SAFETY INSIGHTS **FOR AMMONIA AS A MARINE FUEL**

March 2025

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EXECUTIVE SUMMARY

Alternative fuels, energy efficiency devices and performance optimization are widely regarded as the pillars supporting the decarbonization of the maritime industry. Among these emerging solutions, ammonia as a fuel offers significant long-term potential to help the industry achieve net-zero emissions.

This publication highlights ABS' current activities in safety, dispersion and emergency evacuation related to using ammonia as a marine fuel. Some activities stem from regulatory obligations, while others proactively address emerging issues. These efforts are based on significant technological advancements in software and hardware technologies and current industry best practices.

HAZID – Safety

Identify potential safety hazards and ensure compliance with regulations

CFD – Ammonia Dispersion

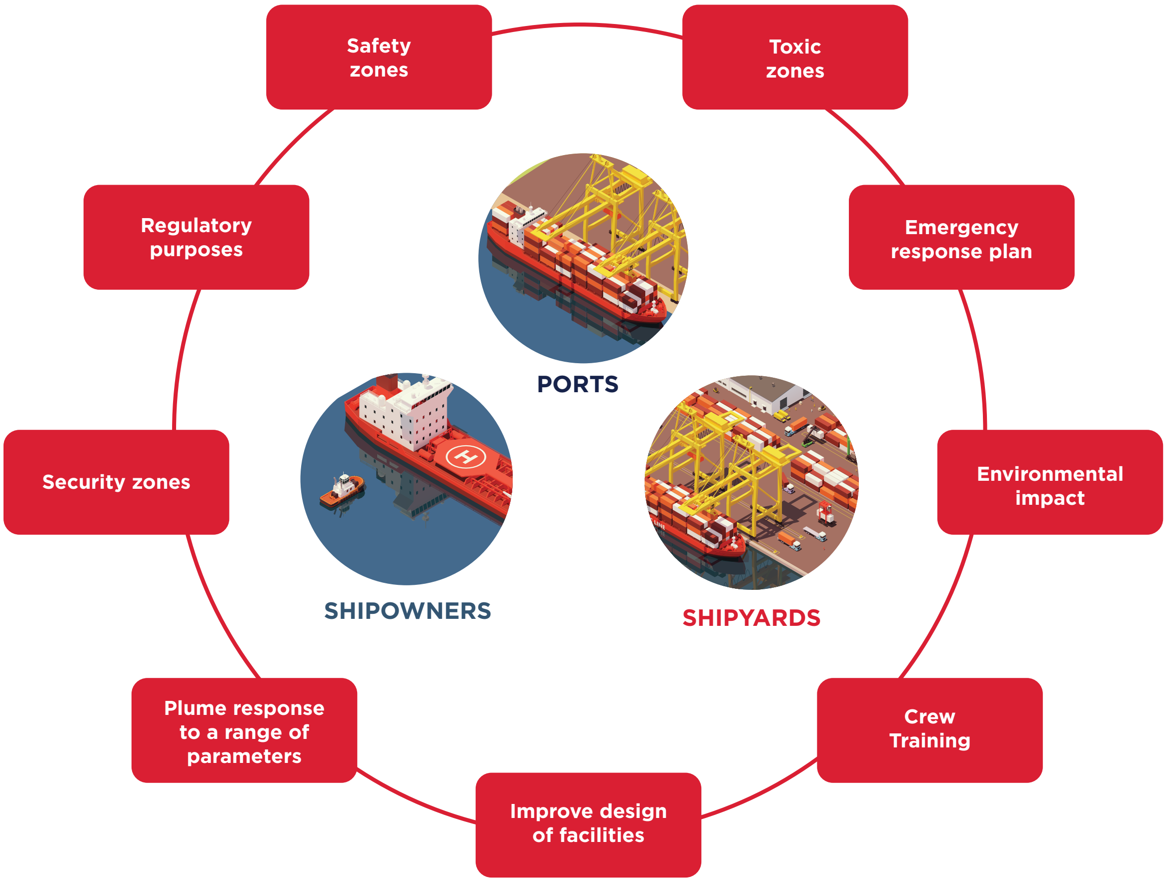
Predict the ammonia dispersion in realistic leakage scenarios

Risk Evaluation – Optimized Emergency Response Plan

Probabilistic risk analysis to evaluate the emergency response plan

Acoustic Cameras – Safety

Detect and visualize ammonia leakage, update personnel and systems in real-time



Hazard identification (HAZID) studies can help identify the major hazards associated with ammonia as marine fuel and their causes. The preventive and mitigative safeguards and recommendations are investigated for various ship types. ABS suggests detailed training requirements are needed to be in place for safe operation by an expanded class of mariners.

ABS performs computational fluid dynamics (CFD) simulations using modern tools to quantitatively assess the risks associated with ammonia dispersion in leakage scenarios. Computational fluid dynamics simulations using modern tools to quantitatively assess the risks associated can define ammonia hazards or toxic zones, examine the placement of gas detectors, and compare different ventilation strategies. This publication presents several ammonia dispersion scenarios studied by ABS.

To enhance realism and provide a more objective evaluation of potential risk hot spots, ABS is developing advanced probabilistic risk analysis, which accounts for uncertainties in ammonia plume behavior, as well as human factors during emergency evacuation and response. By integrating CFD results with realistic leakage scenarios, these capabilities simulate how crew members respond under various hazards identified, enabling more effective development of evacuation procedures, enhanced safety measures and improved coordination among participants. This comprehensive approach ensures a more robust and informed emergency response strategy.

In conclusion, this report aims to provide a comprehensive overview of ABS' efforts to address the challenges and opportunities presented by ammonia as a marine fuel. Through detailed analysis of ammonia dispersion studies and emergency evacuation protocols, ABS strives to contribute to the discourse on safe and sustainable maritime fuel alternatives.

INTRODUCTION

The maritime industry is facing growing pressure to reduce emissions as regulatory bodies, such as the International Maritime Organization (IMO) and the European Union (EU), continue to implement increasingly stringent environmental regulations. To achieve this, the industry is investigating a shift away from traditional fossil fuels and a transition toward cleaner, more sustainable alternatives.

Among the alternative fuels the industry is considering, ammonia offers a compelling option. Ammonia does not contain any carbon and, when produced renewably, would offer a carbon-free pathway to reducing well-to-wake emissions. However, the adoption of ammonia introduces significant challenges, primarily concerning its toxicity, its corrosiveness and the need for robust safety protocols.

