A PRIORITY-BASED FAILURE MODE AND EFFECTS ANALYSIS (FMEA) METHOD FOR RISK ASSESSMENT OF HYDROGEN APPLICATIONS ONBOARD MARITIME VESSELS

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ABSTRACT

The maritime industry is gaining momentum towards a more decarbonized and sustainable path. However, most of the worldwide fleet still relies on fossil fuels for power, producing harmful environmental emissions. Hydrogen, as a clean fuel, is a promising alternative, but its unique properties pose significant safety challenges. For instance, hydrogen has a wide flammability range, inherently increasing the risk of ignition. Moreover, its comparatively low volumetric energy density necessitates faster filling rates and larger volumes for bunkering and onboard storage, leading to higher risk rates. Therefore, the use of hydrogen for maritime applications requires the development of specialized risk-based approaches according to safety engineering principles and techniques. The key safety implications are discussed and reviewed with focus on onboard hydrogen storage, handling, and refueling, while a priority-based Failure Mode and Effects Analysis (FMEA) method for risk assessment is proposed based on the revised guidelines of Automotive Industry Action Group (AIAG) and German Association of the Automotive Industry (VDA). The revised AIAG-VDA FMEA method replaces the conventional Risk Priority Number (RPN) with a new Action Priority (AP) rating, enabling the prioritization of recommended actions for risk reduction. The paper aims to a more profound understanding of the safety risks associated with hydrogen as a maritime fuel and to provide an effective risk assessment method for hydrogen applications onboard maritime vessels.

1.0 INTRODUCTION

The maritime industry is exploring the potential of using hydrogen as an alternative fuel for both existing vessels and new buildings. However, current technologies are still in their early stages of development for different types of ships and navigation distances. Numerous projects worldwide have tested hydrogen as a fuel for ships' propulsion or power supply systems. As of 2022, at least 18 ongoing and 22 completed projects have installed hydrogen-based systems [1]. While technological advancements of hydrogen applications are promising, hydrogen has unique physical and chemical properties that require new safety practices and thresholds, even though methane-based applications can be useful in the initial development phase. The first section of the paper presents the hydrogen properties associated with safety. Next, the key safety considerations are reviewed with focus on onboard hydrogen storage, handling, and bunkering and the main regulatory gaps are discussed. Following this, a priority-based Failure Mode and Effects Analysis (FMEA) method is presented and demonstrated in an indicative case study. Finally, the advantages of the method are summarized, and conclusions are drawn based on the results.

2.0 HYDROGEN PROPERTIES ASSOCIATED WITH SAFETY

Hydrogen has a high energy per mass but a low energy per unit volume compared to other maritime fuels [2]. Its physical and chemical properties, such as its small molecular size, high diffusivity, low specific gravity, and wide flammability limits, pose safety challenges that require special attention [3]. One of the significant safety concerns related to hydrogen is its wide flammability range (4-75% vol. H_2

in NTP) [4], making it more challenging to control and handle than conventional fuels. Additionally, hydrogen has a very low minimum ignition energy compared to other flammable gases [5], making it highly susceptible to accidental ignition and explosion, even from weak ignition sources such as sparks from electrical equipment, electrostatic discharges, mechanical sparks from rapidly closing valves, and thermal sources. Furthermore, hydrogen flames are more difficult to detect than flames of other gases due to the non-luminous, almost invisible, pale-blue flame it produces. Hydrogen when ignited can combust either by deflagration or detonation, resulting in extreme pressure increases with catastrophic consequences. [6]. Additionally, the small molecular size and high diffusivity of hydrogen present additional safety concerns related to the hydrogen embrittlement effect. These properties can lead to material failures at low stresses, such as brittle failure mechanics, microscopic fractures, material cracks, and leakage. [7]. Therefore, a detailed understanding of hydrogen's unique properties is needed to identify and evaluate the safety risks that could emerge, and to ensure the safe use of hydrogen as a maritime fuel.

3.0 KEY SAFETY CONSIDERATIONS

In this section, the key safety considerations of hydrogen use onboard maritime vessels are briefly discussed focusing on onboard hydrogen storage, hydrogen handing and bunkering procedures.

3.1 Onboard hydrogen storage

Hydrogen has a low volumetric energy density, which poses challenges for its storage. Compared to conventional fuels, storing hydrogen requires larger volumes, which inherently increases safety risks. Hydrogen can be stored through physical-based or material-based methods [8]. Physical-based methods include compressed hydrogen, typically stored at pressures of 350-700 bar, or liquid hydrogen, stored at a temperature of 253°C. Hydrogen storage tanks are classified into five types, designated by Roman numerals I to V, based on the material used and the pressure range they can withstand [9].

In a maritime environment, hydrogen storage tanks face different conditions, including corrosive sea environment, high-frequency vibrations, and high stress concentrations, which should be considered during the design phase. Additionally, it is crucial to protect the location of hydrogen tanks from external damage resulting from potential collision incidents. Therefore, to ensure the safety onboard, it is necessary to establish new hazardous areas and safety zones by carefully considering the fuel storage tank's location relative crew and passengers' areas.

