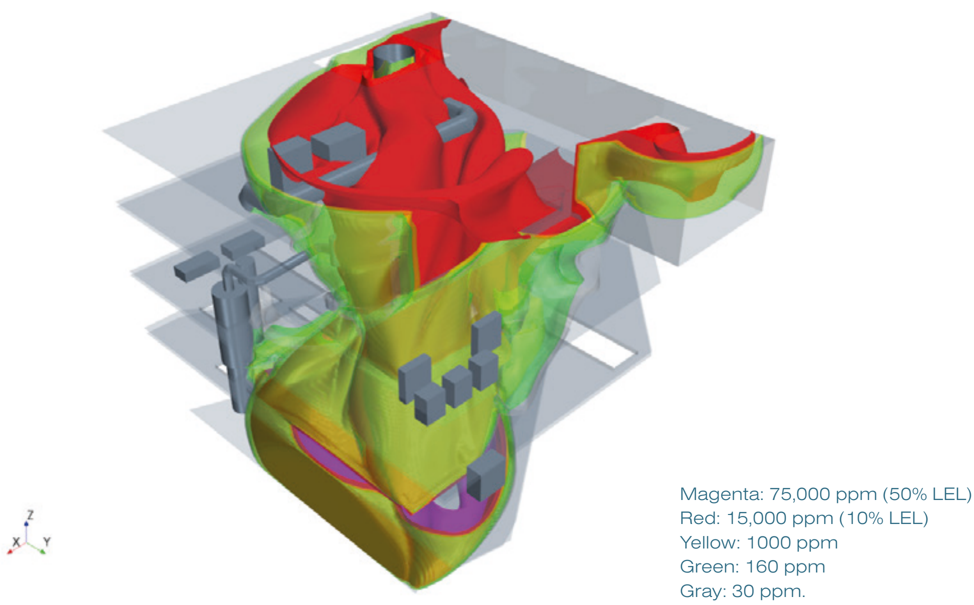


Figure 20: CFD simulation of 0.23 kg/second leak of ammonia for 300 seconds into an engine room ventilated at 30 air changes per hour, against the ventilation air flow.

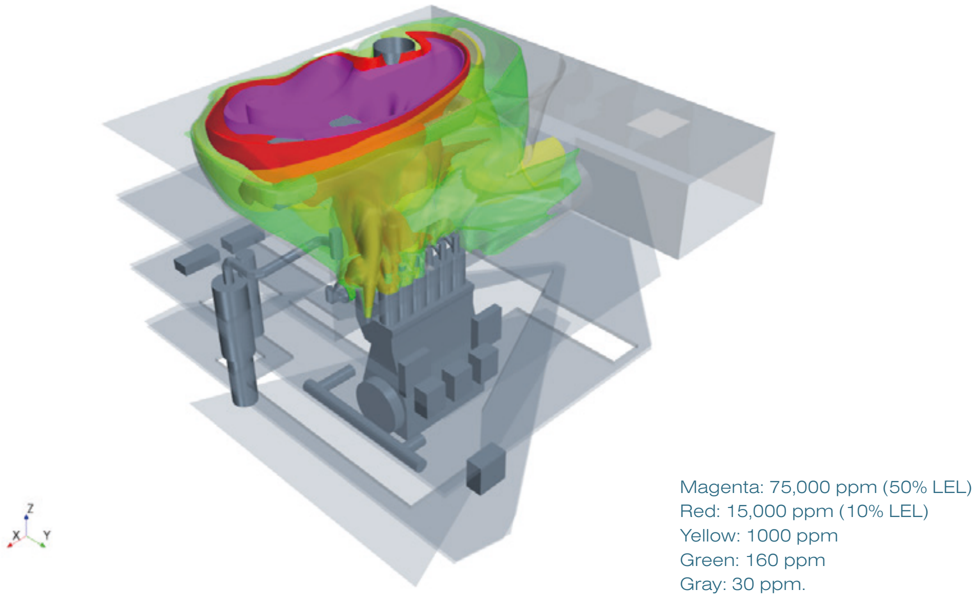


Figure 21: CFD simulation of 0.23 kg/second leak of ammonia for 300 second into an engine room ventilated at 30 air changes per hour, along the ventilation air flow.