At low concentrations, ammonia can be irritating to the eyes, skin and lungs. At high concentrations, it becomes immediately life-threatening. Contact with carbon steel surfaces causes stress corrosion cracking (SCC), raising concerns about the robustness of the ammonia supply systems. Finally, ammonia is colorless under atmospheric conditions, complicating leak detection. Therefore, ammonia is classified as a hazardous substance and is subject to strict reporting requirements by facilities that produce, store or use it in significant quantities. Concentration and duration of exposure limits are regulated by several national and international standards. To help the industry prepare for potential leakage incidents, it is vital to predict and understand the risks and hazards of ammonia.

In general, ammonia's safety concerns need to be considered and mitigated by all stakeholders in the value chain, including ports, shipowners and operators, and shipyards:

PORTS:

A. **Toxicity and Exposure Risks:** Ports must manage risks of ammonia vapor exposure to personnel, infrastructure and surrounding communities.

B. **Emergency Preparedness:** Robust safety protocols and emergency response plans are needed to handle accidental releases or operational incidents.

C. **Regulatory Compliance:** Safety standards to ensure safe bunkering and storage operations should be met.

SHIPOWNERS AND OPERATORS

A. **Crew Safety:** Mitigating risks to onboard personnel during bunkering or ammonia leaks requires enhanced crew training programs for ammonia-specific emergencies.

B. **Operational Risks:** Addressing risks during ship-to-ship bunkering, ensuring system reliability and maintaining operational efficiency.

C. **Vessel Design Requirements:** Demand for ammonia-ready designs that prioritize containment, leak mitigation and crew evacuation routes.

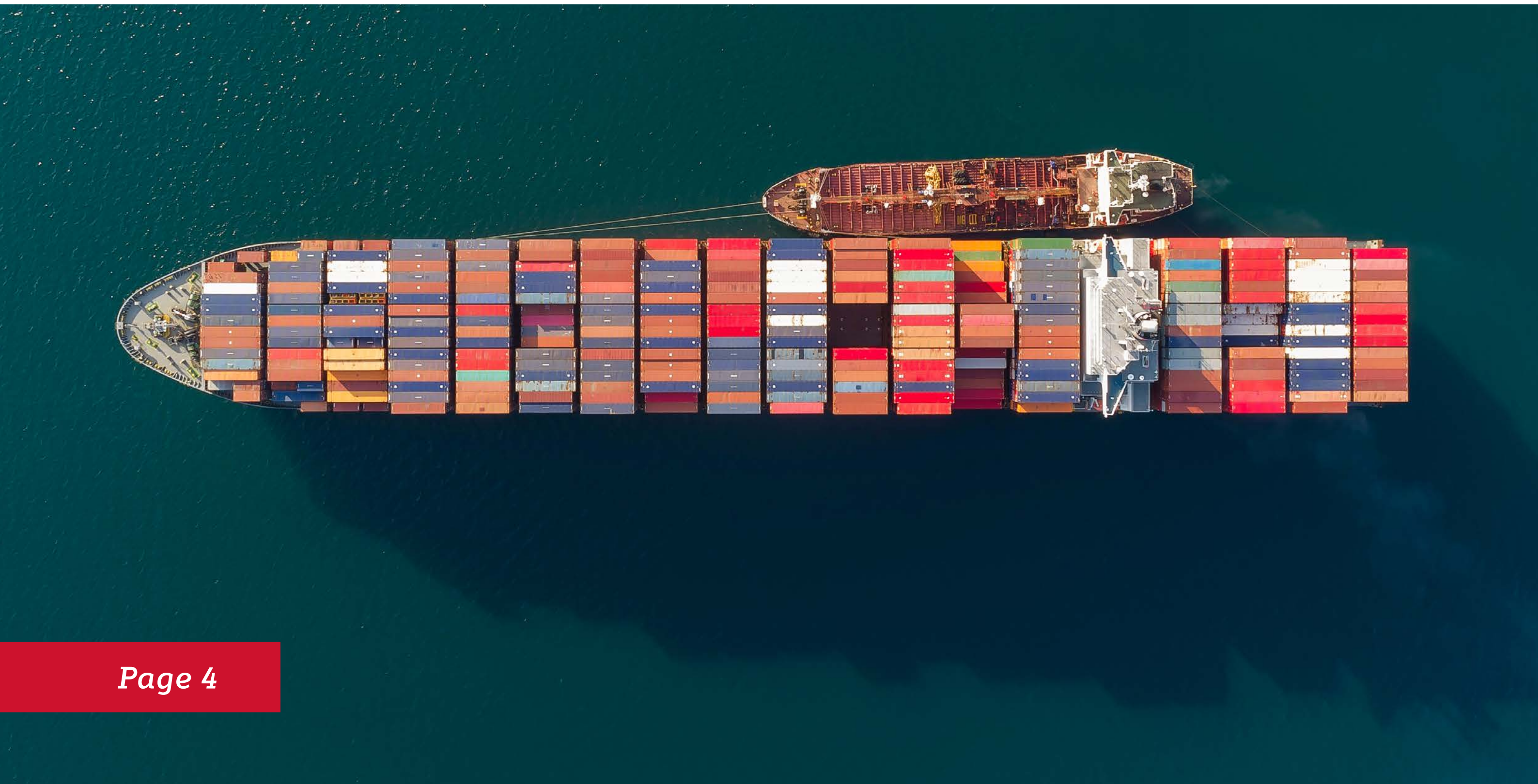
SHIPYARDS:

A. **Safety Management Systems:** Incorporating advanced safety protocols to handle ammonia-related risks during vessel construction and repairs.

Therefore, a proactive and meticulously planned approach is essential to the successful and safe integration of ammonia into maritime operations. This approach requires a comprehensive strategy that addresses the following three interconnected areas:

1. **Proactive Regulatory Engagement and Risk Anticipation: The first crucial step involves anticipating and actively engaging with future regulatory developments pertaining to ammonia as a marine fuel. This requires:**
    - Identifying Evolving Standards: Proactively monitoring and addressing emerging concerns and regulatory requirements related to the handling, storage and combustion of ammonia in marine environments. This promotes early adaptation and helps avoid costly retrofits later.
    - Understanding Regulatory Impact: Anticipating the impact of regulations and proactively planning operations and technologies that are compatible with future regulatory changes.
2. **Development and Implementation of a Multifaceted Safety Framework: Given ammonia's inherent risks, building a strong safety framework is paramount. This involves:**
    - Qualitative Risk Assessment Through HAZID Studies: Conducting HAZID studies to systematically identify potential hazards related to ammonia throughout its life cycle on board a vessel, from bunkering to combustion. This structured process intends to facilitate the consideration of numerous risk scenarios, which can then inform targeted mitigation strategies
    - Quantitative Risk Assessment Through CFD Modeling: Employing CFD dispersion studies to quantitatively assess the potential impact of ammonia releases under various scenarios. These simulations predict vapor concentration and spread, enabling optimized design of ventilation systems, gas detection and emergency response protocols.
3. **Real-Time Monitoring and Optimized Emergency Response: A robust system must be in place to detect and rapidly respond to ammonia-related incidents:**
    - Emergency Response Optimization Through Probabilistic Risk Analysis: This method simulates each step of an emergency plan under different scenarios — such as how an ammonia plume might spread and how people react. Simulating these situations highlights where changes could reduce the chances of injuries and improve emergency response. This information helps improve evacuation strategies and supports better decision-making during emergency planning.
    - Early Leak Detection with Advanced Technology: Implementing real-time monitoring systems, such as acoustic cameras, for the rapid and precise detection of ammonia leaks. These technologies facilitate immediate intervention, minimizing potential exposure risks and preventing escalation.

