Formal Safety Assessment of Ammonia Bunkering Process

Table of Contents

List of Figures

List of Tables

1. Introduction

1.1 Background

The world maritime industry has contributed immensely towards global trade, and its reliance on fossil fuel poses a significant environmental challenge. IMO's Marine Environment Protection Committee (MEPC), set out a vision to reduce GHG emissions from international shipping [1]. Numerous world shipping companies are shifting their focus from ships running on fossil fuels to green energy solutions such as LNG, ammonia (NH_3), wind propulsion, electric propulsion, etc. Ammonia is the most promising alternative zero-carbon fuel to mitigate climate change, as it produces only nitrogen and water as combustion by-products. However, the usage of ammonia (NH_3) as a fuel poses various design and operational challenges such as dispersion, fire, explosion, toxicity due to leakage, high pressure storage and structural integrity of components.

The most significant challenge is toxicity of ammonia and its severe health effects, including respiratory issues, eye irritation, and skin burns, with high concentrations potentially being fatal [2]. These effects spark the ultimate need for studying the hazards related to its usage, transport and storage onboard marine vessels. Further a clear and concise risk analysis followed by implementation of the risk control option is a structured approach towards a definite Formal Safety Assessment.

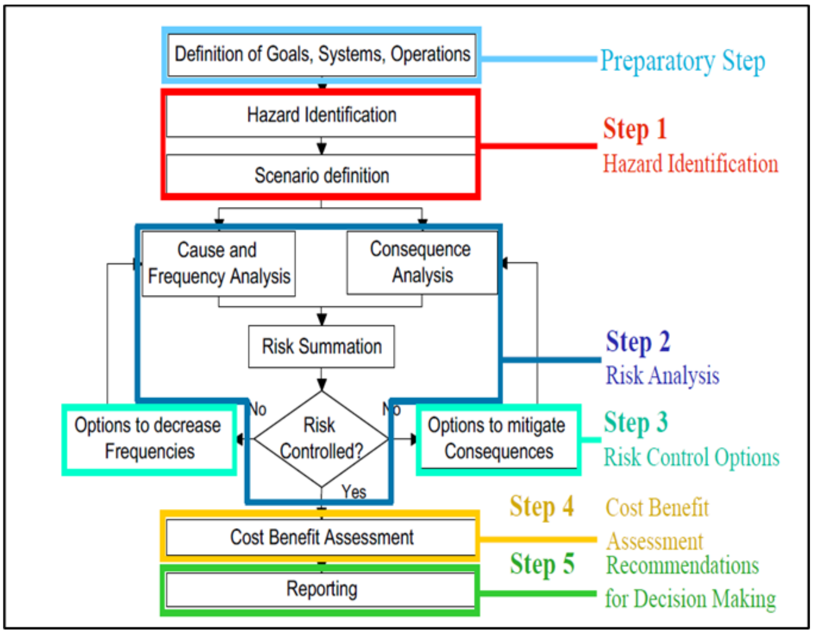

Figure 1. Steps Involved in Formal Safety Assessment (IACS, MSC 75-2002)

Formal Safety Assessment (FSA) is a structured methodology to enhance maritime safety and environment protection through systematic risk analysis and cost-benefit assessment of risk control measures [3]. In FSA, Event Tree Analysis (ETA) and cost-benefit assessment play a vital role in successful risk analysis and assessment of Risk Control Options (RCOs). Figure 1 illustrates a flow chart on steps involved in FSA procedure.

1.2 Objectives

The most critical aspect of using ammonia as marine fuel is its storage and transport onboard. Ammonia exists as a gas at room temperature, but can be liquefied under high pressure, which simplifies its handling, storage, and transportation. Due to the toxic nature of NH_3, this report focuses on FSA for a model ship, as outlined in Table 1. Here we will be considering the scenario of the Ammonia Bunkering from shore to ship and carry out detailed safety assessment for risk and hazards involved, using a HAZID table and carrying out a cost-benefit analysis with event tree analysis.

Description	Details
Name	M/V Fortescue Green Pioneer
Flag State	Singapore
Type	Offshore Supply Ship (OSS)
Fuel	Dual Fuel (Ammonia & Diesel)
Dimensions	LOA: 75m, Beam: 16.4m
Crew Size	Maximum 25 Crews
Remarks	The world's first dual-fuel configuration vessel used to demonstrate the use of ammonia as sustainable marine fuel.

Table 1. Ship's Specification

The objective is to conduct risk analysis and hazards identification during the ammonia bunkering process using HAZID. The two highest-risk scenarios identified through HAZID will be further evaluated via Event Tree Analysis, which will be used to conduct a cost-benefit analysis of three proposed Risk Control Options. The findings will support practical recommendations to enhance safety and operational efficiency.

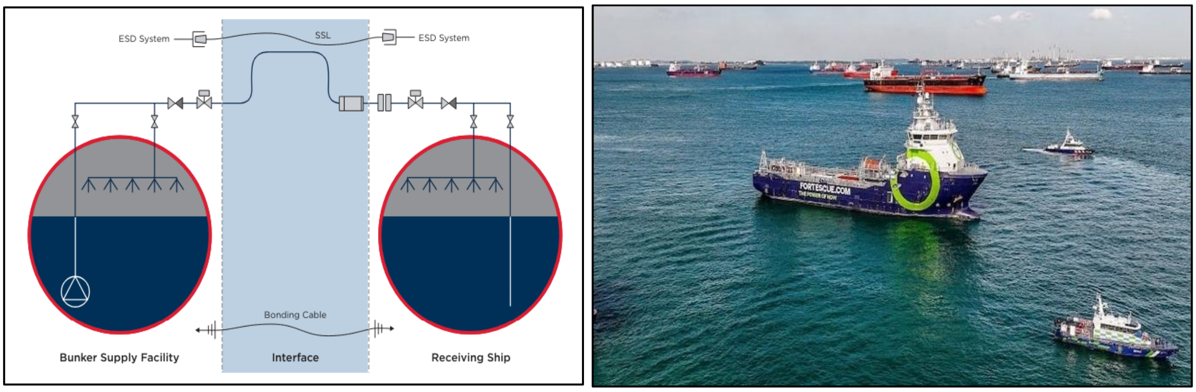

Figure 2. Shore to Ammonia Bunkering Process [4], MV Fortescue Green Pioneer [5]

2. Hazard Identification & Risk Assessment

2.1. Hazard Identification

The HAZID process systematically identifies potential hazards, evaluates their consequence, and proposes preventive or mitigative measures. For this study, the ammonia bunkering process was analysed at the subsystem level (e.g., transfer lines, emergency shutdown systems, mooring equipment).

HAZID analysis begins by identifying hazards that may pose risks to people, assets, or the environment. It then determines possible causes and analyses the consequences based on their impact. Each hazard is ranked by evaluating the likelihood and severity, often using a risk matrix. Existing controls are reviewed to assess their effectiveness. If controls are inadequate, additional risk-reduction measures are recommended. This structured approach helps prioritize hazards and ensures appropriate safeguards are in place. During the HAZID of the bunkering process, the following hazards had been identified:

- Hose Failure
- Leak at Connection points/Coupling
- Overpressure in Transfer System
- Venting Failure
- Improper Hose Handling
- Mooring Failure
- Emergency Shutdown System (ESD) Failure
- Communication Failure

2.2. Risk Assessment

The next step of FSA is conducting risk assessment by means of Failure Modes, Effects and Criticality Analysis (FMECA). The task of the FMECA is the detection of hazards and a ranking of these hazards in order of their severity and risk. Subsequently two main accidental events as risk contributors are investigated during the quantitative analysis.

