HAZOP AND FAULT TREE ANALYSIS OF AMMONIA LEAKAGE IN A SHIP'S AMMONIA FUEL SYSTEM

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ABSTRACT
Ammonia is considered as the future alternative fuel to overcome emissions from low-quality fuel. Despite ammonia being a promising alternative fuel, its toxic and corrosive properties are the main drawbacks and increase risks on a ship. This study aims to determine the events and failures that lead to ammonia leakage from the high-pressure ammonia fuel system of a ship. Five experts from the maritime industry and academy prepared the basics of the study by doing HAZOP. After this step, an FTA diagram was formed to show which basic and intermediate events result in ammonia leakage.

Keywords: Ammonia, Fault tree analysis, Fuel system, HAZOP, Maritime transport

1. INTRODUCTION

Maritime transportation is the most important transportation mode worldwide. There were 108,789 merchant ships of 100 gross tons and above in January 2024, and the ship number increased by 3.4% from 2023 to 2024 [1]. Since 98% of these ships use low-quality fossil fuels [2], maritime transportation accounts for 9.84% of global sulfur oxide (SO_X) emissions, 14.74% of nitrogen oxides (NO_X) emissions, 6.75% of particulate matter 2.5 (PM2.5) emissions, 3.56% of particulate matter 10 (PM10) emissions, 0.61% of carbon monoxide (CO) emissions [3], and 2.89% of global carbon dioxide (CO_2) emissions [4]. To overcome these emissions, using alternative fuels on ships is the most promising and attractive solution due to a higher emission reduction potential [5]. There are various alternative fuels, such as liquefied natural gas (LNG), methanol, ammonia, and hydrogen. But ammonia is considered as the future alternative fuel for maritime transportation. Despite ammonia being a promising alternative fuel, its toxic and corrosive properties are the main drawbacks and increase risks on a ship.
In this study, an ammonia leakage event at a high-pressure ammonia fuel system is investigated. Possible events and failures that lead to ammonia leakage are determined by hazard and operability analysis and a fault tree diagram of the events and failures is formed.

2. PROPERTIES OF AMMONIA

Ammonia consists of one nitrogen atom and three hydrogen atoms, and it does not contain carbon or sulfur atoms. Therefore, its combustion is free of carbon dioxide, carbonaceous emissions, sulfur oxides, and particulate matter. On the other hand, ammonia combustion results in water, nitrogen, NO_X, nitrous oxide (N_2O), and a small amount of ammonia slip [6]. Ammonia is a low-reactivity fuel with a low heating value (LHV) of 18.5 MJ/kg. The auto-ignition temperature of ammonia is 651 ℃ and the flammability limits in the air are between 16 -25% by volume. The low burning velocity of ammonia at 14 cm/s affects the combustion reactivity of this fuel [7]. Although it has low reactivity, ammonia is suitable for large marine diesel engines thanks to their large cylinder displacement volume, low engine speeds, and constant high engine loads [8]. The storage options for ammonia as a fuel are either at -33 ℃ at 1 bar or at room temperature at 10 bars [9]. Thus, ammonia-fueled ships require 2.4 times larger tank volume than the conventional-fueled ships [10]. Using ammonia as a fuel brings some risks that are associated with its properties. Ammonia is a toxic chemical that has a toxicity level of more than three times higher than other marine fuels, marine diesel oil, and methanol [11], [12]. The toxicity of ammonia causes dehydration, caustic burning, and freezing when human contact [9]. The toxicity of ammonia to aquatic life is an issue. Ammonia spilling into the sea can cause extreme risk to aquatic life. Corrosiveness is another risk of ammonia. Ammonia is incompatible with aluminum, brass, copper, magnesium, and zinc alloys [8]. Moreover, ammonia can cause stress corrosion in tanks and fuel supply lines. The last risk of ammonia is fire and explosion risk. Due to its low combustion reactivity, the risk of fire and explosion is lower than the other alternative fuels, such as LNG, LPG, methanol, etc. But ammonia has a high reaction speed with halogens and oxidizers that may lead to explosions [6].

3. METHODOLOGY

This study uses a combination of hazard and operability analysis (HAZOP) and fault tree analysis (FTA). The opinions of the specified experts in Table 1 are taken at a brainstorming session to apply the methodology.