Thermal protection of hydrogen storage tanks in case of a fire incident remains one of the most critical safety concerns, as a catastrophic tank rupture due to pressure built-up inside the tank can potentially result in blast wave or fireball effects [10], [11]. To mitigate the risk of a tank rupture, safety devices such as Thermally activated Pressure Relief Devices (TPRD) are installed to relieve excessive pressure. However, the release of hydrogen even unignited can cause unacceptable overpressures in confined spaces and damage or collapse surrounding structures [12]. To enhance the safeguarding against overpressure, Rupture Disk valves are also employed as an additional safety mechanism. However, it is worth mentioning that the discharge of hydrogen from Rupture Disk valves, especially under high-pressure, may lead to self-ignition at the venting tube exit [13].

Another important safety issue regarding storage tanks pertains to the phenomenon of material embrittlement, especially in cryogenic applications such as LH_2. To avoid high stresses and structural failures caused by different contraction coefficients, materials such as austenitic stainless steels, copper, and aluminium are mostly preferred for cryogenic applications [14]. Therefore, high-pressure hydrogen storage tanks or cryogenic tanks should be designed to minimize the risk arising from material degradation, tank rupture, and high-pressure leaks.

3.2 Hydrogen handling

The unique properties of hydrogen require specialized handling practices to ensure safe operations and mitigate safety risks in the event of a hazardous incident. When hydrogen is accidentally or forcibly released in an open space, it rapidly disperses into the atmosphere or undergoes weak deflagration. However, within a confined space, its deflagration can lead to a severe pressure impulse that may transition to detonation. To ensure safe handling of gaseous hydrogen, a comprehensive assessment must be conducted for possible leakage scenarios, safe discharge of released hydrogen through the venting system, efficient room ventilation rates, and safe operation of the Fuel Cells (FC) or Internal Combustion Engines (ICE).

One of the highest safety priorities is to ensure the prevention of hydrogen leakage in confined spaces. Previous studies [15] proposed the use of gas-tight, ventilated ducts to house hydrogen supply pipelines running through enclosed spaces as a secondary measure to prevent the formation of flammable gas mixtures in a leakage incident. Additionally, remotely operated isolated safety valves may be used to shut off a faulty pipe branch or component in case of an emergency shutdown situation. A detailed risk assessment should be conducted with respect to hydrogen dispersion during leakage and self-ignition scenarios.

Ensuring the proper operation of the venting system is crucial to reduce the risk and potential adverse consequences in case of a forced hydrogen release into the atmosphere. The gas discharged from safety devices should be safely directed into the vent mast through the venting pipelines. The venting mast's outlet should be positioned away from potential sources of ignition and located at the highest point of the vessel. The hazardous distances should be determined at the design stage, considering the rooting of the venting pipes in relation to the vessel's arrangement, the crew and passengers' areas.

Ventilation rates in critical spaces, such as the FC compartment, should be reassessed for hydrogen considering possible leakage scenarios. Hydrogen is lighter than air or other conventional gases, leading to higher buoyancy and quick dispersal from an incident scene, accounting as a safety asset. However, hydrogen's wide flammability limits and low minimum ignition energy make it highly susceptible to accidental ignition and explosion. The ventilation rate should be determined during the early design, considering the characteristics of each system [16].

In FC powered vessels, the FC compartment is a crucial part of the system as it is where hydrogen is supplied and consumed. Therefore, potential safety incidents such as pressure or temperature increases inside the FC, as well as leakage through FC gaskets [17], should be assessed, and the efficiency of hydrogen leakage detection systems should be re-evaluated. The simulation of hydrogen dispersion in locations where FCs are installed can significantly contribute to the understanding of the risks associated with hydrogen releases. Additionally, these simulations can provide crucial design criteria for determining ventilation rates in different compartments of the vessel, thereby ensuring optimal onboard safety.

In the context of Internal Combustion Engine (ICE) systems, the use of hydrogen introduces safety considerations due to its distinct properties. More specifically, the wide flammability limits, high flame speed, and low minimum ignition energy of hydrogen can engender undesired combustion phenomena commonly referred to as combustion anomalies [33]. These anomalies encompass surface ignition, backfiring, and autoignition, which vary depending on the specific technology being used.

3.3 Hydrogen bunkering

In the shipping industry, the term "bunkering" refers to the refuelling of shipping vessels, in contrast to loading and unloading cargo. The fuel supply to maritime vessels can be delivered through various means, including shore-to-ship and ship-to-ship bunkering, depending on the ship's mission profile, energy requirements, available storage space, and time constraints in port. However, due to the uncertain delivery time of hydrogen bunkering infrastructure at ports, temporary solutions such as hydrogen refuelling with trailer trucks or swappable containers are currently being used.

While the experience gained from developing refuelling systems for buses, trucks, and trains that utilize hydrogen can provide valuable insights for ship applications, it is crucial to assess additional considerations to ensure the safety of bunkering operations. These include accounting for sailing effects (e.g., mechanical vibrations) as well as addressing the larger volumes and faster filling rates required for ships. For example, the greater volumetric flow rates compared to conventional fuels could impact the amount of fuel released in case of a loss of containment event during bunkering [18].

