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The path to zero: a safe deployment of ammonia as maritime fuel

Operators Perspective

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ABSTRACT

As we strive to decarbonize the global shipping industry and make a sustainable future possible, it is crucial that we find alternatives to fossil-based fuels.

Ammonia has emerged as one of the leading alternative contenders, due to its limited carbon dioxide emissions when combusted. However, using ammonia as a shipping fuel creates potential safety hazards including toxicity, onboard fires, and explosions. Therefore, it is crucial to understand ammonia risks to crew, including those associated with operational human factors (HF), and the safeguards that can be implemented to reduce these risks to tolerable levels.

The main objectives of the proposed paper are to provide a preliminary account of the HF that should be addressed to prepare for ammonia fuel, outline detailed highest-impacted themes and share the latest insights from our ongoing HF-related work programme at Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (the MMMCZCS).

Method(s) and data

The MMMCZCS has studied ammonia safety since its founding in 2020. To date, we have conducted various risk assessment work packages with the Maritime Decarbonisation Hub, the latter being a joint initiative between Lloyd’s Register Group and the Lloyd's Register Foundation. These packages have included:

Early human factors analysis (EHFA): Identify HF safety challenges associated with industry preparedness for implementing ammonia as a fuel and establish further risk assessment approaches.
Risk reduction workshop: explore HF considerations and challenge assumptions of risk associated with various design risk nodes.
Safety critical task analysis (SCTA): qualitative risk assessment method to assess human error opportunities contributing to process safety for various scenarios.
Working environment health risk assessment (WEHRA): assess conceptual vessel designs to address personnel health and safety for bunkering, maintenance and fuel preparation activities.
Competency needs analysis: Identify key areas of upskilling based upon a high-level concept of new operations.

We are also in the process of conducting several ammonia safety projects. Findings from these reports will appear in the final paper. The projects include:

Competence and training framework development: identify and develop competency and training framework for operating ammonia-fueled vessels.

Investigating maritime community perceptions of ammonia as a marine fuel: Assess the risk perception of deploying ammonia as fuel across the maritime industry both ashore and on board. This enables us to identify gaps and potential barriers to the implementation of ammonia as maritime fuel.

Findings

The paper will present the status of our ammonia safety work programme, which aims to address HF considerations. We will outline the results of the above analyses and survey, pointing to the need for the maritime industry to apply HF design criteria and principles in its preparations for ammonia fuel use.

1 INTRODUCTION

The International Maritime Organization's (IMO) 2023 Strategy on Reduction of GHG Emissions from Ships has three interlinked ambitions: a reduction in carbon intensity of international shipping by at least 40% by 2030 compared with 2008; the uptake of zero or near-zero Greenhouse Gas (GHG) emission technologies, fuels, and/or energy sources representing at least 5% of the energy used by 2030; and GHG emissions from international shipping to reach net zero by or around 2050[1].

Decarbonization of all vessels in the worldwide shipping sector is critical for reaching the IMO ambitions and will be achieved by using alternative fuels and reducing fuel consumption. Methanol, methane, and biofuels, as well as ammonia, are promising fuels for zero-emissions ocean transport.

Ammonia has emerged as one of the leading alternative contenders for deep sea shipping due to its limited carbon dioxide emissions when combusted. Implementation of ammonia as a marine fuel is expected to be technologically feasible by 2025-2026, but its implementation will create new challenges for the maritime community. In particular, ammonia's toxic and gaseous nature requires the industry to develop new approaches to safety. Fortunately, some sectors of the industry already have extensive experience in safely handling and transporting ammonia as cargo at sea, with approximately 18-20 million tonnes of ammonia traded annually through around 120 global ports [2],[3].The safe use of ammonia as a marine fuel will draw heavily on this experience, and it will be important for the industry to transfer such knowledge into tailored and/or new operational concepts for ammonia-fueled vessels.

The Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (the MMMCZCS) is an independent, not-for-profit, fuel-agnostic research and development center. Established in 2020 with initial funding from the A.P. Møller Foundation, our purpose is to be a significant driver of, and to accelerate the sustainable decarbonization of the maritime industry by 2050. This complex challenge requires unprecedented collaboration across sectors, industries, and geographies, requiring us to work with shipping partners, governments, authorities, public sector bodies, scientists, academia and organizations from across the maritime industry and around the globe.