By systematically addressing these three interconnected areas, the maritime industry can confidently transition to ammonia as a cleaner fuel source. This approach will help ensure not only environmental sustainability but also the safe, reliable and efficient operation of ammonia-fueled vessels.



REGULATIONS FOR AMMONIA AS A MARINE FUEL

The onboard storage of ammonia and its use as a marine fuel are governed by multiple conventions, regulations and codes. A summary of key regulations pertaining to onboard storage, utilization and consumption of ammonia follows.

SOLAS CONVENTION

The IMO's safety-related regulations for international shipping are regulated through the International Convention for the Safety of Life at Sea (SOLAS, 1974, as amended). SOLAS has historically prohibited the use of conventional fuel oils with less than a 60° C flashpoint, except for emergency generator use (where the flashpoint limit is 43° C) and subject to additional requirements detailed under SOLAS Chapter II-2, Regulation 4.2.1. To accommodate the interest in using gaseous and liquid fuels with a flashpoint of less than 60° C, the IMO adopted the International Code of Safety for Ships using Gases or Other Low-Flashpoint Fuels (IGF Code) by including a new Part G to SOLAS II-1 in 2015.

STCW CONVENTION

Part D of the IGF Code, which covers all gases and low-flashpoint fuel applications for IGF Code ships under SOLAS, requires companies to ensure that the seafarers on board these ships have completed the training that will give them the ability to fulfill their designated duties and responsibilities. This is applied through the IMO International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW). When the SOLAS amendments were adopted for the IGF Code, the STCW Convention and Code was also amended (by MSC.396(95) and MSC.397(95)) to add specific training requirements and certification for IGF-Code seafarers. To support the application of ammonia as fuel, member states should develop national training and certification suitable for certification to the STCW Convention.

Besides the STCW convention, the regulatory gaps in IGF/IGC/ISM Codes for ammonia as a marine fuel are summarized in Table 1.

Subject	Rule/Guidance	Comment on Code Gaps
Onboard Storage	IMO IGF Code	IGF Code Part A-1 prescriptive provisions are specifically for natural gas (methane). Alternative design process enables approval of other gases and low-flashpoint fuels but could be revised to include specific provisions for ammonia in the longer term. CCC 10 finalized interim guidelines for the safety of ships using ammonia as fuel.
	IMO IGC Code	Provisions could be added to allow toxic ammonia to be used as fuel. The amendment to permit ammonia use as a marine fuel was adopted during the 109th session of the IMO MSC and scheduled to enter into force on July 1, 2026.
Utilization and Consumption	IMO IGF Code	IGF Code Part A-1 prescriptive provisions are specifically for natural gas (methane). Alternative design process enables approval of other gases and low-flashpoint fuels, but it could be revised to include specific provisions for ammonia in the longer term. CCC 10 finalized interim guidelines for the safety of ships using ammonia as fuel.
	ISM Code	Development of operational requirements under the IGF Code, or interim guidelines, would facilitate operators undertaking obligations under ISM Code.
	IMO STCW Convention	Regulation for training of crew for IGF Code ships exists under STCW Convention. The question remains on the application of ammonia under IGF Code, but the development of training courses by flag Administrations is still required to enable crew certification for ammonia as fuel under STCW.

Table 1: Regulatory gap for ammonia shipping storage, utilization and consumption

There is a lack of regulation for the use of ammonia as a fuel at the national, regional and international levels. Ammonia storage, transportation and use rules at sea offer important regulatory references that help make it easier to use ammonia as a maritime fuel. Although this framework would need to be modified to allow for the wider use of ammonia as a marine fuel, class societies currently have access to well-established, goal-based standards that have been used to support shipowners in the absence of harmonized international regulation.

THE INTERNATIONAL ASSOCIATION OF CLASS SOCIETIES (IACS) AND CLASSIFICATION SOCIETIES

Since 2021, most classification societies have released guidelines for vessels powered by ammonia, some of which have been integrated into regulations and specifications. ABS published the latest *Requirements for Ammonia Fueled Vessels* in September 2023.

Most classification societies actively collaborate with designers and builders to grant approval in principle (AIP) for innovative ammonia-fueled vessel designs. By doing so, they aim to address how the unique risks of ammonia can be practically minimized on board various ship types. Moreover, classification societies are offering ammonia fuel readiness notations for newly constructed vessels, encouraging the future use of ammonia fuel as regulations and technology evolve.

Recognizing the challenge of achieving the ambitious decarbonization targets set by the IMO while promoting the safe adoption of new fuels, the IACS Council established the Safe Decarbonization Panel (SDP) in 2022. The SDP is currently developing new Unified Requirements for the Control of Ammonia Releases in Ammonia-Fueled Vessels, reinforcing the industry's commitment to safe and sustainable shipping practices.

QUALITATIVE AND QUANTITATIVE RISK ASSESSMENT APPROACHES FOR AMMONIA DISPERSION

QUALITATIVE RISK ASSESSMENT: AMMONIA HAZID STUDIES

A risk assessment must be conducted to address potential hazards arising from the use of ammonia as fuel, including risks to personnel on board, the environment and the ship's structural integrity. Emphasis should be given to hazards related to the vessel's physical design, layout, operation and maintenance, taking into account any reasonably foreseeable failures. The toxicity of ammonia and its potential release pose significant risks to the crew and the environment and must be thoroughly evaluated.

The scope of this assessment covers nearly every aspect of the vessel, focusing on how various systems interact with one another considering the data that is available. It will include:

- Ammonia storage and vapor/pressure-management system
- Venting and ventilation arrangements
- Engine room and machinery spaces
- Ammonia-consumption equipment
- Ammonia fuel supply and return system

A HAZID analysis is a useful tool for performing high-level risk assessments of specific systems. Hazard identification analysis takes place in a workshop setting including all stakeholders. ABS has used this approach in numerous risk assessment projects, both as a standalone analysis and to compare similar scenarios. Following the workshop, a brief review should be conducted with the participants. A flow diagram for the overall HAZID process is shown in Figure 1 below.