The process is to describe steps and tasks required for ammonia bunkering activity and list the consequences if a task or system fails. All hazards are evaluated with respect to frequency of occurrence and the severity of consequences based on EMSA guidelines [6] and ABS framework [4], as shown in Appendix I.

Detailed HAZID and risk assessment for ammonia bunkering activities described above are placed in Appendix II. Among the events, the following high-risk events have been selected:

1. Ammonia Spillage due to Hose Failure
2. Overpressure in Transfer System

3. Event Tree Analysis

This section conducts a quantitative risk assessment of two critical ammonia bunkering scenarios: spillage due to hose failure and overpressure due to remote control valve (RCV) failure. The analysis begins with the initiating event and systematically evaluates the barriers designed to prevent further escalation. The barriers form a layered defence against catastrophic outcomes. Each barrier's success or failure determines the pathway through the event tree, ultimately describing the severity of consequences. Building on the framework the likelihood of each pathway and its associated asset, environment, and human impacts will be quantified.

3.1.1 Initiating Event

During ammonia bunkering from port to ship, the flexible hose is used to transfer ammonia between the storage tank and the receiving vessel as shown in Figure 3. Failure in the hose may happen due to material fatigue, poor connection, high pressure, or accidental impact. This failure can lead to ammonia spillage. If the spill is not quickly detected or stopped, the leaked ammonia may turn into gas and create a toxic cloud. The impact of this event can increase if safety systems such as leak detection, emergency shutdown, or water curtains do not work properly. Possible consequences include harm to human health, damage to equipment, and pollution of the surrounding environment. The outcome also depends on factors such as how effective the safety barriers are and the weather conditions at the time of the incident.

3.1 Event Tree for Spillage due to Hose Failure

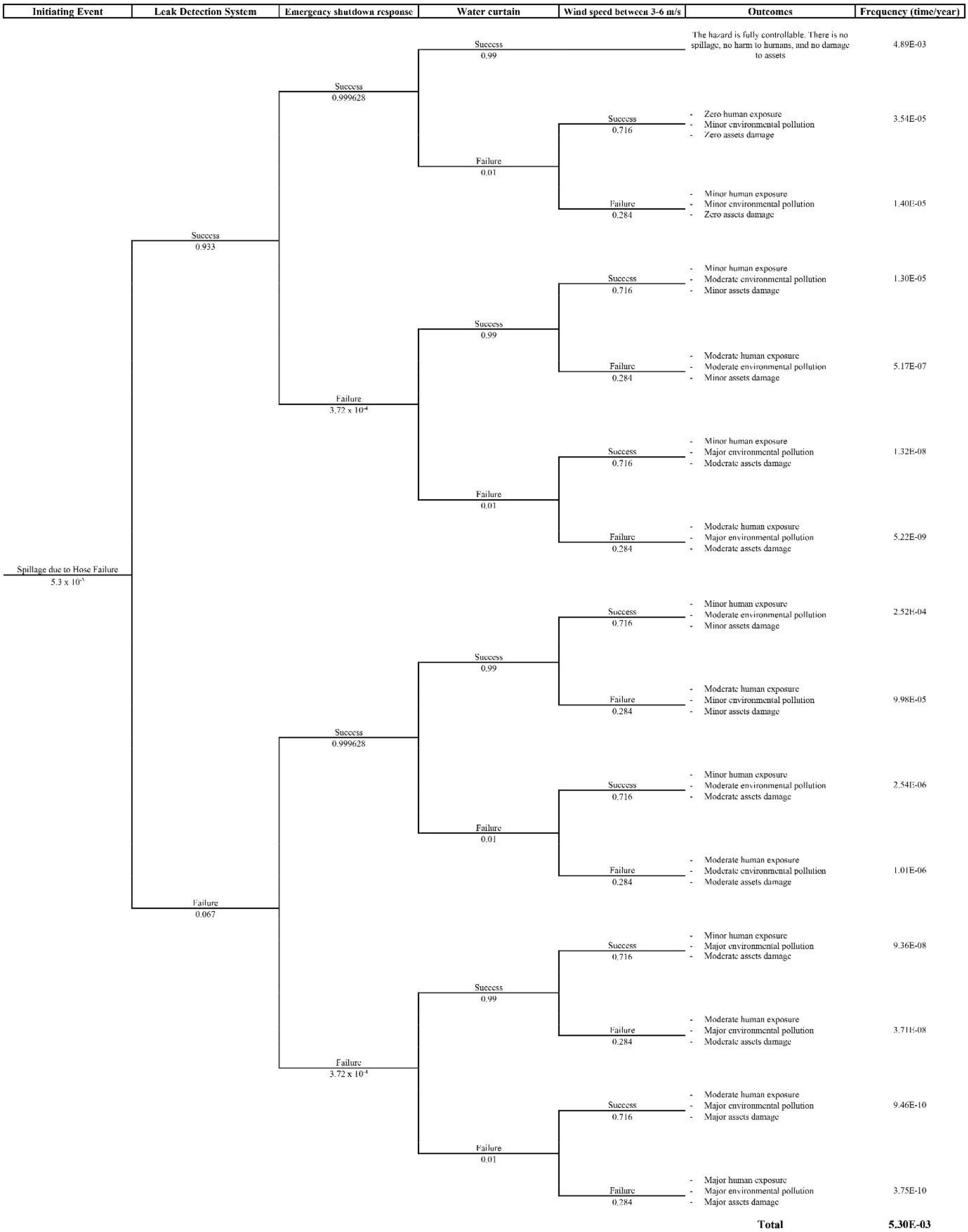

Figure 3. Spillage due to Hose Failure Event Tree Analysis

3.1.2 Barriers and Data Sources

a) Barrier 1: Leak Detection System

The first barrier is the leak detection system, which continuously monitors for ammonia leaks during bunkering using fixed gas detectors and alarms. It provides early warning and triggers emergency shutdown responses to limit ammonia release. According to the study, the Probability of Failure on Demand (PFD) is 0.067 [7]. This value was calculated using the following formula:

$$\mathrm{PFD(GA)} = 1 - \big(1 - \mathrm{PFD(G)}\big) \times \big(1 - \mathrm{PFD(A)}\big) \tag{1}$$

, where PFD(GA) is the combined failure probability of the gas detection and alarm system. When the system works correctly, it enables a quick response that can limit the spread of toxic gas. Failure of this barrier may delay operator response, increasing the severity of the consequences.

b) Barrier 2: Emergency Shutdown Response

The second barrier is the Emergency Shutdown (ESD) response, which is activated when a leak is detected or suspected during ammonia bunkering. This system includes automatic valve closures, pump shutdown, and operator coordination to quickly isolate the transfer line. Its goal is to stop ammonia flow and prevent further spillage. The PFD is 3.72×10^{-4} which obtained from Fault Tree Analysis (FTA) method [8]. When successful, the ESD response limits ammonia release and reduces the risk to people, the environment, and equipment. If it fails, the transfer continues, increasing exposure and damage.

c) Barrier 3: Water Curtain Activation

The water curtain serves as a mitigation system during ammonia release. When activated, it discharges high-pressure water in a curtain-like formation to contain and dilute airborne ammonia. This helps reduce the gas concentration by absorbing, diluting and dispersing both toxic and flammable vapour clouds [9]. For this assessment, the water curtain is assumed to have a success probability of 0.99 and a failure probability of 0.01. If it fails to activate, ammonia dispersion remains uncontrolled, increasing the amount of toxic vapour clouds