At the MMMCZCS, we have been studying ammonia safety through a range of risk, design and human factors (HF) projects since 2020. A 2023 publication jointly produced by the MMMCZCS and Lloyds Register's Decarb Hub presented a quantitative risk assessment analysis and an industry-first preliminary account of the HF considerations that will be impacted by the transition to ammonia as a fuel.

Using ammonia as a marine fuel involves safety hazards – primarily toxicity, but also combustible and flammability risks in confined spaces where sufficient oxygen is present. It is crucial for the industry to understand these hazards and risks, and to develop safeguards that can be implemented to manage them.

By applying a HF perspective to the use of ammonia as a fuel in the shipping industry, we guide the industry to identify and implement appropriate operational and design safeguards to reduce ammonia risk to tolerable levels.

This paper will provide a detailed examination of the principal HF considerations that should be addressed to prepare for ammonia as marine fuel.

As a supplement, we will share an overview of the anticipated HF impact on a range of specific operational phase processes, such as bunkering, fuel storage and transfers, and general maintenance.

We will integrate key insights from a survey of over 2,000 respondents across the maritime community that gathered maritime community perceptions, opinions, concerns, requests, and suggested ways forward, relating to ammonia as a marine fuel. This represents input provided by those who will be most directly impacted by ammonia's use.

The paper will also present and integrate output from the MMMCZCS's latest ammonia safety research, built upon extensive cross-sector collaboration with leading organizations and key stakeholders in the maritime ecosystem and beyond. This will include guidance that addresses associated competence and training impacts.

The MMMCZCS's work programme around qualifying ammonia as a safe marine fuel emphasizes the need for the maritime industry to apply HF engineering principles, such as ergonomics, within the design and operation of ammonia-fueled vessels.

2 PRINCIPAL HF CONSIDERATIONS - AMMONIA AS MARINE FUEL

HF is a scientific discipline 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. As such, HF 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”[4].

As with conventional fuels, using ammonia presents hazards to seafarers. These include toxicity, causticity, and flammability, as well as other hazards associated with its compressed containment, such as pressure release and cold temperatures.

Due to ammonia's novelty as a fuel, it is critical that the HF risks associated with operations and maintenance are understood so that appropriate guidance can be developed to support industry preparedness. This guidance encompasses HF engineering principles and suggests improvements to a company's safety management system, such as modifications to operational practices, workload staffing, competencies and training, and emergency preparedness.

2.1 Scope

In developing principal HF considerations for ammonia as fuel, the focus was upon operations and maintenance activities undertaken by crew members on newbuild, ammonia-fuel reference vessels (container, bulk carrier and tanker). The starting point was to identify changes or enhancements that would be needed to move from operating solely with convention fuel oil to employing dual-fueled engines utilizing conventional fuel oil and ammonia fuel. Initial scope revolves around the engagement of a gap task analysis, initially employed at a design concept stage.

The following HF themes were assessed:

- **Ergonomics design:** workspace arrangements and human machine interface (HMI).
- **Roles and responsibilities:** organizational structure and assigned roles.
- **Competence and training:** technical and non-technical skills, knowledge, understanding and application.
- **Resourcing and personnel:** workload distribution and number of personnel.
- **Processes and procedures:** documented processes and work practices.
- **Occupational health hazards:** exposure to toxicity, fire, noise, musculoskeletal risks, trips and falls, etc.
- **Process safety hazards:** human involvement in the prevention of, as well as contribution to exacerbation and recovery related to a major accident.
- **Management of change:** organizational, operational and technical changes that must be managed to achieve final ammonia preparedness.

Many of these themes align and address safety management system (SMS) sections as defined by International Safety Management (ISM) code.

2.2 Method

During 2023, the MMMCZCS and Lloyds Register’s HF advisory department jointly conducted a range of HF workshops, as part of developing principal HF considerations related to the use of ammonia as fuel.

The workshops considered three project reference designs for container, tanker, and bulk carrier vessels. The following activities were conducted:

Early human factors analysis (EHFA): identification of HF 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 HF considerations and challenge assumptions of risk associated with various design risk nodes.

Safety critical task analysis (SCTA): application of a qualitative risk assessment 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 personnel 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.