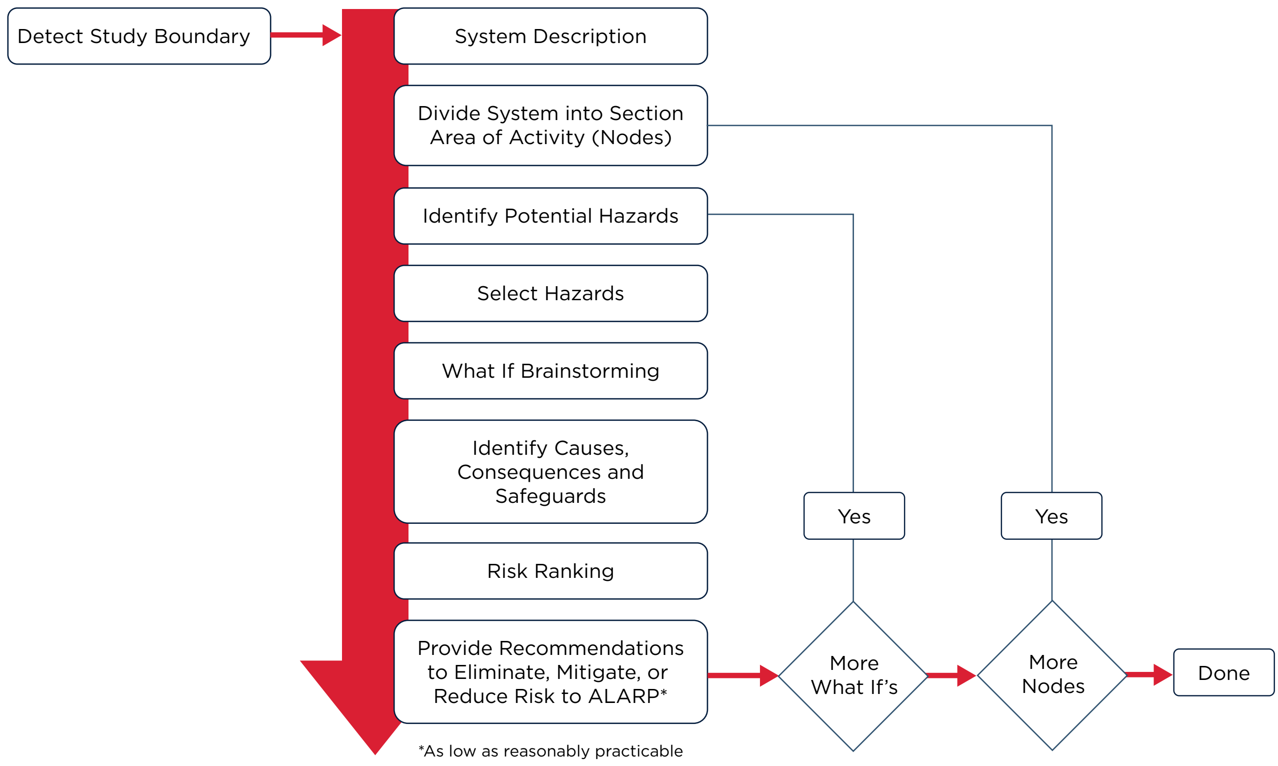


Figure 1: HAZID process.

In selected cases where a scenario leads to multiple impacts, such as environmental and personnel injury, the study documents an overall impact. The risk-ranking process includes:

- Consequence review: Identifying the most credible worst-case outcome for each scenario and placing it on the consequence axis.
- Likelihood review: Determining the frequency of the undesired outcome along the likelihood axis, considering the probability of failure for the preventive, detection and recovery safeguards designed to prevent it.
- Risk: Establishing the risk level for that specific hazard scenario based on the intersection of the likelihood and consequence ratings.
- Action: Using the risk ranking to assess whether existing controls and safeguards are adequate. If not, then additional safeguards/controls are identified or further review or analysis is performed to better understand the risk and potential mitigating measures and recorded as actions to be taken.

Prior HAZID studies demonstrated that the major concerns of using ammonia as marine fuel are related to its toxicity and potential for gas dispersion. To understand the corresponding risks and to determine additional safeguards for the prevention or mitigation of major hazards, further investigation is required.

Ammonia is a toxic, corrosive and flammable gas with a strong, characteristic odor. The odor threshold for ammonia is between 5 and 50 parts per million (ppm of air). While repeated exposure to ammonia does not typically lead to chronic health effects on the human body, exposure to small concentrations can cause severe irritation to the eyes, throat and respiratory pathways.

The HAZID studies identified preventive and mitigative safeguards, and recommendations for various ship types. Some are drawn from the IGF Code for methane as a marine fuel, but many are unique to ammonia and lie outside the IGF Code's existing provisions due to its inherent risks. It is important to note that not all safeguards and recommendations listed in HAZID registers will be applicable to all ship types. Some are practical and of immediate benefit, but others may require further investigation of their effectiveness. However, they are all listed for consideration and may help to inform prescriptive requirements and develop inherently safer designs and arrangements. Importantly, the additional safeguards and recommendations will contribute to further risk reduction.

While the use of ammonia as a marine fuel is new, the seaborne transportation of ammonia as cargo is not. Ammonia is also commonly used on board vessels as a refrigerant. All the necessary practices for the safe handling of ammonia on board, including operational and safety procedures, are well known in marine liquefied gas industries and accepted by crew and operators. However, because most of this experience is concentrated in a specific segment of the maritime industry, extending the use of ammonia as a fuel to a broader range of vessels will introduce new risks. Detailed training requirements will need to be in place for safe operation for a larger pool of mariners, and specific regulations will need to be developed to ensure safe adoption.

System/Area	Hazards	Causes
Bunkering	Ammonia vapor leak	• Material degradation • Connection leak • Joint leak • Operator error
	Liquid ammonia leak — hose failure/ loading arm	• Vessel movement • Mooring line failure • Extreme weather • A passing vessel generating a huge wave
Global Risk	Vessel collision leading to ammonia leak and fuel tank damage	• Pilot/human error • Port congestion/traffic density • Low visibility • Adverse weather
	Grounding leading to ammonia leak and fuel tank damage	• Pilot/human error • Adverse weather • Low visibility • Miscommunication/lack of information • Port congestion/traffic density
Fuel Storage	Ammonia vapor leak	• Manufacturing related defects on fuel storage piping and equipment • Over-pressurization of fuel storage tank • Dropped object impacting fuel storage area
	Liquid ammonia leak	• Grounding • Vessel collision • Fatigue crack in piping and equipment • Dome connection/valve leak • Dropped object impacting fuel storage area
Fuel preparation/ handling system	Ammonia vapor leak	• Connection leak • Flange/joint leak • Seal failure • Dropped object impacting fuel preparation/ handling area • Improper or lack of maintenance • Human error
	Liquid ammonia leak	• Dropped object impacting fuel preparation/ handling area • Pipe/joint/connection failure • Seal failure • Human error • Improper or lack of maintenance • Over-pressurization of fuel handling piping and equipment • Blocked flow in system

Table 2: Summary of hazards and causes from ammonia HAZID studies.