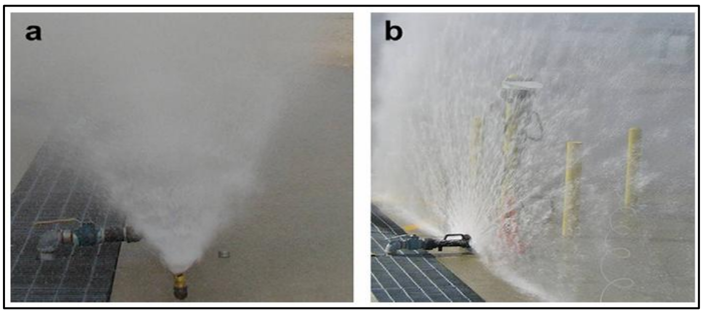

Figure 4. Water curtain example: Full cone spray nozzle (a), Flat dan spray nozzle (b) [10]

d) Barrier 4: Wind Speed (Weather Condition)

Wind speed plays an important role in reducing the concentration and spread of ammonia during a release. According to Yang M (2024), a moderate wind speed between 3–6 m/s can significantly disperse ammonia, reducing the risk of exposure [11].

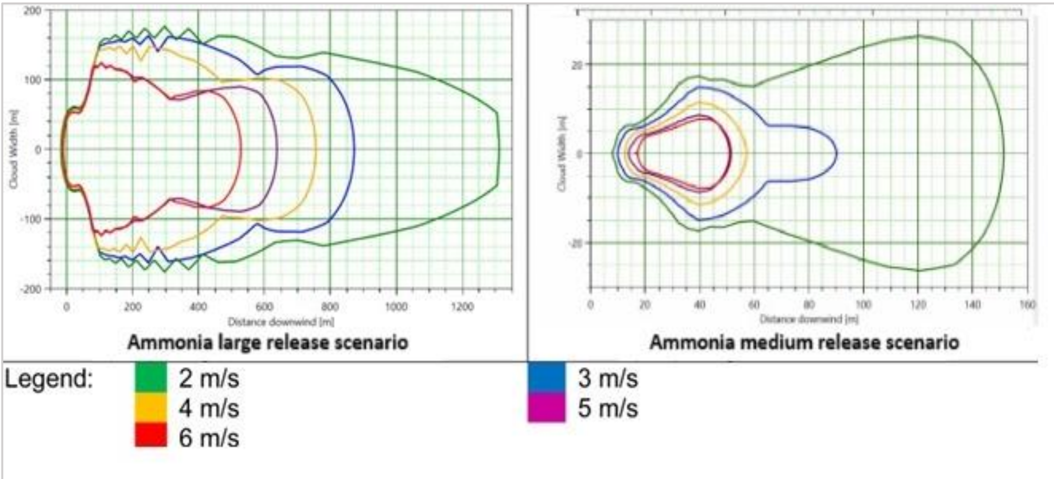

Figure 5. The effect of wind speed on ammonia release scenario [11]

For this assessment, a meteorological data [12] is employed based on Edinburgh Port conditions, indicates that wind speeds within this range occur approximately 71.6% of the time during typical bunkering periods. When this condition is met, the released gas is more likely to be diluted and carried away from critical areas. However, weaker winds may cause ammonia to accumulate near the source or populated areas, leading to increased human exposure.

3.1.3 Frequency and Consequence Analysis

The base frequency of hose failure during ammonia bunkering is estimated at 5.3×10^{-3} per year, is decided based on the DNV report [13]. This frequency represents a credible failure rate under typical operational conditions involving flexible transfer hoses. Consequences are evaluated using fatality rates and exposure levels from EMSA study with previous ammonia-related port incidents [14]. The extent of release and potential harm is further influenced by the success or failure of safety barriers such as leak detection systems, emergency shutdown response, water curtain activation, and prevailing wind conditions during bunkering.

3.2 Overpressure Due to RCV Failure

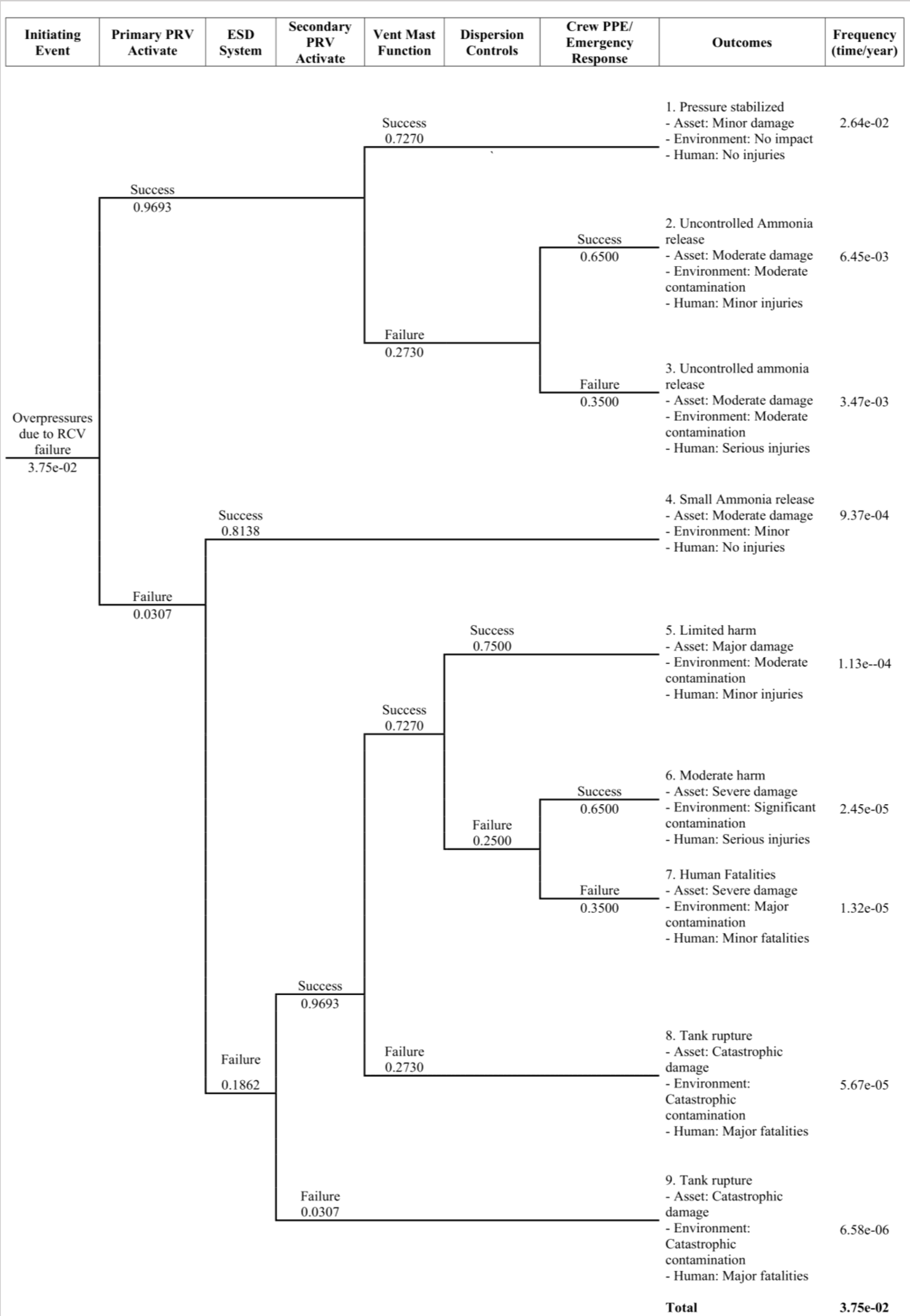

Figure 6. Overpressure due to RCV failure Event Tree Analysis

3.2.1 Initiating Event

During bunkering operations, the Remote-Control Valve (RCV) regulates the ammonia flow between the bunkering facility and the receiving vessel. A failure in the RCV caused by mechanical wear, hydraulic lock, or software errors – can initiate overpressure in piping system and ammonia storage tanks. Without intervention from safety barriers, this overpressure could escalate to catastrophic tank or pipe rupture. The probability of success and failure for each level was calculated using OREDA 2002 handbook.