2.3 Ammonia-fueled vessel features

An ammonia-fueled vessel will present a different work environment for seafarers compared with conventional fuel oil-powered vessels. This is principally driven by vessel arrangements to address the chemical properties of ammonia with regards to its combustion, storage, handling and hazardous nature.

Key features of ammonia-fueled vessels include:

- New systems associated with the processing of ammonia as a fuel, e.g., bunker arrangements, sampling, fuel preparation and transfer, reliquification, and venting. This also includes the addition of support systems to facilitate the operations of these functions.
- Special safety design concepts, such as double barriers, area segregation, isolation methods, detoxification scrubbing, ammonia detection systems, and water systems such as curtains. Selective catalytic reduction systems (SCRs) will be added to enhance environmental performance.
- New, safe methods of crew working with ammonia, e.g., specific personal protection equipment (PPE), remote monitoring of hazardous areas, ammonia exposure level limitations, mustering in toxic conditions, ammonia decontamination showers, modified emergency response procedures and rescue operations.
- Constraints on vessel practices, e.g., ship-to-ship fuel transfer, extended time required for fuel transfer (including preparatory activities), voyage planning for port entry, safe coordination with other vessels or with ports, and limitations related to simultaneous ammonia bunkering and cargo operations.
- Integration with other onboard systems, e.g., dual fuel systems, engine operations, process control and command systems (including alarms), fire and gas detection, and refrigeration.
- Maintenance regimes, e.g., modernization and possible restrictions of maintenance practices, special ammonia corrosive properties, use of special techniques, tools, materials, and metals, classification of fuel areas, such as the tank connection spaces (TCS) and fuel preparation room (FPR), as enclosed spaces.

Although it should be noted that many ammonia operations will have parallels to those practiced on gas-fueled or cargo vessels, the consequence of these key features, in their entirety, is that the seafarer will not only interact with novel systems and situations, but will also encounter an operational environment that presents new challenges to seafarer performance.

For example, the swift spread of ammonia in the event of a leak will put pressure on timely responses and decision-making. Donning additional PPE for occupation health reasons may contribute to a seafarer’s fatigue and physical capability, while the use of new systems, such as remote monitoring CCTV systems for inspection, will require new ways of working and reliance on imagery in decision-making and fault-finding. These examples present areas which should be addressed through further controls and safeguards.

2.4 Findings – principal HF considerations

The results of our HF workshops are summarized in Table 1, Principal human factors considerations[5], below which we provide an overview of the principal HF considerations regarding ammonia fuel use, and rate their impact level as low, medium, or high.

These results highlight the need for companies and the maritime industry to apply HF engineering principles when designing and operating ammonia-fueled vessels.

Table 1: Principal human factors considerations

Stages	Description	Impact	Ammonia-fueled vessels are anticipated to impact the areas below
Ergonomics design	Workspace arrangements and human machine interface (HMI)	Medium	• Deck and bunker stations • Local engine and tank spaces (e.g., fuel preparation room [FPR] and tank connection spaces [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/ maintenance • General ammonia risk awareness across crew • Emergency response • Raised 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 • Increase in requirements for risk assessment and employment of formal safe work practices • Review and, where necessary, change to emergency response processes
Occupational health hazards	Exposure to toxicity, fire, noise, musculoskeletal risks, trips and falls, etc.	High	• Mechanical • 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 maintenance precautions with metals and materials • 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 are addressed through industry practiced guidance and requirements.
Medium	Changes to seafarer tasks from additional complexity, greater time consumption, increased reliance on human reliability. Vessel design/operational practices addressed through further application of HF principles.
High	Significant changes to seafarer tasks from additional complexity, greater time consumption, increased reliance on human reliability. Specific HF studies required to address implication and involvement of human actions around accidents.

2.4.1 High-impact HF considerations

In the following sections, we will provide a synopsis of the key HF considerations that we expect to have the greatest impact during the 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.

2.4.2 Competence and training

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 [6].

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 a 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 with crew on bulk carriers 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.

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

2.4.3 Process and procedures

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 the use of associated systems 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 only 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 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.

2.4.4 Occupational health hazards

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, on the storage method, and on its combination with other chemicals.

We have identified a range of occupational health hazard 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 entities, 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.

