European Maritime Safety Agency



# SAFETY OF AMMONIA FOR USE IN SHIPS

## PART 2 – SAFETY ASSESSMENT AND RELIABILITY ANALYSIS OF MAIN COMPONENTS, EQUIPMENT, SUB-SYSTEMS AND SYSTEMS BY ABS, FVP & NTUA

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# Document History

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# Executive Summary

The first task of this study presented an extensive analysis of ammonia properties and characteristics, including its applicability as marine fuel. Among the relevant hazards of ammonia, toxicity is the most critical in comparison to other conventional and alternative fuels. In addition to its toxicity, the general behaviour of ammonia was investigated; i.e., how its corrosive nature affects other materials' stress corrosion cracking when exposed to air and/or water. The first step was gaining a firm understanding of how the hazards of ammonia affect the ship and the persons onboard. The outcome of Task 1 noted that there are gaps to be filled in the regulatory framework to foster the adoption of ammonia as marine fuel. Classification societies have issued requirements on ammonia fuel and the International Maritime Organization (IMO) is working towards the development of interim guidelines.

Although ammonia is a well-established product with extensive land-based understanding and transportation history via dedicated liquefied gas carriers, its use as marine fuel has just recently been demonstrated when the offshore supply ship Fortescue's *Green Pioneer* had its two four-stroke engines converted to operate on ammonia. Although specific guidelines are not finalised yet, technology providers such as engine, fuel supply system, and fuel treatment system vendors currently work to develop systems and equipment that can safely handle ammonia fuel. A challenging task, considering the technology is being developed in parallel with regulatory development.

The principle of ammonia fuel engines and systems is based on experience of other liquefied gaseous fuels. Due to similarities, LPG engines are often referenced for ammonia operating conditions. However, ammonia's toxicity hazard requires even more stringent measures and careful consideration to mitigate toxic vapor release. This is the main concern that drives development of ammonia-relevant systems and is highlighted in safety concepts and Failure Mode, Effects and Criticality Analysis (FMECA) developed by vendors. This report aims to provide reliability assessment for an ammonia-fuelled vessel.

First, the selection of critical equipment subject to analysis is carried out with respect to a high-level categorisation that follows the hierarchy below:

- FTA 1: Internal Combustion Engines (ICEs) / Ammonia Engine Fuel System
- FTA 2: ICE / Engine Fuel Oil System
- FTA 3: ICE / Common Engine Component
- FTA 4: ICE / Engine Auxiliary Systems
- FTA 5: ICE / Hydraulic and Sealing Oil Systems
- FTA 6: Fuel Supply/Recirculation System[2]
- FTA 7: Bunkering System
- FTA 8: Reliquefaction Plant

Method of work:

- A workshop with engine vendors' experts was conducted to validate components selected for the Fault Tree Analysis (FTA) in a hierarchical structure. This is also termed as critical component list.

- In-depth fault tree analysis was performed by interviewing SMEs in ammonia fuel, engine makers, alternative fuel and bunkering equipment vendors, and ship experts. 8 FTA reliability models (FTA 1 to FTA 8 described in section 3.5) were constructed based on information from LPG application modified to assess for ammonia fuel applications. In each system, a critical component list was used to build the failure scenarios.

- Upon careful evaluation of the failure scenarios, FTA models were transferred to the Windchill Risk and Reliability (WRR) simulation application[3] by inputting the estimated probability of failure or lifetime for each failure scenario (termed as basic event in WRR). Vendor equipment failure rate information or Mean Time To Failure (MTTF), industry consortium (OREDA) equipment failure rates, American Institute of Chemical Engineers (AIChE) equipment failure rates, human error probability (NUREG), etc. are referenced and

[2] Fuel supply system includes ammonia fuel supply, pilot oil fuel supply, inert gas and venting and ventilation systems.
[3] PTC Windchill Enterprise Product Lifecycle Management Software/Quality Management/Risk and Reliability https://www.ptc.com/en

adjusted for the ammonia fuel application in basic events. Finally, the computer then outputs the reliability curves and MTTF for the entire system and subsystem[4].

Top contributors to the weakness of the systems are summarised below:

- FTA 1-5: Internal Combustion Engines (ICEs)
  - Ammonia injector design
  - Valve spring life (jammed spring cannot fully open injector valve)
  - Spring failure in booster injector hydraulic
  - Fuel injector corrosion risk
  - Booster injection valve failure
  - Incorrect piston ring material property
  - Incomplete combustion process (incorrect autofrettage process)
  - Ammonia injector valve fatigue life

- FTA 6: Fuel Supply/Recirculation System
  - Insufficient vibration design of ammonia components leading to exceeded fatigue load
  - Leak of valve components, filters, sealing, gaskets
  - Operational failures
  - Human related errors - operator not following procedures, PM missed, installation errors, etc.
  - Ammonia contamination issues
  - Ammonia leaking issues to engine room, ammonia catch system, equipment
  - Ammonia entrapped in piping issues
  - Insufficient purging length issue
  - Clogging of nitrogen filters
  - Ventilation flow is too low

- FTA 7: Bunkering System
  - Overfill tank above allowed reference limit
  - Over-pressurisation of bunkering manifold
  - Quick release coupling/flange/leak in Emergency Release Coupling (ERC)
  - Manual/Emergency Shutdown (ESD) valve/Non-return valve leaking
  - Bunker hose leaking/pin hole

- FTA 8: Reliquefaction Plant
  - Liquid separator leaking ammonia
  - Ammonia fuel tank overpressure
  - Leaking ammonia in the compressor room via sealing/pipe connection
  - Excessive vibration level on ammonia reliquefaction compressor crankgear
  - Ammonia relique compressor piston seizure
  - Low-pressure ammonia pump failure due to suction of contaminated ammonia
  - Condenser leaking failure

Out of the 8 subsystems, FTA 6 Fuel supply system has the shortest MTTF (9,406 hours) as it is a more complex system which has more failure modes, contributing to a higher failure rate. Effort should be taken to plan for control measures and improving design failures analysed in the model, such as Manual valve/ESD/Non return valve leaking due to incorrect gasket material selection risk.

FTA 5 Hydraulic and sealing oil systems have a shorter MTTF (27,248 hours) compared to other subsystems due to its operation complexity to control sealing oil pressure higher than the ammonia fuel or pump failure. For instance, excessive vibration pump or overheated hydraulic oil can lead to pump bearing failure. Sealing oil failure cannot prevent ammonia backflow leading to ammonia contamination in the equipment. Ammonia contamination could be in sealing oil or hydraulic oil.

[4] Reliability information include reliability curves, top contributors to weakness of the system.

FTA 7 Bunkering system has a shorter MTTF (35,537 hours) compared to other subsystem due to design failure. Manual valve, ESD, or return valve could be leaking due to incorrect gasket material selection and causes fuel spill during bunkering operation. Bunkering hose leaking due to wear and tear should be mitigated by following OEM recommendation and inspection plan.

FTA 8 Reliquefaction system has a shorter MTTF (50,000 hours) due to the compressor design life. Despite the compressor used being reliable when used with conventional fuel, the compressor requires a higher speed type to process the boil-off gas (BOG) for the ammonia fuel reliquefaction system, due to the material properties of the alternative fuel. The conventional BOG compressor is typically designed to align with a ship's design life to not require replacement. The BOG compressor used for ammonia fuel application would require further development to meet the reliquefaction system requirements.

The following assumptions and data sources were used for the reliability analysis:

- Vendor design life estimation of components, such as HP fuel pumps.
- OREDA machinery equipment failure rates/reliability data.
- Measures to reduce the probability of failure from manufacturing defect or installation error were in place, such as operator following manufacturing process or installation procedures.
- An LNG data source for fuel leak probability was used.
- MAN Energy Solution Service Letter SL2019-681/SRJ: Guiding overhaul intervals and expected service life of engine components on two-stroke low speed engines
- Compressor Owner Forum, Copenhagen, 2023 (confidential information)
- *Guidelines for Process Equipment Reliability Data with Data tables from American Institute of Chemical Engineers, such as compressor, high pressure valve, motor, etc.*

As reliability analysis results, the reliability curve for the total system or subsystem is screened for weaknesses to the system, which can be used for decision making where to focus on the system reliability improvement. The reliability curve is the probability of a unit being operational when called upon as a function of time. It is an indicator of product reliability, which can also be expressed as MTTF or average design life. It is important to keep in mind that the estimated design life from the Fault Tree Analysis is used to weed out the weakest component in the system, and the estimated numeric value does not equate to the actual operational hours.

After the reliability model for the system is functional, the model can be further used to perform sensitivity analyses, also termed as what-if scenarios. In other words, if a particular reliability issue (e.g., failure scenarios in component design such as in ammonia pump sealing and membrane) leads to weakest components, the sensitivity analysis is carried out to investigate how much would the system's (e.g. fuel supply system's) MTTF change if the component's MTTF were to double or triple.

The following sensitivity analyses for the ammonia-fuelled propulsion system have been analysed to demonstrate the change in MTTF when the operation mode changes, or equipment configuration is modified.

- Engine Fuel System (FTA 1 & FTA 2 Model)

Failure in the ammonia fuel system leads to a stop of ammonia operation and to changeover to diesel mode for seamless operations. This is modelled as redundancy in the engine fuel system.

1. Dual Fuel Redundancy Concept Design: MTTF = 4,590 hours for ammonia-fuelled propulsion system. If the ammonia fuel engine system fails, the propulsion system can continue its operation and switch over to diesel mode. In this case, the operation is not interrupted, and the mission reliability[5] is met.
2. Ammonia Fuel Engine Design Without Redundancy Design: MTTF = 3,822 hours for ammonia-fuelled propulsion system.
   Either the ammonia fuel engine or diesel fuel engine system fails, it will interrupt the operation. Therefore, MTTF is expected to be shorter than dual fuel redundancy concept design.

[5] Mission reliability is defined as being able to provide the required function during the T-day mission, even under a degrading capacity.

FTA 6, FTA 7 and FTA 8 were selected to further use for sensitivity analyses. Collaboration has been made with ammonia equipment vendors[6] to provide equipment MTTF for the fuel supply system, bunkering system and reliquefaction plant. MTTF came from another ammonia project that is confidential with the original data source published by AIChE.[7] The provided MTTF information has been used to investigate its reliability improvement margin when integrated into the propulsion system. The purpose of the sensitivity analysis is to advise how much improvement the overall system MTTF can gain from a component MTTF. This methodology is intended for the use of ship owner and operators to assist in making a decision based on reliability data even in the early stage of design.

- Fuel Supply/Recirculation System (FTA 6 Model)
  1. Rotating equipment pumps motor driven pressure centrifugal MTTF = 8,000 hours vs. Redundancy Multiple Pumps.
     - Results indicate that redundancy design does not significantly improve fuel supply system reliability. If there is an increasing number of pump failures, a re-design using a root cause analysis may be necessary.
  2. Mechanical seals in pumps MTTF = 25,000 hours vs. 50,000 hours.
     - Results indicate that with the improvement of mechanical seals increased the fuel supply system life from 6,834 to 7,916 hours. If the fuel pump seal failure is trending upwards during operations, this information can be used for seal upgrade evaluation.
  3. Protection systems relief valve spring loaded MTTF = 595,238 hours - Not selected

- Bunkering System (FTA 7 Model)
  1. Solenoid valve not open or close on demand MTTF = 20,000 hours vs. 40,000 hours.
     - Results indicate an improvement in bunkering system reliability when a solenoid valve increases its design life. If valve failure is an issue, replacement with an upgraded valve can be considered to improve the bunkering system reliability.
  2. Quick release coupling or ERC (Emergency release coupling) MTTF = 992,000 hours - Not selected
  3. Bunker hose MTTF = 1,754,386 hours – Not selected

- Reliquefaction Plant (FTA 8 Model)
  1. Compressor MTTF = 700 hours (Single vs. Redundancy Multiple Compressors)
     - Results indicate a high-speed type of ammonia reliquefaction compressor is a potential risk for the reliquefaction plant system to address. Field development data received in the industry suggests to provide a reliable operation handling the ammonia vapor and send it back to the ammonia tank, efforts to improve the compressor life are necessary. For the case of compressor MTTF = 700 hours, a redundancy design does not provide enough reliability for the reliquefaction operations.

[6] Lewa GmbH, Trelleborg Westbury Limited, Babcock International Limited.
[7] Guidelines for Process Equipment Reliability Data with Data Tables published by American Institute of Chemical Engineers (AIChE).

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# List of Abbreviations

| | |
|---|---|
| **ABS** | American Bureau of Shipping |
| **ARMS** | Ammonia Release Mitigation System |
| **AVPS** | Ammonia Vapor Processing System |
| **BMEP** | Brake Mean Effective Pressure |
| **BOG** | Boil Off Gas |
| **CCC** | Carriage of Cargoes and Containers Sub-Committee (IMO) |
| **DBBV** | Double Block and Bleed Valve |
| **DF** | Dual Fuel |
| **DFDE** | Dual Fuel Diesel Electric |
| **EMSA** | European Maritime Safety Agency |
| **ERC** | Emergency Release Coupling |
| **ESD** | Emergency Shutdown |
| **FGSS** | Fuel Gas Supply System |
| **FMEA** | Failure Mode and Effects Analysis |
| **FMECA** | Failure Mode, Effects and Criticality Analysis |
| **FPR** | Fuel Preparation Room |
| **FSS** | Fuel Supply System |
| **FTA** | Fault Tree Analysis |
| **FVP** | Fundación Valencia Port |
| **FVT** | Fuel Valve Train |
| **GHG** | Green House Gas |
| **GVT** | Gas Valve Train |
| **GVU** | Gas Valve Unit |
| **HAZID** | Hazard Identification Studies |
| **HAZOP** | Hazard and Operability Study |
| **HP** | High-Pressure |
| **HSE** | Health and Safety Executive |
| **IACS** | International Association of Classification Societies |
| **ICE** | Internal Combustion Engine |
| **IGC** | International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IMO) |
| **IGF** | International Code of Safety for Ships Using Gases or other Low-Flashpoint Fuels (IMO) |
| **IMO** | International Maritime Organization |
| **ISO** | International Organization for Standardization |
| **LNG** | Liquefied Natural Gas |
| **LP** | Low-Pressure |

| | |
|---|---|
| **LPG** | Liquefied Petroleum Gas |
| **MARVS** | Maximum Allowable Relief Valve Settings |
| **MCR** | Maximum Continuous Rating |
| **MDO** | Marine Diesel Oil |
| **MFV** | Master Fuel Valve |
| **MGO** | Marine Gasoil |
| **MGV** | Master Gas Valve |
| **MTTF** | Mean Time To Failure |
| **MVR** | ABS Marine Vessels Rules |
| **$N_2O$** | Dinitrogen Oxide |
| **$NH_3$** | Ammonia |
| **NO** | Nitric Oxide |
| **$NO_2$** | Nitrogen Dioxide |
| **$NO_x$** | Nitrogen Oxides |
| **NTUA** | National Technical University of Athens |
| **OEM** | Original Equipment Manufacturer |
| **PM** | Particulate Matter |
| **PPM** | Parts Per Million |
| **PRV** | Pressure Relief Valve |
| **QCDC** | Quick Connect and Disconnect Coupling |
| **SCC** | Stress Corrosion Cracking |
| **SCR** | Selective Catalytic Reduction |
| **SGMF** | Society for Gas as a Marine Fuel |
| **SIGTTO** | Society of International Tanker and Terminal Operators |
| **SME** | Subject Matter Expert |
| **$SO_2$** | Sulphur Dioxide |
| **$SO_3$** | Sulphur Trioxide |
| **SOLAS** | International Convention for the Safety of Life at Sea, 1974, as amended (IMO) |
| **$SO_x$** | Sulphur Oxides |
| **VFD** | Variable Frequency Drive |

# 1. Introduction

## 1.1 Background

The overall study consists of three specific contracts (SC), if all activated, and seven separate tasks as described below:

- The Specific Contract No 1 (SC1) addressed the characterisation of the ammonia as fuel (see Task 1),
- The Specific Contract No 2 (SC2) will develop a reliability analysis for selected equipment and systems and a series of risk assessments for specific ships' designs (see Task 2 to Task 5),
- The Specific Contract No 3 (SC3) will develop, on the basis of the findings of Task 1 to 5, a goal-based guidance for ammonia as fuel and the final report (see Task 6 and Task 7).

The first task of this study presented an extensive analysis of how the properties and characteristics of ammonia apply to its use as marine fuel. From the relevant ammonia hazards, toxicity is the most critical when compared with other conventional and alternative fuels. In addition to its toxicity, the general behaviour of ammonia was investigated; i.e., how its corrosive nature affects other materials' stress corrosion cracking when exposed to air and/or water. The first step was having a solid understanding how the hazards of ammonia affect the ship and the persons onboard. The outcome of Task 1 also noted that there are gaps to be filled in the regulatory framework in order to support the adoption of ammonia as marine fuel. Classification societies have issued rules, and the International Maritime Organization (IMO) is currently developing interim guidelines. Developments in technology around ammonia run in parallel with regulatory developments, therefore it is essential to ensure that any work being done by vendors addresses all relevant hazards with focus on toxicity, and it is aligned with future guidelines.

Task 2 aims to identify, through reliability analysis, where the ammonia systems appear to be susceptible. This information will serve as input for the subsequent risk assessment tasks, where risk will be assessed to provide mitigation measures for different ship types. Reliability assessment, Fault Tree Analysis (FTA) has been used for reliability prediction when ammonia equipment has not been fully tested.

During the ammonia equipment development effort, sensitivity analysis consisting of what-if scenarios are structured to help make decisions regarding the weak components of the ship system. Sensitivity analysis results offer information that can be used to prioritise the development resources.

## 1.2 Scope and Objectives

This report is the deliverable of Task 2 as the first task of Specific Contract 2 (SC2). Task 2 consists of two subtasks:

<u>Task 2.1 Equipment and Systems Identification</u>

Subtask 2.1 focuses on identifying the relevant equipment, systems and sub-systems of an ammonia-fuelled vessel. Although each manufacturer and designer may have differing design concepts, this task focuses on a generic approach utilising equipment that is commonly found in most available designs. A general description is provided to understand the functional purpose of each system and equipment. Consultation with vendors, shipyards and designers is the main source of information for the analysed systems.

The equipment analysed in the following sections covers the following high-level hierarchy:

- Internal Combustion Engines (ICEs)
- Ammonia Fuel Supply/Recirculation System
- Venting and Ventilation System
- Exhaust Gas Treatment Systems
- Bunkering System
- Reliquefaction Plant

Task 2.2 Safety-assessment and reliability analysis of the main equipment, systems, and sub-systems

Conventionally, to establish product performance metrics, such as mean time to failure (MTTF) or failure rate, a failure depository database is customised for data collection which is then used to calculate reliability performance metrics for monitoring. OEM vendors usually maintain this type of database and track product performance for their products sold globally. A reliability methodology, Weibull analysis, is used to calculate MTTF which is then published to their clients (public information) to promote high product reliability.

The Weibull distribution is widely used in reliability engineering. While the Weibull distribution is important for life data analyses, Weibull packages typically encompass support for various other significant distributions used in statistical analyses, such as exponential, normal, and lognormal. Weibull analysis, also called life data analysis or failure data analysis, is used in a wide variety of applications. For example, you can use Weibull analysis to evaluate field failures or test failures. The idea is to determine the best fit for distribution of the collected sample data so that you can predict trends. Section 3 introduces detailed reliability methodologies.

Weibull analysis is the approach used when failure testing data is available. For an ammonia-fuelled propulsion system, however, there is limited ship operational experience. To research a new technology where MTTF or failure rate information is not established, FTA (fault tree analysis) is employed to bridge the gap by interviewing subject matter experts (SME) to scrutinise each high-risk failure event. Reliability approach leverages fault tree analysis to examine failure modes in the full project lifecycle, categorised as design failures, manufacturing defects, installation failures, or operation failures. Types of failure modes include design errors, technical specification mistakes, and human errors such as misuse of alarms, incorrect operating procedures, and training deficiencies. These types of assessments help identify weak links in the system and allocate resources to address reliability concerns.

FTA is a commonly used approach for innovative technology development as it covers both qualitative reliability information and quantitative reliability assessment for equipment that is in the design concept phase of the project lifecycle. Task 2.2 focuses on ammonia impacted equipment for the entire ship, ammonia engine(s) and ammonia auxiliary systems. For instance, the fuel supply system contains HP and LP ammonia fuel pumps, fuel filters, and several sealings in the valves and components. Designs for an ammonia-fuelled engine have yet to be proven in the commercial scale. FTA is designed to proactively identify the top risks so the resources and research efforts can be properly guided to de-risk the dual fuel engine design prototype. This task focuses on the ammonia-fuelled ship system and the methodology can be implemented in any alternative fuel applications.

The reliability analysis is studied in two phases as follows:

1. Phase I focuses on qualitative assessment to build fault tree failure scenarios structured by a critical component list entailing how each component can fail; and
2. Phase II focuses on quantitative assessment using the Windchill Risk and Reliability simulation tool[8] entailing how often each failure scenario occurs.

Objectives of the reliability study are summarised as follows:

- Select critical equipment that has higher probability of failure or more severe consequences following failure,
- Identify main failure modes and construct the failure scenario using cause and effect relationships,
- Assess the probability of failure for each basic event, including undeveloped events for which little data is available,
- Output a list of top contributors/weak components of the reliability system that is using ammonia as fuel on ships,
- Perform sensitivity analysis (how much system design life will be gained by a component improvement), intended to assist the ship owner and operator in making decisions based on the reliability data.

[8] PTC Windchill Enterprise Product Lifecycle Management Software/Quality Management/Risk and Reliability https://www.ptc.com/en

# 2. Ammonia Systems and Equipment

The development of ammonia engines and fuel supply systems builds on previous experience from other liquefied gaseous fuels (e.g. LNG, LPG, ethane) or methanol. There are certain similarities among systems utilising these types of fuels, especially LPG and methanol which are low flashpoint fuels being delivered to the engine in a liquid form. These systems have been operating for some time in the shipping industry. The first two-stroke methanol engine came into operation during 2015, and in 2020 the first two-stroke LPG engine came into operation. As of August 2024, approximately 200 methanol and 150 LPG two-stroke engines are on order or in service. A high-level categorisation of the basic systems comprising the ammonia fuel concept is shown in Figure 1 below. This section includes a high-level description of these systems and identifies the major components that play important roles and will be the basis of the reliability analysis in Section 3. This section covers the general philosophy, so vendors may have specific designs which differentiate from the presented approach.[9]

The current section covers the supply of ammonia in internal combustion engines. Ammonia can also be used in fuel cells through hydrogen cracking (Appendix A for information only).

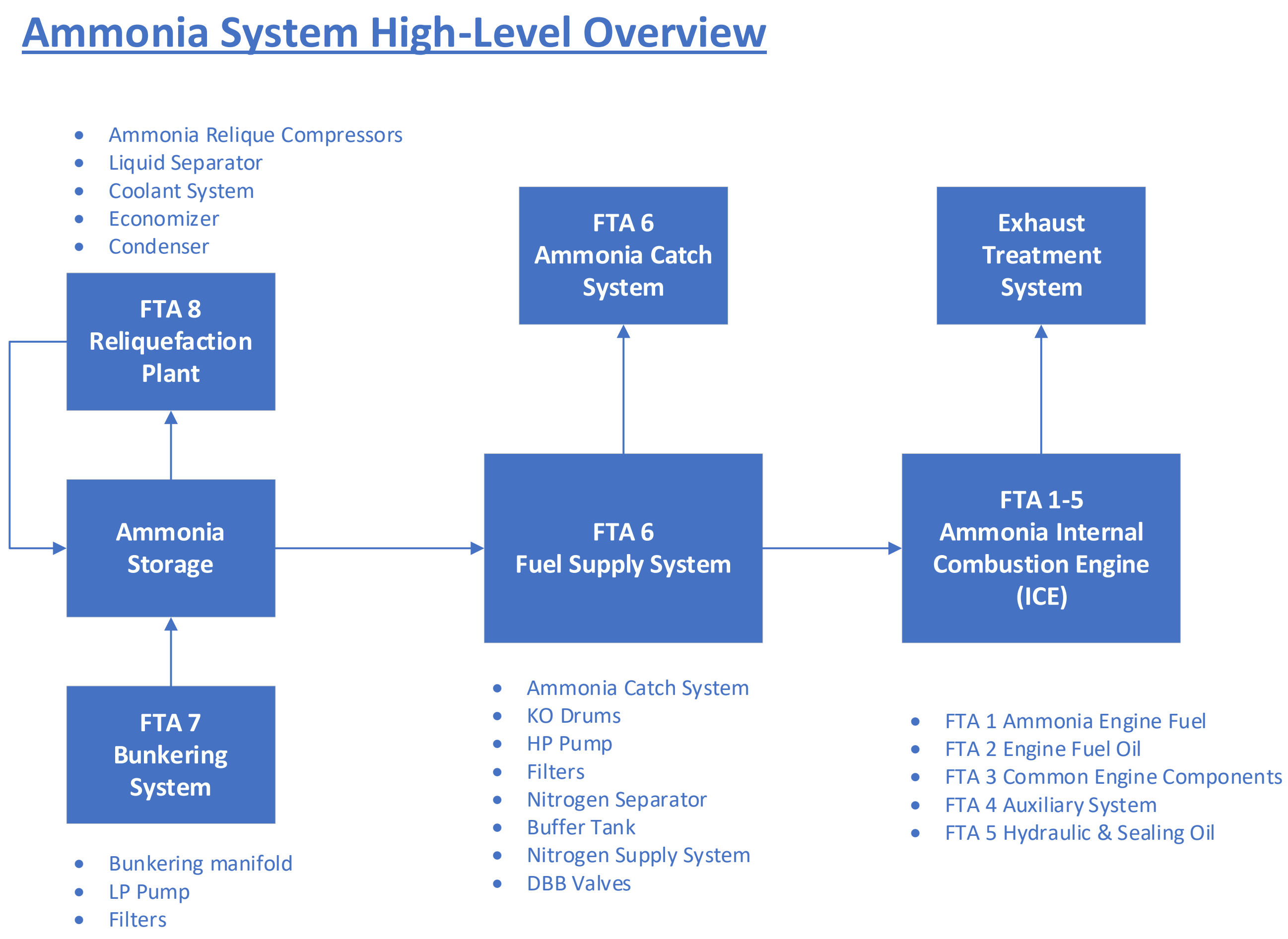



Figure 1: Ammonia systems high-level overview

[9] Disclaimer: Scope of the study is to present a general approach. Equipment and systems terminology used in the report is neutral. Each manufacturer may have their own specific design.

## 2.1 Internal Combustion Engines (ICEs)

Burning ammonia in an internal combustion engine can be done either by using Diesel or the Otto cycle principle. Each combustion cycle comes with its own advantages and challenges with respect to engine and fuel supply system design, engine performance, and emissions. In general, we refer to for engines that adopt Otto cycle as low pressure (LP) and those using Diesel cycle are referred as high pressure (HP).

