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Quantitative Risk Assessment: Frequency Analysis of a Liquid Hydrogen Tank Container Swap Operation on a Passenger Ship

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Abstract. The transition to alternative fuels in the maritime sector necessitates innovative ship designs and refueling strategies in order to meet the European Green Deal 2050 targets on sustainability and emissions. Liquid hydrogen (LH_2), as an energy carrier, presents a compelling option due to its high energy density per unit mass and zero-carbon emissions potential for fuel cell applications. However, LH_2 cryogenic nature (20 K boiling point), low volumetric energy density, and unique safety concerns related to leakage and flammability, introduce significant engineering and operational challenges. One pioneering solution for LH_2-fueled passenger vessels is a tank container swap system, subject of the study, which enables refueling through pre-filled containerized hydrogen tanks, rather than traditional bunkering; offering logistical advantages and flexibility, while also raising critical safety considerations that must be assessed and properly quantified. Recently, the Quantitative Risk Assessment (QRA) methodology has gained significance as Classification Societies require it for alternative design processes involving non-conventional fuel system designs. The study focuses on the Frequency Analysis, which constitutes a key component of QRA. Hazardous scenarios are identified, and component reliability is established according to consolidated databases (e.g. HSE, OREDA) widely accepted for LNG systems. Special attention is given to data consistency issues as a recognized statistical record for LH_2 equipment failure rates is still missing. An influence matrix is composed to quantitatively evaluate the failure scenario frequencies, highlighting the most relevant factors and enabling the design of focused mitigation strategies. The computation provides the estimated frequency of a hydrogen release event, which, subsequently combined with a Consequence Analysis will help define a safe operational domain. The study contributes to the ongoing research on LH_2 system design for maritime applications, through a structured Frequency Analysis approach, essential for effective risk assessment.

Keywords. Liquid Hydrogen, Risk Assessment, Frequency Analysis

1. Introduction

The transition to alternative fuels in the maritime sector necessitates innovative ship designs and refueling strategies in order to meet the targets set by the International

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Maritime Organization (IMO) and the more restrictive European Green Deal 2050 on sustainability and emissions reduction [1,2]. Differently from conventional marine fuels, hydrogen combustion produces no CO_2, sulfur oxides (SO_x), or particulate matter [3], making it an attractive option for reducing the environmental footprint of the shipping industry [4]. Among alternative fuels, liquid hydrogen (LH_2) has emerged as a promising solution for the decarbonization of the maritime sector [5],due to its high energy density per unit mass (120 MJ/kg lower heating value) and its potential for zero-carbon emissions when used as an energy carrier in fuel cells [6].

However, the cryogenic nature of LH_2, with its extremely low boiling point of 20 K (-253°C) at atmospheric pressure [7], combined with its low volumetric energy density and the inherent risks associated with leakage, flammability, and potential hydrogen embrittlement of metals [8], presents unique engineering challenges. Therefore, innovative storage, handling, and refueling strategies are studied, in order to ensure both safety and efficiency of maritime applications.

1.1. Alternative Fuels and Alternative Design

Alternative fuel systems, i.e. systems based on non-traditional fossil fuels such as heavy fuel oil (HFO) or marine diesel oil (MDO), with the exception of liquefied natural gas (LNG), need to be dealt with through an alternative design process in order to prove their safety, consistently with the MSC.1/Circ.1455 [9] issued by IMO. LH_2-based design solutions for ship propulsion are not exempted from such procedure, as only interim dedicated regulations, e.g. MSC.420(97), are available [10]. In fact, the International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels (IGF Code) is developed basing on LNG [11], not explicitly dealing with other promising fuels and energy carriers, such as hydrogen.

The recent commissioning of LNG-powered passenger ships, which have a reduced carbon intensity thanks to their dual-fuel power plants, is a clear signal of a market transition towards sustainability. However, the ambitious goals set to counter climate change necessitate even more effective applications; one viable option is the use of LH_2 as an energy carrier [12].