2.4.5 Process safety hazards

Managing process safety hazards requires continued improvement in standards.

Managing high standards of safety will require shipping 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 the 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 identifying and assessing ammonia releases and for evaluating 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 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.

2.5 Supplementary operational phase impacts

As a supplement to the principal HF considerations, Table 2[4] outlines anticipated HF impacts on a range of specific, operational-phase processes such as bunkering, fuel storage and transfers, and general maintenance.

Table 2: Operational phases impact for ammonia-fueled vessels

Stages	Human factors impact	Key features
Port approach	Low	Minimal additional impact to crew activities compared with existing industry practices. There may be changes to planning and communications with port authorities, marine pilots and other entities.
Mooring	Low	For standard mooring practices, minimal impact is expected. For the ship-to-ship mooring associated with bunkering, changes would especially be related to potential ammonia hazards. This impact would be greatest for vessel personnel without ship-to-ship mooring experience.
Bunkering / transfer	High	Ammonia bunkering will introduce new hazards, safeguards and new crew activities, including changes to interactions with other organizations. For example, the method to may be used for ammonia fuel sampling will differ from that for conventional fuel. Overall, for personnel with LNG / LPG, bunkering or ammonia cargo experience, the overall impact of the changes would be lower.
Fuel storage	Medium	There will be a moderate level of new challenges related to ammonia storage for those with conventional fuel oil experience. The 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 within the engine control room (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.
Steady state	Medium	The introduction of ammonia fuel is expected to impact HF moderately compared with 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 have require little change 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. Potentially, personnel would 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 undertake leak detection, the introduction of ammonia with its toxic nature of ammonia, as well as explosivity and flammability, the task makes the task more complex and requires additional safeguards. 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. There will be new skills required for working with ammonia systems/equipment/components, and potentially 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 occupation/process safety hazards and characteristics of ammonia fuel have been addressed. Complexity and criticality of decision-making under new circumstances will need to be considered. For example, firefighting regimes may need altering where ammonia could be present, or if the systems could be affected. Changes to spill response would be required. Also, activities where outside entities may be involved or impacted would have to be reconsidered and addressed.
Mustering and abandonment	High	With the potential for toxicity, the mustering and abandonment procedures would need to be revised to reduce the potential for exposure of personnel to ammonia. Safe havens for sheltering/mustering would need to be engineered for potential ammonia impacts.
Personnel rescue	High	Various considerations would need to be addressed to ensure that personnel could be safely rescued after exposures to ammonia. This would include a review of high-risk space limitations (FRP, TCS), the use of PPE, suitability of rescue equipment and first aid items. Personnel participating in this operation would need understanding of ammonia and its characteristics/hazards.

Impact in Table 2 is measured through criteria such as task novelty, frequency of human interaction, criticality and known issues.

3 MARITIME COMMUNITY PERCEPTIONS OF AMMONIA AS MARINE FUEL

In October 2023, the MMMCZCS organized a roundtable dedicated to ammonia safety, with multiple key stakeholders from the shipping and ammonia industries. This meeting highlighted the need to assess risk perceptions regarding ammonia as a marine fuel across onboard and ashore maritime communities, which could have a significant impact on ammonia's uptake as marine fuel.

The MMMCZCS has, therefore, undertaken a survey in 2024 on ammonia risk perception and acceptance with the goal of hearing the direct voice of a representative maritime community [7].

Our objective is to help the industry lift the barriers to implementation of ammonia as a marine fuel in a collaborative way, and to facilitate a safe transition to alternative fuels.

3.1 Survey introduction

To understand the perception and acceptance of ammonia as a marine fuel across the maritime community, the MMMCZCS designed an online survey.

The survey was launched in February 2024 and remained open until mid-April 2024. Survey questions primarily focused on a) the prevalence and nature of safety concerns related to use of ammonia as a marine fuel, b) desires for knowledge and training regarding ammonia as a marine fuel, and c) actual and perceived willingness to sail on or work with ammonia-fueled vessels.

The survey reached 2,004 respondents across the maritime community, covering a range of different ages, positions, vessel segments, and level of experience with gaseous fuels or ammonia as cargo.

Throughout the multiple-choice questionnaire, the respondents had the option of sharing their thoughts in the (optional) open fields. More than 1,500 comments were compiled from these open-field responses.