For compressed gaseous hydrogen bunkering operations in marine applications, a dispensing concept similar to that used for land-based trucks or buses can be utilized. Proper handling, connection, and disconnection procedures should be followed to ensure secure integration of hydrogen tanks into the ship's fuel system. It is important to note that in the event of an unexpected hydrogen release, the dispersion of gaseous hydrogen differs from that of natural gas (methane), hence revised hazardous areas should be determined and new safe zones should be established.

Bunkering of LH_2 is more challenging than CH_2 due to the extremely low temperatures involved. At present, the refuelling of LH_2 is limited to using hydrogen truck trailers. A bunkering station transfers the hydrogen from the trucks to the ship's storage tanks, typically using a bunkering hose, connection flanges, pressure gauges, manual stop valves, and remotely operated emergency stop valves. Double-walled austenitic stainless steel is used for bunkering piping due to the very low temperatures, and vacuum insulation is employed to minimize heat ingress. One of the primary safety concerns is the possibility of liquid hydrogen spills. Direct contact with liquid hydrogen or cryogenic vapor can cause severe frostbite or create an asphyxiating atmosphere. Moreover, large spills can result in the dispersion of vapor clouds that are heavier than air, increasing the risk of explosions [19]. Boiling Liquid Expanding Vapor Explosions (BLEVE) can occur if heat transfer into the liquid hydrogen increases significantly, for example, in a fire incident [20],[21].

To develop detailed bunkering procedures for hydrogen, it is necessary to consider the engineering of specific systems. Critical elements of these procedures include defining roles and responsibilities, determining safety zones, establishing control measures within these zones, coordinating bunkering operations with other ship activities, establishing equipment standards and safety systems, providing personnel training, monitoring bunkering operations, and developing emergency procedures. Risk assessment studies should be carried out for all sub-components of the refuelling station, transfer system, and bunkering procedures to ensure a safe hydrogen bunkering.

4.0 REGULATORY GAPS

In the maritime industry, regulatory bodies include international regulations developed by the International Maritime Organization (IMO), national regulations, and class rules. However, despite the growing interest in hydrogen as a clean alternative fuel for shipping, the regulatory framework is still in its early stage. Clear guidelines and regulations for hydrogen use onboard ships are currently missing, which highlights the need for further development.

Recent studies, such as the European Maritime Safety Agency's (EMSA) report [22], are highlighting gaps in regulations that should be addressed to enable the use of hydrogen as a maritime fuel. While the International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF Code) [23] governs ship-side bunkering of gases, it does not include specifications for hydrogen. Current regulations for LNG bunkering (ISO/TC18683) are not sufficient to cover the specific characteristics and hazards associated with hydrogen. However, existing knowledge from LNG bunkering and lessons learned from land-based hydrogen filling stations can serve as a starting point to update regulations.

To address these regulatory gaps, minimum safe distances for bunkering operations should be developed, and appropriate training should be provided to maritime personnel. Additionally, gaps in ventilation requirements, detection and mitigation of hydrogen leaks, safety measures for restricting fire propagation and explosion prevention should be addressed and clear protocols for emergency response in case of safety incidents, including the safe evacuation of crew and passengers should be established. In 2021, the Sub-Committee on Carriage of Cargoes and Containers (CCC 7) of IMO has agreed to a work plan for the development of safety provisions and guidelines for ships using hydrogen as fuel.

Amendments to the regulatory framework are essential to facilitate the adoption of hydrogen as a maritime fuel. These amendments play a crucial role in ensuring the safety and efficiency of hydrogen use, while also addressing the specific design and construction requirements for vessels that will utilize hydrogen as a fuel.

5.0 RISK ASSESSMENT

The use of hydrogen as a fuel introduces safety risks that must be identified, evaluated, and managed to prevent harm to individuals, environment damage, and asset loss. Therefore, the development of risk assessment studies becomes essential, with a variety of methods and techniques proposed to fulfil this purpose.

In land-based applications, numerous studies have been carried out to identify and assess potential hazards using various methods such as Hazard Identification (HAZID), Hazard and Operability (HAZOP) analysis, Fault Tree Analysis (FTA), and Failure mode and Effects Analysis (FMEA) [24]. Additionally, Computational Fluid Dynamics (CFD) models have been utilized to evaluate the consequences of potential failures [25]. More recently, quantitative methods have been employed to examine critical safety incidents involving multiple physical parameters often interrelated [21], [26].

In the maritime industry, guidelines established by the International Maritime Organization (IMO) define the framework for conducting preliminary risk analysis and risk assessment studies. These guidelines outline general requirements and procedures, supplemented in 2017 by the International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF) [23]. The IGF Code mandates the conduction of a risk assessment before ships utilize low-flashpoint fuels. The assessment should consider potential hazards related to physical layout, operation, and maintenance, as well as foreseeable failures. Recognized techniques such as qualitative or quantitative risk assessment are recommended for this purpose.