An innovative solution for hydrogen-fueled passenger ships is the adoption of swappable, containerized LH_2 ISO tanks [13]. Instead of relying on a bunkering infrastructure, as in the case of the Norwegian ferry MF Hydra, which has a fixed, Type C [14], LH_2 tank on the top deck [15], a swappable tank configuration offers supply and refilling flexibility; essential as green hydrogen delivery facilities are not capillary distributed yet. While offering an appealing solution for fuel cell applications and enabling a Zero-Emission Mode (ZEM) navigation profile, this design and fuel introduce unique risks and safety challenges that must be thoroughly analyzed. However, it should be noted that a general lack of standardization for LH_2 technologies and transfer operations persists [16].

1.2. Safety and Risk Assessment

Consistently with the shift from a prescriptive towards a goal-based regulatory framework [17], Classification Societies and Administrations are integrating alternative design principles with a risk-based certification approach, basing on IMO Formal Safety Assessment (FSA) [18]. In Figure 1, the flowchart of the FSA methodology is presented. In order to obtain approval from Classification Societies and Administrations, the risk associated with the proposed design must be quantitatively assessed. This substantially involves answering the following three questions, known as the risk triplet [19].

1. What can go wrong?
2. What is the likelihood?
3. What are the consequences?

A commonly applied methodology, often used in FSA is the hazard identification (HAZID) study, a structured and systematic approach used to identify potential hazards associated with a system, process, or operation. In order to address the first fundamental risk-defining question, Preliminary Hazard Identification (PHA) is typically conducted in the early stages of design and risk assessment in order to proactively recognize and mitigate risks before they escalate into major safety concerns. Several hazard identification methods extended beyond PHA and contribute to addressing also the other two fundamental questions that define risk [20].

The HAZID process involves a multidisciplinary team utilizing brainstorming sessions, checklists, and guidewords to evaluate credible hazards, considering factors such as operational conditions, environmental influences, and human interactions [21]. The outcomes of a HAZID study include a comprehensive list of identified hazards, their possible consequences, preliminary risk rankings, and recommendations for risk reduction measures. This process serves as a foundational step in safety management, supporting subsequent risk assessments such as hazard and operability study (HAZOP) and quantitative risk assessment (QRA).

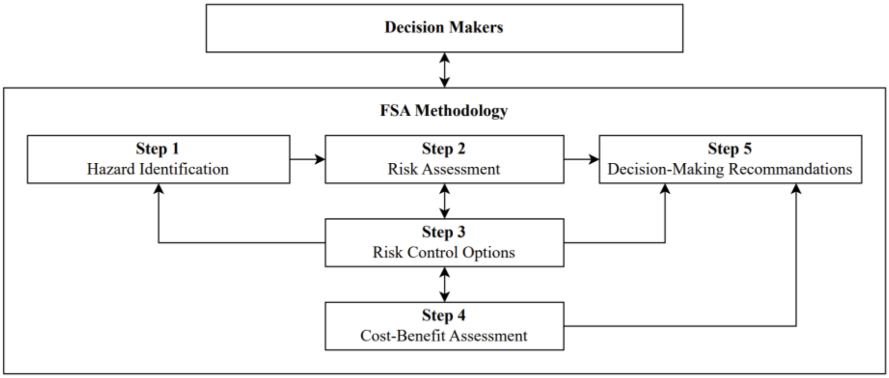

Figure 1. FSA methodology flowchart [18].

1.3. Quantitative Risk Assessment

Quantitative risk assessment (QRA) has its origins in the second half of 20th century, emerging as a formalized approach to systematically evaluate risks in complex engineering systems. Early applications were driven by the nuclear and aerospace industries [22,23], where understanding failure probabilities was critical for ensuring safety. The development of fault tree analysis (FTA) in the 1960s, along with probabilistic risk assessment (PRA) methodologies, laid the foundation for modern QRA practices [24]. Over the decades, QRA expanded into various high-risk industries, including chemical processing [25], offshore oil and gas, and transportation, evolving to incorporate probabilistic models, statistical methods, and computational tools. Nowadays, QRAs play a crucial role in risk-informed decision-making, integrating uncertainty analysis and regulatory compliance to enhance safety and reliability.

