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A priority-based Failure Mode And Effects Analysis (FMEA) method for risk assessment of H_2 applications onboard maritime vessels

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CONTENTS

1. H2 PROPERTIES ASSOCIATED WITH SAFETY

H_2

- small molecular size
- wide flammability limits
- Lower minimum ignition energy (MIE)
- Increased flame velocity
- high diffusivity
- Increased combustion temperatures
- hydrogen embrittlement effect

2. KEY SAFETY CONSIDERATIONS

Onboard hydrogen storage

➢ Lower volumetric energy density of H_2 require **larger volumes** to be stored	inherently increasing safety risks
➢ H_2 storage tanks onboard face **different conditions** (corrosive sea environment, high-frequency vibrations, high stress concentrations, e.tc.)	increased risk of H_2 tank failures
➢ Potential **collision incidents**	increased risk of H_2 tank damage
➢ Onboard **fire incident**, pressure build-up inside the tank	catastrophic tank rupture, risk of blast wave or fireball effects [1]
➢ **Hydrogen embrittlement** effect	material degradation especially in cryogenic applications [2]

2. KEY SAFETY CONSIDERATIONS

Hydrogen handling

- **H_2 leakage** in confined spaces
- **Venting system misfunction**
- **Inappropriate ventilation** rates in critical spaces, combined with a leakage incident
- **Failure of Fuel Cells system**
- **Failure of ICE system,** undesired combustion phenomena (combustion anomalies)

formation of flammable gases, increased fire and explosion risks [3]

potential adverse consequences in case of a forced H_2 release into the atmosphere [4]

formation of flammable gases, increased fire and explosion risks

leakage, increased fire and explosion risks [5]

Increased fire and explosion risks [6]

2. KEY SAFETY CONSIDERATIONS

Hydrogen bunkering

➢ **Larger volumes** and **faster filling rates**	could impact the amount of fuel release in case of a loss of contaminant event
➢ Unexpected **H_2 release** in gaseous bunkering	will result in different hazardous and safety zones
➢ **Liquid H_2 spills**, formation of cryogenic vapors	severe frostbit, asphyxiating atmosphere
➢ **Large H_2 spills**, dispersion of vapor clouds that are heavier than air	increased risk of explosion
➢ **Fire incident** and heat increase into the LH_2	risk of Boiling Liquid Expanding Vapor Explosions (BLEEVE effect) [7]

2. KEY SAFETY CONSIDERATIONS

Pic 1. A tanker truck on fire at the Pilot Travel Center gas statio, USA April 2023

3. REGULATORY GAPS

In the maritime industry, regulatory bodies include international regulations developed by the International Maritime Organization (IMO), national Regulations, and Class rules.

- Current regulations for **LNG bunkering (ISO/TC18683)** are not sufficient to cover the specific characteristics and hazards associated with hydrogen

- **International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF Code)** [8] governs ship-side bunkering of gases, but it does not include specifications for hydrogen

- 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.

3. REGULATORY GAPS

The regulatory framework for hydrogen (H_2) onboard maritime vessels is still in its early stages. Several key areas require attention:

- Establishing **minimum safe distances** and **hazardous zones** for H_2 bunkering operations
- Providing **comprehensive training for maritime personnel**
- Addressing **ventilation requirements**, developing **effective methods for H2 leak detection**
- Implementing safety measures to **prevent fire propagation and explosion**
- Develop **clear protocols for emergency response**

4. RISK ASSESMENT

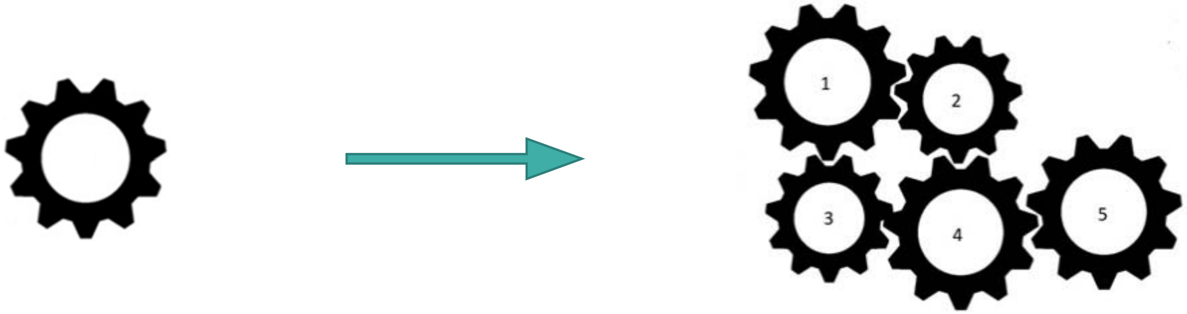
The adoption of H_2 as a fuel introduces new safety risks that require identification, assessment, and effective management to prevent harm to individuals, environmental damage, and asset loss.