5.1 Priority-based FMEA

The Failure mode and Effects Analysis (FMEA) method is widely embraced for its efficacy in identifying potential system failures and enhancing overall reliability and safety. It was originally developed for military system design and has since been applied in various industries, including aerospace, automotive, and maritime [22], [27]. It is also extensively used in risk assessment related to hydrogen applications [28], [29]. FMEA focuses on component-level failures and their impact on higher-level systems. Conventionally, the risk of potential failures has been evaluated using the Risk Priority Number (RPN) method, which is defined as the product of Severity (S), Occurrence (O), and Detectability (D), as shown in Equation (1)

$$\mathrm{RPN}_i = \mathrm{S}_i \times \mathrm{O}_i \times \mathrm{D}_i \tag{1}$$

where i, denotes each identified potential failure mode. However, this method gives equal weight to S, O, and D and could result in similar RPN values for very different combinations. For instance, consider two failure modes:

$$\text{Failure mode 1: } \mathrm{RPN}_1 = \mathrm{S}_1 \times \mathrm{O}_1 \times \mathrm{D}_1 = 5 \times 1 \times 2 = 10$$

$$\text{Failure mode 2: } \mathrm{RPN}_2 = \mathrm{S}_2 \times \mathrm{O}_2 \times \mathrm{D}_2 = 2 \times 1 \times 5 = 10$$

Although both failure modes have the same RPN value, the first failure mode is more critical, with a Severity rating of 5 indicating a potential sudden and catastrophic event, which could occur without warning. Thus, relying solely on RPNs can provide an incomplete picture of the failure, as it does not consider the Severity of the consequences.

To address this issue, a revised FMEA method was introduced in 2019 by the Automotive Industry Action Group (AIAG) and the German Association of the Automotive Industry (VDA) [30]. The fundamental change in this method is the replacement of the RPN with the new Action Priority (AP) rating. This rating enables prioritization of recommended actions without relying on an RPN threshold and regardless of the number of actions identified during the FMEA process.

The AIAG-VDA FMEA method prioritizes risk prevention and reduction by focusing on the most hazardous potential failures. Therefore, the FMEA team prioritizes actions based on the Severity first, followed by the Occurrence and Detectability of the potential failures. The AP rating system has three levels of priority "High," "Medium," and "Low", which correspond to the need for review and action, rather than the prioritization of high, medium, or low risk. The previous example will give:

$$\text{Failure mode 1: } \mathrm{AP}_1 = \text{Hight Priority for review and action}$$

$$\text{Failure mode 2: } \mathrm{AP}_2 = \text{Low Priority for review and action}$$

This approach reduces complexity, helps the FMEA team to focus their resources on high-severity risks which is more aligned with the failure-prevention objectives of FMEA.

5.2 Methodology

The AIAG-VDA FMEA methodology, depicted in Figure 1, presents a structured seven-step approach categorized into three main sections: System Analysis, Failure Analysis & Risk Mitigation, and Risk Communication.

System analysis	1st Step Planning & Preparation
	2nd Step Structure Analysis
	3rd Step Function Analysis
Failure Analysis & Risk Mitigation	4th Step Failure Analysis
	5th Step Risk Analysis
	6th Step Optimization
Risk Comm.	7th Step Results Documentation

Figure 1. The seven steps of the AIAG-VDA FMEA method

The initial three steps fall under System Analysis, encompassing Planning and Preparation, Structural Analysis, and Function Analysis. Steps 4 to 6 shift attention to Failure Analysis and Risk Mitigation, involving Failure Analysis, Risk Analysis, and Optimization. Step 7 is dedicated to Risk Communication, involving the documentation of findings from the preceding steps.

5.2.1 Planning and Preparation

In FMEA development, the Planning and Preparation stage is critical for ensuring the success of the project. This stage typically involves several key activities that must be carefully considered. First, it is important to define the scope of the study, select the appropriate FMEA approach and establish the boundaries of the analysis. By carefully considering the 5T's (InTent, Timing, Task Allocation, Tools) [30] during this stage, the FMEA team can set the foundation for a successful analysis.

5.2.2 Structure Analysis

In the second step of FMEA development, the analysis scope and boundaries are defined. This involves identifying the systems, sub-systems, and components to be analyzed and considering their interactions. It is crucial to define the analysis scope carefully to ensure that all potential failure modes are identified. For hydrogen-powered vessels, the FMEA should at least include key components like hydrogen storage, refueling station, piping, safety devices, and FC/ICE systems. Tools like Structure Trees and Block Diagrams depict the hierarchy and relationships of the analyzed system. See Figure 2 for an example block diagram of a LH_2/FC vessel.

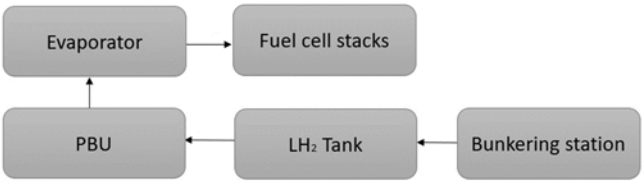


Figure 2. Simplified system Block Diagram of LH_2/FC vessel

5.2.3 Function Analysis

In this step, the functions identified during the design phase are assigned to specific system elements, and their inputs, interfaces, and outputs are reviewed. It is important to ensure that each function is assigned to the appropriate system element. To assist with this, tools such as the P-diagrams, Function Trees, and Form Sheets can be used. An example of a Function Analysis Structure Tree for a hydrogen bunkering station onboard a vessel is presented in Figure 3.