Following the same principle as other liquefied gas fuel engines, ammonia engines currently being developed by manufacturers are dual fuel (DF) engines with distinct ammonia and diesel modes. When the engine operates in ammonia mode and a failure event triggers ammonia trip, the engine changes over to diesel mode. Low pressure DF engines will use the Otto process in ammonia mode and the conventional Diesel process when in diesel mode, as the Otto cycle principle has been identified by one of the engine makers as the best solution, mainly for smaller engines with a power range between 1.7 to 3.4 MW that can be used for propulsion as well as for genset. The high-pressure DF engines use the Diesel combustion process for both ammonia and diesel modes, as most two-stroke and four-stroke engine makers have selected this diesel principle for their ammonia engine design.

In Diesel cycle, the ammonia is injected into the combustion chamber at a high pressure in liquid form. The behaviour of the engine operates the same as it does on diesel fuel. Therefore, it is expected that the ammonia is being burned with very limited slip and the amount of ammonia that will end up in the cylinder lubrication oil is negligible resulting in very limited impact on the wear of the combustion chamber component in the engines, with the injectors taking the biggest impact.

In an Otto cycle, the ammonia is mixed with air prior to combustion, resulting in a higher amount of ammonia slip, $N_2O$ and $NO_x$. Exhaust gases will then have to be treated accordingly with after-treatment systems to reduce such ammonia releasing into the atmosphere. Unburnt ammonia will be present in the combustion chamber, exposing the combustion chamber component to ammonia. Therefore, corrosion of the engine component can potentially be an issue, but it is unknown how big the impact will be on wear and tear of the engine component.

### 2.1.1 Pilot Fuel

To initiate ammonia combustion, a pilot fuel with a high ignition energy level is required. Pilot fuel is usually fossil-based such as MGO/MDO, but biodiesel-based fuel can also be used. For the bigger two-stroke engine, VLSFO can also be used as pilot fuel. Injection of pilot fuel is done either by the conventional fuel injection system such as a common rail system, or it can be individually injected with electronically programmed duration and timing. Alternatively, a dedicated pilot system can be implemented to electronically control fuel injection duration and timing.

Table 1 (revised from 2022 report: *potential of ammonia as fuel in shipping*) shows a comparison between the two engine cycle principles. Table values are preliminary and for reference purposes only, since ammonia engines are expected to vary or improve with further testing over time leading to engine updates.

Table 1: Operational datasheet between Otto and Diesel cycle engines[10]

| | **Low Pressure (LP)** | **High Pressure (HP)** |
|---|---|---|
| **Gas mode cycle** | **Otto** | **Diesel** |
| **Gas Injection** | Gas admission valves located on the cylinder | Gas injection valves located on the cylinder cover |
| **Combustion principle** | Low pressure pre-mixed gas/air and in-cylinder compression | High pressure direct gas injection into the cylinder for diffusion combustion |
| **Fuel supply pressure** | ~5-16 bar | ~80-90 bar |

[10] Note: The ammonia engine is still being tested, so all results in the table are preliminary.

| | Low Pressure (LP) | High Pressure (HP) |
|---|---|---|
| Gas mode cycle | Otto | Diesel |
| Injection pressure | 5-16 bar (Same as supply pressure) | 500-700 bar (two-stroke)<br>four-stroke varies between engine makers. |
| Liquid pilot % @MCR | 15-30% | 5-10% |
| BMEP | 17 bar | 21 bar |
| Min load for DF mode | 30% | 15% |
| IMO $NO_x$ Compliance | Tier II (Oil mode)<br>Tier II (Ammonia mode) | Tier II (Oil mode)<br>Tier II (Ammonia mode) |
| Fuel Quality Sensitive | Yes | No |
| Fuel slip | Large<br>~1000-2000 ppm | Small<br>~30-300 ppm |
| $N_2O$ | High | Insignificant |
| $NO_x$ | Increased by up to 100% | Reduced by 60-70% |
| Knock/Misfire Sensitive | Yes | No |
| Load response | Reduced | Unchanged |
| Temperature inlet | N/A | 25-55°C |

## 2.2 Ammonia Fuel Supply/Recirculation System

The Ammonia fuel supply system is the integration between the fuel storage tank and the engine. Its main function is to deliver the fuel to the engine under proper conditions (e.g. pressure, temperature, flow etc.). It consists of various equipment such as, but not limited to:

- Low- and high-pressure supply pumps
- Heat exchangers (heaters/coolers)
- Filters/strainers
- Manual and automatic control valves
- Instrumentation (pressure/temperature sensors, flowmeters)

A return line is provided to process ammonia returns from the engine or releases from the fuel system. Ammonia return is to be recirculated back to the supply system or fuel storage tank and/or in between storage volume. The vapor remaining after the liquid ammonia has been returned is sent to an ammonia treatment/catch system. Classification societies limit the ammonia that can be released to the atmosphere after treatment to a concentration below 25 ppm (ABS, 2023a). The exact concentration to be permitted by regulations is under discussion within the relevant IMO groups. In September 2024, IMO released the interim guidelines, subject to approval in the next MSC session, for ammonia fueled vessels where the mitigation system limits the ammonia concentration to 110 ppm. In the system currently proposed, the ammonia vapor will typically go through a scrubber system and the ammonia will be kept in a water solution. This water solution will need to be stored onboard in a dedicated bilge tank made for this purpose. Alternatively, salt-water solutions are also being investigated.

At port, the vessel will need to discharge the ammonia-water solution. Alternatively, this ammonia-water solution could be blended into the ammonia flow going to the engine to be burned together within the engine system. However, the engine's fuel quality specifications have both a lower and an upper limit to the acceptable water content (see example in Table 5). In the long run, further consideration is needed on how to deal with ammonia-water mixture.

Fuel supply/recirculation systems are usually located in dedicated spaces, called fuel preparation rooms (FPR), with adequate ventilation of a minimum 30 air changes per hour as required by the IGF code. In the case of a leak, the ventilation amount will likely be increased to 45 times; this is already implemented in the guidelines prepared by several Classification societies.

### 2.2.1 Ammonia Pumps

Ammonia supply pumps draw liquid ammonia from the fuel storage tank and process it through the supply system to deliver it to the engine inlet at the proper pressure. They are categorised as low- and high-pressure pumps.

Low-pressure (LP) pumps are installed on the fuel storage tank to pump ammonia into the fuel supply system. They can be electric motor driven deep-well or submerged type pumps. A high pressure (HP) pump is required to build the ammonia up to the desired pressure prior to the engine inlet. For instance, high pressure diesel engines require fuel to be supplied at a range of 80-90 barg. Pumps that can deliver this type of pressure are so far only reciprocating pumps that can be equipped with Variable Frequency Drive (VFD) and/or use a bypass line to recirculate the ammonia across the pumps to improve the turn-down ratio.

### 2.2.2 Heat Exchangers

To ensure the temperature of the ammonia is maintained within an acceptable range to reach the engine inlet with proper conditions, a heater/cooler is placed within the fuel supply system stream. A cooler may also be fitted in the return line. Heaters/coolers can be shell and tubeplate heat exchangers or equivalent, depending on the heat transfer needs and heating/cooling medium.

### 2.2.3 Filters/Strainers

A filter is provided in the ammonia supply system to prevent any debris, dirt and foreign particles or impurities from entering into the engine. They are usually duplex type for easier maintenance and for uninterrupted operation. Differential pressure sensors with an alarm are fitted to indicate if the filters are clogged.

Specific procedures explaining how to open and clean the filters, including the required safety precautions for ammonia, are to be developed and to be available onboard the vessel.

### 2.2.4 Valves and Instrumentation

Ammonia supply systems include a series of manual and automatic control valves (pneumatic or hydraulic). Control valves rely on solenoid valves and instrumentation (pressure/temperature sensors). Flowmeters indicate ammonia fuel flow to the engine.

### 2.2.5 Fuel Valve Train (Supply/Return)

The fuel valve train (FVT) is an arrangement of double block and bleed valves at the ammonia supply and return lines before the engine to safely isolate the engine in case of engine shutdown or maintenance operations. The maximum allowable distances between these valves and the engines are typically recommended by OEMs. The two shut-off (block) valves are to be of the fail-close type, while the bleed valve is to be fail-open. The FVT may be in a dedicated space outside the machinery space or it could be part of the double-walled piping system enclosure with proper ventilation arrangements. FVT may also be referred to as Fuel Valve Unit (FVU) or Gas Valve Train/Unit (GVT/GVU). In the FVT, a connection to the inert gas system is provided and equipped with a double block and bleed valve to secure full isolation between ammonia and the inert gas system/nitrogen. The nitrogen is used to purge the ammonia system in the engine prior ammonia operation as well as after depressurisation upon completion of the ammonia operation. All remote valves in the FVT are of pneumatic type, to avoid the risk of generating sparks.

### 2.2.6 Ammonia Treatment/Catch System

The purpose of the ammonia treatment system is to collect and handle liquid or gaseous ammonia released to the atmosphere during normal operations, i.e. during fuel bunkering, fuel processing, vent or bleeding operations from double block and bleed valves, purging of equipment, draining, and gas-free operations of fuel pipes, and during any abnormal scenario, i.e. releases from pressure relief valves (PRV) fitted on the ammonia fuel system, purging, or ventilation systems after ammonia gas detection. Different ammonia treatment technologies comprise of knock-out drums (KOD), recovery/buffer tanks, scrubbers, diffusion tanks, and dilution systems (e.g. water seals). Vendor documentation may alternatively refer to ammonia treatment systems as Ammonia Vapor Processing System (AVPS) or Ammonia Release Mitigation System (ARMS). Oxidation of vapors is another method to treat ammonia releases/returns via a gas boiler or a combustion unit.

## 2.3 Venting and Ventilation System

### 2.3.1 Venting

Fuel supply systems are to prevent venting except where necessary for safety and emergency reasons. Tank and piping venting systems consist of pilot operated or spring-loaded type pressure relief valves. For tanks, combined pressure/vacuum or dedicated vacuum relief valves may be provided. The vent lines from the valves are to lead to the vent mast or, alternatively, could be diverted to the fuel treatment system or vent control system, as far as practicable.

International regulations (IGC and IGF Codes) include prescribed requirements for vent locations. However, final determination of vent placement should be validated by a gas dispersion simulation.

### 2.3.2 Ventilation

Ventilation is to be provided for all spaces with potential hazardous or toxic atmosphere, such as fuel preparation rooms (FPR), tank connection spaces (TCS), double wall piping annular spaces, fuel valve train (FVT) rooms, and ammonia treatment systems. Mechanical ventilation in the form of electric motor driven extraction fans is provided with the exhaust positioned at safe areas.

### 2.3.3 Nitrogen ($N_2$) purging

Nitrogen provision is required to purge the engine, fuel supply system, and other system components upon normal or emergency stop of the engine. The nitrogen piping system connects to selected locations in the supply and return piping system and it is activated in a particular sequence and duration to ensure adequate purging. Nitrogen is created by onboard generators, and it is stored in dedicated nitrogen buffer tanks. A nitrogen separator can be used to separate ammonia from nitrogen after purging at a normal engine stop.

## 2.4 Exhaust Gas Treatment Systems

The increasing concern of greenhouse gas emissions and air pollution necessitates a transition towards cleaner fuels for power generation. Ammonia ($NH_3$) has garnered significant interest due to its potential for near-zero sulphur oxide ($SO_x$) and particulate matter (PM) emissions when combusted. However, the combustion process itself introduces new challenges in the form of nitrogen oxides ($NO_x$), nitrous oxide ($N_2O$), and unburned ammonia ($NH_3$ slip) in the exhaust gas (Figure 2). These pollutants pose significant environmental and health concerns, necessitating the implementation of effective after-treatment strategies. While the ideal reaction of ammonia combustion yields only nitrogen ($N_2$) and water ($H_2O$), several factors can lead to the formation of undesirable byproducts.

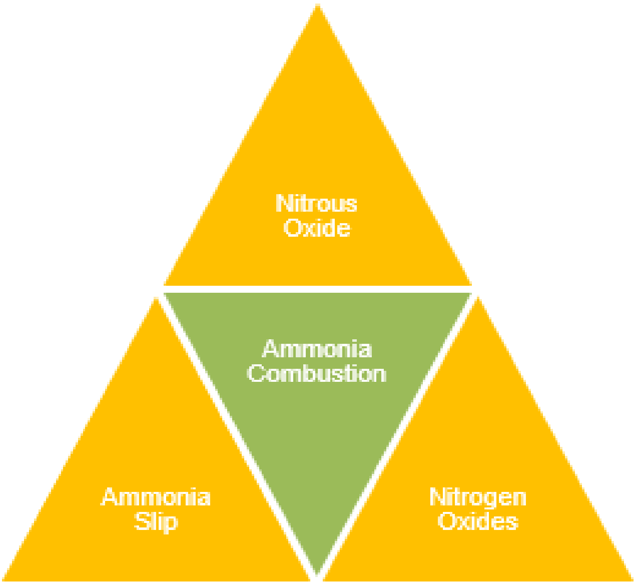



Figure 2: Harmful byproducts from Ammonia Emissions

### 2.4.1 Nitrogen Oxides ($NO_x$)

Similar to conventional engines, under certain conditions ammonia combustion can generate nitrogen oxides ($NO_x$) in the exhaust gas. $NO_x$ encompasses nitric oxide (NO) and nitrogen dioxide ($NO_2$), with their formation heavily influenced by high combustion temperatures exceeding 1,000°C. Two primary mechanisms contribute to $NO_x$ formation:

- **Thermal $NO_x$:** At elevated temperatures, the energy disrupts nitrogen molecules ($N_2$) in the intake air, forming nitric oxide (NO):

$N_2 + O_2$ (high temperature) $\rightarrow 2NO$

- **Prompt $NO_x$:** This mechanism involves the immediate reaction of ammonia radicals ($NH_x$) with oxygen ($O_2$) following combustion, forming NO and water vapor ($H_2O$):

$NH_x + O_2 \rightarrow NO + H_2O$

### 2.4.2 Nitrous Oxide ($N_2O$)

Nitrous oxide ($N_2O$) is a potent greenhouse gas with a global warming potential 265 times greater than $CO_2$. Incomplete combustion of ammonia within the engine can lead to its production:

$2NH_3 + 2O_2 \rightarrow N_2O + 3H_2O$

While combustion optimisation and engine tuning can minimise $N_2O$ formation in the exhaust gas, further considerations might be necessary for complete mitigation.

### 2.4.3 Ammonia Slip

Incomplete combustion or misfiring can result in unburned ammonia escaping into the exhaust gas stream, posing a health hazard and requiring treatment to comply with upcoming regulations.

### 2.4.4 Exhaust Gas Treatment Technologies

Fortunately, existing after-treatment technologies employed for conventional engines can be adapted for ammonia-fuelled engines:

#### 2.4.4.1 Selective Catalytic Reduction (SCR)

This highly effective technology injects ammonia into the exhaust stream upstream of a catalyst. In the presence of the catalyst, the injected ammonia reacts with $NO_x$, converting both into harmless nitrogen ($N_2$) and water vapor ($H_2O$). SCR may require additional equipment for ammonia storage and injection.

#### 2.4.4.2 Exhaust Gas Recirculation (EGR)

This technique recirculates a portion of the exhaust gas back into the engine's intake stream. By diluting the air-fuel mixture, EGR lowers combustion temperature, thereby reducing $NO_x$ formation. EGR is particularly suitable for two-stroke ammonia engines.

#### 2.4.4.3 Engine Design Optimisation for Emission Reduction

Engine design and tuning play a crucial role in minimising emissions at the source. Key strategies include:

- **High-Pressure Injection:** Improves fuel atomisation and mixing for more complete combustion, reducing $NH_3$ slip.
- **Variable Valve Timing:** Precise control over valve timing optimises intake and exhaust processes, enhancing combustion efficiency and minimising pollutant formation.
- **Controlled Cooling:** Innovative engine geometries can maintain the right air-fuel mixture to control elevated temperatures that promote $NO_x$ formation.
- **Precise Fuel Injection Control:** Electronically controlled systems allow for accurate control over ammonia injection parameters, leading to minimised pollutant formation.
- **High Efficiency Turbochargers:** Turbochargers with high compression ratios ensure sufficient air enters the combustion chamber to account for shorter valve timings and complete combustion.

#### 2.4.4.4 Emission Targets and Regulations

International regulations for ammonia engine emissions are still under development. However, a recent study (MMMCZCS, 2023) considered ongoing technology development to propose indicative emission targets that balance safety and environmental considerations with realistic performance expectations (Table 2). These targets require validation. To date, multiple Classification societies have published requirements for ammonia-fuelled vessels, including Acute Exposure guidelines, however the alarm and shutdown levels vary.

Table 2: Indicative Emission Targets for Ammonia Engines (Source: MMMCZCS)

| Emission | Target Level |
|---|---|
| **$NH_3$** | 10-30 ppm |
| **$N_2O$** | 0.06 g/kWh |
| **$NO_x$** | Tier III (≈2 g/kWH) |

#### 2.4.4.5 Tailoring Technologies to Engine Types

The choice of after-treatment technology can vary depending on the engine type (two-stroke or four-stroke) and combustion cycle (Diesel or Otto).

- **Diesel Cycle Engines:** Initial results suggest that these engines may achieve Tier III $NO_x$ emission levels through engine tuning alone, potentially eliminating the need for SCR. Ammonia slip is also expected to be low as initial indications from engine makers, potentially meeting the 30-ppm target without additional treatment. However, if SCR becomes necessary, the fuel consumption penalty is estimated to be like conventional engines using fuel oil.

- **Otto Cycle Engines:** Initial testing indicates higher $NO_x$ and ammonia slip in the exhaust compared to diesel cycle engines. This might require a larger SCR catalyst to remove $NO_x$ and additional ammonia injection in order to achieve Tier III compliance. Moreover, higher $N_2O$ emissions might require an additional $N_2O$ reduction catalyst integrated into the SCR system.

#### 2.4.4.6 Upcoming Technologies for Cleaner Ammonia Combustion

While established technologies offer a solid foundation, continued research and development hold the key to optimised performance and exploring even cleaner solutions. These solutions include:

- **Plasma Reduction System:** This developing technology utilises non-thermal plasma to directly break down pollutants into harmless molecules. While promising, further research is needed for large-scale marine applications.
- **Water Absorption:** This technology has potential to reduce ammonia slip by capturing it in a water spray tower. However, water management and regeneration are crucial to prevent environmental contamination.
- **Exhaust gas Circulating system (EGR/iCER):** Initially this solution didn't get much attention from makers of ammonia-fuelled engines. It was expected not to be feasible because, to reduce $NO_x$ formation, it slows combustion by reducing the concentration of oxygen going to the combustion chamber, thereby eliminating the peak temperatures. Because of ammonia's poor combustion qualities, EGR system implementation was expected to and increase the ammonia slip and significantly reduce the combustion efficiency. However, the latest test has shown that ammonia burns significantly easier than expected, so the EGR system might be a feasible option for ammonia, but it has yet to be tested. The main benefits of the EGR system are that it prevents the formation of $NO_x$, and it can operate without the use of urea as a reducing agent. A smaller additional benefit of the EGR system is that the system includes a scrubber which could also be used to reduce the ammonia slip resulting from combustion.
- **Ammonia Gas Combustion Unit (GCU) or Boiler:** A GCU is primarily used to manage boil-off gas (BOG), or, ammonia vapor in this case, which cannot be utilised in engines. They safely combust the vapor and can be coupled with a boiler to harness the heat for energy production. These technologies can manage ammonia slip by converting it back into fuel and utilising it for energy production.

## 2.5 Bunkering System

Ammonia is transferred to fuel storage tanks through a bunkering station and manifold. A bunkering station consists of bunkering pipelines, manually and remotely operated emergency shutdown (ESD) valves, and pressure relief valves. Bunkering stations can be either located on an open deck with natural ventilation or be of enclosed/ semi-enclosed type, where mechanical extraction ventilation should be used.

A water curtain can be applied around semi-enclosed spaces to hinder the ammonia cloud from escaping. Efficiency of these water curtain systems onboard ships is untested other than gas carriers, and there are no available design standards that define how the system should be made in order to achieve an effective water curtain system within a defined space.

The bunkering manifold is to be designed to withstand the external loads during bunkering. The connections at the bunkering station are to be of dry-disconnect type equipped with additional standard-type safety dry break-away coupling/self-sealing quick release.

## 2.6 Reliquefaction Plant

Depending on the vessel's operational requirements and containment system capabilities, a reliquefaction plant may be installed to handle excess boil-off gas (BOG) from the fuel tanks. Ammonia reliquefaction technologies are already available from LPG/ammonia carriers and are not expected to differentiate much, apart from capacities. A typical reliquefaction skid would include compressors, condenser, and expansion valves and seawater is normally used as coolant. In the reliquefaction process, the pressurised BOG vapor is suctioned into the compressor where it is re-pressurised using piston compressors, typically in two stages. Then it is cooled by seawater, expanded, and condensed in a flash tank. The condensate is then returned to the ammonia tank system as liquid. A flow diagram of the typical reliquefication plant process is shown in Figure 3 below.

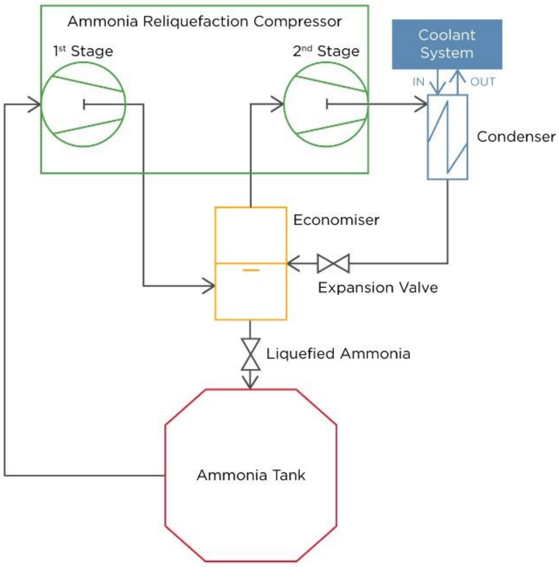



Figure 3: Ammonia reliquefaction cycle

The ammonia fuel system's need for and design capacity of a reliquefaction plant is dependent on its operation profile, tank storage size and conditions (semi-refrigerated or fully refrigerated).

Ammonia-fuelled vessels equipped with Type C tanks will rarely need a reliquefaction plant. Type C tanks are used for fully-refrigerated or semi-refrigerated storage conditions. They are designed to withstand high pressure accumulation and, in combination with the applied insulation, they can achieve long holding times. Bunkering is expected to be done at boiling point of -33ºC and the bunker vessels are equipped with a vapour return line to manage boil-off gas during bunkering, thus negating the need for reliquefaction plants.

On the other hand, vessel types that are designed with a Type A or B tank (e.g. containerships) have a lower design pressure of 0.7 barg. In these vessels, a reliquefaction plant can provide pressure/temperature control as required based on the operational profile. Similar boil-off gas cargo management system exists on conventional LPG/ammonia carriers.

In the typical reliquefaction skids shown above, the operating BOG compressor can eventually leak, releasing large quantities of gas in the fuel preparation room where the skids are located. In the event of a leak, immediate action should be taken to address the situation and minimise the spread of gas. Response to ammonia BOG leakage should include activation of emergency ventilation systems, automatic isolation of the source of the leak, and issuance of an alarm to evacuate personnel to safe areas. The leaked ammonia will be contained to the machinery space, which is equipped with drip trays sized to contain the worst-case leak. The affected machinery room should then be thoroughly ventilated with 45 air changes per hour in order to disperse the ammonia gas so personnel can safely re-enter. Any damaged equipment would need to be repaired or replaced to prevent further leaks from occurring in the future. Safety protocols and procedures should be in place to handle ammonia leaks, and personnel working with or around ammonia systems should be trained on how to respond to such emergencies.

Future ammonia reliquefaction designs may also implement subcooling systems like current LNG systems use. A subcooling system would return the ammonia to the tanks at a temperature lower than its boiling point, thereby reducing generated BOG.

# 3. Safety Assessment and Reliability Analysis

The reliability analysis follows the flowchart in Figure 5. The first step is to select critical equipment in the ammonia-fuelled ship system as main hazards in probability of failure and consequence. As main hazards are identified, critical components of selected equipment are built in a BOM (bill of materials) for application of such equipment in ammonia-fuelled ships. Through this process, a system boundary is specified for the reliability analysis.

In step 2, a concept drawing taken from the Piping and Instrumentation Diagram (P&ID) has been created to aid in the explanation of complex failure scenarios. The design life and operating conditions of critical equipment and components in ammonia-fuelled ships have been used to identify the failure modes of such components when used in ammonia-fuelled ships. Updates in recent developments of such components, as provided by the manufacturers, have been taken into consideration for this step. Step 3is a qualitative assessment produced by a SME interview on the Fault Tree Analysis (FTA). The interview results are constructed in a cause-and-effect format in Step 4. In step 5, the output of the FTA is then transferred into the Windchill FTA application. Windchill FTA is composed of basic events in FTA structure. Data sources (such as OREDA, AIChE, NUREG, MAN service letter, etc.) are used in this step via basic events to calculate subsystem and system reliability or MTTF (mean time to failure). Steps 5-7 are covered in the WRR simulation tool producing quantitative assessment.

The following data forms are generally used as an input for each basic event in WRR:

- Constant probability of failure (this is exponential distribution with constant failure rate)
- Failure Rate or MTTF
    - Fixed failure rate or MTTF
    - Distribution with mean and standard deviation

These basic events are connected using logic (such as “OR”, “AND” or “K out of N”) as causes to the next higher level of failure demonstrated in Figure 4. For instance, two basic events (i.e., preventative maintenance is ignored or bad fuel quality) can lead to a clogged filter. The probability for these two basic events is related to human error, which is a constant probability of failure 0.0001 (per data source NUREG). The probability of a clogged fuel filter is then calculated in a reliability function by either of these two events occurring:

Human Error Probability = <u>0.0001;</u>

Reliability = $(1-p)^2 = 0.9999^2 = 0.99980001$;

Probability of failure (clogged filter) = 1- Reliability = $1-(1-0.0001)^2 = 0.0001999$ or <u>1.999 E-4.</u>

One of the causes of no ammonia in the supply line is a clogged filter. The probability of failure for no ammonia in the supply line is further calculated in a reliability function, along with other failures modes (not shown in the graph) = 8.9964 E-4.

In the final step, all basic events are filled in by various data sources. FTA simulations are executed to provide MTTF or probability of failure for the total ship system and subsystems.