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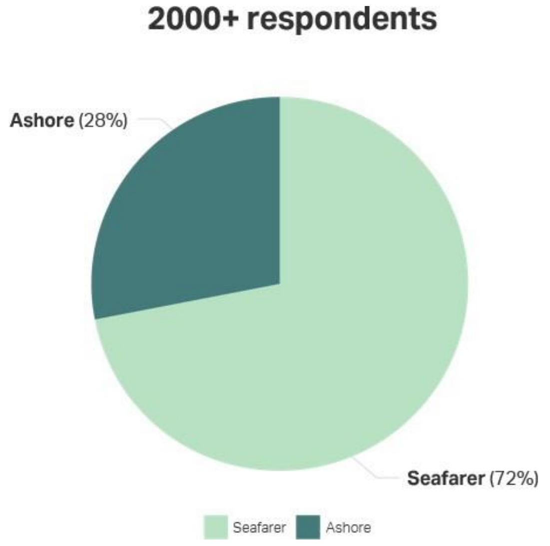

Figure 1: Survey respondents' profile

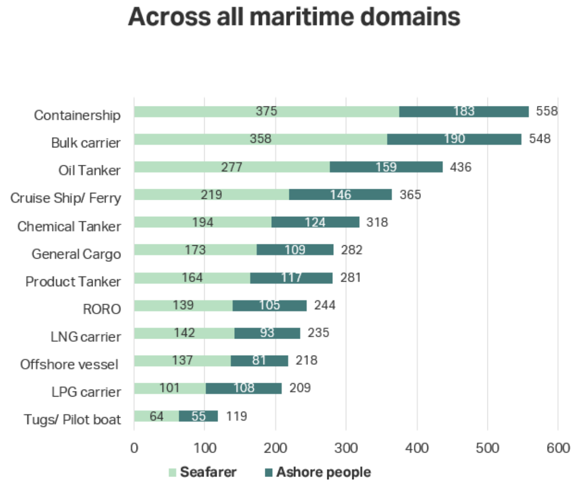

Figure 2: Survey respondents' experience

3.2 Key takeaway 1: The majority of respondents from across the maritime community are willing to sail on or work with ammonia-fueled vessels.

Over half (58.6%) of the total respondents agreed that they would be willing to sail on or work with ammonia-fueled vessels, while 24% were unsure and 12% reported that they would not be willing. More specifically, 59% of seafarers and 57% of ashore personnel who responded to the survey agreed that they would be willing to work with ammonia. While more than half of the respondents were willing to sail on or work with ammonia-fueled vessels, these respondents nevertheless raised some specific concerns, especially regarding training and safety.

3.3 Key takeaway 2: Acceptance of ammonia as a marine fuel is conditional on a comprehensive level of training and certification.

Many of the survey responses emphasized the desire for more knowledge and training around ammonia. When asked what knowledge they needed regarding ammonia as marine fuel, respondents highlighted many topics relating to safety, such as ammonia's impact on humans and the environment, firefighting and other emergency response procedures, and ammonia's characteristics.

Respondents also expressed a desire for comprehensive training – including on safety-focused topics such as leakage management, emergency response, and risk analysis, but also on new engine procedures and maintenance, regulation, and gas as fuel.

3.4 Key takeaway 3: Enhanced, reliable, and safe onboard fuel systems and inherently safer ship designs are seen as critical safety elements.

Survey results shed light on the primary safety concerns of both seafarers and ashore personnel. Respondents' basic perception of the characteristics (e.g., toxicity) and safe handling of ammonia seems to be generally accurate and reflects a good understanding of the possible risks involved. However, the survey showed a lack of knowledge regarding some technical aspects of ammonia handling and operations. Further study, communication, and training on these topics are, therefore, important. The survey responses also highlighted the importance of safer technology and design to support ammonia's introduction as a marine fuel.

3.5 Survey closing remarks

In publishing a survey investigating the perceptions of ammonia as marine fuel, we aim to share the opinions, concerns, and suggested ways forward raised by the community who will be most directly impacted by ammonia's use.

The knowledge shared in the survey report can help the industry to address the concerns and misperceptions shared by first-in-line operators.