For land-based applications, various hydrogen risk assessment methods are available, including:

- **HAZID**
- **HAZOP**
- **FTA**
- **FMEA**
- **CFD** models have been utilized to evaluate the consequences of potential failures [8]
- **QRA** have been employed to examine critical safety incidents involving multiple physical parameters often interrelated [9]

5. FAILURE MODE AND EFFECTS ANALYSIS (FMEA)

The **FMEA** as a risk assessment method



component-level failures

impact on higher-level systems

FMEA originally developed for military system design

Then applied in various industries, including aerospace, automotive, and maritime industry

FMEA has also extensively used in risk assessment related to H_2 applications

6. PRIORITY-BASED FMEA

- In 2019 , the **Automotive Industry Action Group (AIAG)** and the **German Association of the Automotive Industry (VDA)** published a revised guideline for FMEA which was originally developed for automotive industry [10]

- The fundamental change was the replacement of the **Risk Priority Number** (**RPN)** with a new **Action Priority (AP)** rating

In conventional FMEA methods the risk of potential failures is evaluated using the RPN, which is defined as the product of Severity (S), Occurrence (O), and Detectability (D), as shown below:

$$RPN_i = S_i \times O_i \times D_i$$

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

6. PRIORITY-BASED FMEA

For instance, consider two failure modes:

Failure mode 1: $\mathrm{RPN}_1 = S_1 \times O_1 \times D_1 = 5 \times 1 \times 2 = 10$

Failure mode 2: $\mathrm{RPN}_2 = S_2 \times O_2 \times D_2 = 2 \times 1 \times 5 = 10$

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.

To address this issue, the revised FMEA replaced the RPN with the new AP rating to enable prioritization of recommended actions.

The previous example will give:

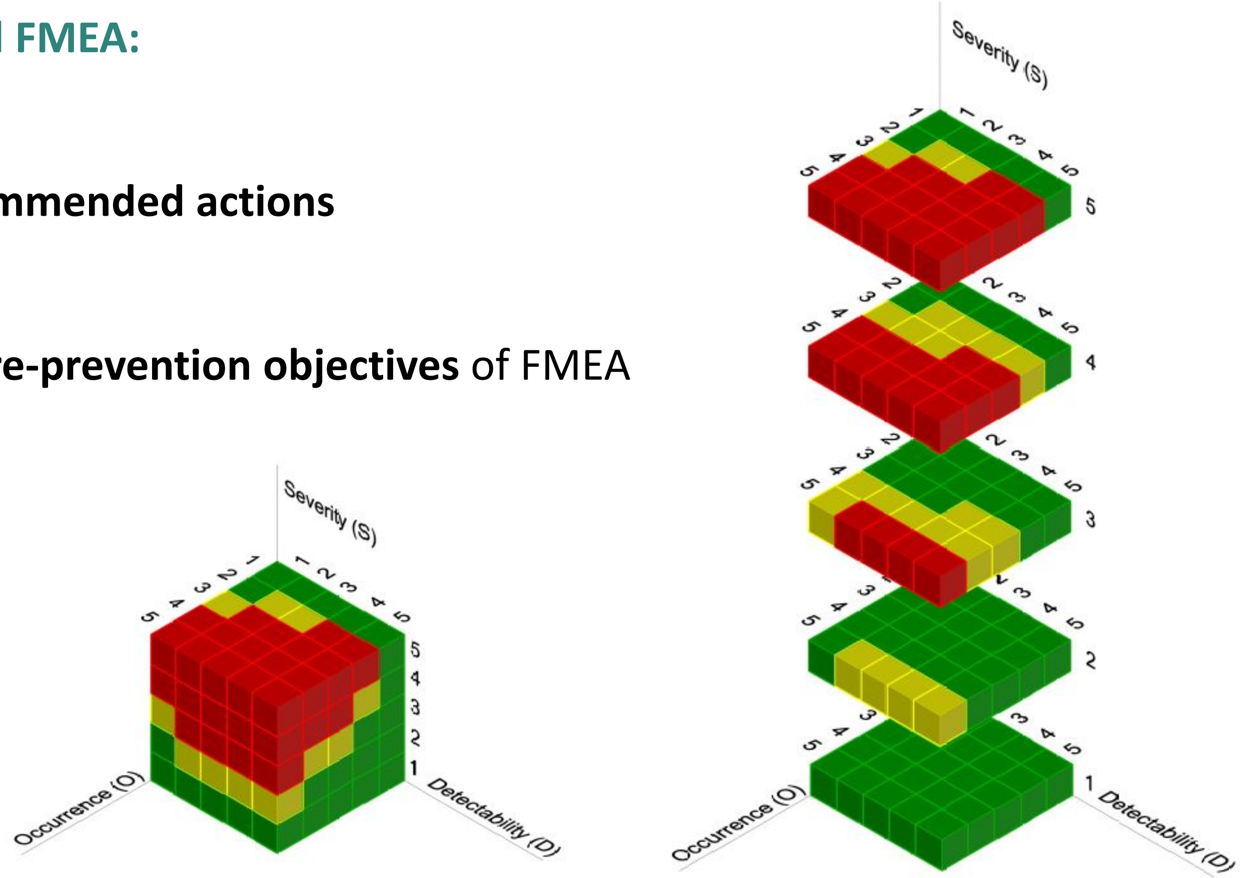
Failure mode 1: AP_1 = Hight Priority for review and action