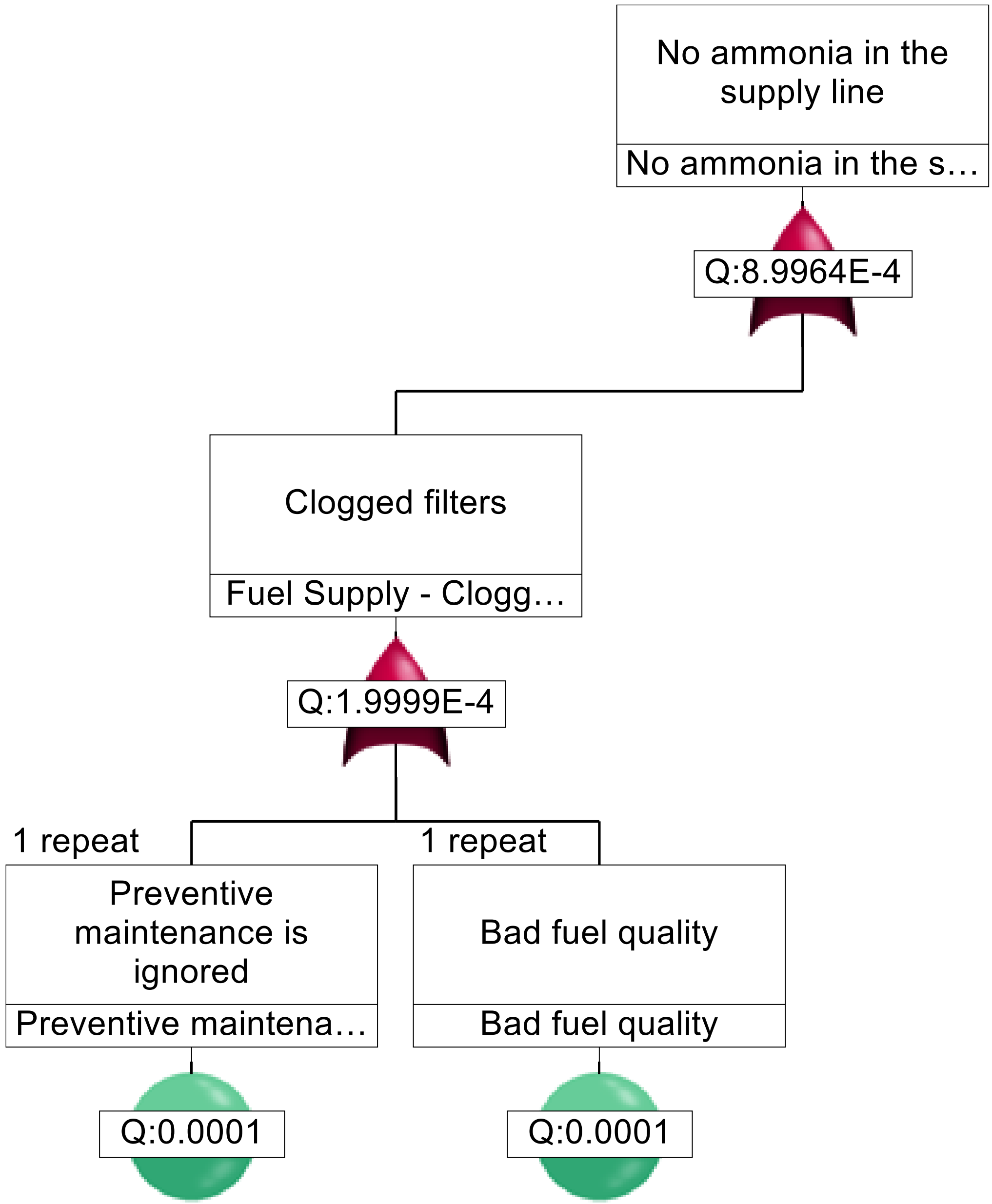



Figure 4: Windchill Risk and Reliability FTA calculation by basic events

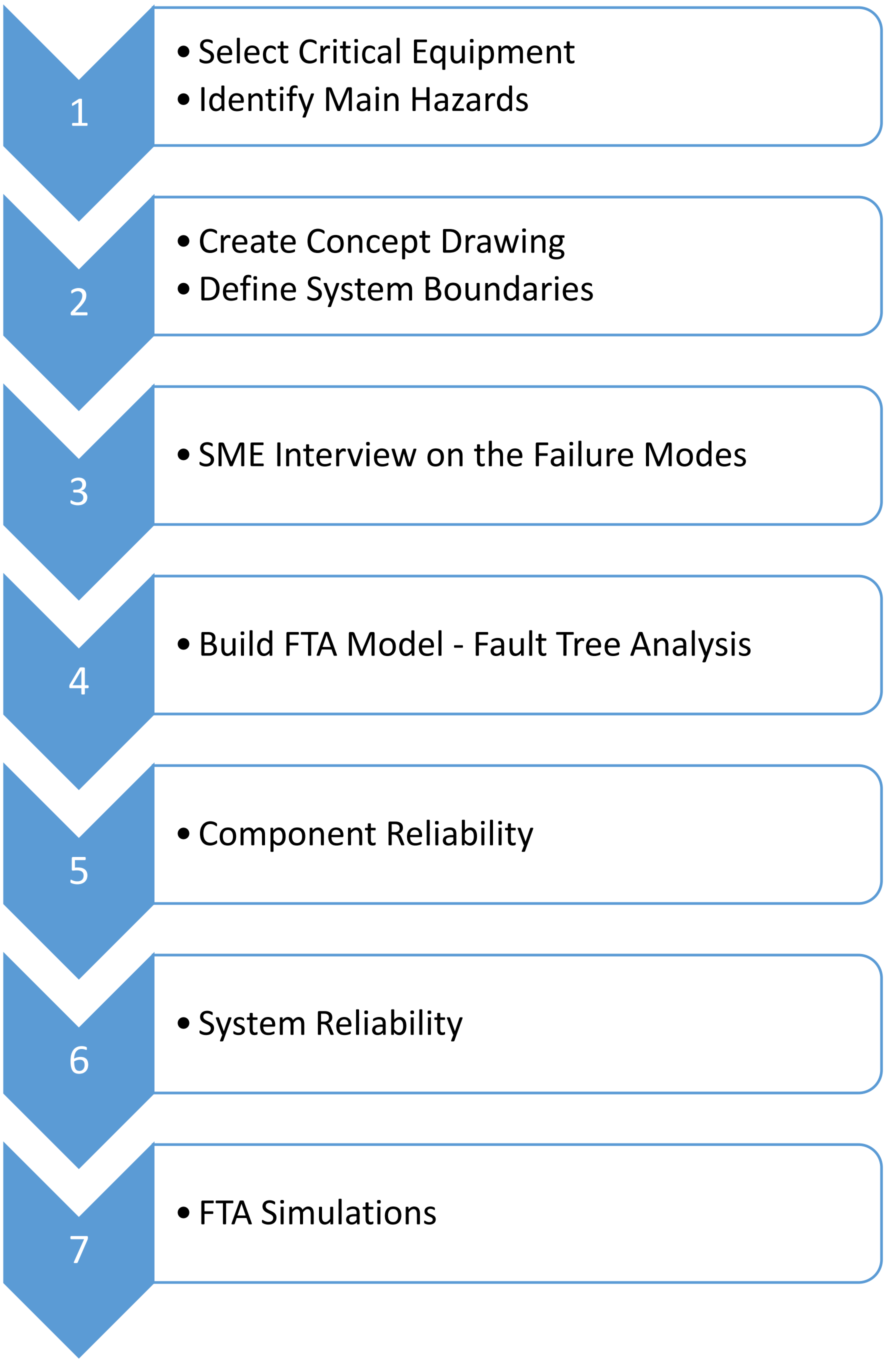



Figure 5 FTA Process Flowchart

## 3.1 ANSI/AIAA S-102.2.18 Reliability Performance Standard and Hierarchy Structure

The standard of AISI/AIAA S-102.2.18 establishes uniform requirements and criteria for a performance-based fault tree analysis (FTA), including the modelling components, symbols, and analytical objectives. The performance-based aspect of this standard requires that the organisation's FTA capability be rated according to predetermined criteria for process capability and data maturity. The primary purpose of FTA is to systematically examine a potential system failure by creating a graphical representation of the system logic. The fault tree represents system relationships and fault paths and provides a means for qualitative or quantitative system evaluation. Fault tree analysis is a deductive, top-down method used to determine how a given system failure can occur. A system top undesired event is either identified or postulated and the analysis attempts to find out what contributes to this undesirable event.

The FTA begins identifying a top event, establishes the component-level to which each system-level fault is examined, and determines the immediate causes for each fault at progressively lower levels until a component-level fault is reached. The FTA determines the various ways in which a particular type of top event or failure could occur. All of the possible system contributing factors and their relationships shall be established and, if possible, a top probability of occurrence calculated for each.

The primary output of FTA is a qualitative (phase I) or quantitative (phase II) evaluation of a system failure, by means of a fault tree structure. In phase I, FTA is particularly useful in the examination of highly complex functional paths in which the outcome of one or more combinations of non-critical basic events may produce an undesirable system failure. Typical candidates for FTA are functional paths or interfaces that could have impact on safety such as the handling of ammonia hazards, safety of operating and maintenance, personnel of the ammonia-fuelled vessel, etc. In phase II, the output produces a design life for the ship system and subsystems using the basic events with probability of failure or MTTF connected by logics and hierarchical structure.

Reliability analysis starts with a definition describing what functions are required for a successful mission despite the equipment status. Reliability can be tested as 'single point of failure' or 'mission reliability'. Mission reliability is expressed as the probability of meeting the system requirements as intended. This includes equipment degradation capability or redundant equipment to continue operations when the primary equipment is not available. As long as the function is fulfilled, the mission is considered successful. The traditional definition of single point of failure regarding reliability is when the equipment is not available upon demand.

The following are basic assumptions in the FTA model/system hierarchical structure (Figure 6, Figure 7, Figure 8):

1. Mission time is defined dock-to-dock (maintenance time is not included in the mission).
2. Mission time is a pre-determined frequency of missions each year.
3. Function is not lost if redundant capability is present.
4. The engine is dual fuel design. When the ammonia fuel system is shut down, the fuel system will switch to fuel oil.

The FTA system hierarchical structure consists of critical components and was constructed in the following tier relationships. The example below is given to demonstrate the asset structure process.

1. High-level – Tier 1
    a. T2 Main Engine
    b. T3 Fuel Supply to Consumers
    c. T4 Exhaust Gas System
    d. T5 Bunkering
    e. T6 Reliquefaction System
2. System/sub-system – Tier 2
    a. T2.1 Internal Combustion Engine
    b. T2.2 Common Engine Components
    c. T2.3 Auxiliary Systems

    d. T2.4 Hydraulic and Sealing Oil Systems
    e. T2.5 Engine Control Module
3. Equipment – Tier 3
    a. T2.1.1 Ammonia Fuel System
        i. Ammonia Fuel Injection System
        ii. Ammonia Control Block (including valves)
        iii. Ammonia Accumulator
        iv. Double Wall Ammonia Fuel Piping
        v. Gas and Liquid Leakage Detector
    b. T2.1.2 Fuel Oil  Pilot Fuel System
        i. Pilot Fuel Injection System
        ii. Pilot Fuel Pump
        iii. Fuel Oil Heat Exchanger
        iv. Fuel Oil Strainer/Filter
        v. El. Governor

Each failure scenario is weaved through the three-tier critical component list and constructed by cause-and-effect relationships, which is the focus of the next section. T1 is the hull integrity, which is not in the scope of the reliability study. Emphasis is given to ammonia related equipment failures since the project goal is to promote ammonia safety. As a result, engine control module (ECM), for instance, is included in the critical component list, but will not be analysed in the fault tree.

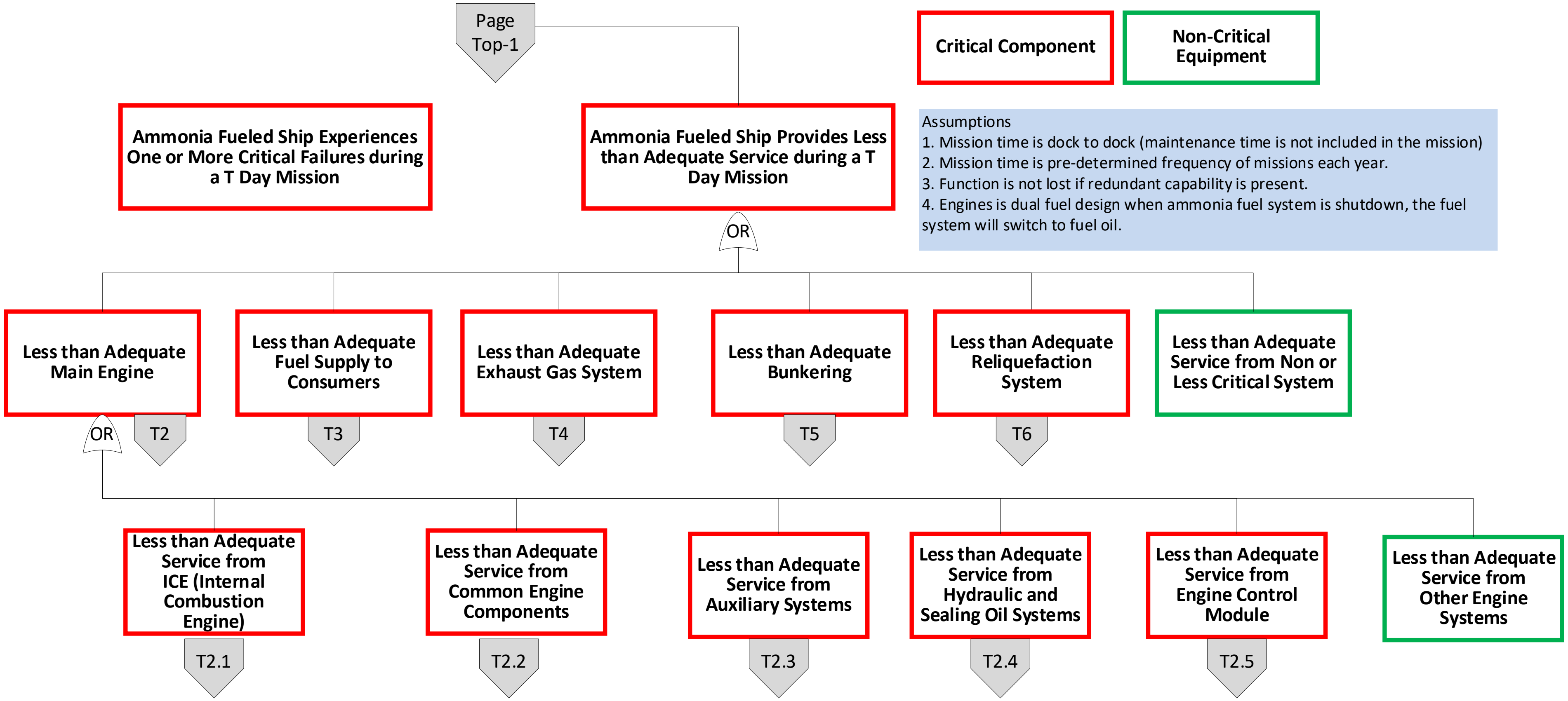



Figure 6: FTA Asset Structure Top 1 – Ammonia-fuelled Ship during a T Day Mission

In the reliability study of ammonia safety as fuel on ships, the system is mostly in a serial configuration, where no redundancy is allotted in the design except T2.1 the ICE engine fuel system illustrated in Figure 7. In the simulation, the ammonia fuel system and fuel oil system are connected via an AND gate which results in a higher reliability.

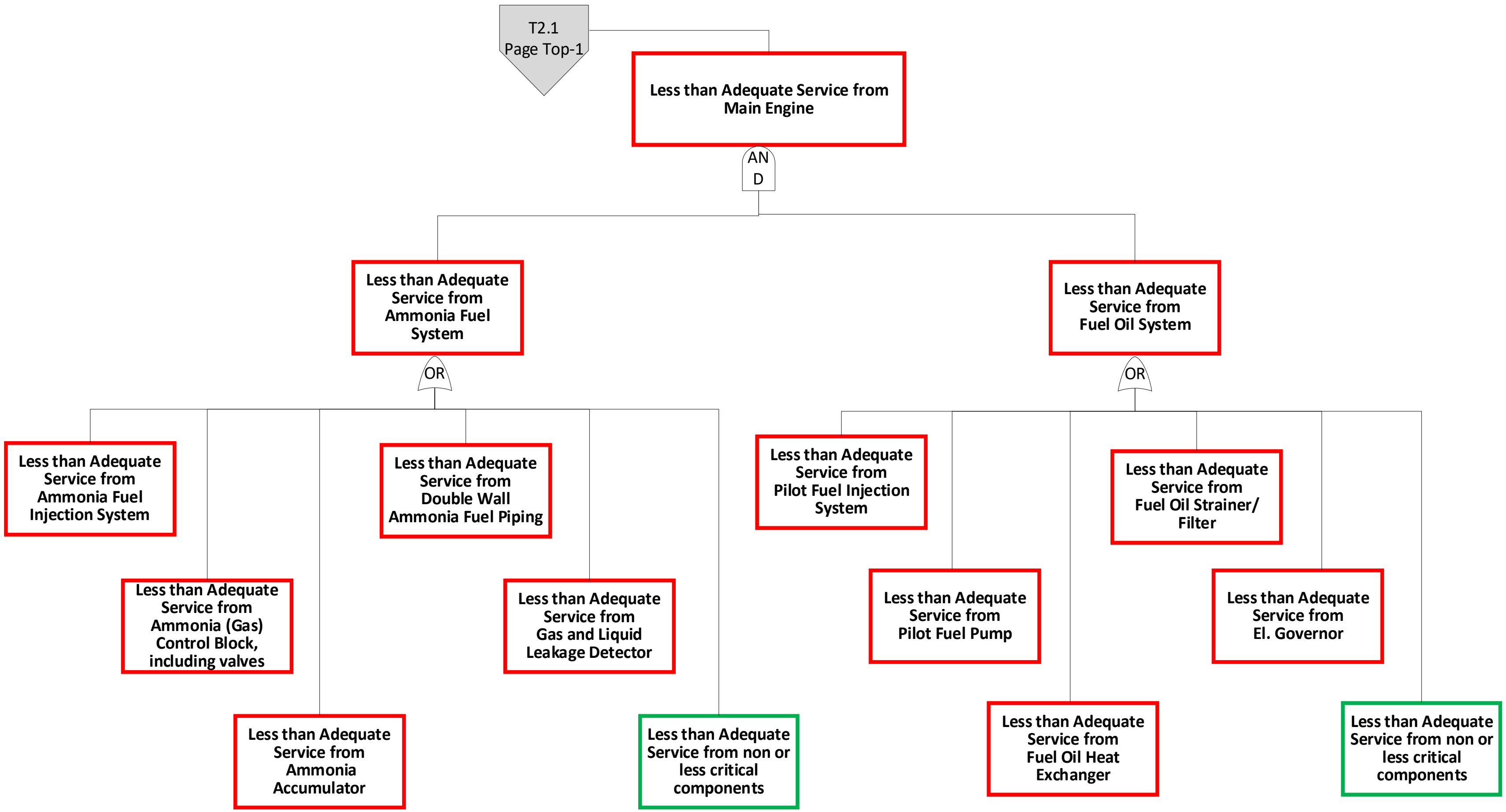



Figure 7: FTA Asset Structure T2.1 – Main Engine

The ammonia fuel supply system has been constructed according to the T3 FTA asset structure in Figure 8. The remaining asset structure in the FTA model can be found in Appendix A.

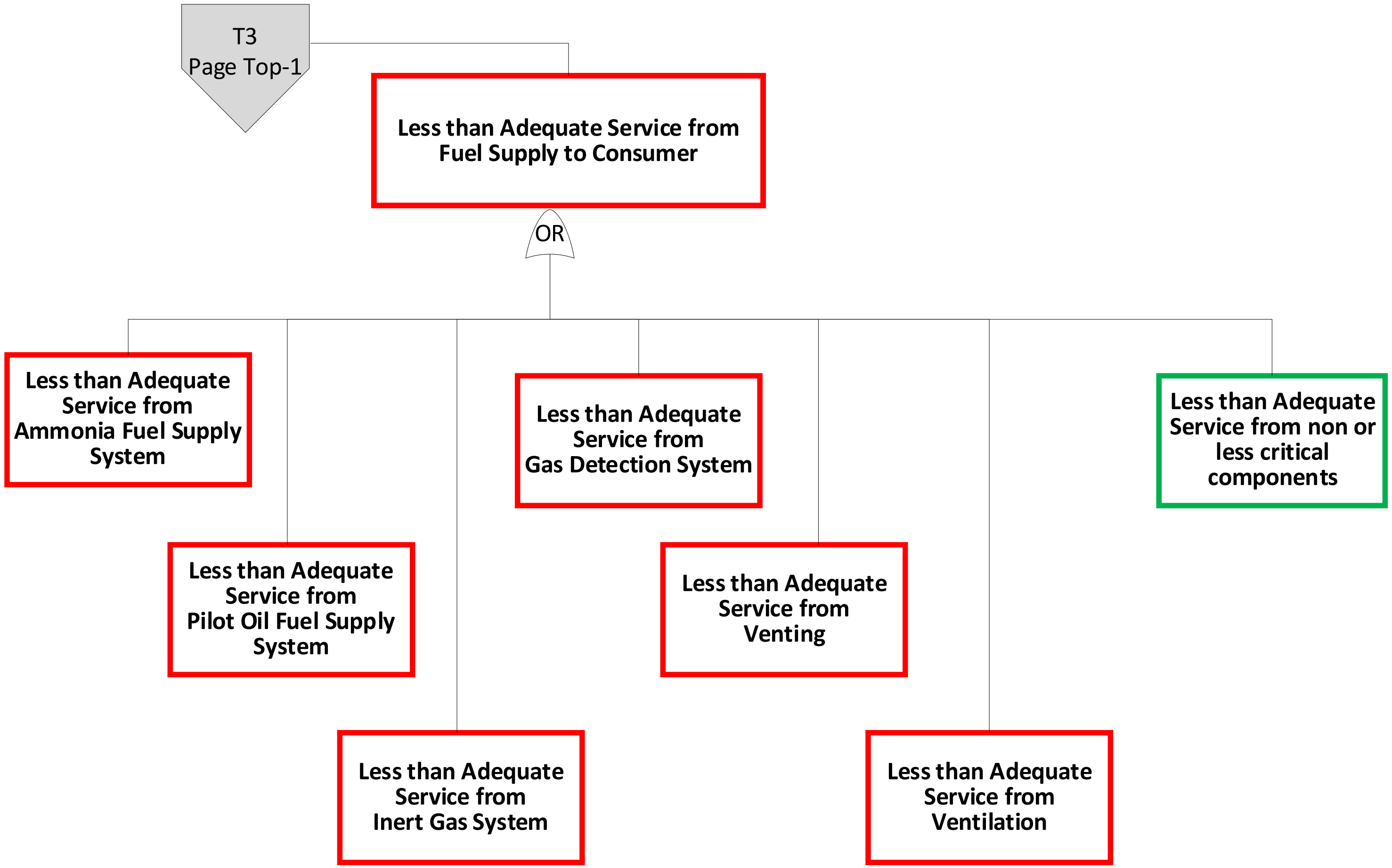



Figure 8: FTA Asset Structure T3 – Fuel Supply to Consumer

## 3.2 Fault Tree Analysis and Critical Component List

In reliability engineering, of the product lifetime information can by derived from one of several reliability methodologies depending on the type and availability of data. As mentioned before, for a conventional approach, the selected product has been manufactured and deployed in the market, warranty is documented, and reliability analysis is used to derive the product lifetime information. In this case, Weibull analysis is commonly used. For instance, refrigerators have been on the market for over a century, so refrigerator manufacturers have a failure data depository system to track field failures reported by customers.

**Weibull Analysis**

Weibull analysis is used extensively in reliability analysis. It can also be used anytime an assumption is made where data is distributed as a Weibull distribution or the goal is to find an appropriate distribution to model a data set. The data set includes a population of samples, where failure times can be failures or suspended data (i.e., product has not failed yet). With failure times, a Weibull plot is used to plot failure times on a logarithmic scale paper.

To perform a Weibull analysis, one must identify the time unit for the age of the component, which can be operational hours, miles or cycles. Once failure data is collected, one can select the distribution and estimation method, calculate and graph results, and predict future trends. For further details, one can refer to The New Weibull Handbook.

The Weibull analysis function is:

$$f(x) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1}$$

$\beta$ is shape parameter, controls the slope of a probability plot, and indicates the failure pattern.

$\eta$ is characteristic life, indicates expected life, and points where 63% of population has failed.

The slope of the plot indicates how fast the failure rate is. If the slope is 1, it indicates a constant failure rate. If the slope is greater than 1, it indicates an increasing failure rate. The higher the slope is, the faster the failure rate is. If the slope is less than 1, it may suggest an infant mortality, such as a manufacturing defect or incorrect installation.

A Weibull plot is often used in a Weibull analysis, which studies the relationship between a component's reliability and its life span. This analysis can be used to describe the time to failure. Failure modes can include cracks, deformations, fractures, or fatigue caused by corrosion, high temperature, or other factors. A Weibull plot can help provide information about product reliability, such as predicting product lifetimes, optimising maintenance schedules, and identifying an ideal warranty period.

The Weibull probability plot in Figure 9 is designed so that if the data follows a Weibull distribution the points will be linear (or nearly linear). An example of the Weibull probability plot is shown below:

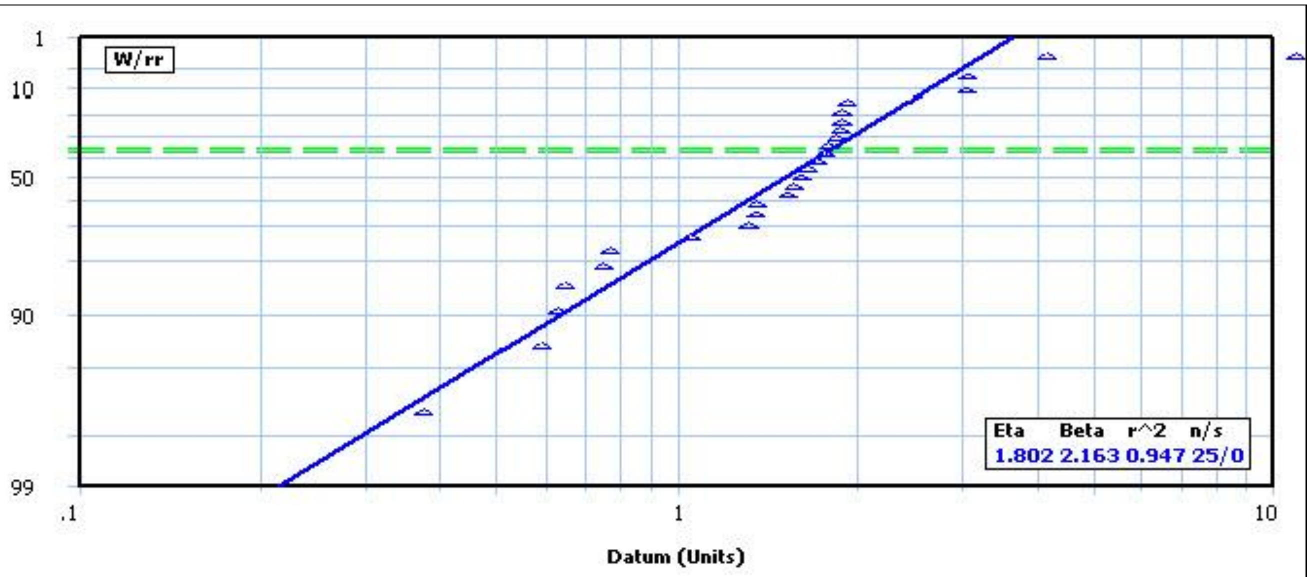



Figure 9: Weibull Probability Plot (©PTC)

When plotting the Time to Failure data on a Weibull probability plot, a regression method is used to find the best straight line placement by using least squares regression (curve fitting) to minimise the sum of the squared deviation from the failure datapoint to the best fit line. The results are shown below (Figure 9 Weibull Probability Plot)

$\eta$ (Eta): is characteristic life, related to the product lifetime.