2.1. Hazard and Operability Analysis (HAZOP)

HAZOP is an analysis that is developed to identify the operational problems and potential hazards of a system [13]. The

analysis was formed to find the possible defects and deviations that result in explosions, fires, and toxic releases [14]. HAZOP analysis is done according to the opinions of the experts related to the specific field of the study.

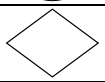
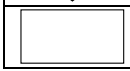
2.2. Fault Tree Analysis (FTA)

The FTA is a top-down approach that starts by identifying the top event. The next steps are the formation of a fault tree diagram, qualitative evaluation, and quantitative evaluation [15]. The fault tree is drawn by using symbols in Table 2. This study focuses on only one top event, and the fault tree diagram of this top event with its intermediate events, basic events, and their logic gates is formed.

Table 1. The specifications of the experts

Expert	Position / Experience / Education	Information
1	Oceangoing Chief Engineer / 11 years / BSc.	The expert has a good knowledge on fuel systems and their risks.
2	Oceangoing Chief Engineer / 2 years / MSc.	The expert has worked on chemical tankers and has a good knowledge on ammonia.
3	Oceangoing Chief Engineer – Academician / 10 years – 19 years / PhD.	The expert had worked on chemical tankers and has academic studies on alternative fuels.
4	Academician / 10 years / PhD.	The expert has academic studies on alternative fuels and their risks.
5	Academician / 4 years / PhD.	The expert has academic studies on alternative fuels and their risks.

Table 2. Fault tree analysis symbols and descriptions [16]

Symbol	Meaning	Description
	AND gate	The output event commences if all input events arise
	OR gate	The output event commences if any of the input events arise
	Basic event	The basic cause of a failure or intermediate event
	Undeveloped event	Undeveloped primary cause due to lack of knowledge
	Intermediate event	An event that commences due to one or more sub-events

4. RESULTS AND DISCUSSION

4.1. Ammonia-fueled Ship Fuel System Components

In this study, it is assumed that the ammonia fuel system is a high-pressure fuel system. Thus, the components of the system are a bunkering station, fuel storage area, fuel preparation, supply and recirculation unit (FPSR), fuel valve train (FVT), double-walled piping, the main engine components, ammonia catch system, and vent mast [17]. The FTA diagram is formed by considering these components.

4.2. FTA Diagram

The FTA diagram of ammonia leakage (TE) from the ammonia-fueled ship fuel system is constituted by brainstorming with the experts. Fig. 1, the FTA diagram, contains 23 intermediate events (IE) and 39 basic events (BE). All events are shown in Table 3. The TE mainly depends on the IEs from 1 to 6. IE-1 is associated with IE-7 to IE-10; IE-2 is associated with IE-11 and IE-12; IE-3 depends on IE-13 to IE-16; IE-4 depends on IE-17 and IE18; IE-5 is associated with IE-19 and IE-20; and IE-6 is associated with IE-21 to IE-23. All IEs are connected to OR gates which means any of the input events arise for the output event to commence. The IEs depend on 39 BEs as the basic events that have to happen to constitute intermediate events. The IEs result in TE, ammonia leakage from the fuel system.