QUANTITATIVE RISK ASSESSMENT: CFD SIMULATION FOR AMMONIA ACCIDENTAL RELEASE

Computational fluid dynamics is widely recognized as a powerful tool for both qualitative and quantitative analyses, providing useful insights into underlying phenomena. In the context of ammonia safety, it can support in understanding the potential health and environmental risks of ammonia dispersion resulting from an accidental leakage incident. The accuracy and computational cost of such simulations strongly depend on the physicochemical models used and the detail of the geometrical description.

ABS performs CFD simulations of realistic ammonia leakage scenarios to quantify the extent of plume dispersion and track its evolution and positions over time. This leads to the identification of critical ammonia concentration levels for human safety and the results can be imported to other analytical tools. Simulations include realistic bunkering scenarios such as ship-to-ship, terminal-to-ship and truck-to-ship, as well as ammonia dispersion from the vessel due to a leakage incident in the engine room.

Purpose/Outcomes:

- Identify levels of exposure and affected areas
- Determine safety evacuation zones
- Improve design of facilities (e.g., ventilation)
- Predict plume response to a range of parameters (wind speed, direction, etc.)
- Support evaluation of emergency response planning
- Environmental impact evaluation

AMMONIA DISPERSION IN THE ENGINE ROOM

Computational fluid dynamics can be used to predict the behavior of an ammonia plume due to an accidental release in the engine room. Current research on engine room release could have a range of outcomes on ammonia-fueled vessel design, such as the arrangement of ventilation, the placement of sensors or the design of evacuation routes. Figure 2 illustrates the ammonia dispersion patterns in the engine room. The ventilation rate is set to a typical value of air changes per hour, but the ventilation and leakage direction are some of the study parameters. For demonstration, a mainly upward ventilation direction (i.e., from the lower decks to the higher decks) is assumed. The simulation results reveal that the release of ammonia perpendicular to the air flow will have less impact on the engine room space, while the its release against the air flow tends to have a broad impact by filling nearly all deck levels with significant ammonia concentrations. Both cases indicate that the ammonia concentration could reach 10 percent of the lower explosive limit (LEL), leading to a potential fire risk. High concentrations could be attained in areas with poor ventilation, such as corners or the space underneath the deck floors.

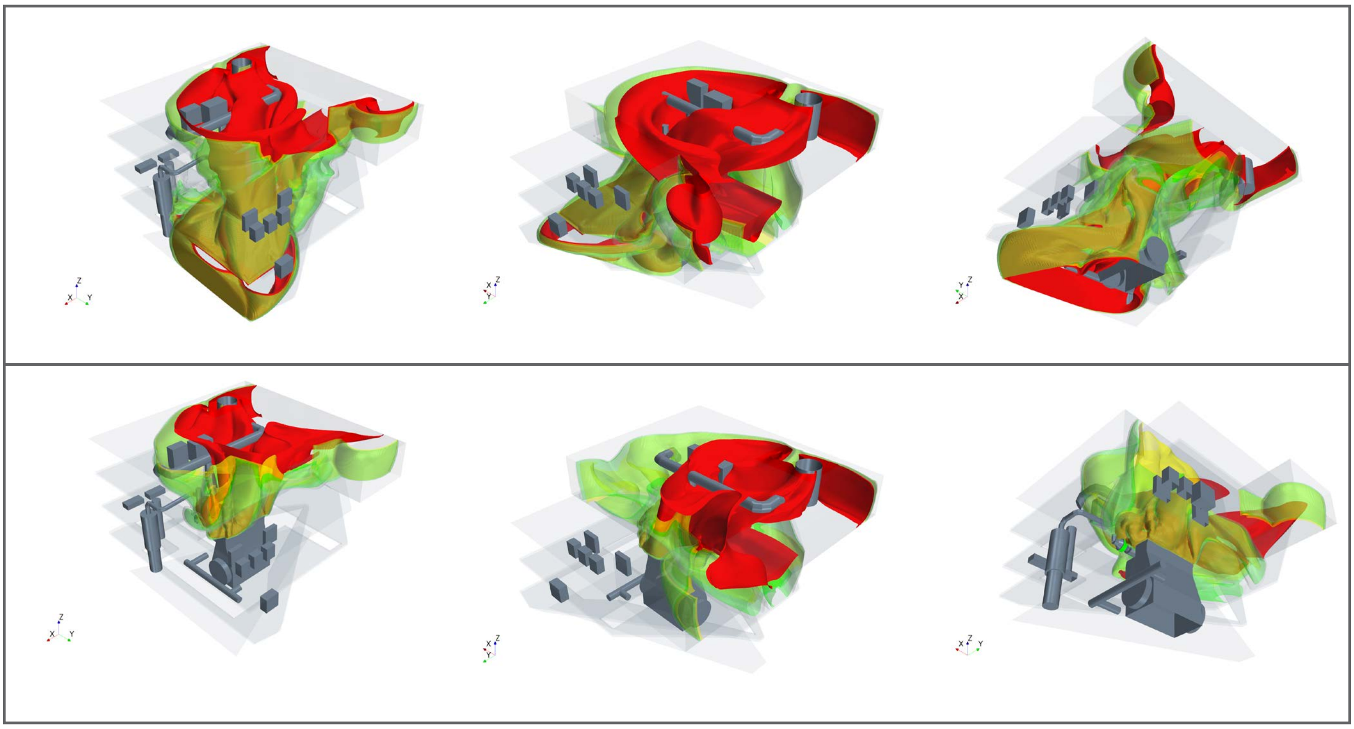


Figure 2: Ammonia dispersion patterns in the engine room (Gray: 30 ppm; Green: 160 ppm; Yellow: 1,000 ppm, Red: 15,000 ppm) with a leakage direction against the air flow (upper row) and a leakage direction perpendicular to the air flow (lower row).

AMMONIA DISPERSION DURING SHIP-TO-SHIP BUNKERING

Computational fluid dynamics simulations can be used to understand the possible environmental and health impacts of ammonia dispersion resulting from an accidental leakage during ship-to-ship bunkering.