$\beta$ (Beta): is the shape of the curve, indicating an increasing failure rate.

r^2: an index to indicate how well a best fit line to the failure points (0-1, where 1 means 100% fit)

n/s: n is the number of failure data points and s is the suspended data point (has not failed).

**Fault Tree Analysis**

Weibull analysis cannot be employed in cases where a failure data set is not available. Several unconventional reliability methodologies have been proposed to mitigate this shortcoming. Fault Tree Analysis is chosen for the ammonia fuel application because of two main factors. First, the failure scenarios can be analysed in a structured logical approach expressed by cause-and-effect relationships. This information provides insight about the design, manufacturing, installation and operation issues of the product. Secondly, FTA is a tool that is designed to provide reliability prediction and identify the key considerations to meet the product design life requirement. In addition, FTA is designed to identify what failure modes should be prioritisedfor mitigation and how much design life may increase.

Fault Tree Analysis (FTA) begins with an undesirable event to determine the primary causes that can lead to the top event. FTA is based on a set of rules and logic symbols (such as “AND” and “OR” gates) from probability theory and Boolean algebra. It consists of generating a logic model that allows for both qualitative and quantitative evaluation of system reliability or availability.

To explain the concept of FTA, Figure 10 illustrates an example of motor overheating as top event. Either of following two events could contribute to a motor overheating: 1) motor failure, or 2) excessive current transmitted to motor. Further analysis of the event of excessive current to motor requires both of the following events to occur simultaneously: 1) excessive current in the circuit, and 2) fuse protection fails to open. This is illustrated in the FTA system hierarchical structure with “OR” and “AND” gates (Figure 10). The mission reliability in the example is motor funtioning without overheating, even though there is an excessive current in the circuit, because the fuse opens up to interrupt the current continuity and acts as a protection layer when the excessive current is detected in the circuit. Mission is considered a success with an excessive current in the circuit.

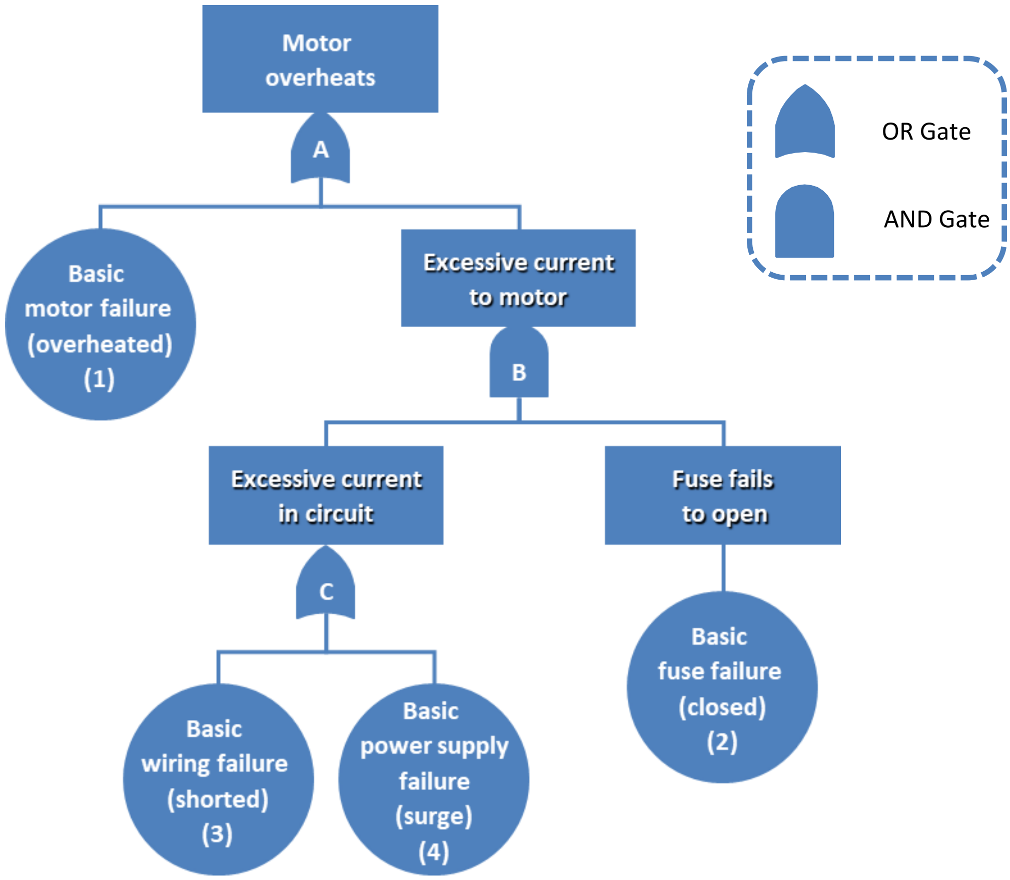



Figure 10: Fault Tree Analysis Example Illustration

**Fault Tree Analysis Phase I**

Failures modes, effect and analysis, and reliability prediction should be addressed by a joint group of experts made up of reliability engineers, designers, research and development team, especially for new technological solutions as for the ammonia as fuel. FTA is sought after to perform risk and reliability assessment in two phases: qualitative and quantitative approaches. Phase I focuses on interviewing SMEs (subject matter experts) including designers, critical system equipment makers, and ammonia producers.

A team of SMEs is carefully selected to produce an effective interview with the following disciplines for this project:

- Ammonia fuel supply system vendors
- Ammonia engine makers
- ABS ammonia experts, ship experts, and reliability facilitator

The fault tree content information was developed using an FMEA (failure model, effect and analysis) from the industry for a similar application (LPG). The reliability facilitator prepared the workshop material including the drafting FTA structure based on the FMEA content as pre-read materials. ABS internal team members were interviewed to review and edit the FTA failure scenarios. There are 8 FTA models for each subsystem. Each FTA interview lasted 1-2 hours. During the review, the reliability engineer collected the team input and continuously updated the fault tree to ensure failure scenario is correctly captured. Following the review, the reliability engineer updated the model to ensure each failure scenario is cohesive.

External review was conducted by distributing the FTA models as pre-read materials. The reliability engineer prepared questions ahead of time to be addressed during external reviews. A list of requested data as agreed by both sides was captured during the external reviews. Post interview, external reviewers sent the requested reliability data. The reliability engineer then updated the FTA model.

For this project, the three vendors were arranged to meet in person during the Gastech Conference[11]. FTA project Task 2 was reviewed onsite with the service equipment vendors and integrator.[12]

**Fault Tree Analysis Phase II**

In phase II, the focus is performing a quantitative reliability assessment using the FTA structure established in Phase I. In each failure scenario, the probability of failure is assigned based on assumptions, industry experience, failure rate consortium, and expert opinions. Figure 11 is a graphical representation of how the FTA structure is modelled in the commercial reliability software.

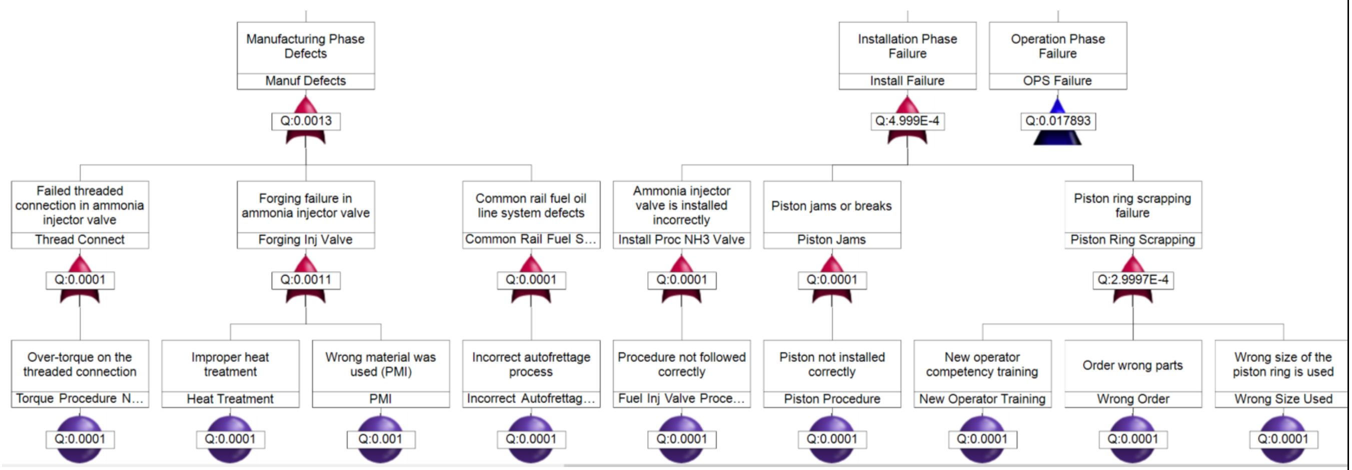



Figure 11: Windchill Risk and Reliability Simulation Tool FTA Model

The critical component list is the basis for the failure scenarios for each component, where failure scenarios are structured as a cause-effect relationship. If the project data is not readily available, ISO 14226[13] provides a system hierarchical structure and failure modes for application to internal combustion. SME input has been gathered for the

[11] Gastech 2024, September 18th, 2024, George R. Brown Convention Center, Houston, TX
[12] Trelleborg, Lewa, and Babcock.
[13] ISO 14224 International Standard Petroleum, petrochemical and natural gas industries – collection and exchange of reliability and maintenance data for equipment, Third Edition, 2016

development of the critical component list for the ammonia-fuelled ship system. In other words, this project does not need to leverage the above-mentioned ISO standard.

A critical component list is selected based on the following criteria:

1. The asset comes into direct contact with ammonia fuel,
2. The probability of component failure is high, or
3. The consequences resulting from the component failure is high.

## 3.3 Concept Drawing for Ammonia-fuelled Propulsion System

Concept drawing is used to illustrate the reliability boundary and outline the key systems that are in the reliability analysis. Figure 12 is a concept drawing for ammonia-fuelled propulsion system.

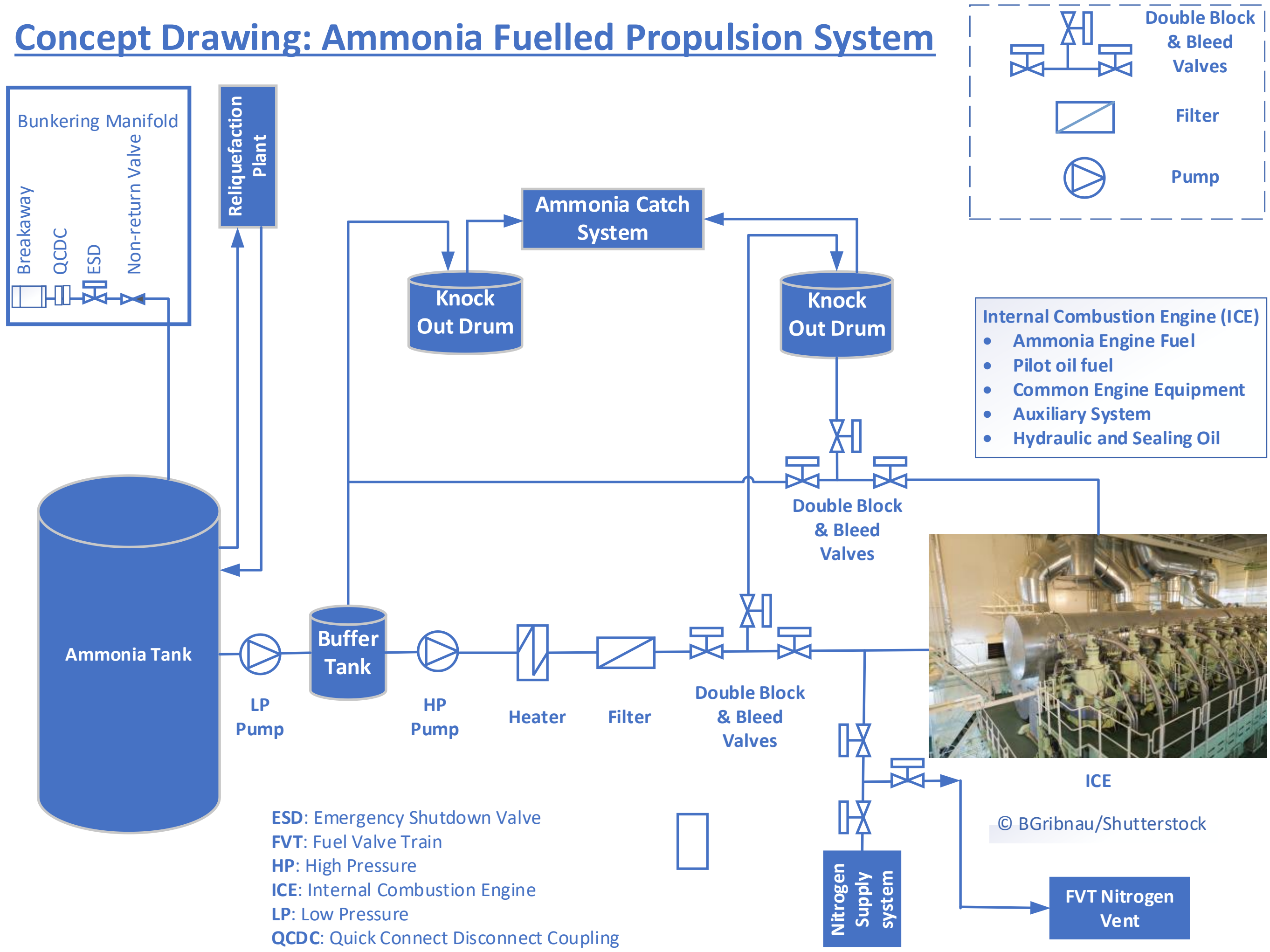



Figure 12: Ammonia Fuel System Concept Drawing

## 3.4 Critical Component List Results

Following the concept drawing, a critical component list is used to guide the brainstorming of the fault tree analysis. The list serves as a general guide to construct failure modes i.e., how a critical component could fail in its design, manufacturing, installation and operation phases. Table 3 summarises the results of a critical component list.

Table 3: Critical Component List

| High-level Description | FTA No. | System or Sub-system Information | Equipment Identification |
|---|---|---|---|
| **Internal Combustion Engine (ICEs)** | FTA 1 | Ammonia engine fuel system | Ammonia fuel injection system |
| | | | Ammonia (Gas) control block, including valves |
| | | | Accumulator |
| | | | Double wall ammonia fuel piping |
| | | | Gas and liquid leakage detector |
| | FTA 2 | Secondary fuel oil system | Pilot fuel injection system (same as fuel injection valve) |
| | | | Pilot fuel pump |
| | | | Fuel oil heat exchanger |
| | | | Fuel oil strainer/filter |
| | | | El. governor |
| | FTA 3 | Common Engine Components | Piston/piston ring |
| | | | Turbocharger |
| | | | Cylinder cover |
| | | | Cylinder liner |
| | | | Exhaust valve |
| | | | Actuator |
| | FTA 4 | Auxiliary systems:<br>- HT freshwater cooling<br>- System lube oil<br>- Piston cooling lube oil<br>- Cylinder lube oil | Cylinder liner HT water cooling space |
| | | | System lube oil pump |
| | | | Electric motor (pump) |
| | | | System lube oil heat exchanger |
| | | | System lube oil strainer/filter |
| | | | Piston cooling lube oil pump |
| | | | Piston cooling lube oil strainer |
| | | | Cylinder lube oil accumulator |
| | | | Cylinder lube oil strainer |
| | | | Cylinder lube oil booster injector |
| | | | Scavenging receiver |
| | | | Exhaust valve |
| | FTA 5 | Hydraulic (actuation) and sealing oil systems | Hydraulic pump |
| | | | Hydraulic electronic control valves |

| High-level Description | FTA No. | System or Sub-system Information | Equipment Identification |
|---|---|---|---|
| | | | Hydraulic system strainer/filter |
| | | | Hydraulic system accumulator |
| | | | Sealing oil pump/electric motor |
| | | | Sealing oil control valves |
| | | | System safety valves |
| **Fuel Supply to Consumers** | FTA 6 | Ammonia fuel supply system | Low pressure ammonia fuel pump |
| | | | High pressure ammonia fuel pump |
| | | | Electric motor (pump) |
| | | | Ammonia buffer tank |
| | | | Heat exchanger |
| | | | Strainer/filter |
| | | | Control valves (MFV + DBBV) |
| | | | Control valves (MFV + DBBV) control system (pneumatic, hydraulic) |
| | | | Pressure sensor and alarm |
| | | | Temperature sensor and alarm |
| | | | Nitrogen separator ($NH_3$ return system) |
| | | | Knock-out drum |
| | | | Catch system water seal unit |
| | | Pilot oil fuel supply system | Low pressure fuel pump |
| | | | Electric motor (pump) |
| | | | Fuel tank |
| | | | Heat exchanger |
| | | | Strainer/filter |
| | | | Control valves (MFV + DBBV) |
| | | | Control valves (MFV + DBBV) control system (pneumatic, hydraulic) |
| | | | Pressure sensor and alarm |
| | | | Temperature sensor and alarm |
| | | | Oil viscosity sensor and alarm |
| | | Inert gas system | $N_2$ generator |
| | | | $N_2$ bottles |
| | | | Air compressor |
| | | | Air filter/separator |
| | | Gas detection system | Gas detector |
| | | Venting | Pilot operated pressure relief valve(s) |

| High-level Description | FTA No. | System or Sub-system Information | Equipment Identification |
|---|---|---|---|
| | | | Spring loaded pressure relief valve(s) |
| | | Ventilation | Ventilation fan, electric motor, damper |
| **Bunkering** | FTA 7 | Bunkering system | Emergency shut-down valves |
| | | | Quick release couplings |
| | | | Bunkering hose |
| | | Control and monitoring system | Bunker valves control system (pneumatic, hydraulic) |
| | | | Pressure sensor and alarm |
| | | Leak and gas detection system | Gas detector |
| | | | Liquid ammonia detector |
| **Reliquefaction System** | FTA 8 | Reliquefaction System | Suction Drum/Separator |
| | | | Compressor |
| | | | Electric motor (compressor) |
| | | | Economiser |
| | | | Condenser |
| | | | Receiver |
| | | | Instrumentation sensor and alarm |

## 3.5 FTA Interviews | Phase I: Qualitative Reliability Assessment

Using ammonia as fuel is at the forefront of the decarbonisation journey of the shipping industry, which has increased the importance of enabling the new technology. FTA models are built based on interviews with SMEs on ammonia technology research and development. A list of companies who have contributed to the reliability assessment is summarised in Table 4 below.

Table 4: FTA Reliability Assessment Contributors

| Vendor Name | Technological Domain |
|---|---|
| MAN Energy Solutions | two-stroke ammonia engine |
| Babcock International Group | Ammonia fuel supply system equipment vendor |
| Lewa GmbH | Ammonia fuel supply system equipment vendor |
| Trelleborg Westbury Limited | Bunkering system equipment vendor |

FTA facilitation workshop presents a tool that focuses on ammonia safety and machinery reliability to construct failure scenarios for the selected system and gather their inputs on the probability of failure estimation.

Workshops were conducted in a 2-hr format to brainstorm the failure scenarios system by system. Pre-workshop material was prepared for participants to review. Pre-read material included:

- Concept drawing
- Critical component list
- Design basis document
- Engineering analysis reports
- Drafted Fault Tree Analysis, when available

During the workshop, SMEs from all disciplines worked together to construct or review the failure scenarios and probability of failure estimations. Failure modes were structured in the following 4 project lifecycles in the Fault Tree Analysis:

- Design failures
- Manufacturing defects
- Installation failures
- Operation failures

Eight (8) FTA models were completed as follows:

1. Ammonia Engine Fuel System
2. Engine Fuel Oil System
3. Common Engine Components
4. Auxiliary Systems
5. Hydraulic & Sealing Oil Systems
6. Fuel Supply System
7. Bunkering System
8. Reliquefaction System

Note that venting, ventilation and exhaust gas systems have been analysed as part of FTA 6: fuel supply system. The FTA models have been also peer reviewed by MAN ES to capture an engine maker perspective on dual fuel engines.

### 3.5.1 FTA 1 – Ammonia Engine Fuel System

The **failure modes caused by design** include, but are not limited to:

- Ammonia leak in the ammonia fuel injector valve,
- Ammonia nozzle is damaged from cyclical stress, injection pressure or cyclical thermal load coming from the heat of the combustion,
- Ammonia nozzle is damaged from high heat,

- Ammonia fuel injector valve cannot open fully, and
- Leak in the fuel filter.

For instance, the ammonia fuel injector valve leak failure could be due to corrosion or wear allowance being exceeded for the selected valve material in the environment condition of high temperature and high pressure.

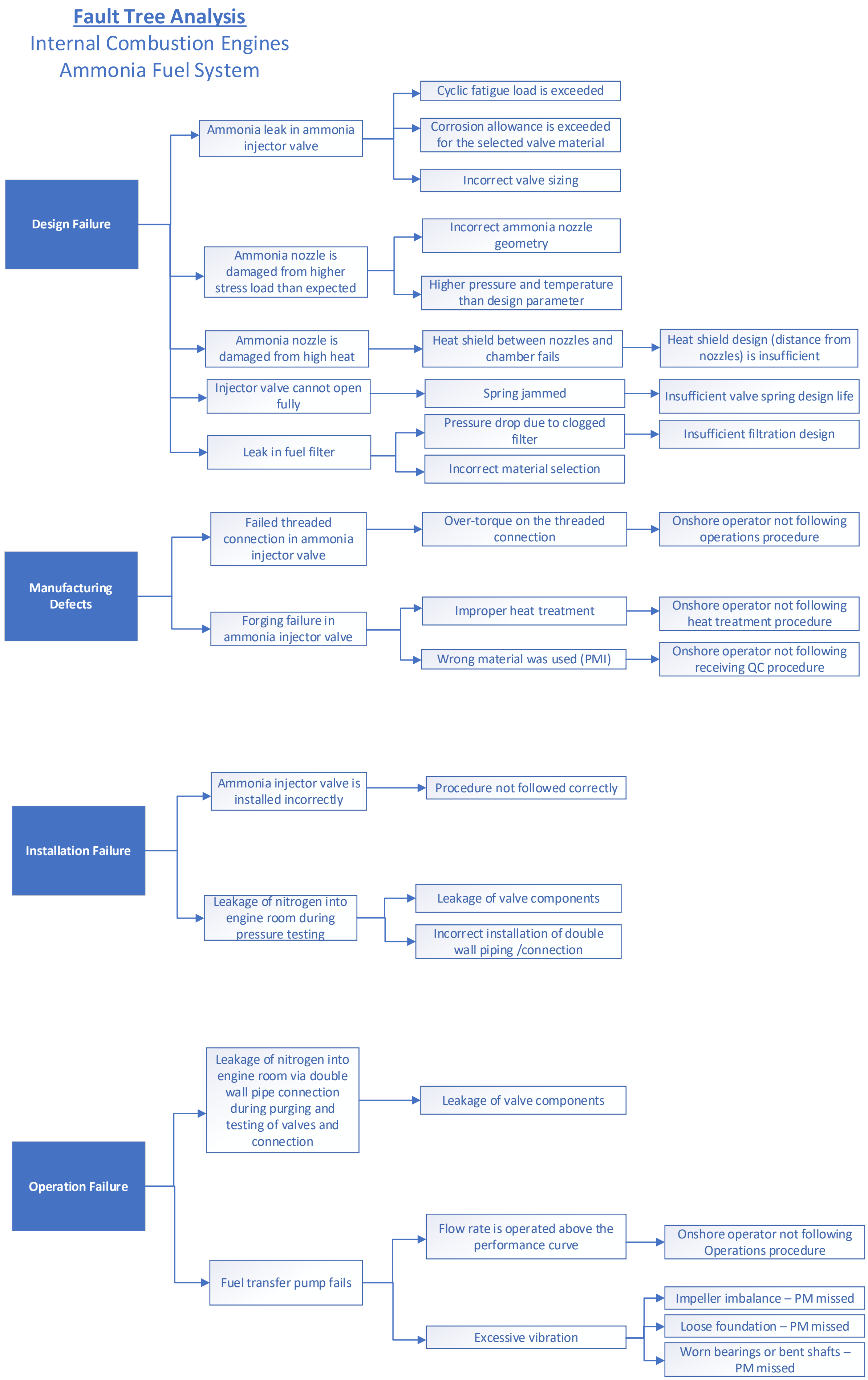
**Manufacturing defects** include failed threaded connection in ammonia fuel injector valve, forging/machining failure in ammonia fuel injector valve.

**Installation failures** include ammonia fuel injector valve is installed incorrectly or leakage of nitrogen into engine room during pressure testing.