3.2.2 Barriers and Data Sources

a) Barrier 1: Primary PRV Activation

As shown in Figure 6, the first barrier is the Primary Pressure Relief Valve (PRV), which activates when pressure exceeds the Maximum Allowable Working Pressure (MAWP) by 10% [15]. The valve releases excessive ammonia through a vent mast, ensuring concentration below 300 ppm at the discharge point [16]. In 96.93% of cases, the primary PRV successfully stabilizes pressure, resulting in minor asset damage and no environmental or human harm when vent mast functions. However, if the PRV fails, pressure continues to rise, necessitating intervention by subsequent safety barriers.

b) Barrier 2: Emergency Shutdown (ESD) System Activation

If the primary PRV fails, the ESD system engages. According to DNV guidelines, a typical ESD system integrates gas detectors, ESD valves, and pump shutdown mechanism to isolate the affected section [13]. The equipment is located on both ships and bunkering facilities. With a success rate of 81.38 %, the ESD system limits release to small quantities of ammonia, causing moderate asset damage, localised environmental contamination, and no human injuries. However, a failure rate of 18.61% allows pressure to continue rising toward critical thresholds.

c) Barrier 3: Secondary PRV Activation

The redundant PRV, required by IMO, works when both primary PRV and ESD have failed, activating at 5% above the primary PRV's setpoint [17]. By this point, the system has been under stress for an extended period, leading to higher ammonia ppm and increased pressure. A 3.06% failure rate probability escalates overpressure in the tank, resulting tank rupture, catastrophic environment contamination, and significant fatalities.

d) Barrier 4: Vent Mast functionality

A vent mast is a passive discharge pathway during PRVs operation. As per IMO guidelines, it is designed to release ammonia at a minimum height of 6 meters [16]. The vent mast functionality succeeds in 72.7% of cases. However, in 27.3% of cases, failures occur due to blockages caused by debris, corrosion, and design flaws. The failures can result in catastrophic consequences, including tank rupture, air and ocean contamination, and significant human fatalities.

e) Barrier 5: Dispersion Controls

Ammonia discharged through the secondary PRV has higher concentrations (ppm) and pressures compared to releases from the primary PRV. Dispersion controls are therefore positioned as a critical barrier. A typical dispersion system, such as an ammonia-catching system, minimizes the toxic impact of vented ammonia by reducing concentrations up to 30ppm [2]. With 75% success rate, it can prevent further harms, resulting in major damage in assets, moderate contamination, and minor injuries. However, if dispersion controls fail, a toxic cloud may form, with outcomes determined by the crew's response and mitigation actions.

f) Barrier 6: Crew PPE/Emergency Response

The final barrier relies on crew adherence to emergency protocols, including the proper use of personal protective equipment (PPE) and evacuation from hazardous zones. According to guidelines, crew must evacuate the bunker station and vent mast area within 60 seconds [18]. This rapid response is critical, as ammonia vapour can cause severe health effects. With a 65% success rate, this barrier can prevent major fatalities despite severe damage to assets and local contamination.

3.2.3 Frequency and Consequence Analysis

For data validation and assumptions, the base frequency of RCV failure is estimated at 3.75×10^{-2} per year, as derived from the IOGP hydrocarbon release database (1991-2015) and supported by relevant studies [19, 20] as well as malfunction of PRVs, ESD and vent mast failure. Human factors, such as crew response probabilities reflect training effectiveness in cargo ship incidents [14]. Additionally, fatality rates are derived from [14], and historical ammonia incidents [21].

4. Risk Control Options (RCOs)

The aim of the Risk Control Options (RCOs) is reducing the frequency of failures through better design, procedures, organizational polices, training, etc and mitigating the effects of failure to prevent accidents. They also enhance the circumstances in which the failure may occur and reduces the consequences associated with the accidents. These may or may not have cost implication on the project and hence implementing the right RCOs play a vital role in risk analysis and safety assessment process. The purpose is to identify and compare benefits and costs associated with the implementation of each RCO. The RCOs implemented after the risk assessment are as follows

4.1 VR Simulation for Crew Training

Recent studies have revealed that the safety assessment of ammonia bunkering and accident are related to ammonia leakage [20, 21]. Also, the accident analysis of burns occur due to leakage of anhydrous ammonia in refrigeration plant [22]. A Canadian government report documents the ammonia leak incidents in British Columbia between 2007 and 2017, with 14 casualties [2]. Considering the accidents, injuries and high toxicity of ammonia, additional crew training requirements and emergency response planning becomes essential. Crew members need extensive training to handle ammonia safely and respond to potential emergencies.

Virtual reality (VR) is a technology that creates a simulated environment and help users experience the actual scenario by using VR headsets. The VR training simulations improve knowledge retention and increase user engagement, enable situational awareness and improve understanding of training procedures and effective learning occurs when the body senses are stimulated, particularly the visual one and its proficiency in safely replicating hazardous situations [23]. Various studies have been conducted to state the effectiveness of VR simulation towards crew training in fields like cabin crew training, pilot training, maritime navigation, and health care of workers. Also, the potential of new simulation technologies to enhance safety and security education in the maritime industry was introduced [24]. This revealed the significant improvements in trainees' skills and confidence in handling real-life maritime emergencies.

Figure 7. Benefits of VR Simulation in training

Thus, with the available literature and research in the field of VR, there are readily available companies like Force Technologies, VR Marines, DigiTech, VR Simulations etc. have pioneered the design and supply of user-based VR simulation training system.

4.2 Reliability-Centred Maintenance (RCM): ESD System Optimisation

RCM analyses ESD systems to avoid major failures during process operations through strategic material selection and system configuration. The optimisation method integrates RCM principles with a multi-objective optimisation algorithm, NSGA-II (Non-dominated Sorting Genetic Algorithm II), to balance reliability and cost. The reliability analysis was conducted using failure data from the OREDA database [25], focusing on calculating the Probability of Failure on Demand (PFD). Additionally, the cost analysis incorporated various factors including initial equipment costs, replacement costs based on Mean Time to Failure (MTTF), proof test costs (labour and frequency), and estimated production losses during testing.

a) Upgrading the quality of sensor on ESD system

The shutdown system uses the pressure safety indicators (PSI), which is a pressure measuring device to display or alert when the pressure exceeds a specified value. It is generally used to make personnel aware of abnormal pressure in the system. However, it does not have a direct duty to order the system to stop. Thus, a failed PSI unable to display or alert, leads to the delayed shutdown. For this reason, this study proposes pressure safety element (PSE). It is a critical safety sensor type pressure measuring device designed specifically to work with a safety instrumented system. When overpressure occurs, it sends a signal to the Logic Unit to automatically shut down the system.