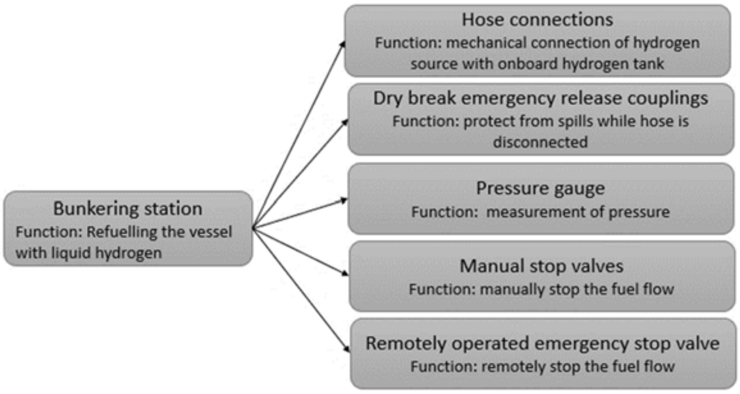


Figure 3. Function Analysis Structure Tree

5.2.4 Failure Analysis

The purpose of Failure Analysis is to identify potential causes, modes, and effects of failure and to demonstrate their interrelationships, which are essential for risk assessment. In this step, the sequence of events leading to the end effect is described in the context of the relevant scenario. The primary objectives of Failure Analysis are to establish the failure chain (failure effect, failure mode, and failure cause) for each function. Parameter diagrams or failure networks are commonly used tools in this step. Primary focus is given to the reliability of the safety components such as TPRDs in storage systems. For example, if a TPRD fails to detect an increase in temperature during a fire incident and does not open, a tank failure mode may occur, leading to the end effect with a corresponding severity level. However, if the TPRD detects the temperature increase and opens, the system will respond, and the end effect will have a lower severity compared to the original failure effect. The results of the Failure Analysis serve as the basis for the next step of Risk Analysis.

5.2.5 Risk Analysis

In the Risk Analysis step, the FMEA team evaluates the Severity (S), Occurrence (O), and Detectability (D) of each identified failure mode to assess the risks associated with it. Table 1 provides definitions for each of these parameters. The primary objective is to assign appropriate controls to mitigate the risks associated with each failure mode, including prevention and detection measures, for both existing and planned controls.

Table 1. Severity, Occurrence, and Detectability definition

Severity (S)	Represents the scale of the failure effect
Occurrence (O)	Represents the frequency of a failure occurrence during the vessel's lifetime
Detectability (D)	Represents the detection potential of problem before it causes a failure

As mentioned earlier, one of the significant changes in the revised method is the adoption of the AP rating system to prioritize risk reduction actions. The AP rating has three levels: High, Medium, or Low, as shown in Table 2, which represent the level of urgency for review and action, rather than the level of risk. For example, High Priority failures require the most urgent attention for review and action, while Low priority failures require the least urgent level of attention, but the team should still consider identifying actions to improve prevention or detection controls. The terms "could," "should," and "needs" are used to communicate the level of urgency for addressing the associated risk effectively.

Table 2. Action Priority rating levels

High Priority (HP)	Require immediate attention for review and action. The team must prioritize identifying an appropriate action plan that improves prevention and/or detectability.
Medium Priority (MP)	Require a medium urgent level of attention for review and action. The team should focus on identifying appropriate actions to strengthen prevention and/or detection controls.
Low Priority (LP)	Require the least urgent level of attention for review and action. However, the team should focus on identifying appropriate actions to strengthen prevention and/or detection controls.

The aim of this step is to assess the risk of each failure mode and prioritize risk reduction actions based on their urgency level. The FMEA team should assign prevention and detection controls and use the AP rating system to guide their decision-making process.

5.2.6 Optimization

In this step, the FMEA team reviews the results of the Risk Analysis to identify appropriate actions to mitigate the safety risks. The team then evaluates the effectiveness of these actions in a cyclic process, as depicted in Figure 4, until the desired level of risk reduction is achieved. This involves updating the ratings of Severity (S), Occurrence (O), and Detectability (D) and conducting the revised AP rating.