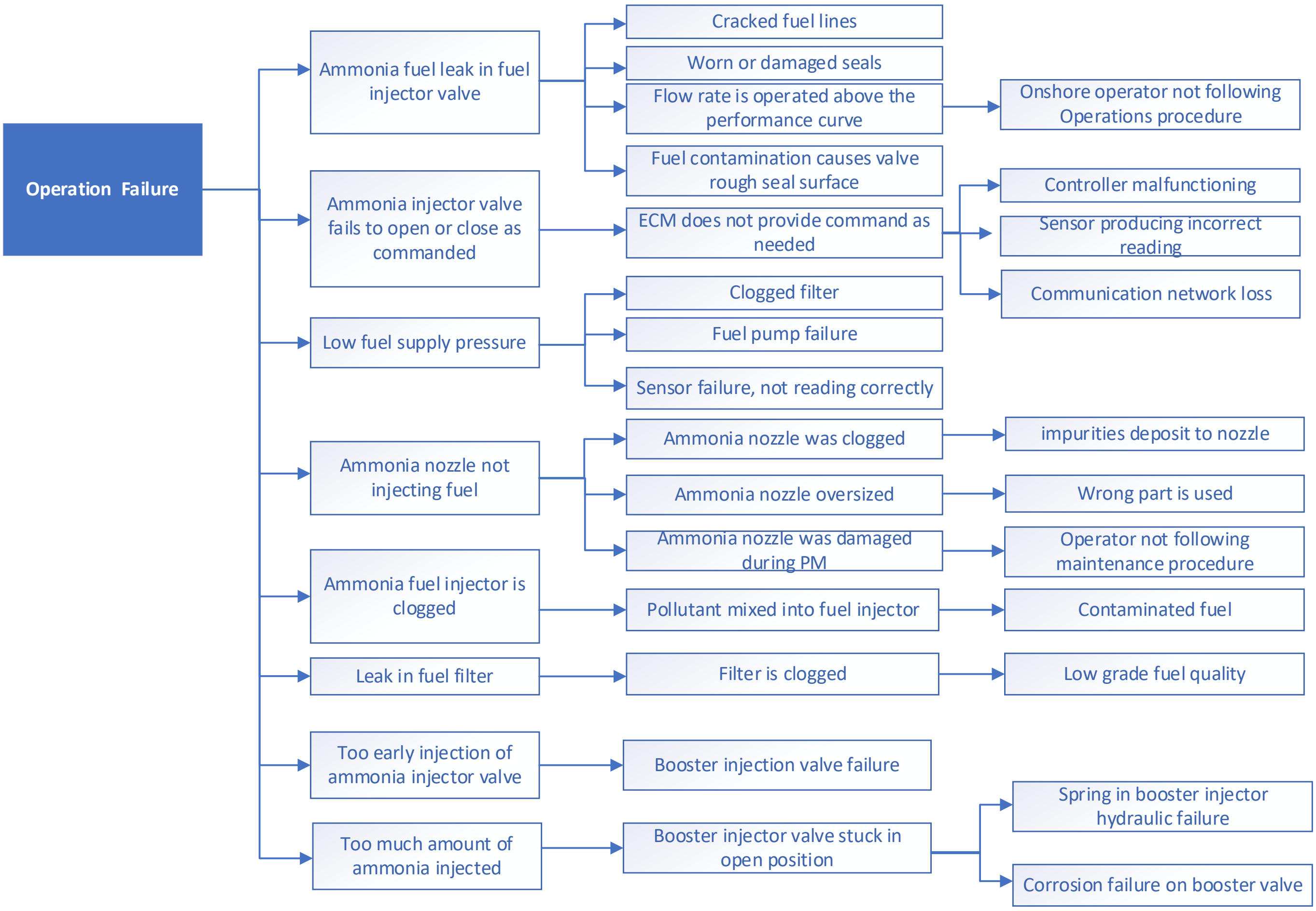
**Operation failures** include:

- Leakage of nitrogen into engine room via double wall pipe connection during purging and testing of valves and connections,
- Fuel transfer pump fails,
- Ammonia fuel leak in ammonia fuel injector valve,
- Ammonia injector valve fails to open or close as commanded,
- Low ammonia fuel supply pressure,
- Ammonia nozzle not injecting fuel,
- Ammonia fuel injector is clogged,
- Leak in fuel filter,
- Too early injection of ammonia fuel injector valve,
- Too much amount of ammonia injected,
- High temperature of ammonia due to less circulation flow,
- Fuel booster pressure is too high,
- Excessive flow to combustion chamber, and, but not limited to,
- Excessive pilot fuel injection at high load in addition to ammonia fuel that lifts cylinder cover, leading to unburned ammonia and exhaust in the engine room.

Detailed fault tree analysis showing how each failure scenario can occur is provided in Figure 13.



Fault Tree Analysis
Internal Combustion Engines
Ammonia Fuel System
Design Failure
Ammonia leak in ammonia injector valve
Cyclic fatigue load is exceeded
Corrosion allowance is exceeded for the selected valve material
Incorrect valve sizing
Ammonia nozzle is damaged from higher stress load than expected
Incorrect ammonia nozzle geometry
Higher pressure and temperature than design parameter
Ammonia nozzle is damaged from high heat
Heat shield between nozzles and chamber fails
Heat shield design (distance from nozzles) is insufficient
Injector valve cannot open fully
Spring jammed
Insufficient valve spring design life
Leak in fuel filter
Pressure drop due to clogged filter
Insufficient filtration design
Incorrect material selection
Manufacturing Defects
Failed threaded connection in ammonia injector valve
Over-torque on the threaded connection
Onshore operator not following operations procedure
Forging failure in ammonia injector valve
Improper heat treatment
Onshore operator not following heat treatment procedure
Wrong material was used (PMI)
Onshore operator not following receiving QC procedure
Installation Failure
Ammonia injector valve is installed incorrectly
Procedure not followed correctly
Leakage of nitrogen into engine room during pressure testing
Leakage of valve components
Incorrect installation of double wall piping /connection
Operation Failure
Leakage of nitrogen into engine room via double wall pipe connection during purging and testing of valves and connection
Leakage of valve components
Fuel transfer pump fails
Flow rate is operated above the performance curve
Onshore operator not following Operations procedure
Excessive vibration
Impeller imbalance – PM missed
Loose foundation – PM missed
Worn bearings or bent shafts – PM missed



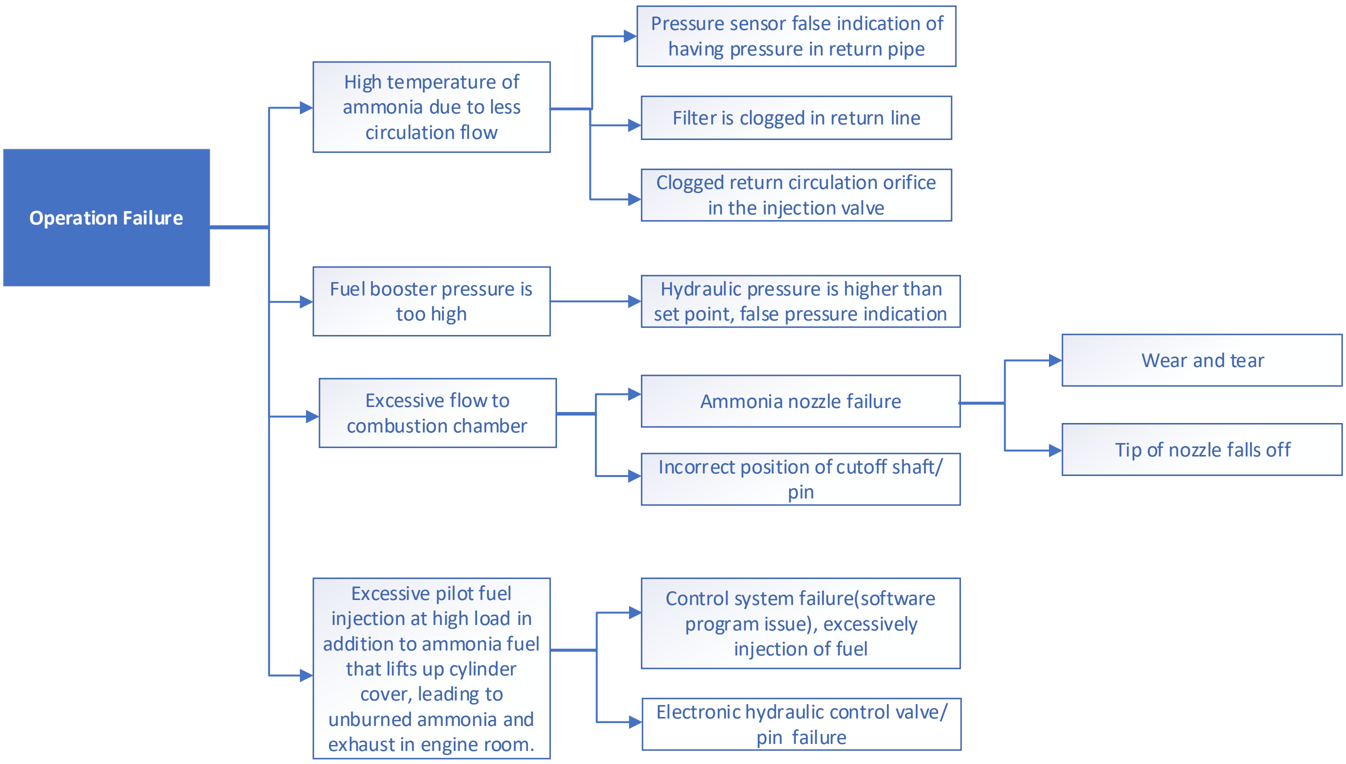




Figure 13: FTA 1 – Ammonia Fuel System

### 3.5.2 FTA 2 – Engine Fuel Oil System

Engine fuel oil system is secondary to the primary ammonia fuel system as a redundancy in case of primary fuel system failure. Compared to FTA 1 ammonia fuel technology, FTA 2 engine fuel oil system is more robust and contains a subset of fuel system failure scenarios. FTA detailed analysis is in Figure 14.

**Design failures** include fuel leak in injector valve and fuel filter and valve is not open fully.

**Manufacturing defects** include forging defects in the valve body and threaded connection failure.

**Installation failure** in general is the valve procedure not followed.

common engine equipment is robust and potentially can have low probability of **operational failure** such as: :

- Fuel pump fails,
- Fuel leak in injector valve,
- Injector valve not open or close as commanded,
- Low fuel supply pressure,
- Nozzle not injecting fuel or clogged,
- Leaking in fuel filter or heat exchanger.

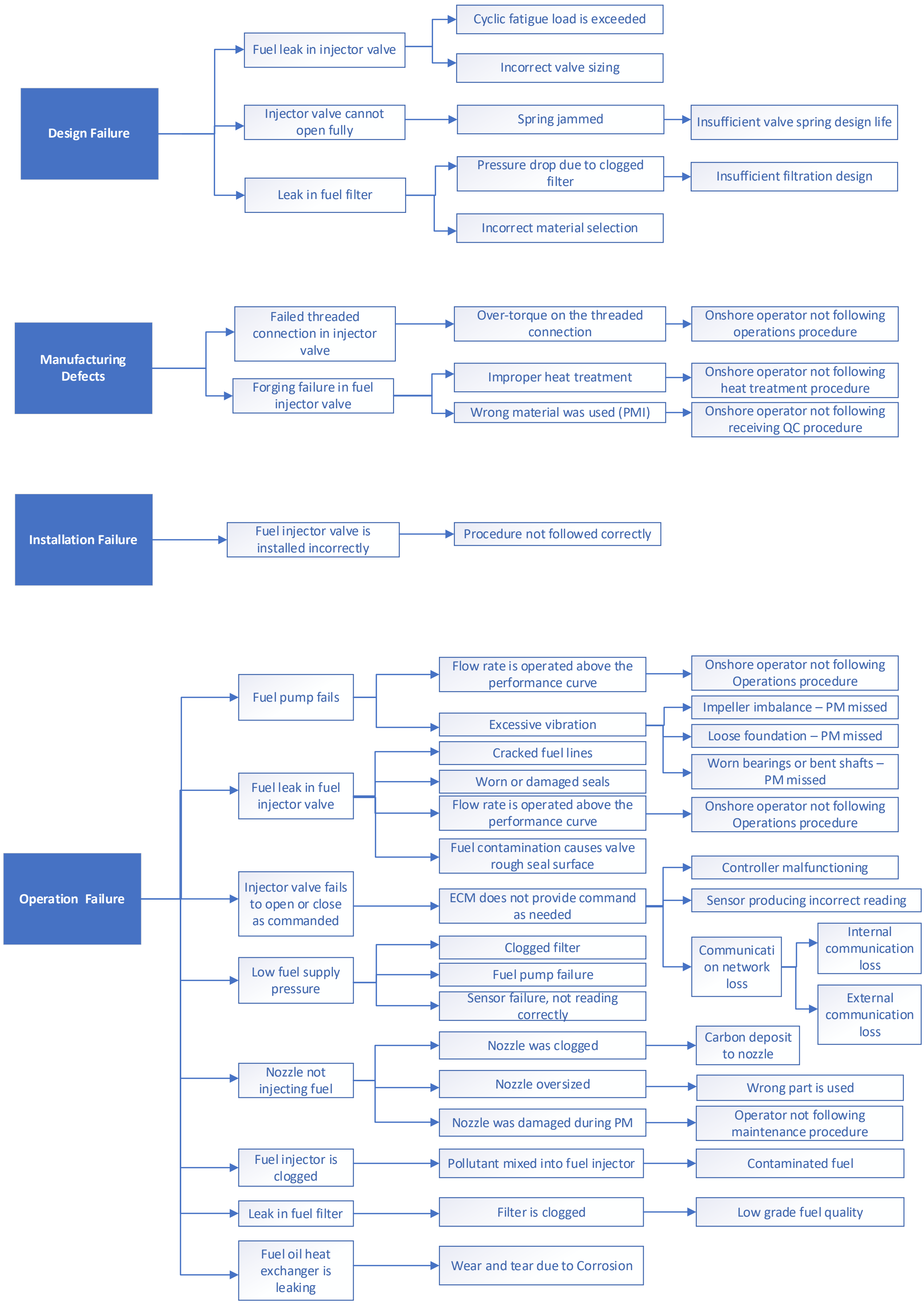



Figure 14: FTA 2 – Engine Fuel Oil System

### 3.5.3 FTA 3 – Common Engine Equipment

FTA 3 contains failure scenarios for the common engine equipment of FTA 1 (ammonia fuel system) and FTA 2 (fuel oil system). Compared to FTA 1 ammonia fuel technology, FTA 3 common engine equipment system (shown in Figure 15) is more robust and contains a subset of fuel system failure scenarios, including piston, piston rings, cylinder cover, cylinder liner, common rail fuel oil line, turbocharger and exhaust valves.

Based on the SME interviews, as common equipment is used in the conventional design engines, the common engine equipment design is conventional. The failure modes in the design phase, installation and operation phase are well understood and are usually mitigated with an acceptable level of risk. Mitigation strategy includes parts replacement frequency and optimising operational procedures put in place to achieve high product reliability.

**Design failures** considered in the interview workshop include:

- Piston failure,
- Cylinder liner failure,
- Common rail fuel oil line system,
- Cylinder cover leaks.

Manufacturing defects and installation failure are relatively low probability of failure and include common rail fuel oil line manufacturing defects and piston jams and piston ring scrapping failure during installation.

**Operation failures** include:

- Cylinder liner failure,
- Piston and piston ring failure (piston blow by, low level lube oil, wear and tear, wrong dozing of lube oil),
- Turbocharger bearing housing overheating,
- Turbocharger clearance b/t shaft and bearing or bearing and housing is out of spec,
- Turbocharger vibration increased,
- Exhaust valve failure (overheating).

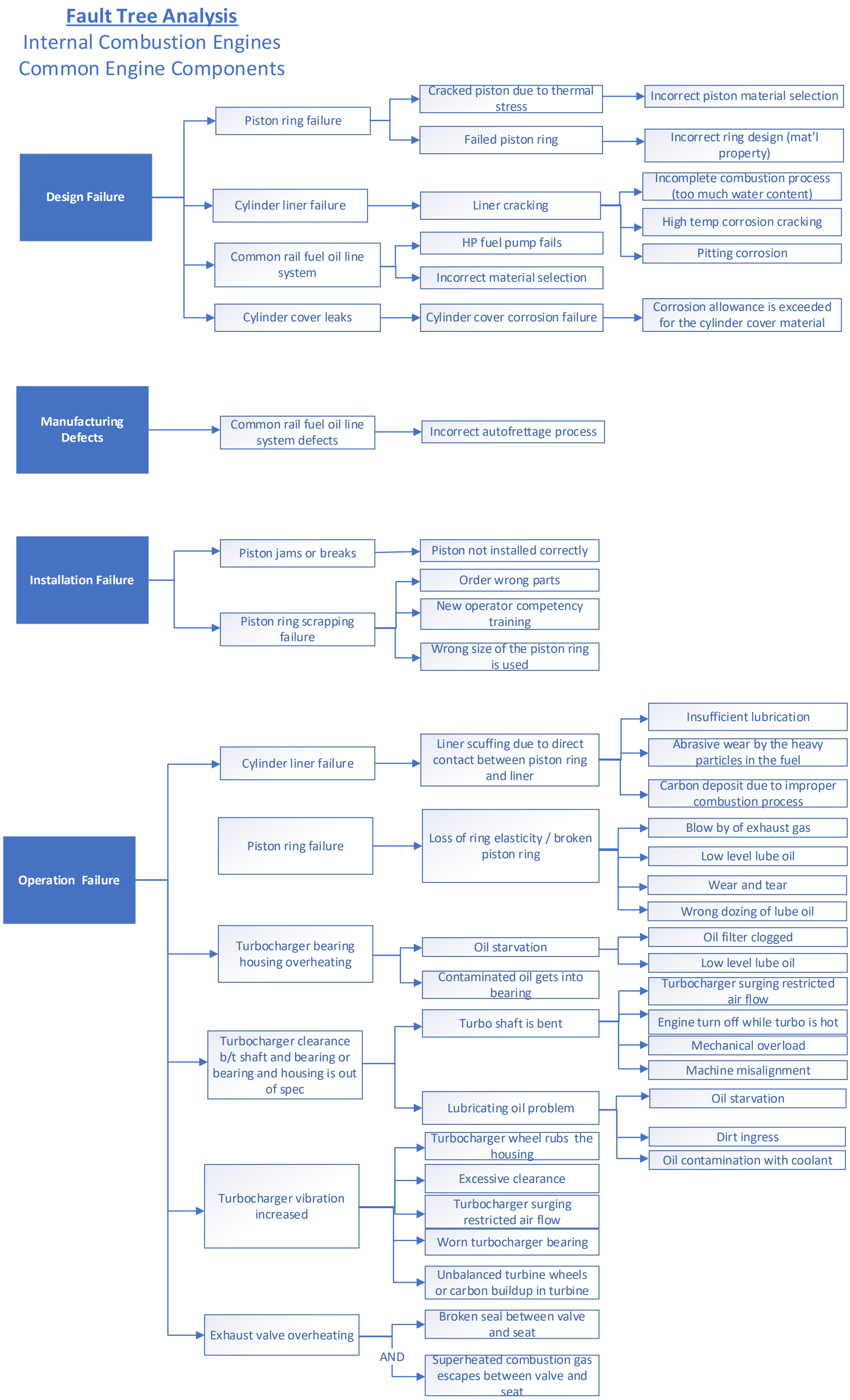



Figure 15: FTA 3 – Common Engine Equipment

### 3.5.4 FTA 4 – Engine Auxiliary Systems

Auxiliary systems analysed in Fault Tree (Figure 16) include the following equipment:

- HT freshwater cooling
- System lube oil
- Piston cooling lube oil
- Cylinder lube oil
- Exhaust gas system

Auxiliary systems have relatively robust design. Failure modes in manufacturing and installation are better understood. Most failures modes focus on design and operation phases.

**Design failure** involves ammonia design, including:

- High temperature freshwater cooling contaminated with ammonia, and
- Cylinder lube oil contaminated by ammonia and leak in lube oil filter (piston and cylinder).

Lube oil system is one of the focus areas in the auxiliary systems for the design phase.

**Operations failure**: Historically, explosion is a possibility when fuel oil or lube oil drips into scavenging receiver. A newer operation failure mode is exhaust gas leaking into ammonia and sealing oil when the ammonia fuel injector valve is leaking or stuck due to particles preventing injector valve to close fully.

Ammonia contamination is a key risk in the auxiliary systems. Wear and tear of cylinder head could cause cylinder head coolant leak, which allows ammonia to enter the HT freshwater cooling system.

The lube oil system is one of the main focus areas in the auxiliary systems for the operation phase. Lube oil dozing failure has been studied by the engine makers to optimise lube oil dozing frequency by ammonia fuel injection profile, engine load, ambient condition/heavy weather condition to the liner (thermal expansion), and fuel quality. Too much lube oil can cause soot build-up in the liner, while too little cylinder lube oil can cause seizing of liner. Lube oil is also sensitive to water which can lead to cylinder liner damage, high temperature, and low level of lube oil which can cause lube oil pump bearing damage. Another factor that could cause lube oil overheating is low level in lube oil tank or incorrect lube oil is used.

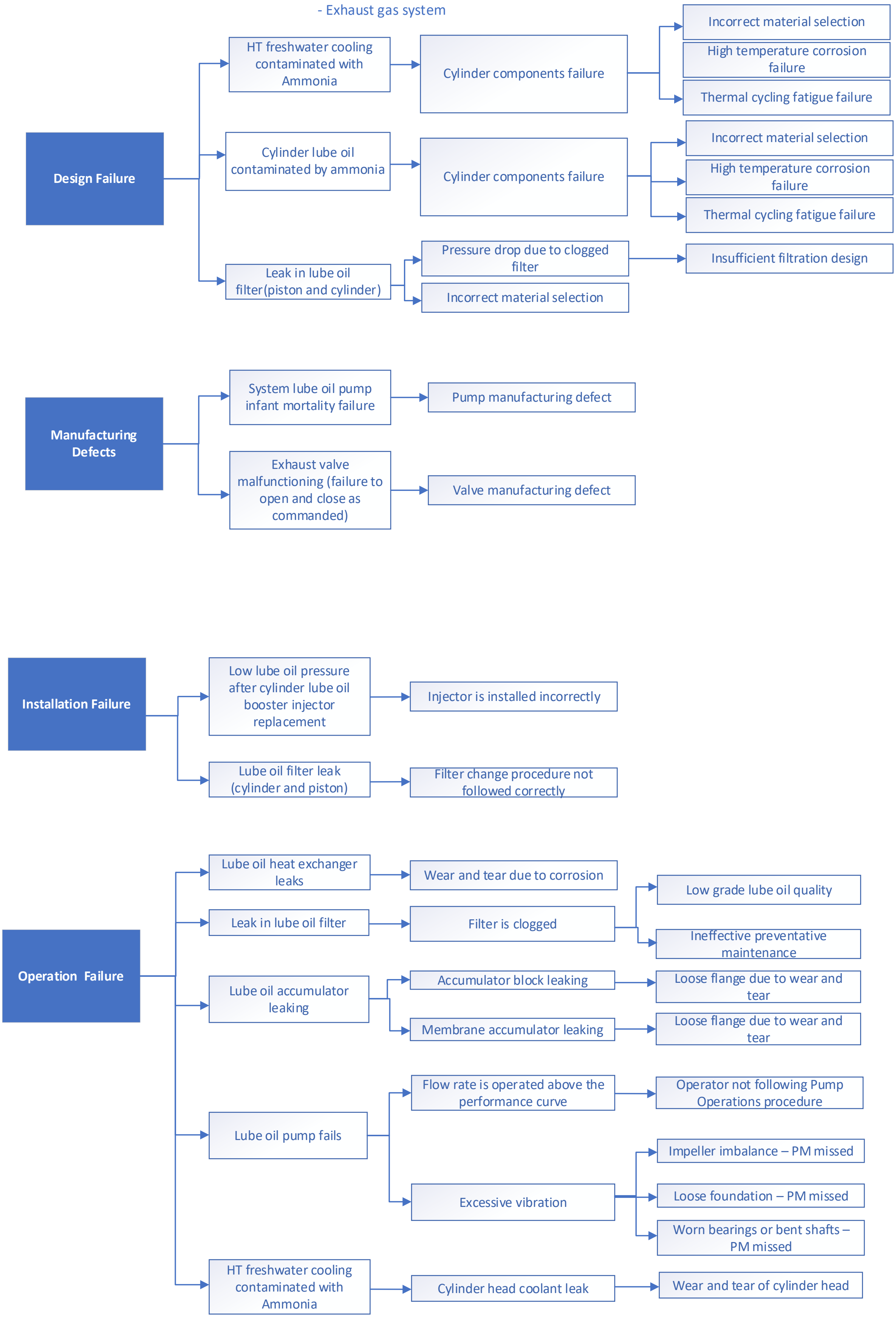
In summary, **operation failures** include the following:

- Lube oil heat exchanger leaks,
- Leak in lube oil filter,
- Lube oil accumulator leaking,
- Lube oil pump fails,
- HT freshwater cooling contaminated with Ammonia,
- Secondary fuel (SF) in scavenging receiver explosion,
- SF in exhaust receiver/funnel explosion,
- Low pressure in lube oil system,
- Cylinder liner high temperature alarm/ lube oil overheating,
- Lube oil pump bearing damage,
- Exhaust gas leaking into Ammonia and sealing oil,
- Cylinder liner damage due to cylinder lube oil failure.