b) Designing the 1oo2 control logic unit (CLU) architecture

Upgrading the logic control unit structure from a 1oo1 (single controller) to a 1oo2 (dual controller with redundancy). When a pressure safety element (PSE) detects a hazardous condition (e.g., ammonia leak), the signal is sent simultaneously to both logic units which two logic controllers can independently process the signal and issue the shutdown command to the final element. Moreover, the existence of a spare part improves reliability because when one part is non-functional, another can be replaced immediately, reducing repair time (MTTF).

c) Reducing Proof Test Interval on Reliability

It can enhance the overall reliability of the Emergency Shutdown (ESD) system by lowering the PFD. By decreasing the interval frequent inspections, it allows earlier detection and correction of latent failures that may otherwise remain unnoticed. This study set the test interval target as 1 year/time for inspection [26]. However, it can optimise to suitable interval by collecting and analysing data further (Data-driven maintenance concept)

4.3 AI-Driven Predictive Maintenance

This RCO integrates advanced technologies to enhance the reliability of PRVs and systems during ammonia bunkering. Below is a detailed breakdown of the system, supported by industry standards and academic research.

a) IoT Sensors installations

Conventional bunkering systems are only equipped with analogue thermometer and pressure sensor on bunker manifold, and sensors are placed in downstream systems such as bunker storage tanks. The sensors below are installed directly on PRVs, vent mast, and transfer lines, enabling real-time valve health monitoring and detection of early signs of failure [27]:

- Pressure sensors: Track differential pressure across valves to detect abnormal pressure buildup
- Temperature sensors: Identify overheating due to friction or seal degradation
- Ultrasonic thickness gauges: Measure corrosion levels in valve bodies and piping
- Valve position sensors: Confirm open/close status and detect sticking.

b) Machine Learning (ML) Model

The ML model studies historical and real-time data and predicts valve failure. The model integrates two data: historical valve performance (failure logs, maintenance records) and real-time data from IoT sensors. Supervised learning models then correlate sensor data with failure events (e.g., valve sticking at 10 bar pressure and 10°C). At the same time, anomaly detection algorithms identify deviations from typical operational patterns, such as sudden pressure increases or unusually fast corrosion rates.

c) Integration with Bayesian Network (BN) Framework

The integration of Bayesian Network (BN) framework enables dynamic risk assessment by updating failure probabilities in real time using sensor data. The BN structure consists of nodes representing variables (e.g., RPV health, corrosion rate, valve position) and edges defining probabilistic dependencies between them (e.g., corrosion → PRV failure). This model starts with baseline failure probabilities derived from historical data.

As IoT sensors detect new conditions (e.g., 3% increase in corrosion level), the BN refines its Conditional Probability Tables (CPTs). For example, corrosion risk automatically adjusts the PRV failure probability from 1% to 10%, reflecting the system's degraded states. This real-time adaptability ensures risk assessment remains aligned with current operational conditions, rather than relying on static historical averages.

5. Risk Level and Cost-Benefit Assessment

This section quantifies reduced failure rates and conducts cost-benefit analysis after implementing three RCOs discussed in Section 4. Cost Benefit Analysis for RCOs will be synthesised in Section 5.4.

5.1 VR Simulation for Crew Training

5.1.1 Failure Rate Reduction

VR training simulation enables effective learning by immersing trainees in realistic scenarios that stimulate multiple senses, making it possible to safely replicate hazardous situations [7]. Recent studies reported that the VR training can be effective in reduction in of human based error and thus enhancing the crew response during emergency by 70 - 80% [28, 29]. With the reference to the available sources and data, the risk reduction by the VR crew training system is assumed to be minimum 80%. The change of probability after implementation of crew training will directly impact on the crew response time and decision-making in the Event tree 2 (Figure 6), overpressure due to the RCV failure.

The revised failure rate after this RCO is reduced from 0.35 to 0.07 as shown:

$$\begin{aligned} P_{Crew\ fail\ (revised)} &= P_{Crew\ fail\ (original)} \times (1 - Reduction\ Rate) \\ &= 0.35 \times (1 - 0.80) = 0.07 \end{aligned} \tag{2}$$

5.1.2 Initial and Operating Costs

a) Initial Costs

Component	Cost	Rationale (Assumption)
System Design	$50,000	Design and customisation of the VR training program to match specific requirements of bunkering operation
Hardware	$30,000	Ouftitting10 crews in charge of bunkering process with individual VR setups ($3,000 each)
Software and Console	$40,000	VR training software licenses, setup of a control console
Installation & Training	$30,000	Physical setup of hardware, software installation, and initial user training
Total Initial Cost	$ 150,000	

Table 2. Initial cost for VR crew training

b) Annual Operational Costs

Component	Cost	Rationale (Assumption)
Maintenance and upgrade	$5,000	System maintenance and upgrades, calibration

Table 3. Operational cost for VR crew training

5.2 Reliability-Centred Maintenance (RCM): ESD System Optimisation

5.2.1 Failure Rate Reduction

The emergency shutdown (ESD) response barrier has a failure rate as 0.000372 (Event tree 1, Figure 3). The RCO's implementation by materials' optimisation can achieve the 81% failure reduction [26], leading the ESD's failure rate decreases from 0.000372 to 0.00007 and increases the success rate from 0.999628 to 0.99993 as following equations:

For the spillage due to hose failure rate:

$$P_{ESD,\,failure\,rate\,(revised)} = 0.000372 \times (1 - 0.81) = 0.00007 \tag{3}$$

This RCO also affects the second barrier in Event Tree 2 (Figure 6), revising failure rate as:

$$P_{ESD,\,failure\,rate\,(revised)} = 0.1862 \times (1 - 0.81) = 0.0354 \tag{4}$$

5.2.2 Initial and Operating Costs

a) Initial Costs

Component	Cost	Rationale (Assumption)
Pressure safety element	\$ 5,000	5 points \$1,000 each, including devices and installation cost
Control logic unit	\$ 7,500	5 points \$1,500 each, including devices and installation cost
Total Initial Cost	\$ 12,500	

Table 4. Initial cost for ESD system optimisation

b) Annual Operational Costs

Component	Cost	Rationale (Assumption)
Maintenance and inspection cost	\$10,000	Calibration devices, labour costs

Table 5. Operational cost for ESD system optimisation

5.3 AI-Driven Predictive Maintenance

5.3.1 Failure Rate Reduction

Reduced failure rates of PRV and vent mast by employing AI-Driven predictive maintenance system are supported by real-world case studies and industry reports as shown in Table 6. These improvements specifically impact the overpressure scenario in Event Tree 2 (Figure 6).

Source	Key Findings	Reduction Achieved
[30]	Predictive maintenance reduces PRV failure rates by addressing root causes	Up to 89% reduction
[31]	Real-time monitoring via IoT sensors reduces unplanned downtime	40% downtime
[32]	Dynamic risk assessment improves accuracy of failure predictions	97% accuracy
[33]	AI-driven predictive maintenance in oil/gas pipelines reduced blockages, a proxy for vent mast debris mitigation	40% reduction

Table 6. Failure reduction rate case study

a) PRV Failure Rate Reduction

According to the study [30], the failure rate of PRVs from Event tree 2 (Figure 6) could be decreased to 89%. It results the failure rate from 0.0307 to 0.0034.

$$P_{PRV\ fail\ (revised)} = 0.0307\ \times (1 - 0.89) = 0.0034 \tag{5}$$

b) Vent Mast Failure Rate Reduction

Study [33] demonstrated 40% reduction in vent mask failure using AI. The revised failure rate for Event Tree 2 (Figure 6) is:

$$P_{Vent\ fail\ (revised)} = 0.2730 \times (1 - 0.40) = 0.1638 \tag{6}$$

5.3.2 Initial and Operating Costs

a) Initial Costs

Component	Cost (USD)	Rationale (Assumption)
IoT Sensors	$ 40,000	20 sensors $2,000 each (pressure, temperature, position)
Machine Learning Software	$ 30,000	Cloud-based platform for data analytics and failure prediction
Crew Training	$ 10,000	VR simulations and protocol familiarization for 10 crews
Total Initial Cost	$ 80,000	