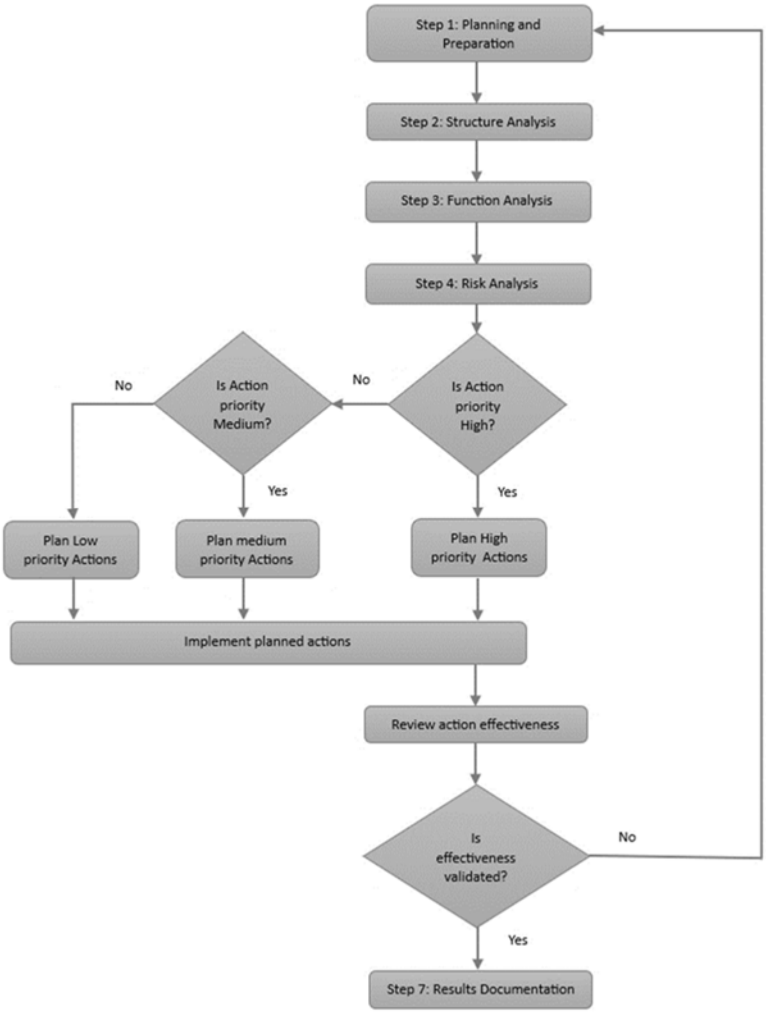


Figure 4. Optimization process

5.2.7 Results Documentation

The final step in the FMEA process is to document and communicate the results of the risk assessment. This step ensures accurate recording of the findings and implementation of appropriate actions to mitigate or eliminate risks. Effective communication of the findings, significant risks, and proposed actions is crucial for engaging and informing all relevant stakeholders.

6.0 INDICATIVE CASE STUDY

This section presents an illustrative case study that employs the priority-based FMEA method to assess the risks onboard a hydrogen-powered passenger ferry. The purpose is to demonstrate the benefits of the AP rating addition. The vessel used for the case study is based on the SF-BREEZE ferry [31], designed by Sandia National Laboratories. This high-speed catamaran passenger vessel is 33m long, 10m wide, and 3.4m high, and can transport up to 150 passengers in inland waters. Figure 5 shows the conceptual design of the vessel. The total installed power of the SF-BREEZE is 4.92MW, with 4.40MW for propulsion and 120kW for auxiliary power. The FC system comprises 41 proton exchange membrane (PEM) FC, each with a capacity of 120kW. The hydrogen is stored in a 1,200kg (approximately 4,500 gallons) storage tank in liquid form on the top deck, which is sufficient for two 50nm round trips (4 hours of continuous operation) at a maximum speed of 35 knots. The LH_2 flows from the storage tank to the FC compartment through the vaporizers. The SF-BREEZE also includes a battery system that can power communications and navigation equipment for 1-2 hours.

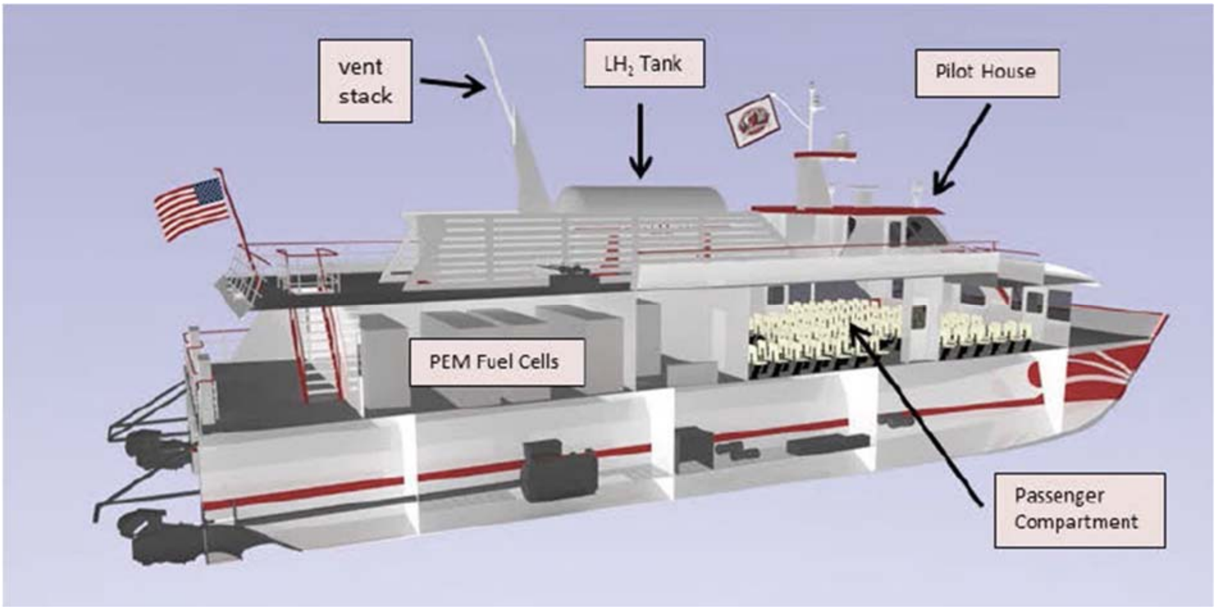


Figure 5. SF- BREEZE vessel conceptual design [31]