# Fault Tree Analysis

## Internal Combustion Engines Auxiliary Systems

Auxiliary systems:
- HT fresh water cooling
- System lube oil
- Piston cooling lube oil
- Cylinder lube oil
- Exhaust gas system



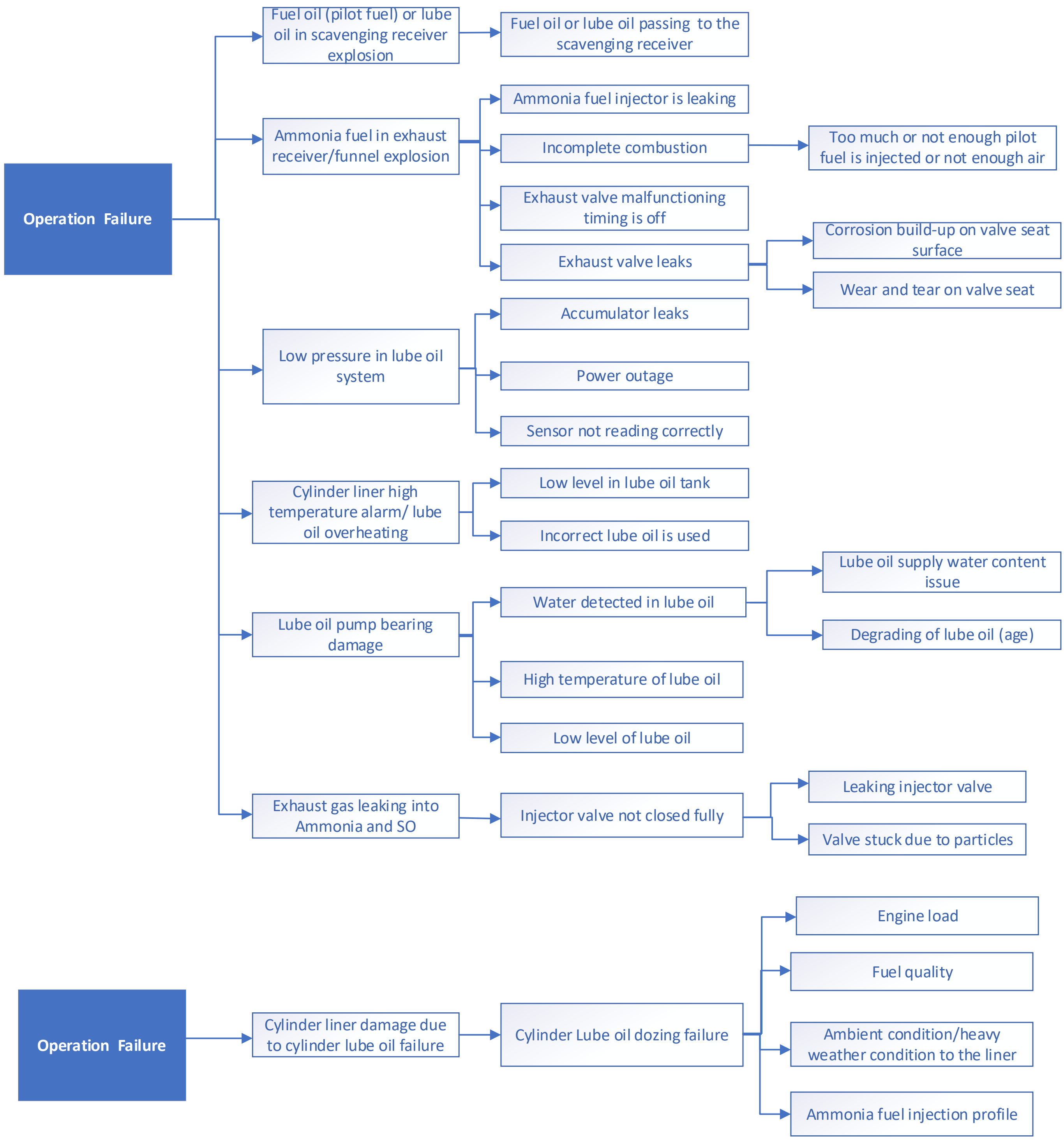



Figure 16: FTA 4 – Auxiliary Systems

### 3.5.5 FTA 5 – Hydraulic and Sealing Oil System

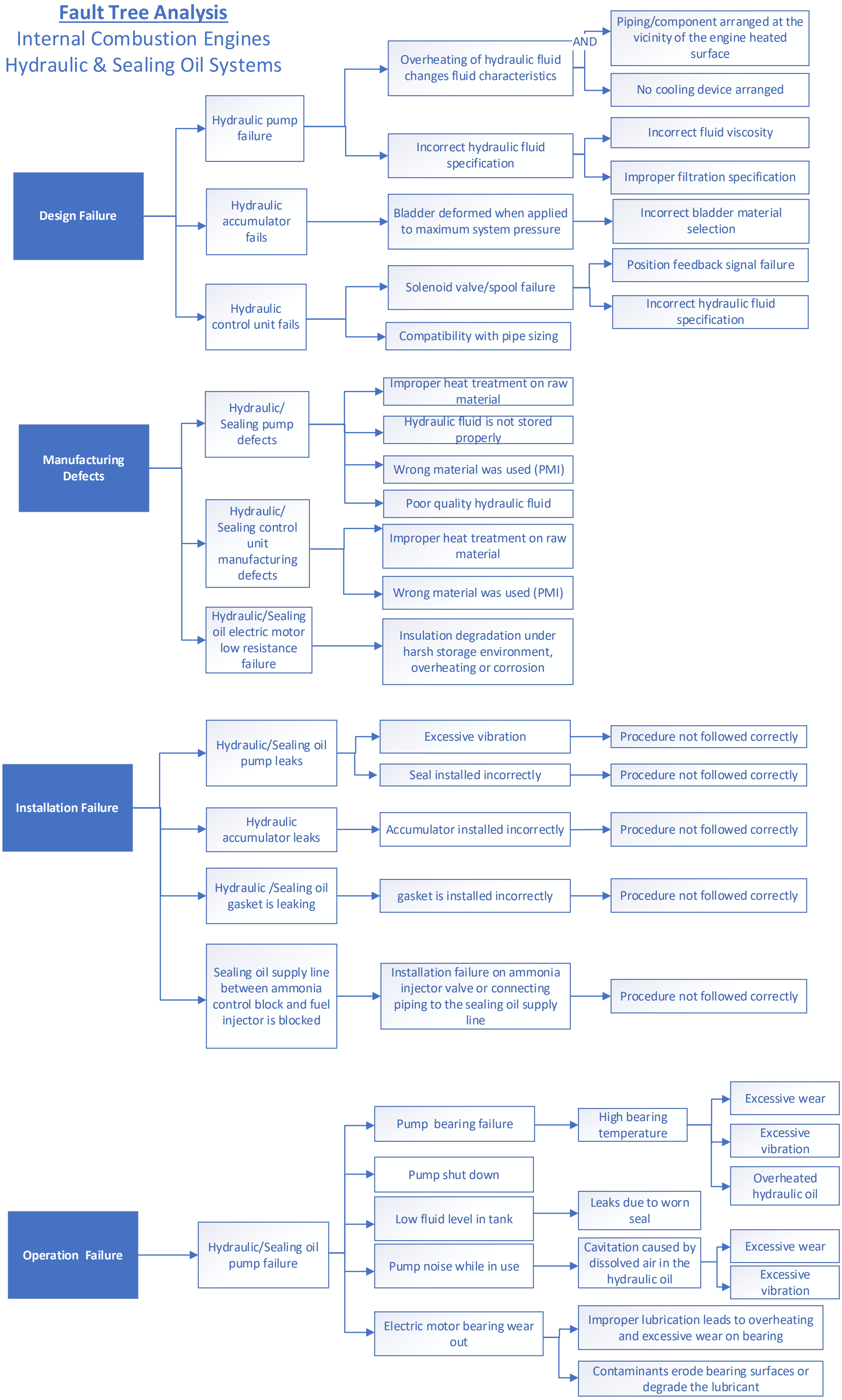
Hydraulic and sealing oil systems (FTA in Figure 17) is a conventional design for a dual fuel engine concept where sealing oil is used as a barrier to suppress ammonia without getting into hydraulic oil system by maintaining it at a higher pressure than ammonia fuel. Design failure, manufacturing defects and installation failures are conventional, and failure modes include incorrect gasket installation that causes pump leaks. Another installation failure is sealing oil supply line between ammonia control block and ammonia fuel injector is blocked due to incorrect installation of the ammonia fuel injector valve or the connecting piping to the sealing oil supply line.

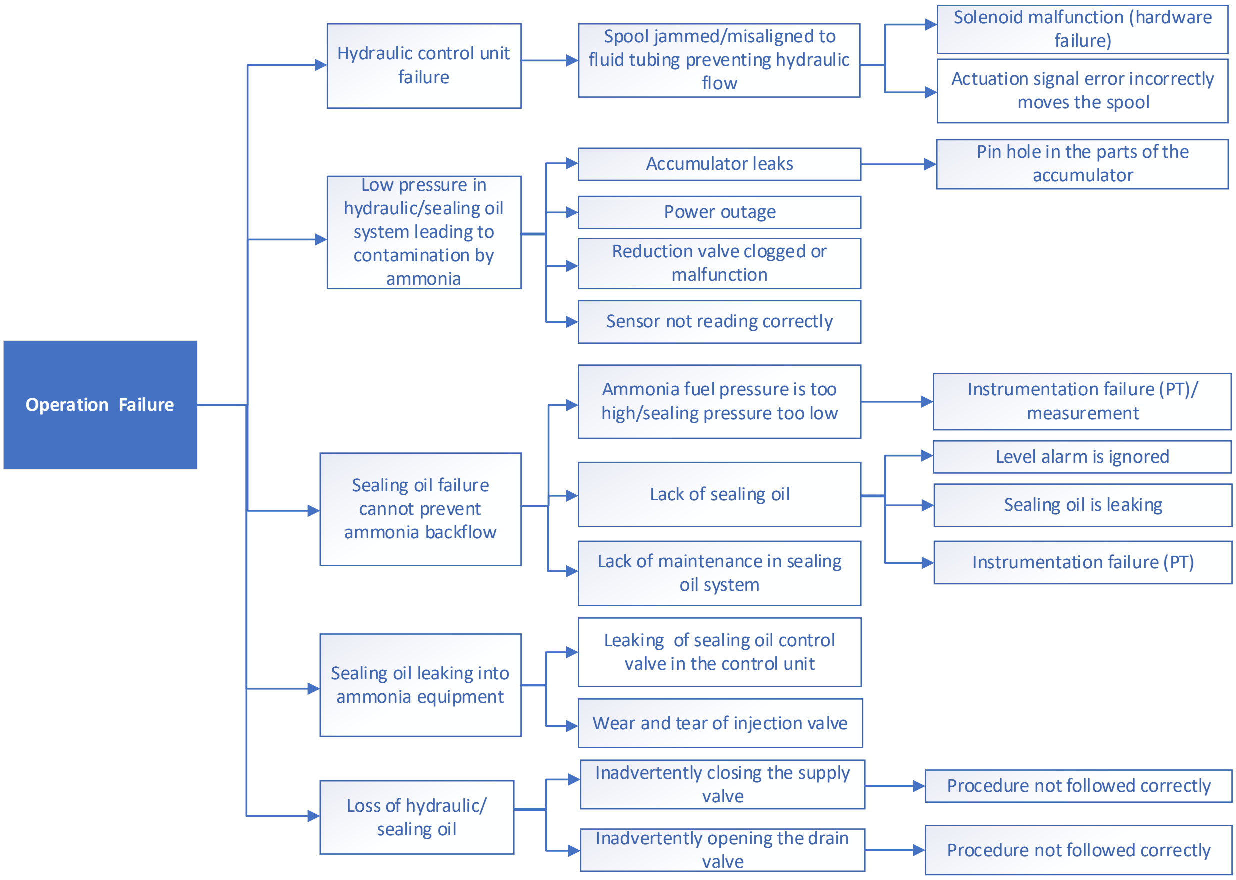
In this system, the major failure modes are from sealing oil and ammonia contamination issues in operation phase, when the sealing oil pressure is to be maintained higher than ammonia fuel. If not maintained at a higher pressure, ammonia contamination to the hydraulic oil system could happen. If ammonia fuel pressure is too high/sealing oil pressure is too low due to instrumentation failure sealing oil failure could occur, which could inhibit ammonia back flow prevention. Another major failure mode is sealing oil leaking into ammonia equipment if injector valve wear and tear or sealing oil control valve leaking. Ammonia contamination can occur in sealing oil and hydraulic oil. For sealing oil, incorrect valve pressure set point, loss of sealing oil pressure, sealing oil decreases faster than expected or clogged reduction valve could lead to ammonia contamination in sealing oil. For hydraulic oil, loss of sealing pressure or higher nitrogen pressure than sealing oil pressure could lead to ammonia contamination in hydraulic oil.

The nitrogen pressure in accumulators for maintaining sufficient hydraulic oil and sealing oil pressures during operation is also a cause for failures. Accumulator membrane failure could cause sealing oil pressure to become too low, which causes nitrogen accumulator leaks into hydraulic/sealing oil.

In summary, hydraulic and sealing oil systems **operation failure modes** are summarised below:

- Hydraulic and sealing oil pump failure,
- Low pressure in hydraulic/sealing oil system leading to contamination by ammonia,
- Sealing oil failure cannot prevent ammonia backflow,
- Sealing oil leaking into ammonia equipment,
- Loss of hydraulic and sealing oil,
- Ammonia contamination in sealing oil,
- Ammonia contamination in hydraulic oil,
- Hydraulic/Sealing oil gasket is leaking,
- $N_2$ accumulator leaking into hydraulic/sealing oil,
- Ammonia entrapped in injection valve and fails to inject ammonia,
- Ammonia inlet pipe rupture.


Fault Tree Analysis
Internal Combustion Engines
Hydraulic & Sealing Oil Systems
Design Failure
Hydraulic pump failure
Overheating of hydraulic fluid changes fluid characteristics
AND
Piping/component arranged at the vicinity of the engine heated surface
No cooling device arranged
Incorrect hydraulic fluid specification
Incorrect fluid viscosity
Improper filtration specification
Hydraulic accumulator fails
Bladder deformed when applied to maximum system pressure
Incorrect bladder material selection
Hydraulic control unit fails
Solenoid valve/spool failure
Position feedback signal failure
Incorrect hydraulic fluid specification
Compatibility with pipe sizing
Manufacturing Defects
Hydraulic/ Sealing pump defects
Improper heat treatment on raw material
Hydraulic fluid is not stored properly
Wrong material was used (PMI)
Poor quality hydraulic fluid
Hydraulic/ Sealing control unit manufacturing defects
Improper heat treatment on raw material
Wrong material was used (PMI)
Hydraulic/Sealing oil electric motor low resistance failure
Insulation degradation under harsh storage environment, overheating or corrosion
Installation Failure
Hydraulic/Sealing oil pump leaks
Excessive vibration
Procedure not followed correctly
Seal installed incorrectly
Procedure not followed correctly
Hydraulic accumulator leaks
Accumulator installed incorrectly
Procedure not followed correctly
Hydraulic /Sealing oil gasket is leaking
gasket is installed incorrectly
Procedure not followed correctly
Sealing oil supply line between ammonia control block and fuel injector is blocked
Installation failure on ammonia injector valve or connecting piping to the sealing oil supply line
Procedure not followed correctly
Operation Failure
Hydraulic/Sealing oil pump failure
Pump bearing failure
High bearing temperature
Excessive wear
Excessive vibration
Overheated hydraulic oil
Pump shut down
Low fluid level in tank
Leaks due to worn seal
Pump noise while in use
Cavitation caused by dissolved air in the hydraulic oil
Excessive wear
Excessive vibration
Electric motor bearing wear out
Improper lubrication leads to overheating and excessive wear on bearing
Contaminants erode bearing surfaces or degrade the lubricant



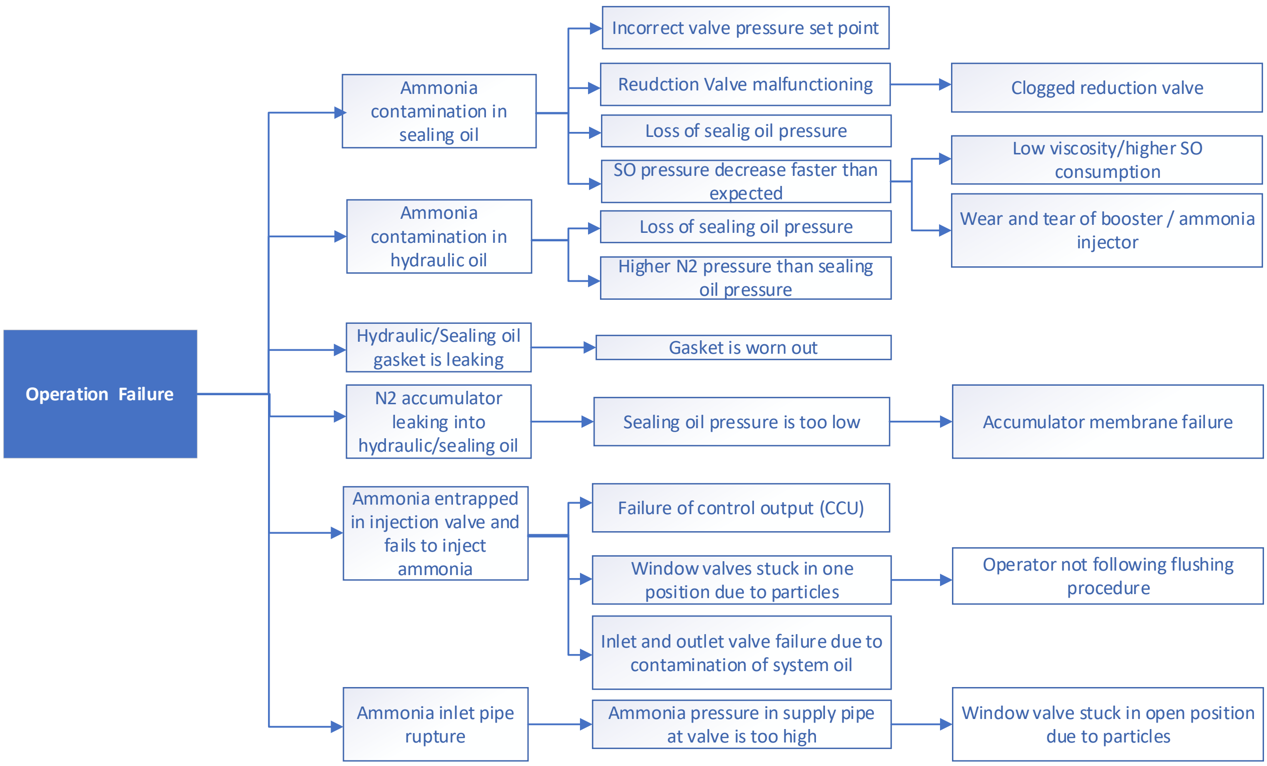




Figure 17: FTA 5 – Hydraulic and Sealing Oil Systems

### 3.5.6 FTA 6 – Fuel Supply System

Fuel Supply System is the most complex FTA (Figure 20) in the ammonia-fuelled propulsion system, and the analysis covers the following equipment:

- Ammonia fuel supply system
- Pilot oil fuel supply system
- Inert gas system
- Gas detection system
- Venting
- Ventilation

In the fuel supply system, design and operation failures are of the primary concern. In the design phase, the design consideration covers a vast number of issues.

In summary, the following **major failures in the design phase** are considered:

- Ammonia components stress or fatigue load is exceeded,
- HP ammonia fuel pump leaking,
- Ammonia fuel buffer tank leaking,
- Fuel system piping pressure loss greater than expected,
- Corrosion allowance for piping may be exceeded,
- Damaged of valve sealings/gaskets,
- Liquid ammonia in KOD during disassembly causing personal injury,
- Vapor ammonia in KOD during maintenance of return system and engine,
- In the ventilation system, corrosion of double wall pipes and ventilation fan, and,
- Ammonia vapor/liquid at ventilation outlet.

For the **operation phase**, due to the complex fuel supply system, a Piping and Instrumentation Diagram (P&ID) concept drawing (Figure 19) is created to support the failure scenarios described below:

**Failure Scenario 1:** Overfilled nitrogen separator with ammonia

During ammonia operation, the inlet valve of nitrogen separator is leaking (supposed to be closed), the nitrogen separator is over-flowed with liquid ammonia.

**Failure Scenario 2**: No ammonia fuel to engine

During ammonia operation, the fuel filter is blocked or the valve position (e.g., MFV or DBBV) is incorrect. As a result, no ammonia is supplied to the engine.

**Failure Scenario 3**: MFV+ DBBV leaking

During ammonia operation, DBBVs or vent valves leak, causing liquid ammonia leading to the knockout drum via vent pipes.

**Failure Scenario 4**: No or reduced ammonia in the supply line to engine

Malfunction of the pressure relief valve (supposed to be closed) on the supply system side causes the ammonia to leak. As a result, no or reduced ammonia is supplied to the engine.

**Failure Scenario 5**: Leaking valve on the supply line

- Due to increased temperature, flash ammonia vapor occurs which caused the valve on the supply line to leak.

- Low ammonia temperature due to heat exchanger failure or temperature monitoring system failure that causes the valve seating failure which leads to MFV or DBBVs leaking.

**Failure Scenario 6**: No ammonia in the supply line

- Due to pump malfunctioning (HP or LP), clogged ammonia filters or incorrect valve positioning, it may cause interruption of the ammonia supply line.
- Due to the bleed valve leakage or pipe rupture.

**Failure Scenario 7**: Knock-out drum failures

- Due to relief valve failure or leaking or flash-off of ammonia during blow-off/depressurisation (pressure sudden drop causes unexpected low temperature), cold ammonia may be observed in the knock-out drum, which may cause failure of the drum.
- Sealing oil from engine in the return line leaking into knock-out drum.

**Failure Scenario 8**: Pump failure

- Due to the pressure control valve failure on the ammonia return line, the pressure drops, which creates cavitation at the inlet of the pump.

**Failure Scenario 9**: Bleed valve stuck in closed position

- During ammonia shut-down the bleed valve is supposed to open, but it is stuck in a closed position. The double block valves are supposed to be closed (Normal Closed during shutdown). The ammonia in the piping (highlighted yellow) is entrapped. With high pressure (such as 80 bar) and warm ammonia (such as 40 degree Celsius) in the supply line, the risk is to have leaking valve or rupture of the pipe shown in the sketch (Figure 18) below.

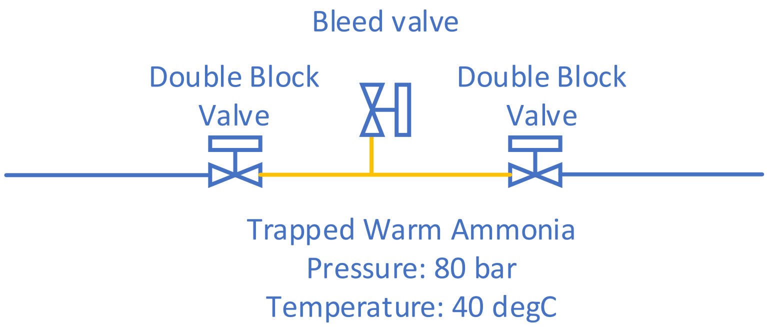



Figure 18: Scenario 9 bleed valve stuck in closed position

**Failure Scenario 10**: Insufficient purging

- Insufficient purging causes ammonia fuel to remain in engine/piping. In addition, the vent valve is open and lets ammonia flow to knock-out drum instead of sending back to nitrogen separator. Causes may be clogged nitrogen filter or nitrogen supply flow is blocked.

**Failure Scenario 11**: Ammonia in nitrogen vent

- Due to nitrogen bleed valve stuck in open position or non-return valve failure, causes low pressure in the nitrogen supply line. This results in ammonia leaked into the nitrogen vent line.

**Failure Scenario 12**: Ventilation is too low

- Ventilation flow rate has a specific requirement regarding how many air changes per hour. Flow switch malfunction (control failure), fan failure, fan electric motor failure, or damper stuck in closed position may cause a low ventilation flow rate than required, which will trigger an engine shutdown.

**Failure Scenario 13:** Pressure regulating valve failure

- The pressure regulation valve is installed to meet the engine pressure requirement. If the supply line pressure exiting the HP pump is higher than the engine required pressure, the pressure regulating valve will adjust the pressure.

- The solenoid (hardware) on the valve or the control system failure could cause high pressure in the supply system.