The peculiar characteristic of QRA is the ability to quantitatively analyze the likelihood, effect, and resulting risk associated with Low-Probability High-Consequence (LPHC) events. In fact, once the process or system under study is defined, and the hazardous scenarios are identified during PHA/HAZID, the core of a QRA consists of the Frequency Analysis and the Consequence Analysis, which consent the production of a risk assessment. In Figure 2 is reported a schematic illustration of QRA, consistent with the ISO 31000 approach [26].

The Frequency Analysis is the study which answers the second fundamental risk-defining question, as the objective is to calculate the probability of the previously identified accident scenarios. For systems failure it is common practice referring to historical accident records. Alternatively, FTA is adopted for accidents due to components failure; such failure frequencies are typically collected in recognized reliability databases.

The Consequence Analysis, answering the third risk-defining question, quantifies the negative impact of an event occurrence. Consequences to people are usually expressed in terms of severe injury or fatalities deriving from thermal radiation, overpressure due to explosion, and harmful exposure (e.g. chemicals, nuclear radiation).

The product of Frequency and Consequence Analysis gives a risk profile which is to be confronted with a risk acceptability criterion. This methodology highlights the most critical aspects for safety and can address mitigations from early design stages, in order to achieve an acceptable risk level. When the cost of a further risk-reduction measure would exceed its benefits, the residual risk can be considered As Low As Reasonably Practicable (ALARP), and therefore, no additional measures need to be taken [18].

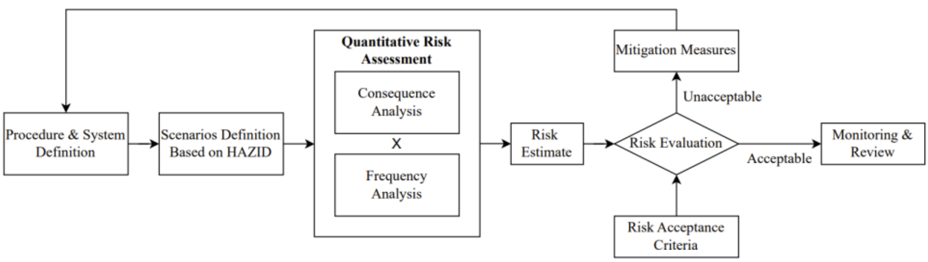

Figure 2. Quantitative Risk Assessment methodology.

1.4. Research Objectives

The research focuses, in the context of QRA, on the Frequency Analysis of an innovative LH_2 tanks swap operation. Particularly, due to the unprecedented engineering and technical aspects, components failure rates and leakage frequencies have to be carefully analyzed and selected. The objective is to establish a time-based Frequency Analysis of a major uncontrolled hydrogen release, highlighting the most critical scenarios, enabling the suggestion of effective mitigation strategies.

2. Methodology

The study focuses on the Frequency Analysis of an LH_2 containerized tank swap operation QRA. Particularly, the objective is to quantify the probability of a major hydrogen leakage that could lead to a catastrophic fire/explosion. In order to investigate such occurrence, a hybrid HAZID/FTA methodology was adopted to identify the hazardous scenarios and failure modes.

Established the tanks possible status and location with respect to the ship, the cumulative time associated with each configuration was estimated. Consequently, all critical failure scenarios were identified. Failure frequencies were then selected reviewing reliability databases, e.g. HSE, IOGP, OREDA [27–29], and latest available studies. It should be noted that most of recognized values for components failure rates are derived from surveys conducted by the oil and gas industry, on offshore hydrocarbon production facilities. In fact, hydrogen-based systems are relatively scarcely widespread yet, and recognized consolidated datasets are still missing. However, when no detailed information is available, LNG-native components behavior adoption is generally accepted for LH_2 systems QRA purposes, due to the cryogenic nature of both fuels.