For the FMEA purposes, the system was divided into nine subsystems: hydrogen storage, FC system, propulsion system, onboard bunkering station, ventilation system, hydrogen supply system, venting system, safety devices, and batteries. The team consisted of cross-functional members with different backgrounds, academic and practitioners, with subject matter knowledge and experience in naval architecture and marine engineering, system engineering, mechanical engineering, and cryogenics. Additionally, the team has experience in facilitating and understanding the FMEA process.

Tables 3, 4, and 5 were developed to evaluate the Severity, Occurrence, and Detectability potential of the failure modes identified, respectively. A five-scale rating was used to reduce complexity. The failure modes were identified primarily from recorded safety incidents from land-based applications, and the team assigned ratings based on datasets such as leak frequencies and ignition probabilities obtained from acknowledged databases such as HAID2.0 (Hydrogen Incident and Accident Database), FACTS (Failure Accidents Technical Information System), and ARIA (Analysis, Research, and Information on Accidents) [32].

A total of 82 failure mode effects were identified and analyzed across 19 functional blocks. Among them, 48 were deemed insignificant in terms of severity. For the remaining 34 failure mode effects, only 4 were categorized as high priority. Most of these failure scenarios were related to fire and explosion incidents due to storage tank failures and FC system malfunctions. Addressing these issues would require further investigation to determine hazardous zones and thresholds that can minimize the consequences, improve detectability, or reduce the likelihood of occurrence. Additionally, 4 failure mode effects were identified as posing a safety hazard with a high consequences rating of 4 or 5 and were related to external parameters such as collision and fire incidents not related with the fuel system.

Table 3. Severity (S) rating scale

S	Severity scale of the effect	Severity criteria
5	Catastrophic	Most severe type of failure, can result in fatalities or damage without warning
4	Major	Significant injuries or damage/loss to the system, but no fatalities
3	Moderate	System damage/breakdown, no injuries, or fatalities
2	Minor	Disturbance in the operation of the system but doesn't lead to system breakdown.
1	No effect	Failure doesn't affect normal system operation

Table 4. Occurrence (O) rating scale

O	Likelihood of failure occurrence	Occurrence criteria
5	Extremely likely	Failure almost inevitable
4	High likelihood	Failure is likely to occur
3	Moderate likelihood	Failure could occur, but the likelihood is considered moderate
2	Low likelihood	Failure may occur, but the likelihood is low
1	Unlikely failure	Preventions controls eliminate failure, or failure is unlikely

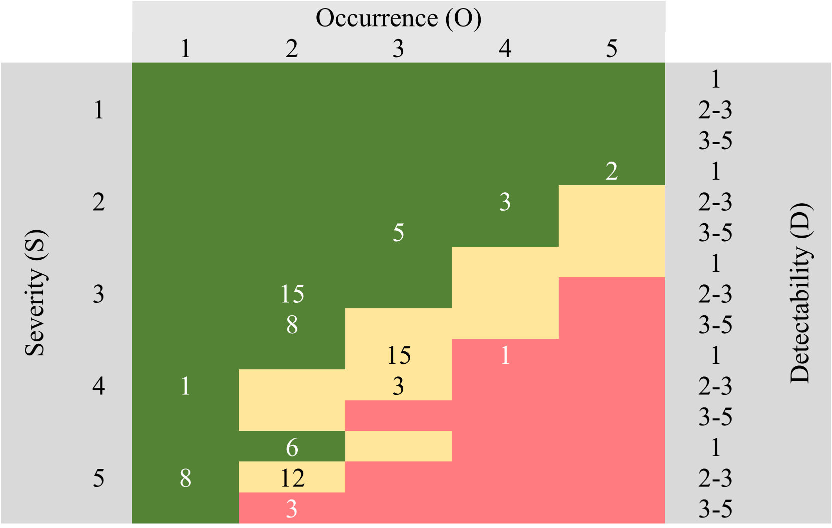
Table 5. Detectability (D) rating scale

D	Ability to detect mechanism of failure	Detection method maturity
5	Almost impossible	Detection procedure yet to be developed
4	Low	New detection method; not proven.
3	Moderate	Proven detection method
2	High	Proven and verified detection method
1	Almost certain	Current control almost certain to detect cause of failure

Next, the FMEA team evaluated the results and revised the risk mitigation actions such as efficient room ventilation, suitable material selection, safety devices installation, and isolation strategies of faulty components and sub-systems. The revised AP table was conducted, as shown in Table 6.2, as part of the optimization process. It is observed that the number of high-priority actions has been reduced but has not been eliminated due to uncertainties derived from a lack of long-term experience of hydrogen application onboard maritime vessels.