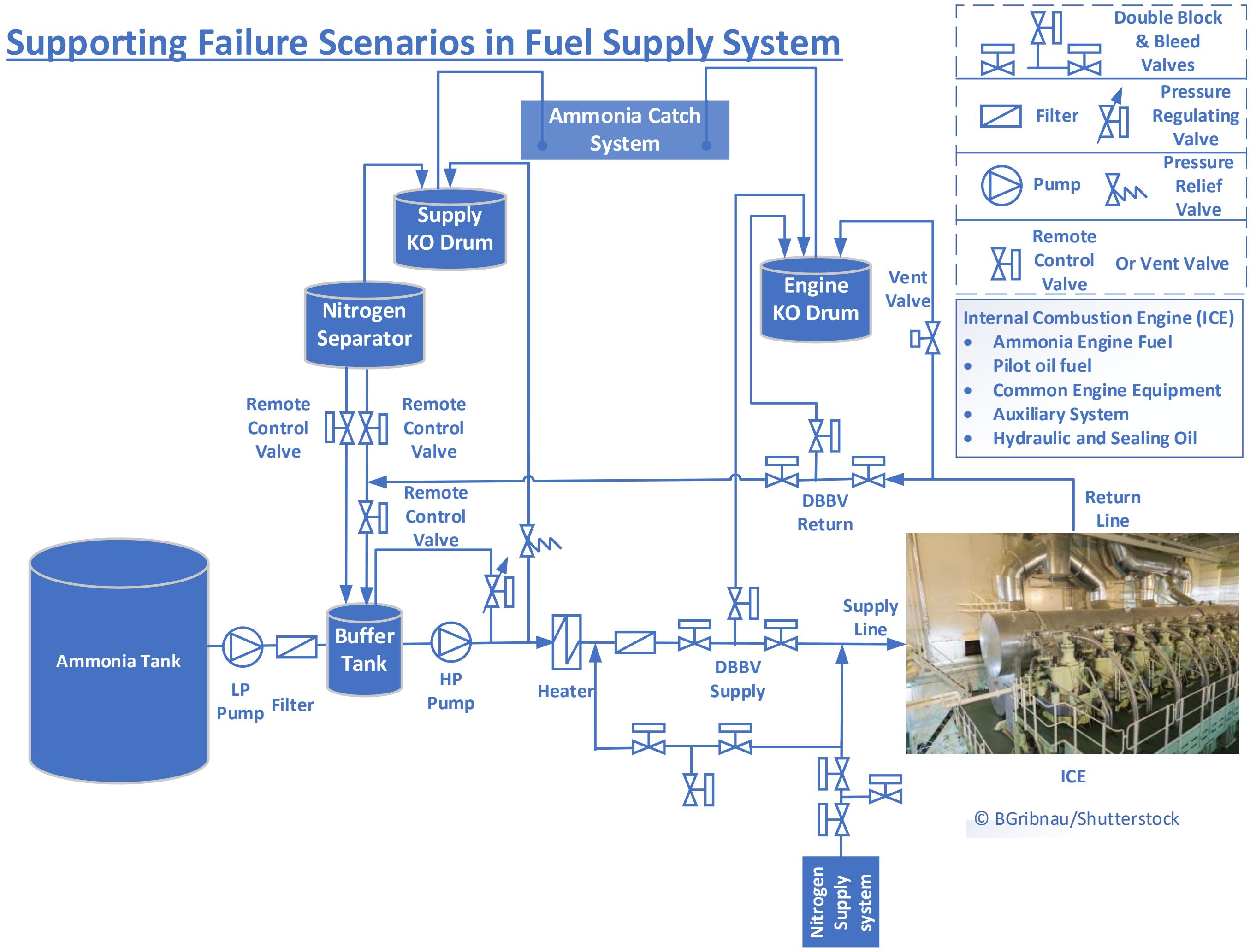
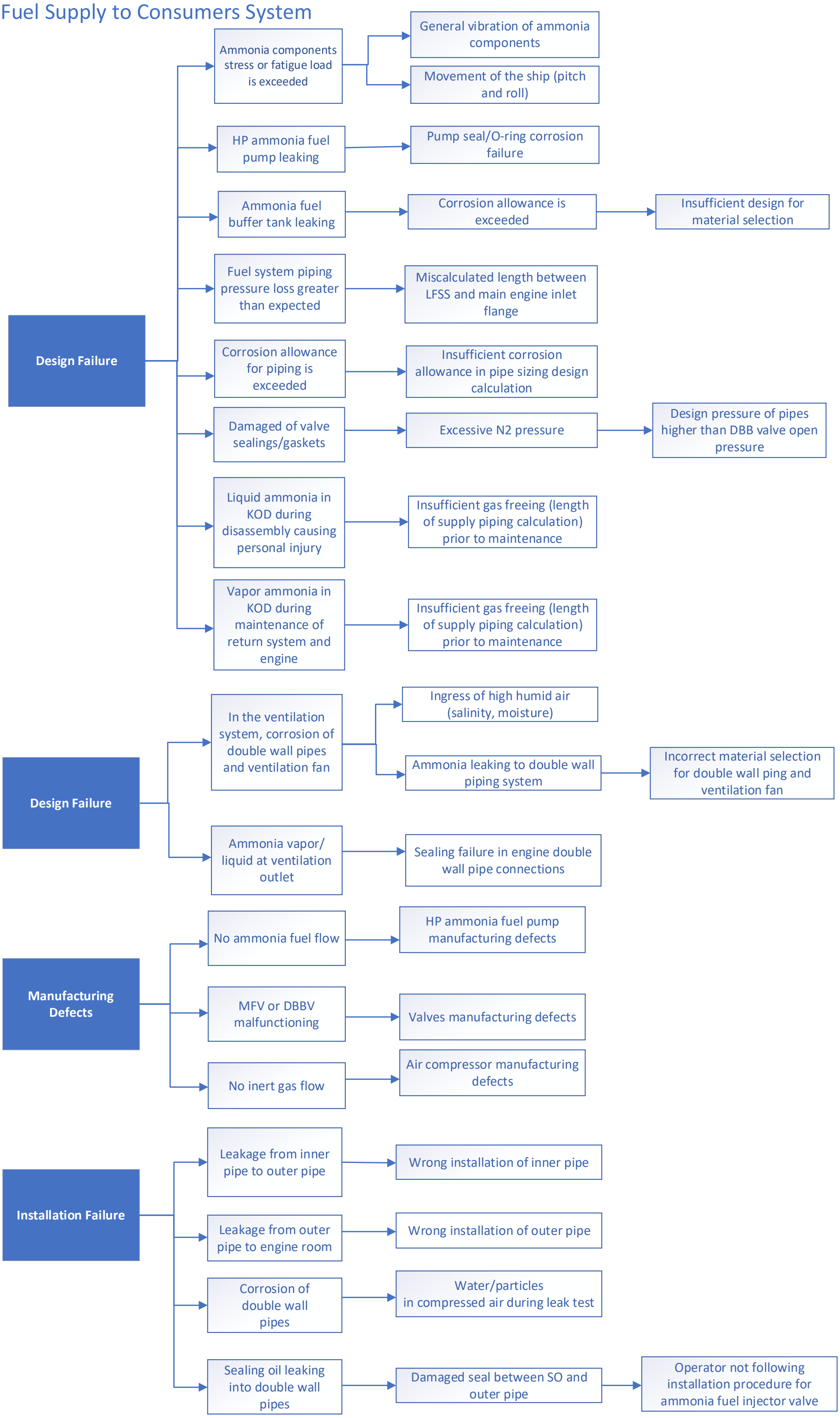
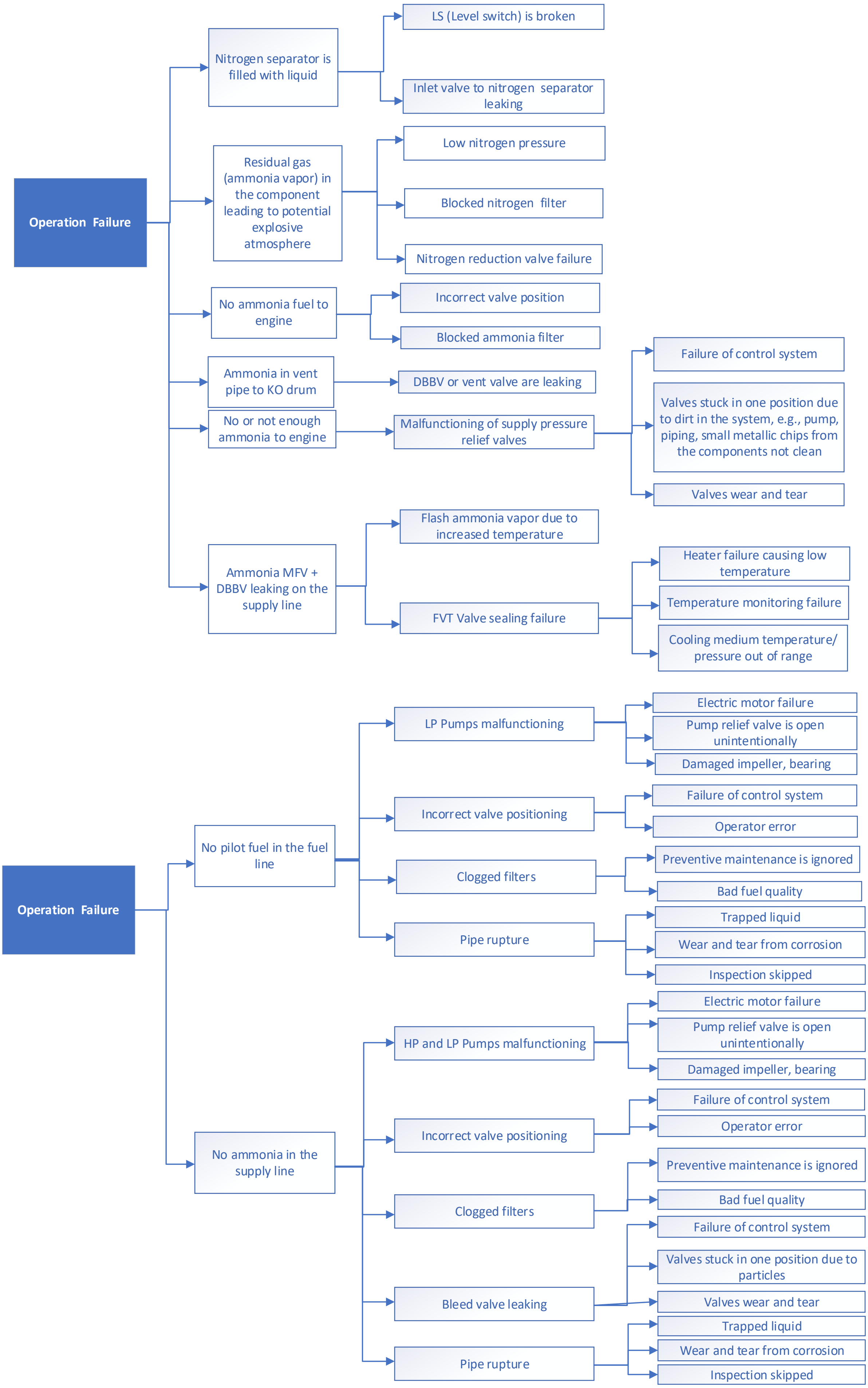



Figure 19: Concept Drawing: Supporting Failure Scenarios in Fuel Supply System

# Fault Tree Analysis

## Fuel Supply to Consumers System




Operation Failure
Nitrogen separator is filled with liquid
LS (Level switch) is broken
Inlet valve to nitrogen separator leaking
Residual gas (ammonia vapor) in the component leading to potential explosive atmosphere
Low nitrogen pressure
Blocked nitrogen filter
Nitrogen reduction valve failure
No ammonia fuel to engine
Incorrect valve position
Blocked ammonia filter
Ammonia in vent pipe to KO drum
DBBV or vent valve are leaking
No or not enough ammonia to engine
Malfunctioning of supply pressure relief valves
Failure of control system
Valves stuck in one position due to dirt in the system, e.g., pump, piping, small metallic chips from the components not clean
Valves wear and tear
Ammonia MFV + DBBV leaking on the supply line
Flash ammonia vapor due to increased temperature
FVT Valve sealing failure
Heater failure causing low temperature
Temperature monitoring failure
Cooling medium temperature/ pressure out of range
Operation Failure
No pilot fuel in the fuel line
LP Pumps malfunctioning
Electric motor failure
Pump relief valve is open unintentionally
Damaged impeller, bearing
Incorrect valve positioning
Failure of control system
Operator error
Clogged filters
Preventive maintenance is ignored
Bad fuel quality
Pipe rupture
Trapped liquid
Wear and tear from corrosion
Inspection skipped
No ammonia in the supply line
HP and LP Pumps malfunctioning
Electric motor failure
Pump relief valve is open unintentionally
Damaged impeller, bearing
Incorrect valve positioning
Failure of control system
Operator error
Clogged filters
Preventive maintenance is ignored
Bad fuel quality
Bleed valve leaking
Failure of control system
Valves stuck in one position due to particles
Valves wear and tear
Pipe rupture
Trapped liquid
Wear and tear from corrosion
Inspection skipped

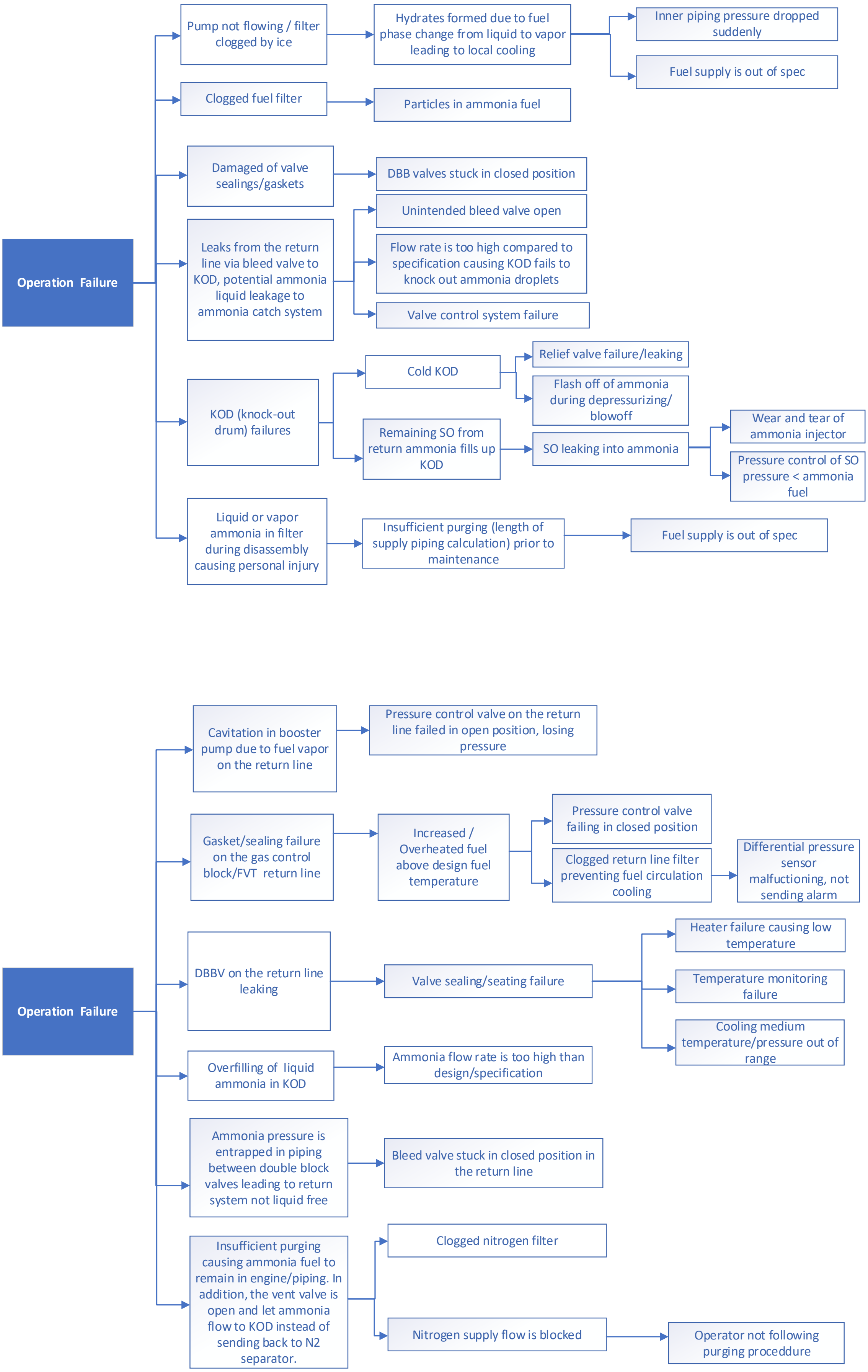



Figure 20: FTA 6 – Fuel Supply to Consumers System

### 3.5.7 FTA 7 – Bunkering System

Bunkering system needs to be monitored due to ammonia fuel flammability and toxicity. However, this area has not been evaluated as extensively as the fuel supply system and ammonia engine fuel system. Key risks are summarised in the FTA 7 – Bunkering System (Figure 22). Bunkering System (concept drawing created in Figure 21) is a relatively complex FTA in the ammonia-fuelled propulsion system, and the analysis covers the following equipment:

- Emergency shut-down valves
- Quick release couplings
- Bunkering hose
- Bunker valves control system (pneumatic, hydraulic)
- Pressure sensor and alarm
- Gas detector

The **design issue** that has been considered is the height difference between manifold and tank that could make challenging the draining of ammonia inventory. Fuel spills from three components are considered: 1) quick release coupling/flange/ERC, 2) manual valve/ESD valve/ Non-return valve and 3) bunkering hose failure. ERC is emergency release coupling and ESD is emergency shutdown.

In the **operation phase**, the bunkering system is relatively complex, and the following failure scenarios are summarised for better readability.

**Failure Scenario 1:** Overfilled ammonia tank

- Due to liquid level sensor failure, pressure sensor failure, or draining of the inventory in bunker piping, ammonia tank is overfilled above the allowable limit.

**Failure Scenario 2:** Overpressure of bunkering manifold

- During bunkering operation, due to valves closed incorrectly (ESD, Non-return valve), the bunkering manifold is over-pressured (see Figure 19).

**Failure Scenario 3:** Quick release coupling/flange/ERC/Non-return valve leak

- Due to wear and tear, operating above normal design pressure or exceeded vibration limit, it could lead to a leak in the quick release coupling (breakaway), on the flange (QCDC), emergency release coupling or non-return valve in Figure 19.

**Failure Scenario 4:** Bunker hose leaking

- Due to wear and tear or improper inspection of the bunker hose, it could lead to bunker hose leaking.

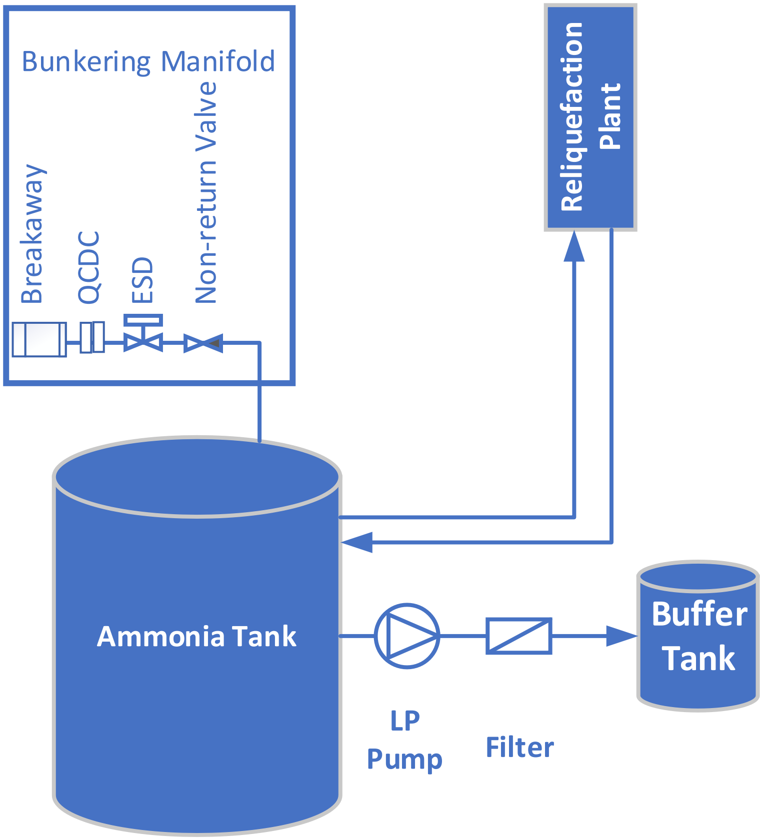
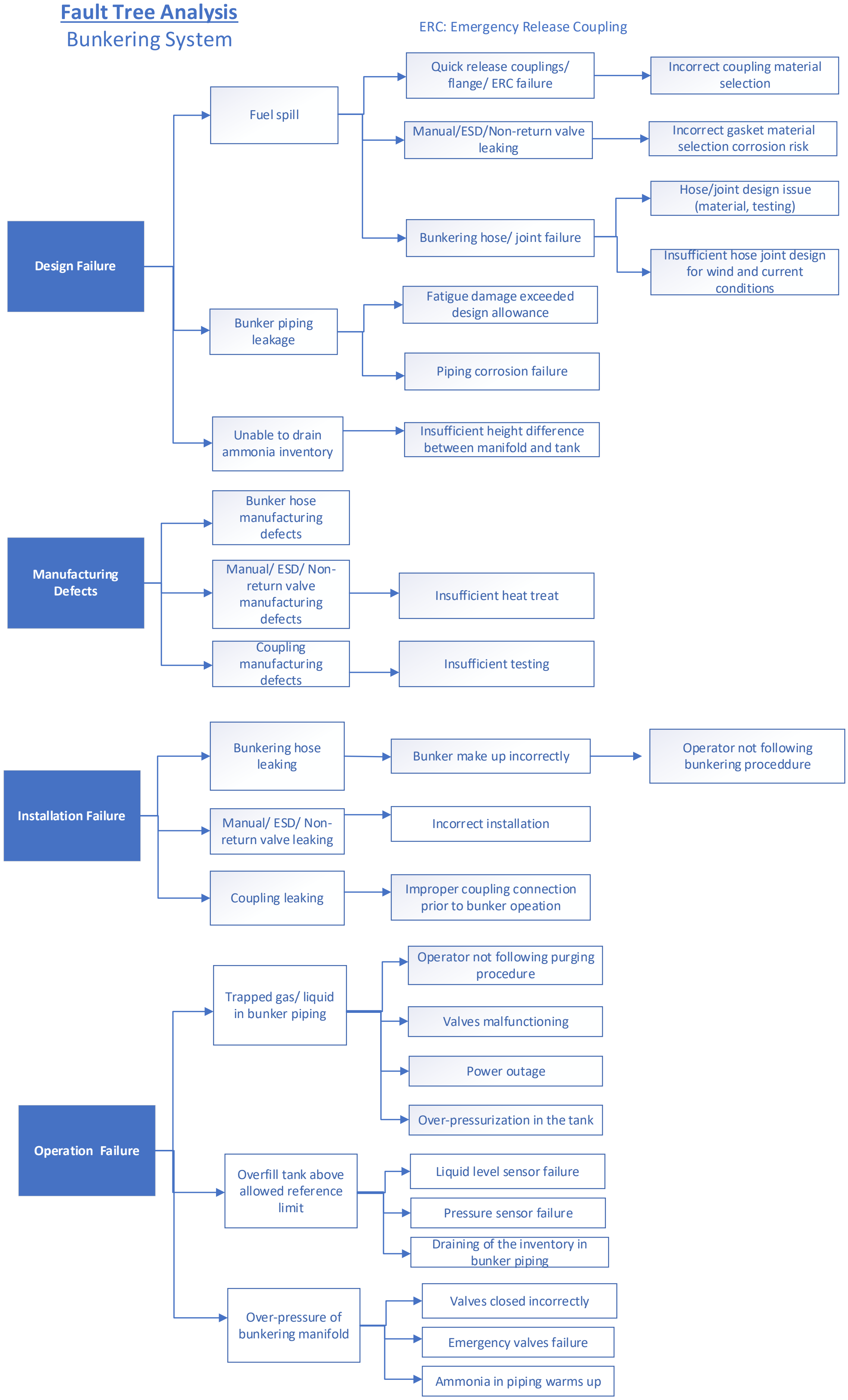



Figure 21: Bunkering Manifold Concept Drawing

**Fault Tree Analysis**

Bunkering System



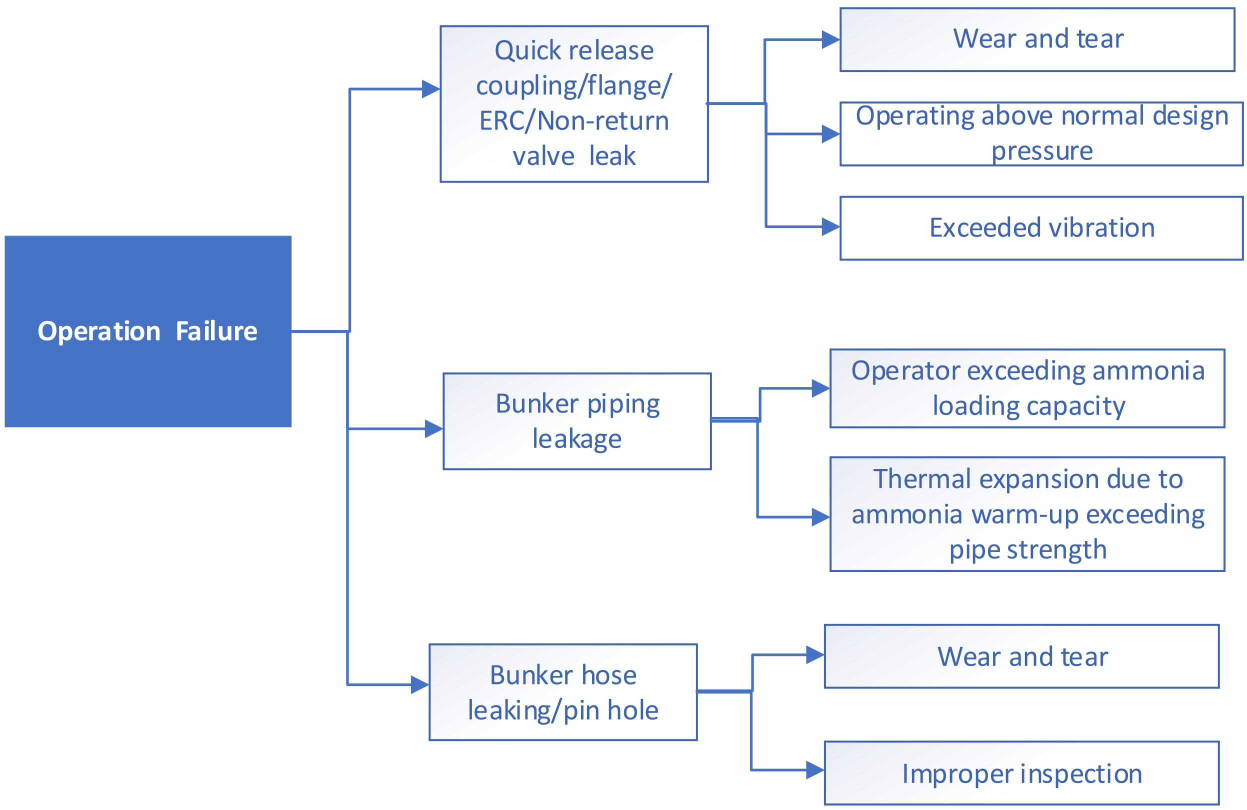



Figure 22: FTA 7- Bunkering System

### 3.5.8 FTA 8 – Reliquefaction System

Reliquefaction System is a relatively complex FTA (Figure 24) in the ammonia-fuelled propulsion system, and the analysis covers the following equipment:

- Compressors[14]
- Liquid separator
- Expansion valve
- Economiser
- Condenser
- Coolant system

During the FTA interview workshop, a concept drawing in Figure 23 was created to support failure scenarios in the FTA model. Failure scenarios for the reliquefaction system are summarised below:

**Failure Scenario 1:** Liquid separator leaking ammonia

- Due to insufficient design of material selection for corrosion resistance, cold liquid ammonia in the separator tank exacerbates corrosion that leads to leaking ammonia in the liquid separator.

**Failure Scenario 2:** Ammonia fuel tank overpressure

- Incorrect sizing of the reliquefaction system for compressor, condenser and expansion valve could cause the system to overpressurise.

**Failure Scenario 3:** Leaking ammonia in the compressor room via sealing/pipe connection

- Due to high BOG pressure on the line caused by wear and tear of sealing/pipe connection or clogged strainer in the piping, it may cause ammonia to leak.

[14] BCAG Owner Forum, LABY-GI Service Experience, Burckhardt Compression, Copenhagen, 15 May 2023.

**Failure Scenario 4:** Compressor failure

- In Figure 23, excessive ammonia vaporisation in the economiser could cause ammonia to backflow into compressor leading to compressor shutdown.

- Excessive vibration is detected and leads to compressor shutdown. Due to wear and tear of damper on the skid, it is not absorbing the vibration as designed. There are two root cause analyses reported in the Compressor Company Owner Forum, high vibration level on compressor crankgear and deformed piston rod due to high heat impact.

**Failure Scenario 5:** LP ammonia pump failure due to suction of contaminated ammonia

- In Figure 23, ammonia fuel is contaminated by compressor oil in the compressor crankcase. As a result, when LP ammonia fuel pump suction flow from ammonia tank, LP fuel pump initiates a shutdown due to detection of compressor oil in the LP ammonia fuel pump.

**Failure Scenario 6:** Condenser leaking failure

- In Figure 23, the coolant system can leak into ammonia in the condenser if condenser has a pin hole leak. Coolant system goes in and out to cool down ammonia in the condenser.

- When ammonia is detected in the coolant system, the reliquefaction coolant system will initiate a shutdown.

**Failure Scenario 7:** Reliquefaction coolant system shutdown

- Figure 23, the coolant system can leak into ammonia in the condenser if condenser has a pin hole leak. Coolant system goes in and out to cool down ammonia in the condenser. When ammonia is detected in the coolant system, it will initiate a coolant system shutdown.

**Failure Scenario 8:** Pressure drop in the ammonia reliquefaction system

- In the event when the safety valve is leaking (normally closed) due to wear and tear, the pressure will drop in the reliquefaction system.