Failure mode 2: AP_2 = Low Priority for review and action

6. PRIORITY-BASED FMEA

Advantages of the priority-based FMEA:

- focuses on **high-severity risks**
- enables **prioritization of recommended actions**
- **reduces complexity**
- is more aligned with the **failure-prevention objectives** of FMEA



7. METHODOLOGY

Table 1. The 7-step methodology of priority-based FMEA

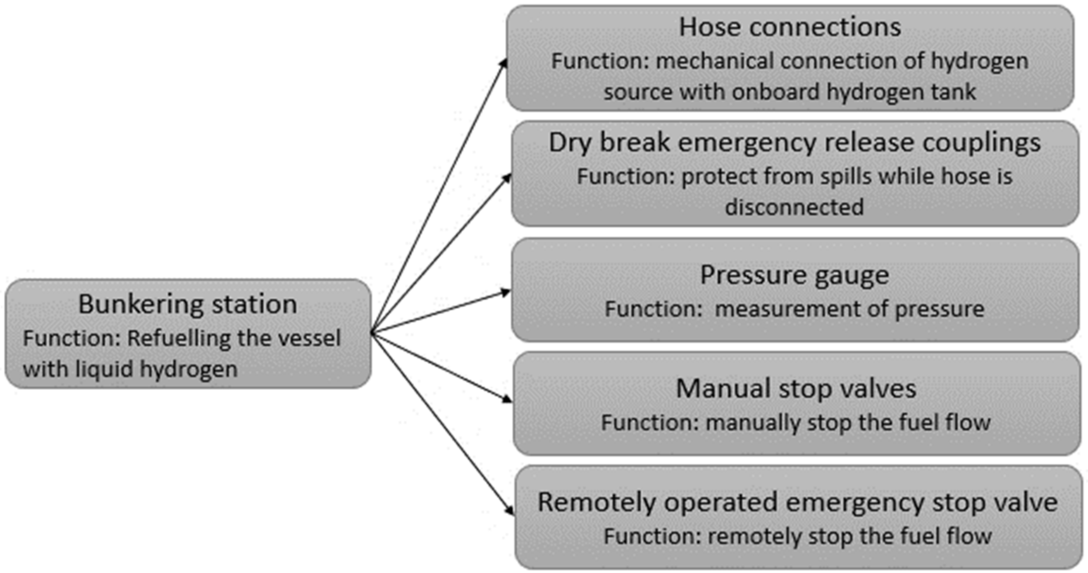
System analysis	1st Step Planning & Preparation
	2nd Step Structure Analysis
	3rd Step Function Analysis
Failure Analysis & Risk Mitigation	4th Step Failure Analysis
	5th Step Risk Analysis
	6th Step Optimization
Risk Comm.	7th Step Results Documentation

7. METHODOLOGY

1st step: Planning and preparation

- scope of the study should be defined
- boundaries of the analysis should be establis