To achieve realistic results, ABS considered real-life cases with actual vessel geometries. Figure 3 and Figure 4 display the bunkering of an ammonia-fueled containership vessel (AFCV) 15,000 twenty-food equivalent (TEU) from an ammonia bunker vessel (ABV), as well as the bunkering of an ammonia-fueled dual-fuel very large crude carrier (VLCC) ammonia fueled tanker vessel (AFTV) from an ABV respectively.

The dispersion of ammonia for the case of AFCV bunkering is demonstrated with air flowing from sea-to-port and port-to-sea at different time instances after the leakage starts.

SEA TO PORT IN BRIEF

Following the leakage incident, the bunkering station starts to fill up with ammonia. Thirty seconds after incident, ammonia has already dispersed in the surroundings, as shown in Figure 5. At 60 seconds, ammonia plumes have escaped the containers and have reached the port side. The transverse dispersion is significant only downstream, and only after the container region. However, at the 120-second mark, the dispersion scenery dramatically changes. In this case the dispersion is massive in all directions, with the ammonia plume covering almost half of the ABV deck and enveloping almost four containers upstream. Notably, the plume is no longer a single structure but breaks into multiple independent clusters.

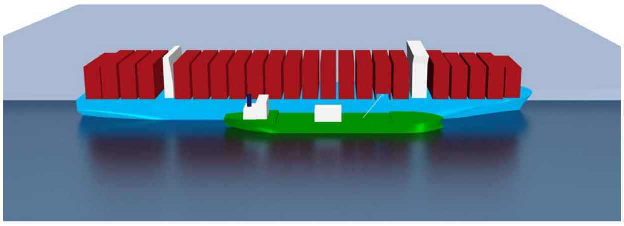


Figure 3. 3D CAD model of the ABV and the AFCV

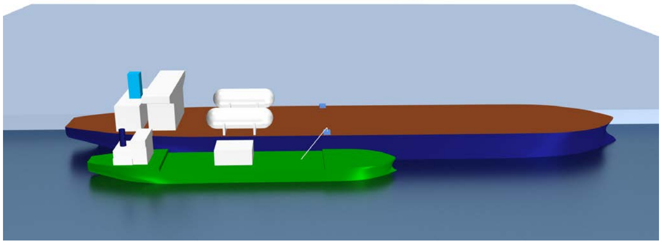


Figure 4: 3D CAD model of ABV and AFTV

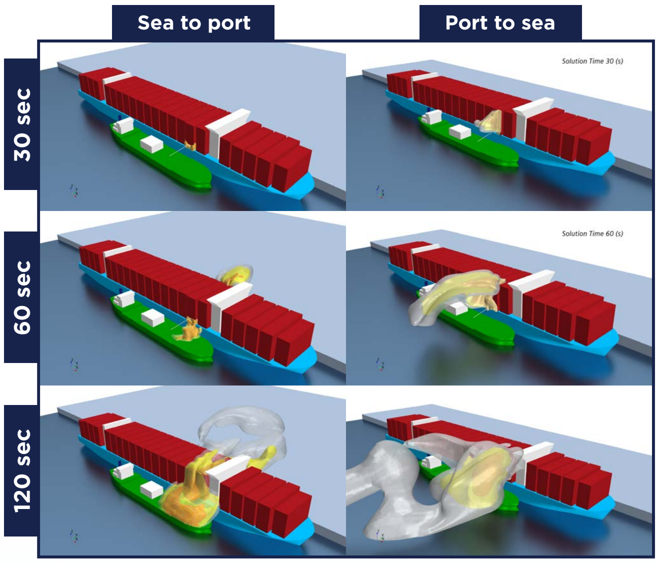


Figure 5: Gaseous ammonia dispersion at 30/60/120 sec after leakage starts for an ammonia fueled containership. Wind direction: sea to port (left), port to sea (right).

DISPERSION OF LIQUID AMMONIA

Ammonia SCC is a significant concern when using ammonia on board. Stress corrosion cracking occurs when carbon steel comes into contact with ammonia, potentially leading to cracks that penetrate the entire thickness of the metal despite appearing small on the surface. This poses a serious risk to the integrity of the ammonia supply system (storage tanks, auxiliary parts, etc.).

To mitigate this risk, ABS not only predicts the dispersion of gaseous ammonia under leakage incidents, but also the dispersion of liquid phase ammonia. This is simulated through the Eulerian Multiphase (EMP) model, with Figure 6 presenting the surfaces covered by liquid ammonia under a ship-to-ship bunkering leakage incident. In this scenario, wind significantly impacts the ammonia-covered area. The quantity of liquid ammonia on the receiving vessel's deck increases when the wind blows from the supply vessel to the receiving vessel, compared to when the wind blows in the opposite direction.

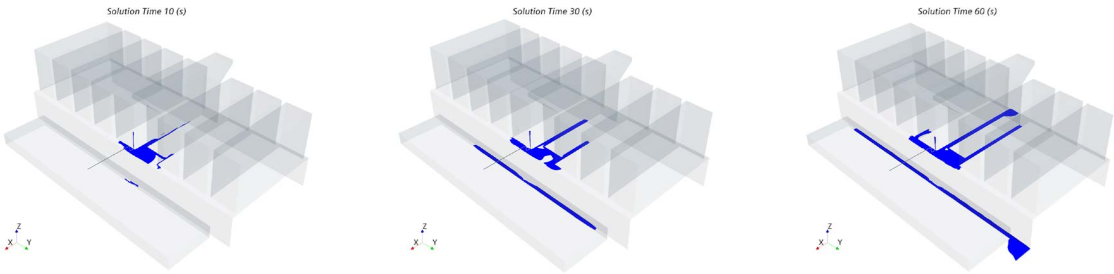


Figure 6: Dispersion of liquid ammonia at different time instances after the leakage starts.

TRUCK-TO-SHIP BUNKERING

Ammonia incidents can also occur during truck-to-ship bunkering, with the effects differing from other bunkering methods. Figure 7 illustrates the velocity flow field 60 seconds after the leakage incident occurs during the bunkering of a tugboat. In this scenario, the wind has minimal effect on ammonia dispersion because the nozzle is aimed horizontally at the middle of the tugboat and the jet speed is relatively low.