The core of the research focused on the literature review of system components failure rates suitable for the Frequency Analysis of a hydrogen system dealing with both liquid and gaseous phase. The found values of interest, expressed in different units of measures (e.g. 10^{-6} hours^{-1}, years^{-1}, lifts^{-1}), were then homogenized.

The operation phases and failure scenarios are treated as vectors and are used to construct an influence matrix containing the failure frequencies for each tank configuration-failure scenario couple. The same structure is used for the mitigation matrix, where the effect of safety measures and operational limitations is quantitatively assessed, basing on qualitative considerations.

Finally, the homogenized failure frequencies are weighted basing on the effective operative time and multiplied by the number of yearly swap operations foreseen. The overall frequency obtained is, therefore, the occurrence of a major hazardous hydrogen release per year, associated with the total number of swap operations. In conclusion, assuming an ignition probability model, the frequency of a hydrogen fire scenario can be quantitatively assessed.

Additionally, by combining the Frequency Analysis results with a Consequence Analysis, the QRA process can be concluded, outputting a risk metric. Nevertheless, the Consequence Analysis, which involves its own critical assumptions (e.g. thermal model, harmful dose definition, exposure assumptions), is beyond the scope of the present study.

3. Case Study

3.1. Ship Operative Profile

Passenger ships will inevitably need to adapt to the increasing severity of regulations concerning the environmental impact of ship tourism and the extension of Emission-Controlled Areas (ECAs) [30]. In fact, zero-emissions requirement will progressively become a fundamental technological innovation driver in the upcoming decade, as national authorities are already issuing laws in such direction. In Norway, e.g., by January 2026, navigation in World Heritage fjords will be permitted only to tourist ships and small ferries complying with zero-emission requirements [31].

Therefore, the selected case study is a small passenger ship, which for commercial reasons needs to be able to sustain a ZEM operative profile, for a limited amount of time. The vessel presents a conventional MDO power plant which ensures ordinary operativity. Additionally, in order to guarantee ZEM navigation in naturalistic reserves or port stops, the ship is equipped with a LH_2 and fuel cells system capable of sustaining both the propulsion and auxiliaries loads.

3.2. LH_2 System Description

The general system architecture is IGF Code compliant, based on two swappable containerized LH_2 Type C ISO tanks. Once embarked, the tanks are stowed inside the Fuel Storage Hold Space (FSHS) and are coupled to the Tank Connecting Spaces (TCS), which are adjacent to the Fuel Preparation Rooms (FPR). The tanks are connected to the ship hydrogen and venting systems by means of flexible hoses. Pressurizing the tanks, LH_2 is transferred to the FPR, where it is vaporized and sent to the Proton Exchange Membrane Fuel Cells (PEMFC).

The tanks are equipped with their own vent piping, complying with road transportation standards for dangerous goods [32], in case of an overpressure event during the transfer, the opening of the Pressure Relief Valve (PRV) conveys the gaseous hydrogen to the Road-Side Vent (RSV). Once the containers are successfully coupled to the ship, venting is managed through the onboard line leading to the vent mast.

3.3. Frequency Analysis

The LH_2 tanks swap operations assumed are 50 per year (ca. one per week). The top event identified is the uncontrolled hydrogen release through the RSV. Additionally, flanges and valves leakage are also taken into account. In order to adequately evaluate risk during the different swap operation phases, it is important to track the RSV position relative to the ship enclosed spaces and the filling level of the tank, as it is never completely emptied for cooling down reasons. In Table 1, the assumed timings of the operations are reported along with the tank configuration. The considered failure scenarios, leading to a hydrogen release, and their relative expected frequencies is reported in Table 2.