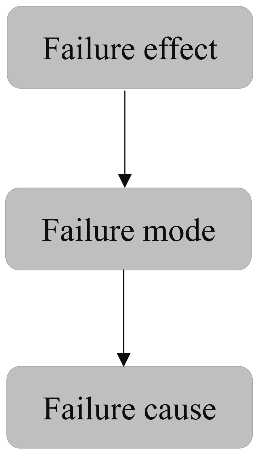
3rd step: Function Analysis



2nd step: Structure Analysis

7. METHODOLOGY

4th step: Failure Analysis



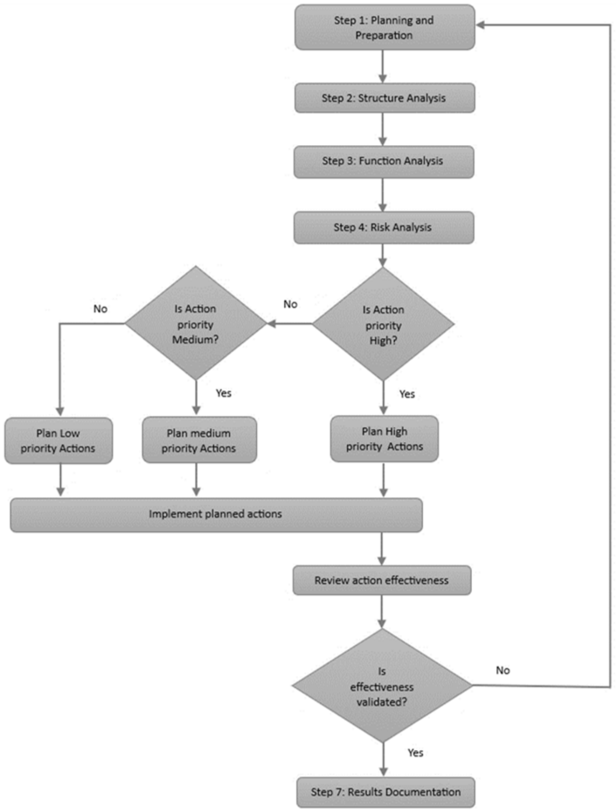
5th step: Risk Analysis

Table 2. Action Priority (AP) rating system

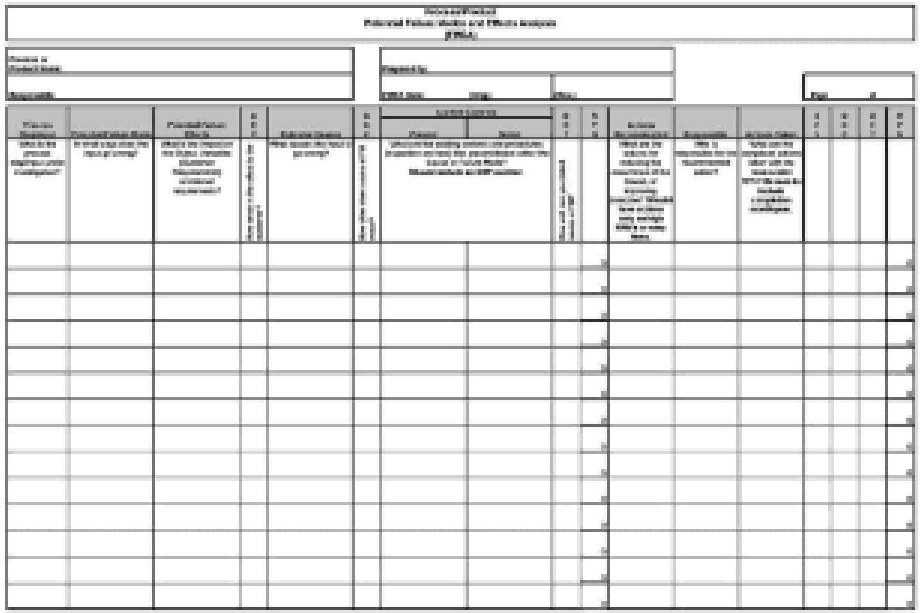
High Priority (HP)	Require immediate attention for review and action. The team must prioritize identifying an appropriate action plan that improves prevention and/or detectability.
Medium Priority (MP)	Require a medium urgent level of attention for review and action. The team should focus on identifying 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.