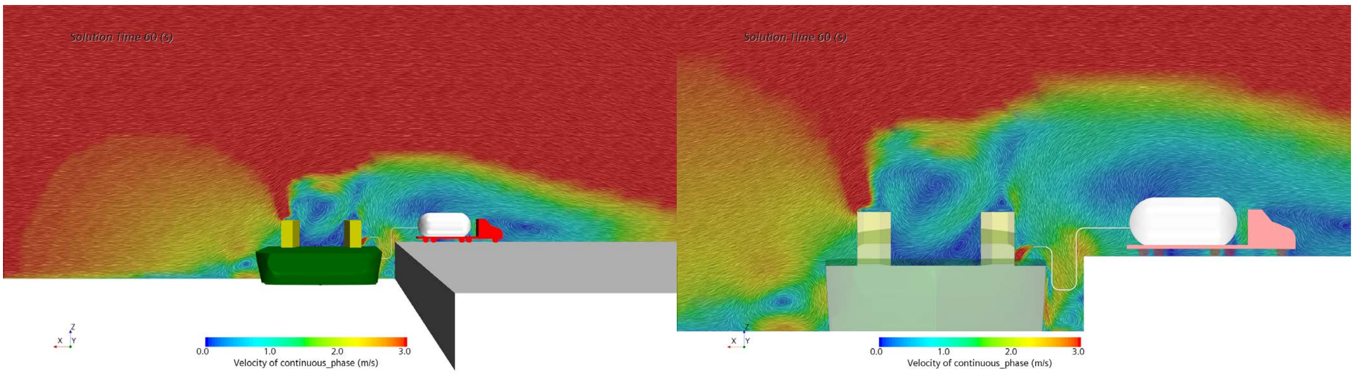


Figure 7: Dispersion of ammonia during a truck-to-ship leakage incident.

OPTIMIZED EMERGENCY RESPONSE PLAN AND REAL-TIME MONITORING

OPTIMIZED EMERGENCY RESPONSE PLAN USING PROBABILISTIC RISK ANALYSIS

Ammonia-fueled vessels present unique operational challenges due to the combination of the chemical's hazardous properties, human factors and emergency preparedness requirements. Typically, emergency response plans (ERPs) for ammonia-fueled vessels can be developed by building upon existing plans for oil and chemical spills, which provide a foundational framework for tiered response levels and multi-agency coordination. However, these plans must be adapted for the shipping industry to address ammonia's specific hazards and toxicity. Validation of these plans typically involves conducting live drills and exercises to test their effectiveness.

Simulation plays an important role in verifying and enhancing ERPs under diverse conditions that may not be practically tested in real-world environments. By creating safe and controlled scenarios, simulations enable the evaluation of emergency procedures, identification of potential risks and pinpointing of critical areas for improvement. These controlled environments provide valuable insights into crew behavior, response patterns and system interactions, ensuring that emergency plans remain robust, adaptive and well-structured to handle unforeseen challenges.

To enhance realism and provide a more objective evaluation of potential risk hot spots, ABS is developing advanced probabilistic risk analysis, which accounts for uncertainties in ammonia plume behavior, as well as human factors during emergency evacuation and response. By integrating CFD results with realistic leakage scenarios, these capabilities simulate how crew members respond under various hazards identified, enabling more effective development of evacuation procedures, enhanced safety measures and improved coordination among participants. This comprehensive approach ensures a more robust and informed emergency response strategy.

Below is an illustrative framework outlining the typical considerations and steps for simulating ERP scenarios, particularly focusing on ammonia dispersion. This serves as a reference to guide simulation planning and design, emphasizing essential factors to ensure effective risk evaluation and response optimization.

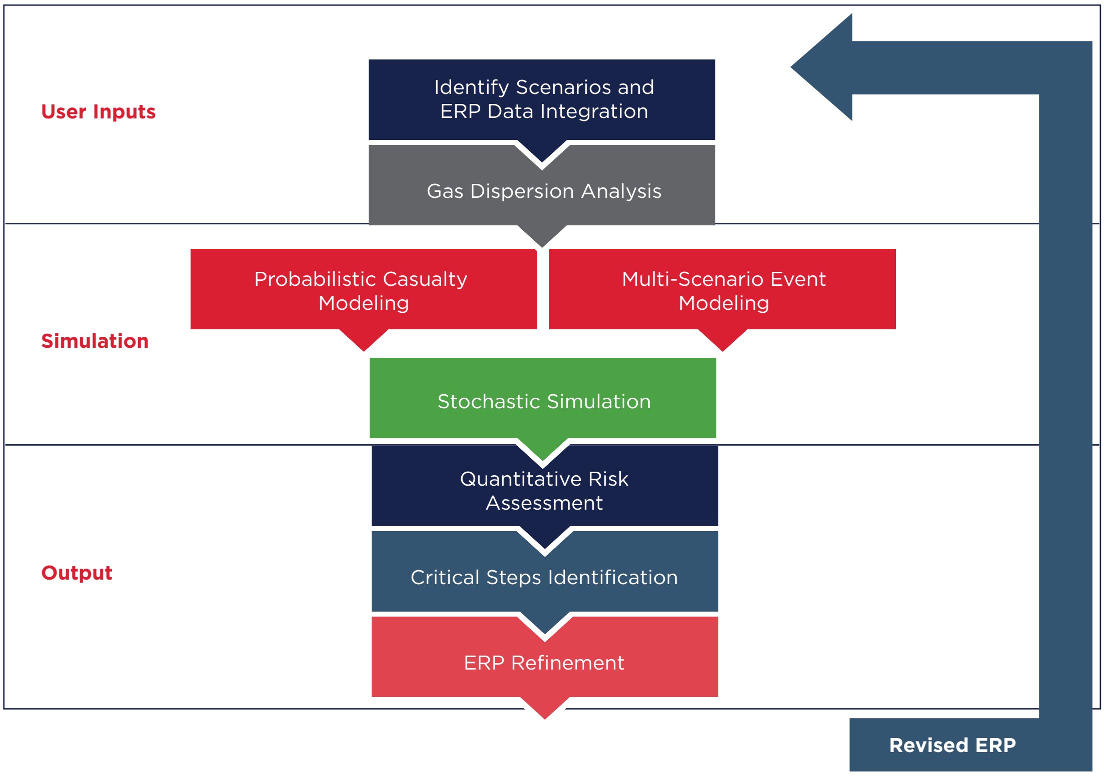


Figure 8: Approach for emergency response plan optimization.

In this approach, there are eight steps to be conducted for ERP optimization.

Step 1: ERP Data Integration
Import and digitize the existing ERP, including all relevant procedures, resource allocations and response protocols. This step involves converting paper-based plans into a digital format compatible with simulation software.

Step 2: Gas Dispersion Simulation
Conduct CFD simulations (or any other numerical method or measurements) to model the dispersion of ammonia leakage under various environmental conditions. This involves creating detailed 2D/3D models of the facility, incorporating factors such as wind patterns and release characteristics to predict the propagation and concentration of ammonia gases over time.

Step 3: Probabilistic Risk Modeling
Develop a probabilistic risk model to simulate human behavior during emergency scenarios. This step includes programming individual personnel with realistic attributes, decision-making processes, movement speed and evacuation patterns to accurately represent personnel responses to alarms and evacuation procedures.