Table 7. Initial cost for AI-Driven predictive maintenance

b) Annual Operational Costs

Item	Cost (USD)	Rationale (Assumption)
Sensor Maintenance	$ 4,000	10% of sensor cost including replacement and calibration
Cloud Subscription	$ 8,000	AWS/Azure IoT Core with SageMaker ML services
Total Annual Cost	$ 13,000	

Table 8. Operational cost for AI-Driven predictive maintenance

5.4 Cost Benefit Analysis

This section evaluates the cost-effectiveness of the proposed RCOs using the Gross Cost of Averting a Fatality (GrossCAF), per IMO's Formal Safety Assessment (FSA) guidelines. Calculation integrates risk reduction data from Sections 5.1.1, 5.2.1, and 5.3.1, with results summarised in Table 9.

a) Fatality Rate Calculation Rationale

Historical data from ammonia-related incidents [19-21] indicate an average of 4 fatalities per year attributed to tank ruptures in maritime industry. While broader industry studies report higher averages (12 fatalities /year), these figures include shore-based plants and non-marine sectors, necessitating a focused adjustment for maritime applications.

According to the EMSA report [14], there were 29 fatalities and serious injuries in ship accidents in 2023, with 22 of these occurring on cargo ships. Since 13,820 accidents out of a total of 29,116 accidents involved cargo ships, we assume that the likelihood of accident occurrence is higher on cargo vessels.

Of these fatalities, 18 involved crew members in marine vessel accidents, with approximately 3 crew fatalities per year attributed to ammonia-specific hazards such as emissions, bursting, vapour, flow, or leakage.

b) Potential Loss of Life (PLL) Reduction

PLL formula in Eq. (7) is derived from before and after RCO individual risk data. The ship's crew size is 25 and the ship's life (n) is 25 years.

$$\Delta PLL = (Original\ Risk - Revised\ Risk) \times Crew\ Size \times n \tag{7}$$

c) Present Value (PV) of Costs

The total cost of implementing the RCOs are discounted to reflect the time value of money:

$$PV = Initial\ Cost + Annual\ Operational\ Cost \times \frac{(1-(1+r)^{-n})}{r} \tag{8}$$

where r represents interest rate (5%) and n is ship's life (25 years). Initial cost and annual operational costs for each RCOs are described in Sections 5.1.2, 5.2.2, and 5.3.2.

d) Gross Cost of Averting a Fatality (GrossCAF)

The cost per statistical life saved is:

$$GrossCAF = \frac{PV\ of\ Costs}{\Delta PLL} \tag{9}$$

e) IMO Compliance and Threshold

The IMO FSA guidelines specify a GrossCAF threshold of $3 million for cost-effectiveness. All RCOs in this study achieve GrossCAF values below the threshold, confirming their feasibility. The summary of CAF calculations for each RCO is shown in Table 9:

Parameter	Unit	RCO 1	RCO 2	RCO 3
Risk reduction	%	80%	81%	89% for PRV and 40% for vent mast
Frequency Reduction	fatalities/ship year	9.13E-04	9.90E-05	1.80E-03
PLL after RCO	fatalities/ship year	5.71E-01	6.18E-02	1.13E+00
CAPEX	USD	150,000	12,500	80,000
Yearly OPEX	USD	5,000	10,000	13,000
Interest Rate	%	5%	5%	5%
Crew Size	Persons	25	25	25
Ship's Life	Years	25	25	25
PV	USD	220,470	153,439	263,221
CAF	USD	386,190	2,481,068	233,542

Table 9. Summary of CAF calculations

Figure 8 illustrates the comparison of PLL and CAF for each RCO. The CAF comparison shows that RCO 3 has the lowest cost of risk reduction at USD 233,542, despite its higher PLL. RCO 2 achieves the highest risk reduction with the lowest PLL, but at the highest CAF. RCO 3 provides a balanced option in terms of risk reduction and cost-effectiveness.

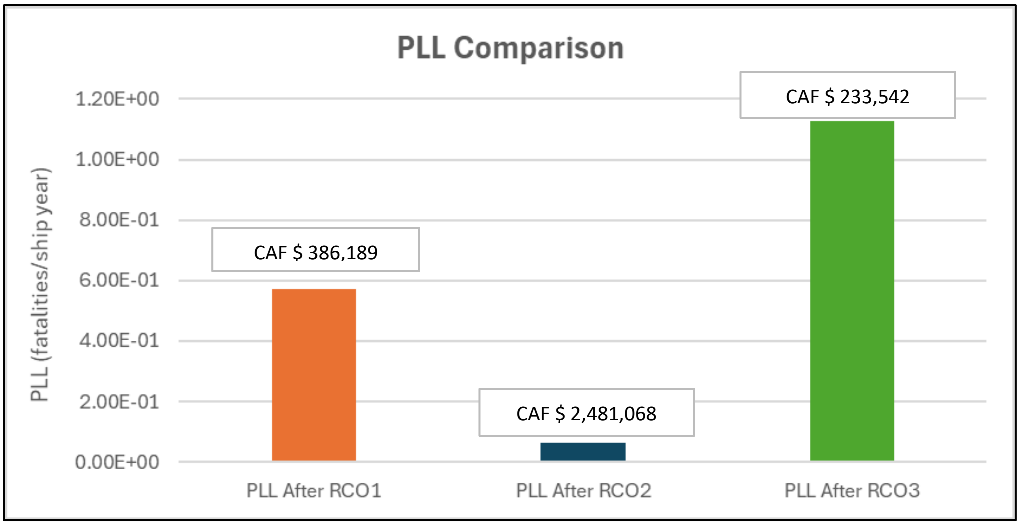

Figure 8. PLL and CAF comparison for each RCO

6. Discussions and Recommendations

This report conducted a Formal Safety Assessment (FSA) to evaluate risks in ammonia bunkering port to ship, focusing on two significant failure events: spillage due to hose failure and overpressure due to RCV failure. While existing safety barriers, such as leak detector, ESD system, and water curtains are already installed, additional Risk Control Options (RCO) need to be proposed to maximise the risk reduction of these events.

Three control options are investigated in this study, namely Virtual Reality Training (RCO1), Reliability-Centred Maintenance for ESD optimization (RCO2), and AI-driven Predictive Maintenance (RCO3). The calculation showed that RCO3 emerged as the most cost effective and recommended strategy with the lowest CAF of $233,542. However, all proposed RCOs proved to be economically justifiable as the CAF are below IMO's $3 million threshold, making them all viable for implementation.

The study's limitations include reliance on only theoretical failure rates and generalised cost assumptions that may vary across different vessel types and operational conditions. The examination of long-term crew exposure risks during routine operations also could enhance the safety assessment of the ammonia fuelled ship. Additionally, implementing specialised software to calculate failure probabilities and generate event tree analyses could significantly improve the accuracy and efficiency of the risk assessment process.

In summary, as the shipping industry begins to adopt ammonia fuel, these findings establish an important basis for development of safety standards. The financial viability of all proposed RCOs, based on IMO parameters, supports their implementation during the industry transition to this cleaner fuel.