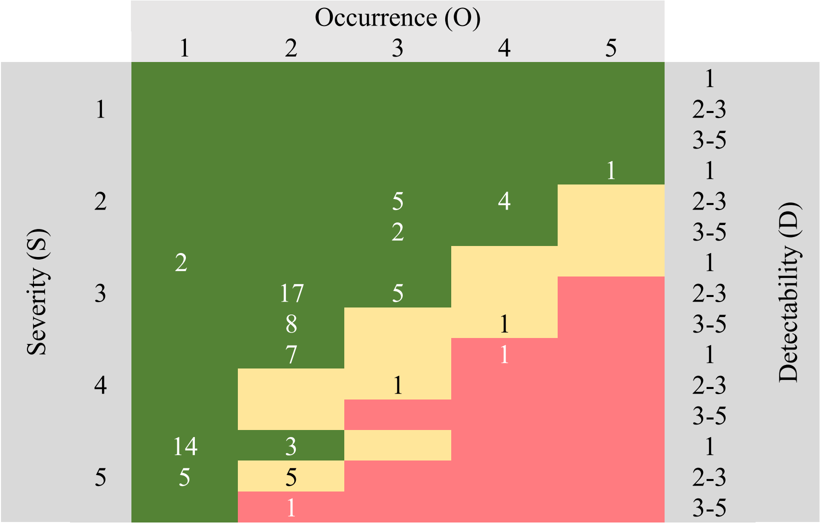
While interpreting the results of this risk assessment, it's essential to note that they are specific to this case study. However, the framework proposed in this study is modular and can be implemented in other systems as well. Moreover, it's important to acknowledge that the outcomes of a risk assessment can be subjective, depending on the team's characteristics conducting the assessment. Nationalities, safety cultures, knowledge, and experience are some of the factors that can influence the results. Nonetheless, it's important to emphasize that risk assessments are a valuable tool in transforming the maritime industry's approach from reactive to proactive.

Table 6.1 Action Priority (AP) rating



		Occurrence (O)				
Severity (S)	Detectability (D)	1	2	3	4	5
1	1	🟩	🟩	🟩	🟩	🟩
	2-3	🟩	🟩	🟩	🟩	🟩
	3-5	🟩	🟩	🟩	🟩	🟩
2	1	🟩	🟩	🟩	🟩	🟩 2
	2-3	🟩	🟩	🟩	🟩 3	🟨
	3-5	🟩	🟩	🟩 5	🟩	🟨
3	1	🟩	🟩	🟩	🟨	🟨
	2-3	🟩	🟩 15	🟩	🟨	🟥
	3-5	🟩	🟩 8	🟨	🟨	🟥
4	1	🟩	🟩	🟨 15	🟥 1	🟥
	2-3	🟩 1	🟨	🟨 3	🟥	🟥
	3-5	🟩	🟨	🟥	🟥	🟥
5	1	🟩	🟩 6	🟨	🟥	🟥
	2-3	🟩 8	🟨 12	🟥	🟥	🟥
	3-5	🟩	🟥 3	🟥	🟥	🟥

Table 6.2 Revised Action Priority (AP) rating



		Occurrence (O)				
Severity (S)	Detectability (D)	1	2	3	4	5
1	1	🟩	🟩	🟩	🟩	🟩
	2-3	🟩	🟩	🟩	🟩	🟩
	3-5	🟩	🟩	🟩	🟩	🟩
2	1	🟩	🟩	🟩	🟩	🟩 1
	2-3	🟩	🟩	🟩 5	🟩 4	🟨
	3-5	🟩	🟩	🟩 2	🟩	🟨
3	1	🟩 2	🟩	🟩	🟨	🟨
	2-3	🟩	🟩 17	🟩 5	🟨	🟥
	3-5	🟩	🟩 8	🟨	🟨 1	🟥
4	1	🟩	🟩 7	🟨	🟥 1	🟥
	2-3	🟩	🟨	🟨 1	🟥	🟥
	3-5	🟩	🟨	🟥	🟥	🟥
5	1	🟩 14	🟩 3	🟨	🟥	🟥
	2-3	🟩 5	🟨 5	🟥	🟥	🟥
	3-5	🟩	🟥 1	🟥	🟥	🟥

7.0 CONLUSIONS

The maritime industry is actively exploring the potential of hydrogen as a clean fuel for ships, as a response to growing environmental concerns and the need for green energy alternatives. It is important to note, however, that the use of hydrogen as a fuel on board ships is still in the demonstration phase, and ongoing research and development is being conducted to ensure its safety. This paper aims to propose a systematic FMEA risk assessment approach that overcomes the limitations of conventional techniques and improves prioritization of mitigation actions. The proposed method has been shown to be more effective than conventional FMEA approaches in solving the risk prioritization problem. The AP rating method reduces complexity and utilizes more efficiently the available team resources for risk assessment. However, it is important to incorporate tools and methods that can handle uncertainties arising from incomplete datasets and the subjective judgment of the team. The FMEA method remains a useful tool for assessing safety risks, particularly during the early design phase, and can provide insightful information for risk reduction. Further research is needed to integrate the proposed approach with other risk management techniques.

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