An influence matrix (Table 3) is then composed, accounting for each phase timing and possible failure occurrence. The matrix is the fundamental tool developed, enabling a rapid quantitative evaluation of the most impacting conditions on risk. In Table 3, the lower coefficients are the most impacting, as the associate failure events are more frequent.

In order to account for risk mitigation strategies and design safety arrangements, a mitigation matrix (Table 4) is composed, basing on arbitrary coefficients estimating the risk reduction associated with each measure.

In Table 3, the final influence matrix values, i.e. accounting for mitigations, assuming the total number of swap operations in a year, are reported. The lower coefficients are the most impacting, as the associate failure events are more frequent.

Finally, two different ignition probability models are confronted, assuming a hydrogen release event with an outflow rate of 0.80 kg/s [33]. The first one is the step function model [34], adopted by HyRAM+ [35], while the second one, proposed in [36], developed by Hansen, is continuous.

Table 1. Assumed timings of the tanks swap operation.

ID	Tank	RSV	Status	Duration
a	Empty	Inside	Connected Vent	1500 s
b	Empty	Inside	Disconnected Vent	270 s
c	Empty	Inside	Unloading	270 s
d	Empty	Outside	Unloading	600 s
e	Empty	Outside	Awaiting	300 s
f	Full	Outside	Awaiting	90 s
g	Full	Outside	Loading	600 s
h	Full	Inside	Loading	270 s
i	Full	Inside	Disconnected Vent	270 s
j	Full	Inside	Connected Vent	1500 s

Table 2. Relevant failure scenarios identified.

ID	Assumed Failure Scenario	Parts Count	Total Frequency	Unit	Ref.
1	Valve leakage	4	8.00E-04	1/year	[27]
2	Flange leakage	2	1.00E-05	1/year	[27]
3	PRV spurious operation	2	5.43E-03	1/year	[29]
5	Vacuum loss	1	5.00E-06	1/year	[28]
6	Tank holding-time exceedance (human error)	1	1.00E-03	1/year	[37]
8	Dropped objects leading to vacuum loss	1	1.00E-04	1/year	[38]
9	Dropped tank leading to vacuum loss	1	6.00E-07	1/lift	[27]
10	Dropped tank leading to 50mm hole	1	6.00E-07	1/lift	[27]
11	Dropped tank leading to pool fire	1	3.00E-08	1/lift	[27]

Table 3. Influence matrix expressed as $-\log_{10}(frequency)$.

ID	1	2	3	5	6	8	9	10	11
a	5.42	7.32	-	-	-	-	-	-	-
b	6.16	8.07	5.33	8.37	9.07	-	-	-	-
c	6.16	8.07	5.33	8.37	9.07	7.07	-	-	-
d	5.82	7.72	4.99	8.02	8.72	6.72	6.22	6.22	7.52
e	6.12	8.02	5.29	8.32	9.02	7.02	-	-	-
f	6.64	8.54	5.81	8.85	9.54	7.54	-	-	-
g	5.82	7.72	4.99	8.02	8.72	6.72	6.22	6.22	7.52
h	6.16	8.07	5.33	8.37	9.07	7.07	-	-	-
i	6.16	8.07	5.33	8.37	9.07	-	-	-	-
j	5.42	7.32	-	-	-	-	-	-	-

Table 4. Mitigation matrix applied.

ID	1	2	3	5	6	8	9	10	11
a	1	1	-	-	-	-	-	-	-
b	1	1	1	1	0.001	-	-	-	-
c	1	1	1	1	0.001	1	-	-	-
d	1	1	1	1	0.001	1	0.01	0.01	0.01
e	1	1	1	1	0.001	1	-	-	-
f	1	1	1	1	0.001	1	-	-	-
g	1	1	1	1	0.001	1	0.01	0.01	0.01
h	1	1	1	1	0.001	1	-	-	-
i	1	1	1	1	0.001	-	-	-	-
j	1	1	-	-	-	-	-	-	-

4. Results and Discussion

A literature review of reliability databases and components failure frequency was conducted, and a lack of hydrogen system component information was found. Recognized standards, e.g. HSE and OREDA, were adopted where possible. However, it should be noted that most of the data concern LNG, and depending from the source, a significant variability can be observed, in some cases up to four orders of magnitude [39].