In addition, the survey findings can be used to shape and inform future training content and address upcoming ship and fuel systems designs, as well as guidelines for safe bunkering and in-port handling of ammonia.

At the MMMCZCS, we have integrated key takeaways from the survey into our ongoing work programme on ammonia safety research. Specifically, respondents' highlights around knowledge and training needs have been fed into our latest ongoing research project, *Ammonia as fuel - competence and training*. In the following section, we present our latest HF research on competence and training.

4 ADDRESSING HIGH IMPACT HF CONSIDERATIONS - COMPETENCE & TRAINING

In section three, we introduced the principal HF considerations and detailed high-impact areas that must be addressed for safe operation, including seafarer competence and training.

At the end of 2023, the MMMCZCS and the Lloyds Register's Decarb Hub initiated Phase 3 of their collaborative work programme: the *Ammonia as fuel – competencies and training* project. The project aimed to answer the following questions:

- How will seafarers' roles change with the introduction of ammonia as a fuel?
- What are the minimum standards of competency required across the seafarer community?
- What specific additional competencies will be required for specialist roles at sea?
- In what areas will additional training need to be developed and introduced?

The *Ammonia as fuel – competencies and training* project continued through 2024. This project has brought together a wide group of stakeholders from across the maritime industry – including participants with relevant ammonia experience. The project was enhanced by input from contributors with previous experience in adjacent areas, including:

- Conventional fuel oil.
- Transition to liquefied petroleum gas (LPG) and liquefied natural gas (LNG).
- LNG/LPG operations, maintenance, emergency response, and the structure and content of the training associated with this transition.
- Manufacture of ammonia for industrial use.
- Ammonia transfer to seagoing vessels.
- Carriage of ammonia as a cargo.
- Onshore ammonia emergency response.

Concurrently, members of this project team have participated in other related initiatives. These include the investigation into training considerations for future shipping fuels by the Maritime Just Transition Task Force (MJTTF) [8] and the work of the Society for Gas as a Marine Fuel (SGMF) relating to ammonia bunkering guidelines [9].

The project results include two technical reports from the *Ammonia as fuel – competencies and training* project. Each technical report describes the outcomes of a specific stage within the project:

1. **Proposed overall framework for competency and training standards**: Provides minimum competency and training standards for all seafarers. This framework is modelled on the IMO's International Convention on Standards of Training, Competency and Watchkeeping for Seafarers (STCW) Code relating to the specifications for minimum standards of competence for training for ships subject to the International Code of Safety for Ships Using Gases or other Low-Flashpoint Fuels (IGF Code). The proposal addresses both basic and advanced training. The primary audience for this 'proposed overall framework' report is technical teams within regulatory bodies.
2. **Operations, maintenance and emergency response tasks**: Detailed competency requirements and training standards for specific operations, maintenance and emergency response tasks beyond those outlined in a typical STCW framework. The primary audiences for this 'operations, maintenance and emergency response tasks' report are ship operators/managers and training organizations.

The collective findings of the entire *Ammonia as fuel – competency and training* project will be of interest to a broad range of stakeholders in the maritime ecosystem.

The reports are expected to become publicly available during Q1 2025.

4.1 Competency and training requirements for ammonia as fuel

4.1.1 Seafarers and shore-based staff will require new skills and training

This is not the first time that the shipping community has had to navigate introduction of new fuels and resulting changes to competency and training requirements. For example, the expertise required of seafarers has already undergone a step change for those vessels that have moved from conventional fuels to LNG propulsion. Operating vessels on conventional fuel primarily required proficiency in managing internal combustion engines, diverse fuel properties and fuel treatment systems. The shift to LNG, a cryogenic gaseous fuel, introduced new demands, including knowledge of specialized storage and systems, handling gas as fuel, cryogenic safety protocols and advanced engine technologies such as dual-fuel engines.

The STCW Tables A-V/3-1 and A-V/3-2 relating to the IGF Code establish mandatory competencies and training requirements for seafarers working on ships using low-flashpoint fuels, including LNG. These tables emphasize safety in handling and in operating with gas or low-flashpoint fuel. The existing training is structured into two levels. Namely, basic training is for seafarers needing an overview of LNG, its hazards and operational requirements. Advanced training is for those with more critical roles and responsibilities related to leadership, as well as LNG fuel-handling and management.