7. METHODOLOGY

6th step: Optimization



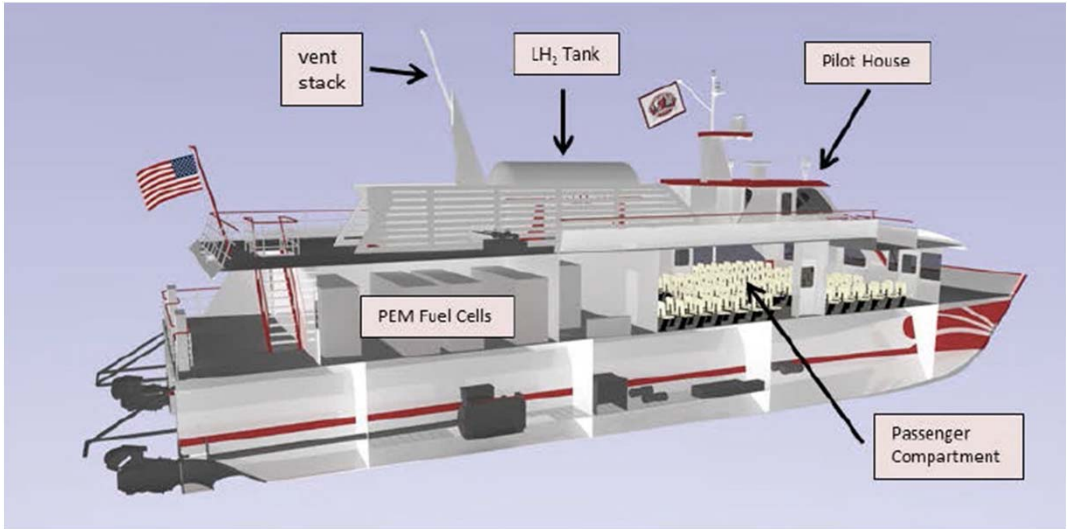
7th step: Results Documenation



8. INDICATIVE CASE STUDY

The vessel used for the case study is based on a high-speed catamaran passenger vessel SF-BREEZE ferry [11], designed by Sandia National Laboratories.

- 33m long, 10m wide and 3.4m high,
- up to 150 passengers
- total installed power of is 4.92MW
- 41 PEM FC each with a capacity of 120kW.
- The liquid H2 tank of 1,200kg (approximately 4,500 gallons)on the top deck
- two 50nm round trips (4 hrs of operation) at a maximum speed of 35 knots



8. INDICATIVE CASE STUDY

- The failure modes were primarily identified from recorded safety incidents on land and datasets, including leak frequencies and ignition probabilities obtained from reputable databases such as HAID2.0, FACTS, and ARIA
- Severity, Occurrence, and Detectability potential for the identified failure modes were assessed using SOD rating tables (Tables 3, 4, and 5), respectively. A five-point scale was employed to reduce compexity
- Subsequently, the AP rating table (Table 6.1) was generated based on the information from the SOD tables
- Following this, the FMEA teams conducted a review of the results in an iterative process (Optimization step) until the desired risk level was achieved and produced the Revised AP rating table (Table 6.2)

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

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8. INDICATIVE CASE STUDY

- A total of 82 failure mode effects were identified and analyzed across 19 functional blocks. Among these, 48 were considered insignificant in terms of severity
- Out of the remaining 34 failure modes, only 4 were categorized as high priority. Most of these high-priority modes were associated with fire and explosion incidents resulting from storage tank failures and FC system malfunctions
- Further investigation is essential to determine hazardous zones and thresholds that can minimize the consequences, enhance 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. Notably, these effects were related to external parameters, such as collisions and fire incidents, which were unrelated to the fuel system

Table 6.1 Action Priority (AP) rating

Severity (S)	Detectability (D)	Occurrence (O) 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

Severity (S)	Detectability (D)	Occurrence (O) 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			

9. CONCLUSIONS

The use of H_2 as a fuel on board ships is currently in the demonstration phase, with ongoing research and development efforts focused on ensuring its safe utilization

- The proposed priority-based FMEA method addresses the limitations of conventional techniques and enhances the prioritization of mitigation actions
- 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 continues to be a valuable tool for assessing safety risks, especially during the early design phase, thereby shifting the maritime industry's approach from a reactive to a proactive stance.

Further research is necessary to seamlessly integrate the proposed approach with other risk management techniques

Thank you!

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Maritime Risk Group (MRG)

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