The final results of the Frequency Analysis concerning the LH_2 tanks swap operation are reported in Table 5. It should be noted that the ignition frequencies obtained assume the same outflow rate of hydrogen for each failure scenario, even if, rigorously, Scenarios 1 and 2 would lead to a minor leakage and therefore a lower ignition probability. Nevertheless, considering all the assumptions and uncertainties of the analysis, it is reasonable to pursue a conservative approach. In fact, the hydrogen ignition model adopted significantly influences the outcome of the analysis. Particularly, the Hansen model, being more articulated, leads to higher frequencies.

Assuming a fatal injury probability of 1.0 for each exposed person, the results obtained can be leveraged to preliminarily evaluate the risk associated with the operation, by confronting it with the risk acceptance criteria of interest [18].

Table 5. Frequency Analysis results.

Event	Value	Unit
Hydrogen release	6.37E-05	1/year
Hydrogen release + ignition (HyRAM+)	5.10E-06	1/year
Hydrogen release + ignition (Hansen)	1.52E-05	1/year

The influence matrix was essential to assign the mitigation coefficients to each scenario, reflecting operational procedures and design safety measures. It should be noted that when the coefficient is 1, no mitigation effects are considered.

The Scenario 6 coefficients (human error) were assigned to reflect a double independent false instrument reading (10^{-6} $year^{-1}$ total frequency), assuming an independent check by two different operators in order to proceed with the swap operation. Similarly, it is assumed that the overall likelihood of the tank dropping and leading to a pool fire (Scenario 11) is reduced by implementing operational lifting height limitations, properly maintaining lifting and locking devices, ensuring the area underneath is clear of obstacles; analogous suppositions were made for Scenarios 9 and 10. These considerations are numerically taken into account through the adoption of the mitigation coefficients 0.01.

It should be noted that the mitigation matrix is constructed on arbitrary considerations, which are usually discussed and approved by field experts involved in QRA process. Moreover, it is also important to emphasize how some failure characteristics are intrinsic of the system components. In fact, e.g., the frequency analysis is dominated by PRV spurious operation, which is not mitigable through operational procedures.

Unfortunately, LH_2 component reliability databases were not found, and recognized LNG-based values were adopted. Component-specific data availability is therefore essential as it can significantly influence the overall analysis outcome, leading to risk over or underestimation. In this regard, the methodology provided is well-suited to incremental refinement and integration of values and scenarios as they become available during the design process, enabling the reduction of uncertainty propagation. Finally, rapid simplified sensitivity analyses can be conducted by varying the parameters of interest in the matrices.

5. Conclusions

The research process highlighted the lack of hydrogen-specific reliability databases for system components. Moreover, it was found that depending on the source used, some failure rates differ by orders of magnitude for the same item, increasing uncertainty in the selection process that is reflected into the risk estimate. Nevertheless, the proposed methodology provided an effective tool to quantitatively develop a Frequency Analysis for a QRA, and it was successfully applied to the case study of an LH_2 tank swap operation on a passenger ship.

The key feature is the influence matrix, the core tool, which enables to quickly assess the most impactful failure scenarios, including LPHC events, and, therefore, design effective mitigations early. Further developments, addressing a Consequence Analysis, will complement the QRA procedure, by generating a risk metric for the acceptability evaluation of the operation.

Finally, the general validity of the presented methodology can be leveraged in future QRA procedures for different types of operations involving alternative fuels, with the proper selection of the characteristic parameters.

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