The IGF Code does not currently address the competencies required for alternative fuels like ammonia, hydrogen or methanol. As ammonia is introduced, seafarers will need to master its specific properties, such as its toxicity, corrosiveness, and the risk of nitrogen-based emissions. This will necessitate training in advanced safety measures, specialized containment systems and new engine designs. Therefore, updates to the IGF Code are required to accommodate the introduction of ammonia as a marine fuel.

4.1.2 Safe operating principles are the foundation

The general principles for safe ship operation are common to all marine fuels. Whichever fuel is used, a seafarer should be able to:

- Contribute to the safe operation of a ship.
- Ensure a safe working environment.
- Take precautions to prevent hazards on a ship.
- Apply occupational health and safety precautions and measures.
- Carry out firefighting operations on a ship.
- Respond to emergencies.
- Take precautions to prevent environmental pollution from the release of fuels.

When applied to ammonia, these principles remain the same as those embodied in the IGF Code. However, the application of the principles can differ for each fuel, both for essential basic training for all seafarers and for advanced training in the management of fuel-related operations. Some seafarers may have already met some expected training requirements by virtue of having worked on ships using gas as fuel or having served on ships carrying ammonia as a cargo.

4.1.3 New or modified knowledge, understanding and proficiencies (KUPs) will be required on board

A key aspect of our collaborative programme was to identify the additional training and competencies needed for personnel assigned on dual-fueled vessels with ammonia as one of the fuels. Our proposed framework is consistent with STCW specifications for basic and advanced standards. Required standards, expressed as competency statements, are broken down into three areas: knowledge, understanding and proficiencies (KUPs).

Seafarers need **knowledge** of:

- The key characteristics of ammonia, such as toxicity, flammability, explosivity, corrosion and material incompatibility.
- A ship's ammonia-related systems and equipment, including storage.
- Ammonia's physical and chemical properties.
- Hazards and hazard controls of ammonia.
- Occupational health and safety precautions and measures.
- How to respond to emergencies, such as leaks, spills, fires and explosions.
- Pollution prevention mechanisms.

Seafarers will need **understanding** of:

- The specific operational and maintenance regimes required by ammonia.
- Dual-fuel changeover procedures.
- How approaches to emergency response differ on board ammonia-fueled vessels.
- How processes change with increased automation.
- The legislative requirements with which they must comply.

Seafarers will need new skills and **proficiencies** in:

- Operation and maintenance of ammonia-related equipment, including increased use of automation to enable remote operations.
- Use of new materials.
- Use of new types of instrumentation and control systems.
- Use of new types of detection and monitoring equipment.
- Use of different personal protective equipment (PPE).

Under the current framework, basic training provides foundational knowledge and skills. This training focuses on general awareness of the risks, properties and safety measures associated with low-flashpoint fuels such as LNG. The training is intended for all seafarers prior to being assigned duties on board a ship using fuels governed by the IGF Code. Any seafarer responsible for designated safety duties associated with the care, use or emergency response to the fuel on board ships subject to the IGF Code should receive basic training.

To upskill seafarers for ammonia fuel use, basic training will need to address the KUPs listed above. The basic training table in our **proposed overall framework for competency and training standards report** details the required knowledge, understanding and proficiencies for each element of this basic training. The table also covers the methods for demonstrating competence and the criteria for evaluation.

4.1.4 Additional skills and competencies are role-dependent

The IGF Code also outlines advanced training requirements for seafarers operating on vessels powered by gases or other low-flashpoint fuels. Advanced training is for masters, engineers and all personnel with immediate responsibility for the care and use of fuels and fuel systems on ships subject to the IGF Code. This level of training includes in-depth education on fuel system design, hazard control, fuel-handling procedures and advanced emergency management.

Advanced training will be required in each of the following competency areas to upskill for ammonia:

- Familiarity with physical and chemical properties of ammonia fuel.
- Operation of fuel system controls related to propulsion plant and engineering systems and to services and safety devices.
- Ability to safely perform and monitor all operations related to ammonia fuel.
- Ability to plan and monitor safe bunkering, stowage and securing of the ammonia fuel on board.
- Precautions to prevent environmental pollution from the release of ammonia fuel from ships.
- Monitoring and control of compliance with legislative requirements.
- Precautions to prevent hazards.
- Application of occupational health and safety precautions and measures on board.
- Knowledge of the prevention, control and firefighting and extinguishing systems.