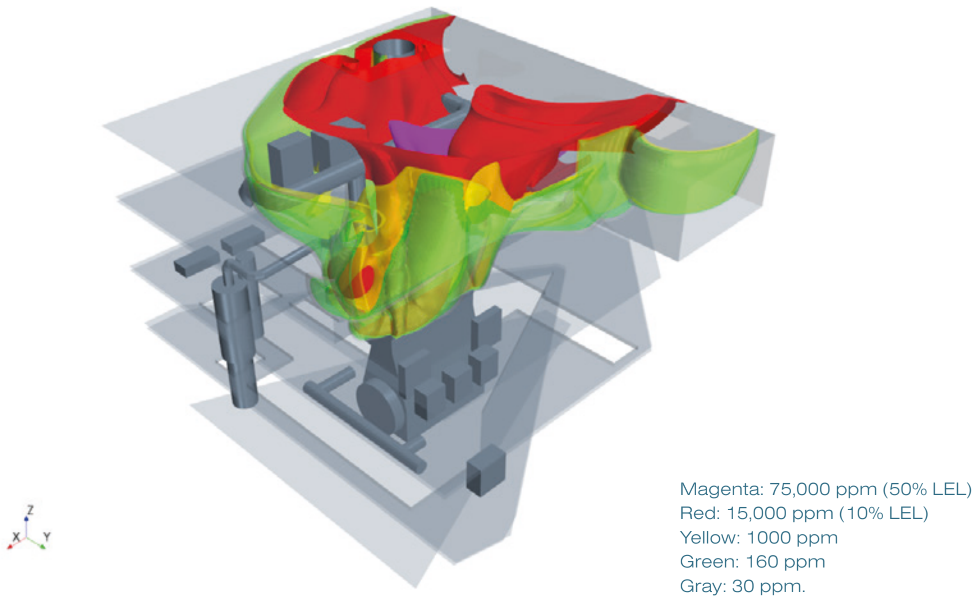


Figure 22: CFD simulation of 0.23 kg/second leak of ammonia for 300 seconds into an engine room ventilated at 30 air changes per hour, perpendicular to the ventilation air flow.

The results show that leaked ammonia in a larger engine room is not evenly dispersed, and that there may be areas within the room where toxic concentrations are reached or exceeded even for relatively small leaks. The QRA model has been modified to accommodate this finding. There are also regions where the ammonia concentrations are quite low (below 30 ppm) so there is a possibility that gas detectors in such locations would not be activated.

Dispersion from vent masts and ventilation exhausts

We also conducted a dispersion analysis of ammonia releases from vent masts and from ventilation exhausts of spaces. The objective was to provide inputs to the design process so as to minimize the toxicity hazard to the crew.

Appendix 3 – Human factors impact on operational phases

This appendix provides a synopsis of anticipated human factors impacts of ammonia fuel on various operational and maintenance phases (Table 2). Impact is measured through criteria such as task novelty, frequency of human interaction, criticality, and known issues.

Table 2: Anticipated human factors impacts of ammonia fuel on maritime operational and maintenance stages.