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Appendix I: Risk Matrix and Severity Level

Category	Consequence Severity (S)				
	Low	Minor	Moderate	Major	Critical
	1	2	3	4	5
Asset	No shutdown, costs less than $10,000 to repair	No shutdown, costs less than $100,000 to repair	Operations shutdown, loss of day rate for 1-7 days and/or repair costs of up to $1,000,000	Operations shutdown, loss of day rate for 7-28 days and/or repair costs of up to $10,000,000	Operations shutdown, loss of day rate for more than 28 days and/or repair more than $10,000,000
Environmental effects	No lasting effect. Low level impacts on biological or physical environment. Limited damage to minimal area of low significance.	Minor effects on biological or physical environment. Minor short-term damage to small area of limited significance.	Moderate effects on biological or physical environment but not affecting ecosystem function. Moderate short-medium term widespread impacts e.g., oil spill causing impacts on shoreline	Serious environmental effects with some impairment of ecosystem function e.g., displacement of species. Relatively widespread mediumlong term impacts	Very serious effects with impairment of ecosystem function. Long term widespread effects on significant environment e.g., unique habitat, national park.
Community/Government/Media/Reputation	Public concern restricted to local complaints. Ongoing scrutiny/ attention from regulator.	Minor, adverse local public or media attention and complaints. Significant hardship from regulator. Reputation is adversely affected with a small number of site focused people.	Attention from media and/or heightened concern by local community. Criticism by NGOs. Significant difficulties in gaining approvals. Environmental credentials moderately affected.	Significant adverse national media/public/ NGO attention. May lose license to operate or not gain approval. Environment/ management credentials are significantly tarnished	Serious public or media outcry (international coverage). Damaging NGO campaign. License to operate threatened. Reputation severely tarnished. Share price may be affected
Injury and Disease	Low level short-term subjective inconvenience or symptoms. No measurable physical effects. No medical treatment required	Objective but reversible disability/impairment and/or medical treatment, injuries requiring hospitalisation.	Moderate irreversible disability or impairment (<30%) to one or more persons.	Single fatality and/or severe irreversible disability or impairment (>30%) to one or more persons.	Short- or long-term health effects leading to multiple fatalities, or significant irreversible health effects to >50 persons.

			Low	Minor	Moderate	Major	Critical
			1	2	3	4	5
Likelihood	**Almost Certain** - Occurs 1 or more times a year	E	High	High	Extreme	Extreme	Extreme
	Likely - Occurs once every 1-10 years	D	Moderate	High	High	Extreme	Extreme
	Possible - Occurs once every 10-100 years	C	Low	Moderate	High	Extreme	Extreme
	Unlikely - Occurs once every 100-1,000 years	B	Low	Low	Moderate	High	Extreme
	Rare - Occurs once every 1,000-10,000 years	A	Low	Low	Moderate	High	High

Appendix II: Hazard Identification Table

No	Hazard	Potential Cause	Consequences	Category	Severity	Likelihood	Risk Ranking	Effective Safeguard	Recommendations
1	**Hose Failure**	1. Material Failure due to deteoriation 2. Detachment of coupling 3.Valve malfunction on downstream 4. Back pressure due to overfilling	1. Ammonia Spillage leding to environment pollution	Equipment & Environment	3	D	3D	1. Gas detector and flow meter installed on the transfer system to detect spillage 2. Splash/ water curtains on ship side, bunkering area. 3. Dip tray at various locatio like joints & bends.	1. Dedicated Watchkeeper for overlooking the bunkering procedure 2.Functional CCTV system with a feed in MCR 3. Provision of adequate size dip tray incoporating the spillage scenerio 4. Regualar inspection of hoses and associated fitting/ sensor for functionality, caliberation and pressure testing.
			2.Human Exposure to NH3	Human	3	D	3D	1.Gas detector 2. PPPE kit 3. 4 hourly watchkeeping system with regular visual inspection.	1. Dosing of PPE (Eye defenders) by all personnels involved in bunkering 2. Availability of respiratory mask at fixed location near the bunkering pooints 3. Cleansing station at fixed location nearby the bunkeing points. 4. Sensor to be integrated with MCS along with audio visual alrams at various locations.
			3. Casualty/ Sever injury if anyone in vicinity	Human	4	C	4C	Hose securing arramgment	1. Hose to be secured at adequate locations where necessary to avoid uncontrolled movement upon rupture. 2. Emergency shut down system for pump upon sudden drop of pumping flow/ pressure.
			4. Equipment & Hull damage due to corrosive nature of ammonia	Asset	2	D	2D	1. Stainless steel/ corrosion resistant material for panels 2. Annual pressure testing of hoses 3. Caliberation of sensors and signal checks. 4. Inspection of control panel for deteriotaton of sealing.	1. Equipment material in nearby vicinity to designed as per recommmended IMO/ DNV/ ABS standard. 2. Miimum IP65 rating of electric equipment and panels 3. Regualar inspection of hoses and associated fitting/ sensor for functionality, caliberation and pressure testing.
			5. Damage to control/ electric panels	Asset	2	D	2D		
2	**Leak at Connection Points/ Couplings**	1. Deteorated sealing 2. Damaged coupling/ fastning arrangment 3. Material / joints deteroation	1. NH3 leakage causing deteoration to Hull/ Equipment	Asset	3	E	3E	1. Regular visual inspection of sealing and fastning arrangment for deteoration and onset of corrosion 2. Application of paints where necessary to avoid corrosion.	1. Regular replacement of reubber joints 2. Use of corrosion resistant material and paints for preservation.

No	Hazard	Potential Cause	Consequences	Category	Severity	Likelihood	Risk Ranking	Effective Safeguard	Recommendations
3	**Overpressure In Transfer System**	1. Equipment failure - Malfunction of remote valve control system - Malfunction of pressure relief valves - Malfuntion of vent masts 2. Operational errors - Flow rate exceeding designed limit - Pressure buildup due to improper valve operation (hydraulic lock) 3. Failure to monitor tank levels or pressure during bunkering 4. Temperature fluctuation leading to thermal expension	1. System damage - Rupture of pipings, hoses, or tanks - Safety system overload to venting system, pressure relief valves)	Asset	4	D	4D	1. Engineering aspect - Use double-wall piping and cryogenic-rated material - Aadopt gasket material competitable with ammonia - Implement insulation sleeves to bunkering hoses - Implement real-time monitoring system with pressure, temperature - Conduct regular insepction for remote valve actuator 2. Operational aspect - Regular pressure test on hoses, pipelines, and PRVs - Limit bunkeing flow rate - Ensure safety systems such as emergency shutdwon devices (ESD), bakcup PRVs 3. Emergency response - Equipt water spray system around bunkeing station - Ensure clear communication protocols between shore and ship	1. Consider using advances monitoring method like flow-rate sensor. 2. Employ redictive maintenance techniques such as ultrasonic testing for pipe wall thickness or thermal imaing. 3. Conduct regular drill sessions for bunkering 4. Conduct calculation for sensors before bunkering
			2. Formation of ammonia vapore cloud due to released ammonia: contaminates air and marine ecosystems	Environment & Government	3	D	3D	1. Engineering aspect - Install elevated vent mast - Employ automated gas detection system near vent mast and areas where prone to leakage 2. Operational aspect - Purge transfer lines with nitrogen after bunkeing to eliminate residual ammonia - Define toxic zones around vent outlets	1. Install water spray system near vent mast and other critical area 2. Perform CFD analysis to ensure vent mast placement minimises the rick of ammonia clouds 3. Implement ammonia recycling system such as absorbers
			3. Exposure to ammonia vapours to human due to releaased ammonia: chemical burns, fatalities at high concentrations	Human	5	C	5C	1. Engineering aspect - Keep positive pressure in crew accomodation spaces to prevent toxic ammonia ingress prone to leakage 2. Operational aspect - Equip PPE and chemial-resistant suits - Train crew members on emergency response procedure - Define toxic zones around vent outlets and restrict human access 3. Emergency response - Install alarm system for ammonia detection at critical points	1. Close fresh air intake valve for air conditioning system in crew accomodation area 2. Conduct regular drill sessions for ammonia bunkering and first aid for ammnonnia exposure 3. Consider installation shower booth near bunkering station 4. Use portable ammonia detectors worn by crew members