Step 4: Multi-scenario Event Modeling
Create multi-scenario events that map out potential incident progressions and response actions. Each scenario is defined by adjusting key variables within the model, such as environmental factors, response plan changes, etc. This step is crucial for understanding how different decisions and events can impact the overall effectiveness of the ERP.

Step 5: Stochastic Simulation
Run multiple simulations of the integrated model using stochastic methods to account for variability in input parameters. This process involves executing numerous simulations with randomly sampled variables to generate a distribution of outcomes for each scenario.

Step 6: Quantitative Risk Assessment
Analyze simulation results to calculate the probability of casualties under various scenarios. This step is to process the outputs from stochastic simulation and identify the factors that most significantly contribute to potential loss of life.

Step 7: Critical Steps Identification
Identify the sequence of events or decisions that lead to the highest risk outcomes. By examining these key points in the emergency response process, organizations or operators can prioritize improvements to enhance the effectiveness of their ERPs.

Step 8: ERP Refinement
Refine the ERP based on insights from previous steps. This final step involves a systematic review of the ERP by incorporating data-driven recommendations. The purpose is to enhance evacuation routes and response procedures for reducing risk to personnel.

KEY TAKEAWAY

Probabilistic risk analysis helps in understanding how individual components (personnel) of a system interact and influence each other, leading to emergent behaviors at the system level. By simulating different scenarios, these simulations can predict how changes in individual behaviors or interactions can affect the overall system. These personnel are autonomous and can interact with other personnel and their environment, which is the space in which they operate. The results of the simulations are analyzed to understand the patterns and outcomes, helping to identify key factors that influence the system's behavior.

Purpose/Outcomes:

- Evacuation route crowd density evaluation
- Evacuation time evaluation
- Resource allocation statistics
- Comparison of different response plans
- Crew training

ACOUSTIC CAMERA TECHNOLOGY

Acoustic cameras are increasingly used on ships to detect dangerous gases and enhance safety responses in real time. They can both qualify and quantify leaks in the machinery space, on deck and within inaccessible areas. ABS collaborates with M2Intelligence, HD Hyundai Heavy Industries (HHI) and HD Korea Shipbuilding & Offshore Engineering (HD KSOE), among other technology vendors, to enhance the automatic safety shutdown and slowdown functionality of the machinery space of ammonia-fueled ships, especially when owners have requested unattended machine space operations extending beyond 24 hours . By visualizing sound waves and pinpointing the sources of gas emissions, acoustic cameras can help to quickly locate and assess potential hazards, reducing the risks to crew members and the environment. These cameras can operate in harsh marine environments, making them an essential tool for both routine maintenance and emergency response.

Purpose/Outcomes:

- **Enhanced safety:** Quickly detects gas leaks, preventing dangerous accumulations.
- **Non-invasive inspection:** Allows detection without physical contact, preserving ship integrity.
- **Real-time monitoring:** Provides instant visual feedback, speeding up response times.
- **Hard-to-reach area access:** Effectively identifies issues in difficult or dangerous locations.
- **Preventative maintenance:** Helps identify potential problems before they become critical.
- **Gas type agnostic:** Can detect a variety of gas leaks — regardless of gas type.

Acoustic cameras are specialized devices that combine microphone arrays and advanced software to visually map sound sources. They use multiple microphones arranged in a grid to detect sound waves and, through signal processing algorithms, create a visual representation of the sound's source location, intensity and frequency. This enables the user to pinpoint sound sources with high accuracy.

When integrated with gas detection sensors, such as those monitoring dangerous gases like ammonia, methane or carbon monoxide, the acoustic camera system can react in the following way:

- Detection of gas leaks: If a hazardous gas like ammonia is leaking, it can cause vibrations or create a sound that can be detected by the array of microphones. That detection and signal can be analyzed by the system integrator and create any type of soft alarm. This alarm could be an email notification, an API create/raise an alarm to any third-party system or raise physical alarms (i.e., light/sound) in the ER/ECR/CCR /Bridge.
- Visual feedback: The software processes the signals and generates a thermal or visual map, highlighting areas with unusual sound levels or vibrations, which could correlate to a leak.
- Alert mechanism: Upon detecting a sound indicative of a gas leak, the system triggers visual or audible alarms to notify operators. The display will show the precise location of the leak, helping to address the danger quickly.
- Real-time monitoring: The system continuously monitors the environment within the field of view (i.e., detection is not limited to a single point at the sensor's location), providing real-time feedback and updates to ensure any potential hazards are promptly addressed.

CONCLUSION

The maritime industry stands at a pivotal moment, trending toward decarbonization while still maintaining and enhancing operational safety and efficiency. The transition to cleaner fuels is not merely a technological shift – it demands a fundamental change in how the industry approaches vessel design, operation and risk management. As highlighted throughout this document, ammonia emerges as a promising candidate in the quest for sustainable shipping, offering a high-potential pathway toward a carbon-free future. However, its inherent toxicity necessitates a meticulous and proactive strategy for successful implementation.

ABS' insight provides the critical framework for navigating this complex transition. ABS recognizes that safe ammonia integration requires a holistic approach encompassing three interconnected pillars. First, proactive regulatory engagement is paramount. By actively monitoring and anticipating evolving standards from bodies like the IMO and EU, ABS empowers shipowners to make informed decisions, helping to avoid costly retrofits or potential compliance issues. This forward-thinking approach minimizes disruptions and maximizes the return on investment in ammonia-powered vessels.

Secondly, a robust multifaceted safety framework is essential. ABS' approach combines a qualitative risk assessment through HAZID studies with quantitative analysis using advanced CFD modeling. Hazard identification meticulously identifies potential hazards throughout the ammonia life cycle on board, informing targeted mitigation strategies. Computational fluid dynamics simulations using modern tools to quantitatively assess the risks associated simulations then quantify the potential impact of ammonia releases, enabling optimized design of ventilation, gas detection systems and emergency response protocols. This combined approach ensures a comprehensive understanding and mitigation of risks.

Finally, real-time monitoring and optimized emergency response complete the safety equation. By integrating cutting-edge technologies like acoustic cameras for early leak detection, the industry can minimize potential exposure and prevent escalation. Furthermore, ABS' utilization of probabilistic risk analysis allows for the simulation and optimization of evacuation procedures, enhancing onboard safety during emergencies. This proactive approach moves beyond reactive measures, fostering a culture of preparedness and resilience.

By systematically addressing these three interconnected pillars, the maritime industry can confidently embrace ammonia as a cleaner fuel source. This comprehensive strategy allows for not only environmental sustainability, aligning with global decarbonization goals, but also the safe, reliable and efficient operation of ammonia-fueled vessels. This marks a significant step toward a future where sustainability and safety are not competing priorities, but rather integral components of a thriving maritime sector.

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