Stages	Impact	Ammonia-fueled vessels are anticipated to impact the following areas:
Port approach	Low	Minimal additional impact to crew activities when compared with existing industry practices. There could be changes to planning and communications with port authorities, marine pilots, and other organizations.
Mooring	Low	For standard mooring practices, minimal impact is expected. For ship-to-ship (STS) mooring associated with bunkering, there would be changes, especially related to potential ammonia hazards. This impact would be greatest for vessel personnel without past STS mooring experience.
Bunkering / transfer	High	Ammonia bunkering will introduce new hazards, safeguards, and crew activities, including changes to interactions with other organizations. For example, the method for ammonia fuel sampling will differ from that for conventional fuel. The overall impact of the changes would be lower for those personnel with LNG / LPG (liquified petroleum gas), bunkering, or ammonia cargo experience.
Fuel storage	Medium	There will be a moderate level of new challenges related to ammonia storage for those with conventional fuel oil experience. New tasks would relate to monitoring and control of pressure and temperature as well as tank levels.
System start-up	Low	The process for system start-up will be largely automated, with crew initiating the process and overseeing its performance and safe working. This is not expected to present a significant change to those with similar automation experience.
Fuel transfer	Medium	The transfer of ammonia fuel will be initiated / monitored / intervened with in the ECR. Although the transfer operation will differ between vessel types depending upon the fuel condition and process methods, the activity is projected to be automatic with control room operatives overseeing the transfer, as per conventional operations. As with other automated operations, personnel will need to understand required actions if automation is lost. New knowledge of ammonia and its characteristics will be paramount.

Stages	Impact	Ammonia-fueled vessels are anticipated to impact the following areas:
Steady state	Medium	The introduction of ammonia fuel is expected to impact human factors moderately when compared to current industry practice. The novelty of engine processes, such as dual fuel use, combined with general exposure to safe working around ammonia fuel, would impact job / task characteristics.
System shutdown (automatic)	Low	As with system start-up, automated system shutdown, including automated fuel switchover, would present minor changes to overall operations. The main impact would be additional monitoring of the automated aspect and responding to relevant alarms.
System shutdown (manual)	High	Manual shutdown could significantly impact the need for monitoring and intervention from various personnel. ECR personnel would need to control / monitor ammonia systems along with conventional systems. Personnel may need to take actions locally and ensure precautions are taken to safely allow such interventions.
Leak detection, isolation, and repair	High	While personnel on conventional fuel oil vessels already undertake leak detection, this task would become more complex and require additional safeguards due to ammonia's toxicity, explosivity, and flammability. Personnel with LNG / LPG or ammonia cargo experience would require less upskilling. Understanding of ammonia and its characteristics will influence all actions related to leaks.
General maintenance	Medium	The introduction of ammonia for fuel use will increase the complexity of planning, conducting, and recording maintenance. New skills will be required for working with ammonia systems / equipment / components, as well as the potential for using new tools and maintenance techniques. Metal and materials incompatibilities will need to be understood.
Emergency response	High	Emergency response processes and procedures will need to be updated to ensure that the novelty of dealing with occupational and process safety hazards and the characteristics of ammonia fuel have been addressed. The complexity and criticality of decision-making under new circumstances will need to be taken into account. For example, firefighting regimes may need alteration where ammonia could be present or if the ammonia systems could be affected. Changes to spill response would be required, and activities where outside organizations may be involved or impacted would have to be rethought and addressed.
Mustering and abandonment	High	Due to toxicity risks, mustering and abandonment procedures would need to be revised to reduce the potential for exposure of personnel to ammonia. Safe havens for sheltering and mustering would need to be engineered to account for potential ammonia impacts. To this point, the totally enclosed motor-propelled survival craft (TEMPSC) may need to be changed to a type similar to that used on chemical tankers.

Stages	Impact	Ammonia-fueled vessels are anticipated to impact the following areas:
Personnel rescue	High	Various considerations would need to be addressed to ensure that personnel could be safely rescued after exposure to ammonia. This would include a review of high-risk space limitations (FRP, TCS), the use of PPE, and suitability of rescue equipment and first aid items. Personnel participating in this operation would need understanding of ammonia and its characteristics and hazards.

Impact	Criteria Description
Low	Small changes to seafarer tasks where vessel design/operational practices addressed through industry practiced guidance and requirements.
Medium	Changes to seafarer tasks through additional complexity, time-consuming nature, and/or increased reliance on human reliability. Vessel design/operational practices addressed through further application of human factors principles.
High	Significant changes to seafarer tasks through additional complexity, time-consuming nature, and/or increased reliance on human reliability. Specific human factors studies required to address implications and involvement of human actions in accidents.

Mærsk Mc-Kinney Møller Center
for Zero Carbon Shipping