No	Hazard	Potential Cause	Consequences	Category	Severity	Likelihood	Risk Ranking	Effective Safeguard	Recommendations
4	**Venting Failure**	1. Blockage in vent-mast or pipes 2. Pressure buildup due to improper valve operation (hydraulic lock) 3. Fail to purge residual ammonia in receiving lines before bunkering 4. Malfunction of pressure relief valves	1. Structural damage to vent pipes, mast due to excessive pressure builup	Asset	3	D	3D	1. Ensure high-enough vent-mast 2. Install ammonia-catching system on vent-mast to reduce vapor concentrations to safe level	Perform CFD analysis to ensure vent mast placement minimises the rick of ammonia clouds
			2. Uncontrolled ammonia vapour forms ammnoia vapour cloud	Environment	3	D	3D	1. Engineering aspect - Install elevated vent mast - Employ automated gas detection system near vent mast and areas where prone to leakage 2. Operational aspect - Purge transfer lines with nitrogen after bunkering to eliminate residual ammonia - Define toxic zones around vent outlets	1. Install water spray system near vent mast and other critical area 2. Perform CFD analysis to ensure vent mast placement minimises the rick of ammonia clouds 3. Implement ammonia recycling system such as absorbers
			3. Exposure to ammonia vaours to human	Human	5	B	5B	1. Engineering aspect - Keep positive pressure in crew accomodation spaces to prevent toxic ammonia ingress prone to leakage 2. Operational aspect - Equip PPE and chemial-resistant suits - Train crew members on emergency response procedure - Define toxic zones around vent outlets and restrict human access 3. Emergency response - Install alarm system for ammonia detection at critical points	1. Close fresh air intake valve for air conditioning system in crew accomodation area 2. Conduct regular drill sessions for ammonia bunkering and first aid for ammnonnia exposure 3. Consider installation shower booth near bunkering station 4. Use portable ammonia detectors worn by crew members
5	**Improper Hose Handling**	1. Incorrect lifting techniques 2. Mishandling during connection/disconnection 3. Sudden pulling or twisting 4. Expired inspection of lifting gear 5. Inadequate bunkering & lifting training 6. Improper risk assessment 7. Fatigue crew 8. Inadequate supervision	1. Hose rupture leading to ammonia leak	Asset	2	D	2C	1. Pre bunkering hose inspections 2. Proper lifting tools and support frames	1. Hose handling procedure 2. Conduct regular crew training 3. Ensure regular inspection and certification of hoses and lifting gear
			2. Ammonia exposure to the crew	Human	4	D	4D	1. PPE 2. Gas detector 3. Emergency response plan and training	1. Improve crew awareness through training/drill 2. To check the gas level before and after bunkering 3. Gas detector to be available all the time during bunkering 4. Eyewash facility
			3. Environmental contamination due to ammonia leak	Environment	2	D	2C	Emergency shut down valves	1. Implement spill response training 2. To install proper drainage system
			4. Damage to the lifting gear and other bunkering equipment	Asset	2	D	2C	Valid certificates of the lifting gears	1. Ensure to do regular inspection of the lifting gears and bunkering equipment 2. Certification of crews in lifting and bunkering process 3. Use automated or assisted lifting mechanisms

No	Hazard	Potential Cause	Consequences	Category	Severity	Likelihood	Risk Ranking	Effective Safeguard	Recommendations
6	**Mooring failure**	- High wind / Strong currents / Rough sea state with ignoring or bad planning for weather condition. - Equipment failure (e.g., failure of bollards or winches, or exceeding strength and fatigue limits) - Inexperienced crew may fail to monitor line tension.	1. - Hose breakaway, causing the breakdown operation - Damage to mooring lines or equipment due to excessive forces from waves or wind.	Asset	3	D	3D	1. Using dynamic positioning or additional tugs during high-risk weather with real-time mooring monitoring 2. Using the high-quality bollards and winches, reated for ship size and expected force. 3. Complying the mooring arrangement as per IGF Code and class rules 4. Trained mooring personnel	- Install tension monitoring & alarms on mooring lines. - Routine inspection - Develop mooring procedures for ammonia bunkering in open sea. - Provide PPE and emergency response drills for ammonia exposure - Updating and reviewing the mooring plan continuously
		- Improper mooring arrangement (wrong angle and position)	2. The hose may stretch, twist, or bend beyond the design limitation, causing an ammonia leak, which creates an area of hazard and leads to environmental damage.	Environment	2	D	2D	1. Mooring monitoring system by Implementing camera surveillance for recognizing and adjusting the wrong position 2. Breakaway coupling (automatically disconnects)	
			3. Excessive stress on the hose cause an ammonia leak, which is a risk to the personnel exposed to ammonia vapors and can lead to shortness of breath, chest pain, and severe irritation.	Human	3	D	3D		
7	**Emergency shutdown system (ESD) failure**	- ESD circuit malfunction and sensor/data signal fault, leading to gas detector not working.	1. Failure to detect hazardous gas leaks and delayed or failed shutdown, leading to more ammonia escapes from prolonged leak which has a risk to environment	Environment	3	A	3A	1. Redundant ESD system by separating circuits (main and backup). 2. Design a manual shutdown backup 3. Gas detectors with auto-trigger before the gas distribution 4. Regular testing and maintenance on related equipment such as pump. 5. Proper training and certification of crew	-Add alarms linked to gas detection to trigger ESD and also link it to bridge and control room. - Implement regular ESD system integrity checks and drills such as test buttons, valve closures, and signal transmission before each bunkering - Ensure training includes manual ESD activation. - Review ESD reliability with vendors and classification society.
		- Pump failure, leading to behave pressure and flow rate erratically.	2. Unstable transfer operations, potentially causing overpressure or underpressure in pipelines Gas dispersion can travel with the wind across deck to accommodation areas.	Human	3	A	3A		
			3. - Hose over-pressurization and burst - Increased wear and tear on connected systems, such as hoses, valves, and flow meters.	Asset	1	A	1A		
		- Human error such as wrong setting/ untrained personal/ misinterpretation of signals	4. - Delayed or wrong response - Reputational risk, particularly if errors lead to incidents requiring investigation.	Reputation	1	A	1A		
8	**Hose Rupture (Fracture or holes in the hose)**	Mechanical stress, mechanical defects (defective flange joints & improper connection), pressure overload	Release of ammonia, forming toxic vapour clouds	Human	5	C	5C	1. Regular maintenance 2. Improve safety protocol	EM'CY shutdown system (how), equip water sprinkler system
9	**Spillage of Ammonia**	Poor mechanical handling, Tank overfilling.	Environmental contamination	Environment	4	C	4C	1. Proper training for competent personnel 2. SOP	Training refreshment, ERP for Spill Combat
10	**Communication Failure**	Language Barrier, Radio frequencies difference.	Overfilling that may lead to over pressure.	Asset	2	C	2C	1. SOP 2. Pre-job Meeting	ERP Standby