Table 3. Definition of the events in FTA diagram

Event	Description	Event	Description
TE	Ammonia fuel leakage	BE-9	Ammonia-induced stress corrosion cracking
IE-1	Storage tank leakage	BE-10	External environmental exposure
IE-2	Piping and valve leakage	BE-11	Leaking flanges or couplings
IE-3	Transfer system leakage	BE-12	Improper assembly
IE-4	Control system failure	BE-13	Faulty valve seals or internal wear
IE-5	External factors	BE-14	Material fatigue from repeated temperature fluctuations
IE-6	Human factor	BE-15	Wear and tear over time
IE-7	Corrosion	BE-16	Poor material compatibility
IE-8	Structural failure	BE-17	Pressure build-up causing weak points to fail
IE-9	Seal failure	BE-18	Frozen ammonia leading to rupture
IE-10	Overpressure	BE-19	Improper closing or wear
IE-11	Corrosion of piping	BE-20	Actuator failure
IE-12	Joint failures	BE-21	Cracks or wear in flexible parts
IE-13	Pump seal failure	BE-22	Misalignment or improper installation
IE-14	Pipeline blockage	BE-23	Failure to detect pressure or temperature abnormalities
IE-15	Valve malfunction	BE-24	Late detection of leaks
IE-16	Hose or flexible connection failure	BE-25	Incorrect valve actuation
IE-17	Sensor failure	BE-26	Inability to trigger safety shutoff systems
IE-18	Control unit malfunction	BE-27	Alarm system failure
IE-19	Operational errors	BE-28	Faulty software leading to incorrect actions
IE-20	Third-party damage	BE-29	Extreme weather conditions causing material degradation
IE-21	Improper operation	BE-30	Mishandling of equipment
IE-22	Maintenance errors	BE-31	Inadequate maintenance or inspections
IE-23	Insufficient training	BE-32	Accidental impact during loading/unloading
BE-1	Material degradation due to exposure to ammonia	BE-33	Fire or explosion near storage or piping
BE-2	Poor maintenance or protective coatings	BE-34	Incorrect valve or pump operation
BE-3	Cracks caused by pressure fluctuations	BE-35	Lack of adherence to procedures
BE-4	Physical damage during operations	BE-36	Failure to detect wear or damage
BE-5	Degraded gaskets or seals	BE-37	Use of incompatible materials during repair
BE-6	Improper assembly	BE-38	Lack of knowledge about system operation
BE-7	Faulty pressure relief valves	BE-39	Failure to recognize early signs of leakage
BE-8	Temperature variations causing pressure build-up		

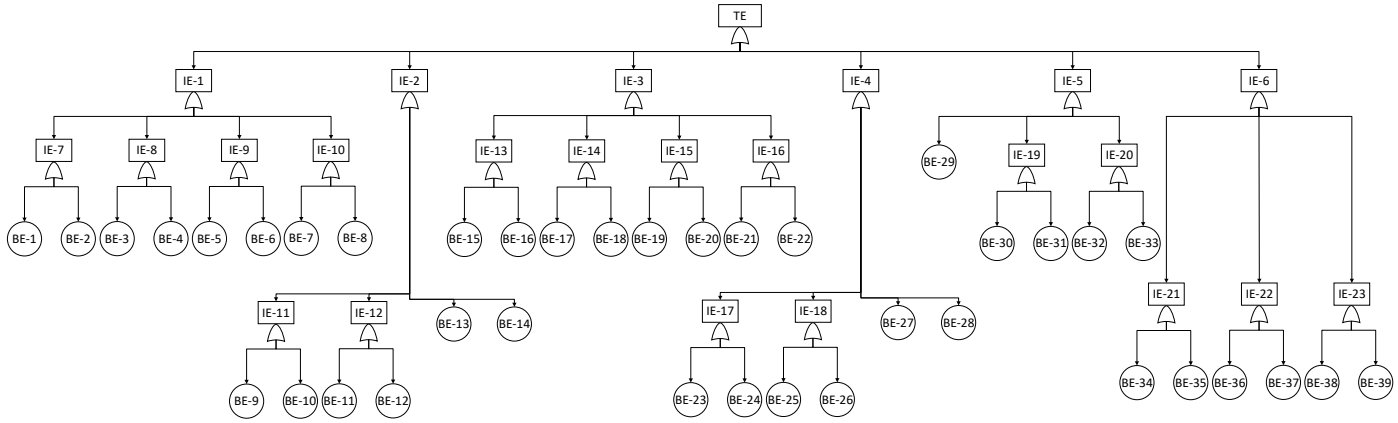


Fig. 1. Ammonia leakage FTA diagram

5. CONCLUSION

This study aims to determine the events and failures that lead to ammonia leakage from the high-pressure ammonia fuel system of a ship. Five experts from the maritime industry and academy prepared the basics of the study by doing HAZOP. After this step, an FTA diagram was formed to show which BEs and IEs result in ammonia leakage (TE). IE-1 Storage tank leakage, IE-2 Piping and valve leakage, IE-3 Transfer system leakage, IE-4 Control system failure, IE-5 External factors, and IE-6 Human factor are the related IEs to TE. The next study will be an extended version that contains quantitative analysis of the ammonia leakage FTA diagram. Furthermore, other TEs will be analyzed by the same expert team to further enlarge the safety analysis of the ammonia fuel system of a ship.

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