The advanced training table in our **proposed overall framework for competency and training standards report** details the required knowledge, understanding and proficiencies for each element of advanced training. The table also covers the methods for demonstrating competence and the criteria for evaluation.

4.1.5 Going beyond the standard framework

Seafarers will require additional knowledge, skills and proficiencies over and above the minimum requirements specified by current frameworks, such as the IGF Code, to carry out their roles. The *Ammonia as fuel – competency and training* project identified and evaluated a wide range of operational, maintenance and emergency response scenarios (both routine tasks and infrequent or specialized tasks) relating to onboard activities:

- Hazards, characteristics and hazard awareness.
- Overall safety and environmental/risk awareness.
- Occupational health and safety.
- Operational and process safety.
- Regulations, local requirements and industry guidelines.
- Storage, management and transfers.
- Gas purging and venting from compartments
- Leak detection, management, isolation and repair.
- Simultaneous operations (SIMOPs).
- Maintenance.
- Emergency response.

The level of KUPs required of individuals depends on their role on board. Similar KUPs will apply to shoreside workers based on their roles. Accordingly, we further examined these KUPs in the context of different professional groupings. We divided seafarers into three distinct groups: management, operations and support. Shoreside personnel were represented by four groups: company corporate, port authority, terminal management and shore support personnel.

The **operations, maintenance and emergency response tasks report** details competency requirements and training standards for specific operations, emergency and maintenance tasks beyond those outlined in a typical STCW framework. As mentioned above, the project technical reports are expected to become publicly available during Q1 2025.

5 CONCLUSIONS

Decarbonization of the shipping industry will require widespread uptake of alternative fuels.

Ammonia is a promising alternative shipping fuel for deep sea shipping, due to its limited carbon dioxide emissions when combusted, and development of ammonia-fueled marine engines and ship designs is at an advanced stage. However, the characteristics of ammonia, including its toxicity and gaseous nature, mean that its implementation as a marine fuel will require much more than technical readiness – the industry will also need to strongly focus on human factors, from a vessel and system concept stage, right through to the adequate training and competency of its crew.

The introduction of ammonia as marine fuel will be accompanied by various technical innovations including automation, new maintenance regimes, operational procedures and modernization of process control. As part of this process, the industry as a whole, and seafarers in particular, will encounter challenges that demand attention to HF themes such as those mentioned in Table 1 and 2.

Together with the Lloyds Register's Decarb Hub and industry partners, the MMMCZCS has developed principal HF considerations, highlighted in Table 1. These are expected to be impacted when transitioning to ammonia as marine fuel. Key HF considerations that we expect to have the greatest impact during transition from conventional to ammonia as fuel were further detailed in this paper.

Additionally, we introduced insights from our latest HF research project, addressing the competence and training high-impact theme. This work provides the maritime industry with tangible guidance and actions, when moving forward towards the safe implementation of ammonia as fuel.

In summary, HF research conducted by MMMCZCS and the Lloyds Register's Decarb Hub to date emphasizes the need for shipping companies and the maritime industry to apply HF design criteria and principles in its preparations for ammonia fuel use. By doing so, the risks to crew of using ammonia as an alternative maritime fuel can be kept to a tolerable level.

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9 ABBREVIATIONS

ECR	Engine control room
EHFA	Early human factors analysis
FPR	Fuel preparation room
GHG	Greenhouse gas
HF	Human factors
HMI	Human machine interface
IGF Code	International code of safety for ships using gases or other low-flashpoint fuels
IMO	International Maritime Organization
ISM	International safety management
KUPs	Knowledge, understanding, and proficiencies
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
MJTTF	Maritime Just Transition Task Force
MMMCZCS	Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping
PPE	Personal protection equipment
SCTA	Safety critical task analysis
SCR	Selective catalytic reduction
SGMF	Society for gas as a marine fuel
SIMOPs	Simultaneous operations
SMS	Safety management system
STCW	Standards of training, competency and watchkeeping for seafarers
TCS	Tank connection spaces
WEHRA	Working environment health risk assessment