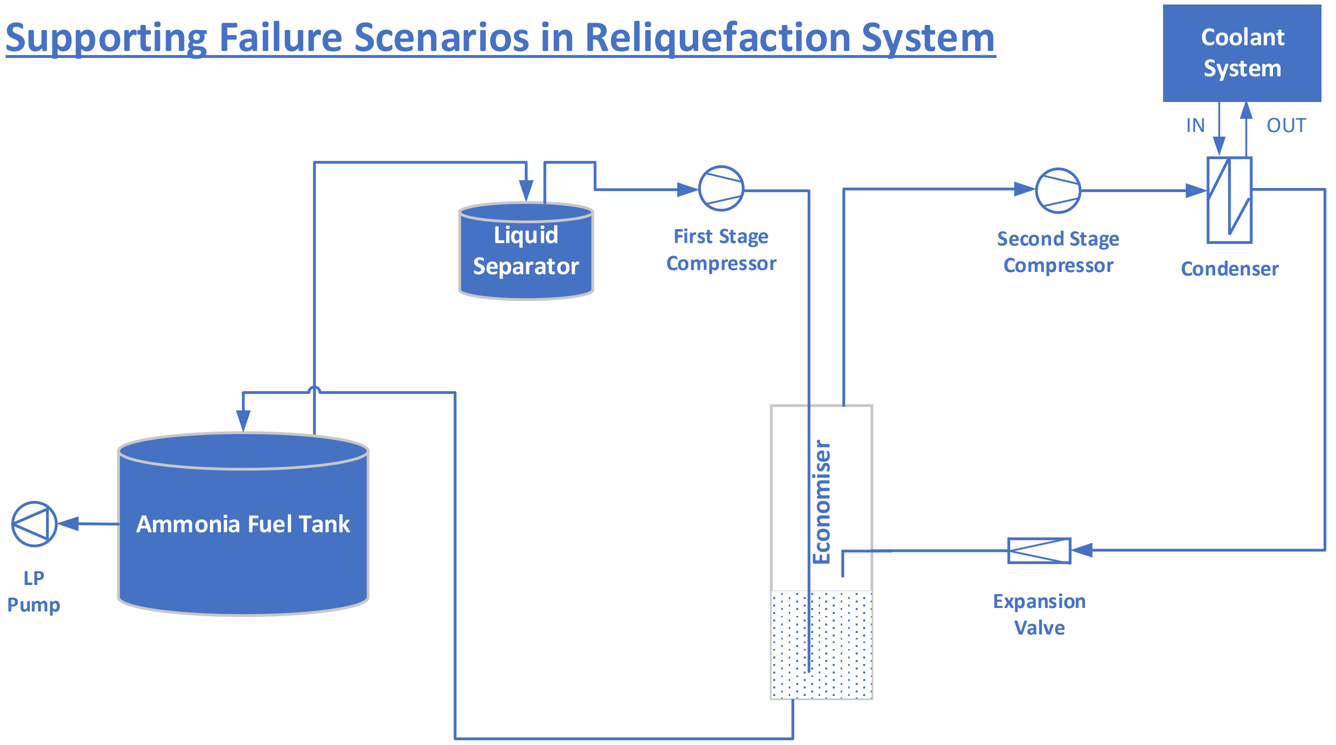



Figure 23: Concept Drawing – Reliquefaction System

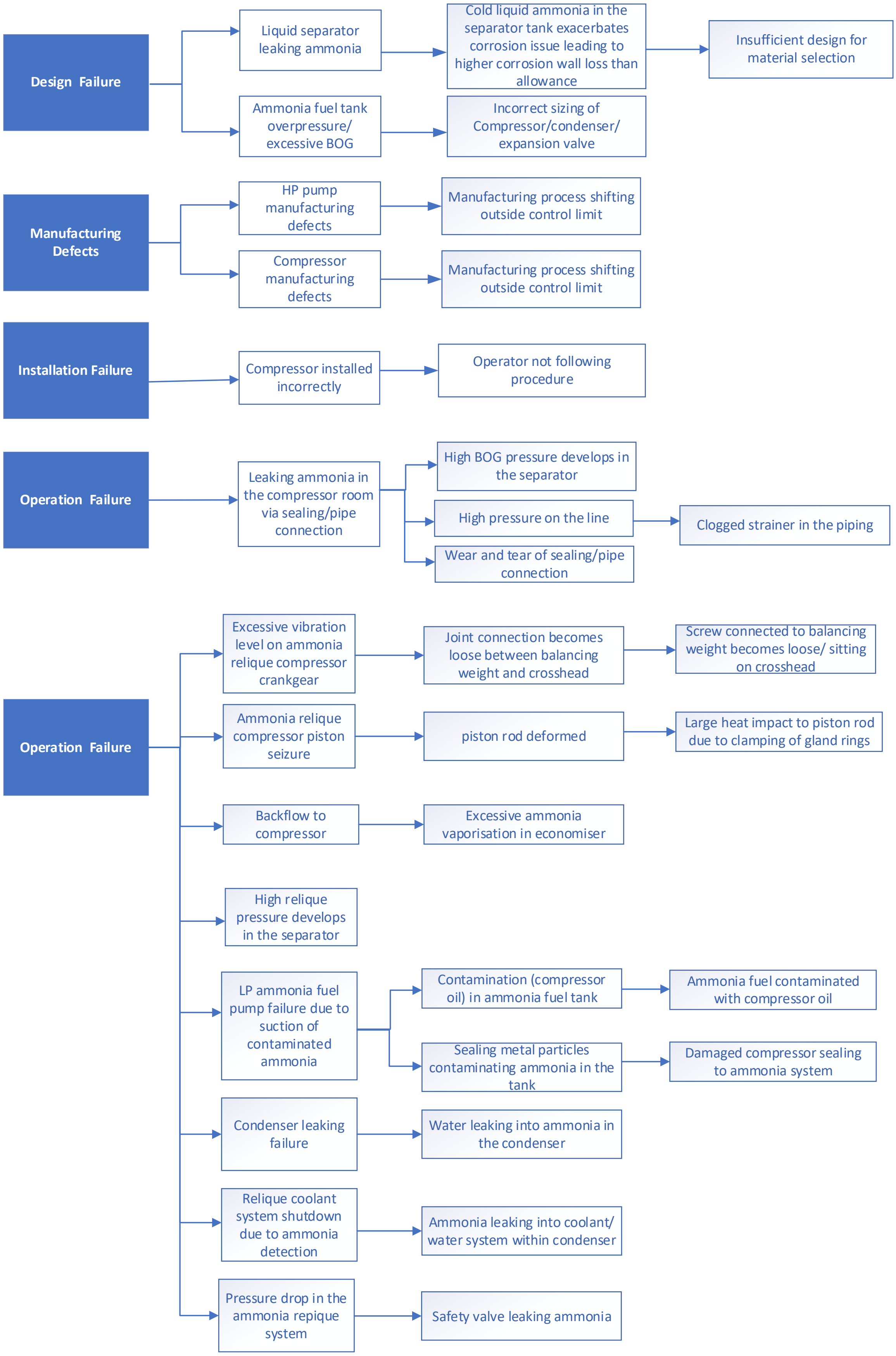



Figure 24: FTA 8 Reliquefaction System

## 3.6 Windchill Risk & Reliability | Phase II: Quantitative Reliability Assessment

Windchill Risk & Reliability Fault Tree Analysis (WRR FTA) is a Monte Carlo simulation program. WRR FTA is structured in two primary elements: 1) Probability of failure for each event and 2) Operator gate that links the events to reach an undesirable event. Monte Carlo simulation uses the estimated probability value for each basic event in the FTA structure. Each event expands to build a range of failure scenarios. The probability of failure uses a probability density function (PDF) with Mean and Standard Deviation or constant probability of failure for Exponential PDF.

Reliability $R(t)$ is defined as a probability a product can meet the required functions at any given time and operating condition. When a failure occurs, it follows a pattern that can be governed by a distribution or probability density function (PDF). A PDF is a mathematical function that describes a continuous probability distribution. It can be represented as a graph or an equation. In graph form, a PDF is a curve as a function of time, and the area under the curve within a certain interval can be used to determine the probability that a value will fall within that time interval. A Cumulative Distribution Function (CDF), $F(x)$ represents the probability that the variable is less than or equal to a particular value $x$. To find a cumulative distribution function (CDF) from a probability density function $f(t)$, you can integrate the PDF from negative infinity to infinity as follows.

$$F(x) = \int_{-\infty}^{x} f(t)dt$$

Typically, in a graphical form, PDF and CDF are illustrated below (Figure 25).

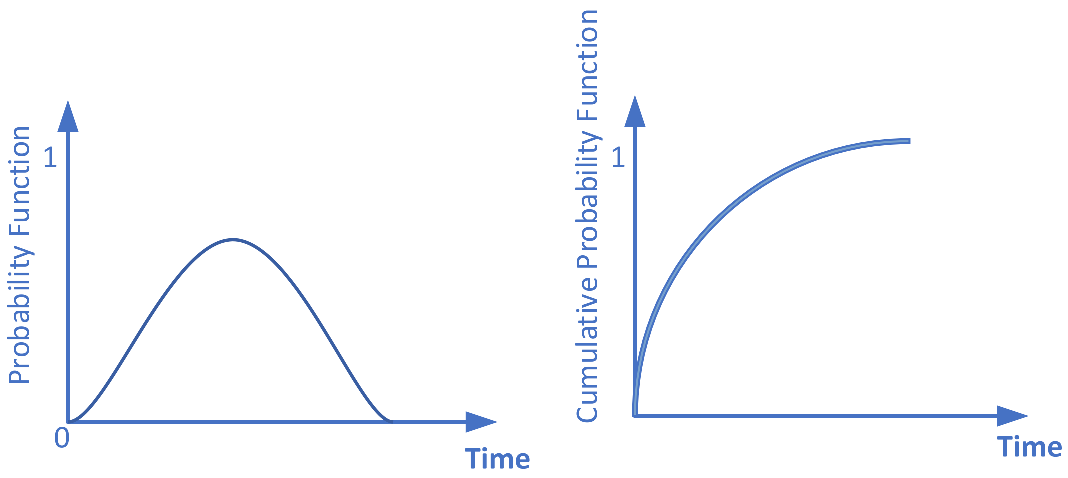



Figure 25: Comparison of Probability Density Function vs. Cumulative Distribution Function

For each event in the fault tree, it follows a distribution (CDF), such as Exponential (constant failure rate), normal, Weibull, Lognormal, etc. Exponential distribution is used to model a product with a constant failure rate. The PDF and CDF are shown below.

$$f(t;\lambda) = \begin{cases} \lambda e^{-\lambda t} & t \geq 0, \\ 0 & t < 0. \end{cases}$$

where $\lambda$ *is the parameter of the distribution.*

$$F(t;\lambda) = \begin{cases} 1 - \lambda e^{-\lambda t} & t \geq 0, \\ 0 & t < 0. \end{cases}$$

Fault Tree Analysis connects these events by logical operations such as OR Gate and AND Gate, which are commonly used in the FTA model. The calculations for both gates are summarised below:

Assume a system is composed of components 1, 2, 3, …, n and the probability of failure for components 1, 2, 3, … n are as follows.

$$Probability\ of\ Failure\ for\ Component\ i\ F_i(t) = 1 - R_i(t)$$

For an OR gate if any one component fails then the gate fails, thus the probability of failure for the gate is:

$$R_{sys}(t) = \prod_{i=1}^{n} R_i(t) = R_1(t) \times R_2(t) \times R_3(t) \ldots \times R_n(t)$$

$$F_{sys}(t) = \prod_{i=1}^{n} (1 - R_i(t)) = \prod_{i=1}^{n} F_i(t)$$

For an AND gate, the model is considering redundancy within the system. If one component fails, and other components are still functioning then the system continues to operate.

In other words, for a AND gate, the reliability calculation is

$$R_{sys}(t) = 1 - \prod_{i=1}^{n} F_i(t) = 1 - \prod_{i=1}^{n} (1 - R_i(t))$$

The probability of failure for the system is

$$F_{sys}(t) = \prod_{i=1}^{n} F_i(t) = \prod_{i=1}^{n} (1 - R_i(t))$$

More theoretical background explanation and literatures, particularly Fault Tree Analysis in NASA (National Aeronautics and Space Administration) application are available in the references.

For proceeding with further analysis, after the FTA is created, to provide a quantitative analysis for each component (such as combustion engine), a reliability calculation for particular physics of failure modes will be performed using a Load-Strength Analysis approach. A Load-Strength analysis is commonly used in component design. We assume Load and Strength follow a distribution with mean $\bar{L}$ and standard deviation $\bar{S}$, respectively. An approximation of standard deviation of 10% $\bar{L}$ or 10% $\bar{S}$ is applied. The probability of failure is then calculated by the following equation [1], integrating the overlapped area by two curves. Furthermore, Equation [2] derives reliability. The probability of failure is depicted in Figure 26, which is the area the two curves overlapped at the bottom of the graph.

Equation [1]

$$Probability\ of\ Failure = \frac{\bar{S} - \bar{L}}{\sqrt{{S_1}^2 + {S_2}^2}}$$

where $S\ is\ stregnth, L\ is\ Load, S_1\ is\ standard\ deviation\ of\ S, S_2 is\ standard\ deviation\ of\ L$

$$S_1 = 10\% \times \overline{S, whereas\ S_2 = 10\% \times \overline{\overline{L}}}$$

Equation [2]

$$Reliability = 1 - Probability\ of\ Failure$$

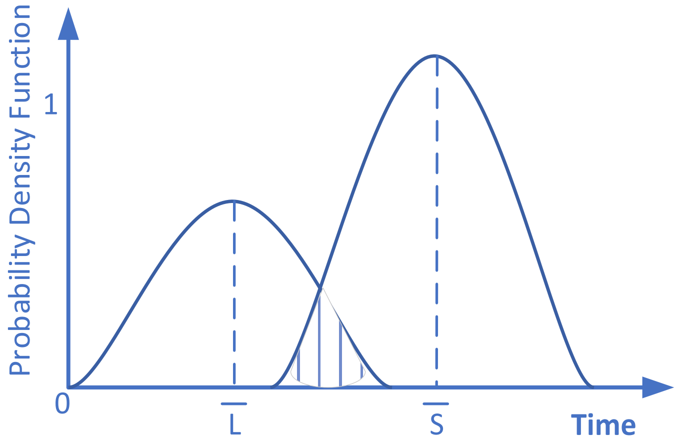



Figure 26: Probability Density Function

where:

- PDF: probability density function
- L: Load function
- S: Strength function

Once the basic events probability estimation for FTA are completed, they can be transferred to a simulation tool, Windchill Risk and Reliability in this case, as the last step of the reliability analysis. Note that there are many commercial tools readily available for FTA simulation.

### 3.6.1 Design Reliability Considerations

This section discusses design reliability concerns. After transferring failure scenarios of how failure modes can occur in the system from FTA model to Windchill Risk and Reliability tool, the probability of failure or MTTF information for each component or failure basic events are entered into the tool as data input. The default simulation duration of 30,000 hours was used to calculate the number of failures predicted for the ammonia-fuelled ship system and its subsystems. This section summarises top contributors based on the simulation results of how many failures for the system/subsystems were predicted. The reliability/ unreliability curves, information is available in the output file. Note the probability of failure (or failure rate), is the complement of reliability as shown below:

$$R(t) = 1 - F(t),$$

where R(t) is reliability function and F(t) is cumulative distribution function.

#### 3.6.1.1 Ammonia Corrosion Risk

The ammonia corrosion risk is one of the key factors in selecting the material according to the following criteria in Table 6. Typical ammonia fuel sample composition limit is in Table 5. For each component in the system that is vulnerable to corrosion risk, a failure mode has been solicited to ammonia designer and engine makers for their evaluation. Table 6 (main data source from Babcock International Group) summarised the assessment. Medium risks were considered for the following components:

- Ammonia high pressure fuel pump due to the PTFE (Teflon) on the diaphragm sealing surface. To mitigate the corrosion risk, pump diaphragm (PTFE) is replaced every 2 years or 12,000 hours.
- Emergency shutdown valves/sealing leaking leads to fuel spill. The cause of leaks could be incorrect material selection at the cryogenic condition (low temperature). Emergency shutdown valve/sealing body is made of 316L stainless steel, and seals are PTFE (Teflon). Corrosion allowance for 316L is 0mm.

For internal combustion engine (ICE), the piping design is double wall and made of 316L or 304L stainless steel. The risk of ammonia pipe leak or pipe rupture is considered low. Corrosion design allowance is predicted 0mm corrosion wall loss. Similarly, the ammonia fuel tank is made of 304L or 316L and double wall and corrosion wall loss predicted is 0mm.

For LPG carriers carrying ammonia, the risk of stress corrosion cracking was first surfaced in 1960's and ships were since redesigned for a safe operation. There has not been any corrosion failure due to ammonia reported for shipping industry since the 1960's.

Despite the clean records of vessels without corrosion failure incidents, the corrosion risk for the following two components remains uncertain due to lack of available corrosion data from engine makers and ammonia designer.

- Ammonia fuel injector: due to high pressure and flow rate, there is no available corrosion test data that can demonstrate that the corrosion risk has been mitigated.
- Bunkering hose corrosion data is also not available to rule out the possibility of leaking fuel, which presents toxicity risk. Transfer equipment material shall be compatible with ammonia as a requirement.

Table 5: Typical ammonia fuel sample composition limits

| Designation | Unit | Limit | Test Method |
|---|---|---|---|
| Ammonia | %(w/w) | 99.5 min. | Evaporative residue |
| Water | %(w/w) | 0.1 min. | CGA G-2.2/ISO 7105 |
| | | 0.5 max. | |
| Oil | ppm | 5 max. | FTIR Analysis/ISO 7106 |
| Oxygen | ppm | 2.5 max. | No specific standard developed yet |

Table 6: Corrosion Consideration Summary for Internal Combustion Engine, Fuel Supply System and Bunkering

| System | Component | Material Grade | Operational Range[15] | Failure Mode | Risk Level (L,M,H) | Corrosion Wall Loss/Allowance |
|---|---|---|---|---|---|---|
| Internal Combustion Engine | Ammonia fuel injector valve | Tungsten | Temperature: 25-55ºC<br>Pressure: 500-700 bar<br>Injector quantity: 2-3 per cylinder<br>Flow Rate: Approx. 5-6 kg ammonia per injection<br>Nozzle temperature: 45ºC-300ºC (at 3 -700 bar) | Ammonia leaking in the valves due to injector corrosion failure, high pressure ammonia flow injection | Unknown | Unknown |
| | Double wall ammonia fuel piping | 316L | Temperature: 25-55ºC<br>Pressure: 500-700 bar | Pipe rupture due to corrosion failure | Low | Corrosion Allowance - 0mm |
| Fuel Supply System | Ammonia fuel pump/ sealing | Pumphead / Valve Body - 316L<br><br>Diaphragm - PTFE | Temperature: -30ºC<br>Pressure: 80-90 bar | Ammonia fuel pump is leaking due to valve/sealing corrosion failure | Median (based on diaphragm failure) | Pump diaphragm is changed every 2 years or 12,000 hours running time. |
| | Ammonia buffer tank | Stainless Steel (304L or 316L) | Temperature: -30ºC<br>Pressure: 5-16 bar | Buffer tank is leaking due to corrosion failure | Low | Corrosion Allowance - 0mm |
| Bunkering | Bunkering hose/connection | Unknown | Temperature: -33ºC<br>Pressure: 0.7 bar | Hose leaking due to corrosion during bunkering operation | Unknown | Unknown |
| | Emergency shutdown valves/sealing | Body - 316 Stainless Steel<br>Seals - PTFE | Temperature: -33ºC<br>Pressure:0.7 bar | Ammonia leaking in the emergency shutdown valve due to corrosion failure preventing shutdown operation. | Low | Corrosion Allowance - 0mm |

[15] Refer to Table 5 for Ammonia concentration.

[16] Another Fuel Supply System vendor solicited for corrosion experience in the fuel supply system documented below.

We always use stainless steel 304L or 316L on deck piping for LPG/ammonia carriers. The same will be used on the ammonia fuel system. I am not aware of any significant corrosion issues on ammonia carriers built the last 20 years

A sudden unexpected ammonia leak is likely the biggest risk in the ammonia fuel system. It does not take a very large leak before it is deadly for personnel nearby. The fuel preparation room and tank connection space would most likely be partly unmanned. Entry is allowed only when the system is pressure relived to the fuel tank pressure. Focus should be to avoid leaks in the engine room, and other places that is manned and difficult to evacuate quickly.

#### 3.6.1.2 External Leaking- Fuel Risk

Safety system for the ammonia engine working on the diesel combustion cycle type is similar to other types of dual fuel engine types using the diesel combustion principle. The dual fuel ammonia engine is equipped with safety systems designed to prevent or mitigate unburned ammonia from entering the following spaces and systems:

- **Engine room** – double wall pipes with extra ventilation surrounding the ammonia supply pipes, and sensors to detect any ammonia leak. The connecting of ammonia piping and ducting to the injection valves are to be completely covered by the ducting. The arrangement is to facilitate replacement and/or overhaul of injection valves and cylinder covers. Double ducting is also required for all ammonia pipes on the engine itself, until fuel is injected into the chamber.
- **Scavenge air space** – measurement of ammonia ignition is constantly monitored for each combustion cycle, and compression pressure is monitored to detect if the piston rings are collapsing. The cylinder monitoring system reacts on deviating pressure conditions in the combustion chamber of each cylinder, more specifically if the specified maximum deviation is exceeded. The cylinder monitoring system oversees the cylinder compression pressure, the maximum cylinder pressure and the cylinder expansion pressure
- **Crankcase** – monitoring of the combustion condition prevents that unburned ammonia arrives below the piston crown, and the chance for getting ammonia in the crank casing is therefore mitigated (however other mitigation measures may be needed such as continuous extraction of vapours).
- **Hydraulic oil system** – a sealing oil or sealing air system is applied in between the ammonia and the hydraulic oil system to prevent ammonia from going back into the hydraulic oil system.
- **Main lube oil cooling system** - monitoring of the combustion condition and of the main lube and cooling oil system secures that leakages are detected quickly.
- **Cooling water system** - monitoring of the combustion condition and of the cooling water system secures that water leakages are detected quickly. Furthermore, sensors are placed in the cooling water system to detect if the water has any ammonia contamination.

**Data Source for Fuel Leak Probability:**

An LNG data source[17] for fuel leak frequency per year is referenced for this study. LNG equipment is more relevant to ammonia fuel in marine shipping applications. This study selects LNG application leak frequency 2.7E-4 as a conservative estimate for ammonia fuel leak in the engine room. LNG, like ammonia, is delivered to the engine through a double wall pipe. In the outer pipe a vacuum exists, the air is exchanged at a rate of 30 times per hour, and the ventilation is monitored for leaks. In case of a small leak, an alarm is issued, but a high leak will result in a shut down on the supply of LNG/ammonia. In order for LNG (or ammonia) to leak into the engine room, two failures would therefore have to happen at the same time. This scenario is unlikely, as can be seen in Table 7 where the likelihood for having two leaks at the same time (i.e., small hole leak in the inner pipe and outer pipe rupture). is shown. The likelihood is calculated for a full-bore rupture of the inner pipe, and either a small, a medium or a full-

[16] Data source: Email correspondence with Wartsila Gas Solutions, dated June 24, 2024.
[17] Dual fuel concept: analysis of fires and explosions in engine room, MAN-ES and DNV consulting, 3 May 2006.

bore rupture in the outer pipe. The likelihood shown is the same for LNG as for ammonia, ignition and the fire will be different as ammonia is not likely to ignite. The concern for ammonia is the toxicity, and the risk of having a release of ammonia at the time when the engineers onboard are close to the rupture.

LNG summary of frequency of fire and explosion is in Table 7. The data takes into account only leak frequency but the probability of toxic exposure has not been considered as it doesn't apply to LNG. There would be the risk with ammonia that personnel working on the engine would be exposed to high concentrations of toxic ammonia in case of leak.

The most conservative leak frequency per year 2.70E-04 per year is used. In other words, one can expect 2.70E-04 failure per 8760 hours. To convert it to Mean Time To Failure (MTTF), the following is used:

$$\frac{8760}{2.70E-04} = 3.24 \times E\hat{}07\ hours.$$

Thus, MTTF for fuel leak is estimated to be $3.24 \times 10^7\ hours$.

Table 7: LNG Summary of Frequency of Fire and Explosions

| | Leak Frequency* (per year) | Ignition probability (per year) | Fire frequency (per year) | Explosion probability (per year) | Explosion frequency (per year) |
|---|---|---|---|---|---|
| **Small** | 2.70E-04 | 0.021 | 5.70E-06 | 0 | 0.00E+00 |
| **Medium** | 5.90E-05 | 0.067 | 4.00E-06 | 0.5 | 2.00E-06 |
| **Full bore** | 3.20E-05 | 0.15 | 4.80E-06 | 1 | 4.80E-06 |

*The leak frequency is found for a high-pressure double wall gas pipe, and it is the likelihood of having a rupture in the outer pipe and a hole in the inner pipe happening at the same time.

#### 3.6.1.3 Fuel Injector Ammonia Nozzle Damage

Engine makers actively contributed to the FTA interviews. Particularly, interview results on the ammonia fuel injector valve and fuel oil injector valve design life are summarised in Table 8 and

Table 9[18] below.

Table 8: Vendor Expected Service Life Data – Ammonia Injector Valve (MAN Energy Solutions)

| **Component (Ammonia Fuel Injector)** | **MTTF (hours)** |
|---|---|
| Ammonia injector valve (or fuel booster injector valve) | 64,000 |
| Valve nozzle | 8,000 |
| Spring guide | 8,000 |
| Non-return valve | 16,000 |
| Spring | 32,000 |

[18] MAN Energy Solution Service Letter SL2019-681/SRJ: Guiding overhaul intervals and expected service life of engine components on two-stroke low speed engines

Table 9: Vendor Expected Service Life Data – Fuel Oil Valve (MAN Energy Solutions)

| Component (Fuel Oil Injector) | MTTF (hours) |
|---|---|
| Valve nozzle | 8,000 |
| Spindle guide | 8,000 |
| Non-return valve | 16,000 |
| Spring | 32,000 |
| Thrust spindle | 16,000 |
| Foot | 32,000 |
| Spring pack | 16,000 |
| Guide rings | 16,000 |
| Back-up ring | 16,000 |
| Holder | 48,000 |
| Head | 48,000 |

- **Failure Scenario 1** – Spring jammed

Spring could be jammed in a way that it causes the injector valve not to fully open. Selecting the spring material that meets the design life is also an important design factor.

- **Failure Scenario 2** – Fatigue damage

Fatigue damage is a common design consideration for the fuel injector. However, based on experience from an ammonia fuel engine maker, fatigue damage is not a prominent failure mode in any fuel injector component. Due to the nature of fatigue damage, it is prudent to continue to monitor this risk.

- **Failure Scenario 3** – Corrosion wall loss

The high pressure, high temperature application of fuel injector that causes higher corrosion wall loss than design or stress corrosion cracking mechanism remains an uncertain risk to manage. Other component corrosion risks have been studied and failures have not been observed in the industry. Detailed corrosion analysis is reported in the previous section.

#### 3.6.1.4 Ship Movement and General Ammonia Equipment Vibration

Based on ammonia engine maker's experience, all components in fuel supply system including machinery and piping are designed according to the vibration limits set forth by the company guidelines. As an example, vibration measurements are taken from the following types and adhere vibration limits accordingly:

- Engines in service,
- Vibration measurements during shop tests,
- Vibration commissioning during sea trials,
- Special test conditions not representative for normal operation.

The vibration risk is mitigated based on the integrity design to protect equipment fatigue damage to the engine structure and personnel / operator comfort. Vibration limits are expressed in a range of frequency value in $mm/s^2$ and are applied to all operational speed range. Equipment is in condition monitoring is classified in recommended, acceptable or unacceptable ranges based on the vibration values.

Data sources from industry are referenced in estimating the probability of vibration failure mean 14.61 per $10^6$ hours and standard deviation 14.16 per $10^6$ hours[19].

#### 3.6.1.5 Fuel Supply System Piping Connection Sealing/Gasket Leaking

This is the most frequent failure mode due to various causes (wear and tear, incorrect installation, manufacturing defects, operating above the allowable range, etc.) and is mitigated by periodic replacement and control monitoring. Depending on the sealing location, the complexity of the control monitoring varies. For instance, the fuel supply system (e.g., fuel pump) in the engine room has much higher consequence (safety concern) than the seawater pump gasket leaking.

#### 3.6.1.6 Nitrogen purging pipe length to prevent ammonia contamination

Before engine startup, nitrogen is used to purge the fuel supply system and remove any ammonia residue in the piping system. Purging is required from the inlet of the engine to all piping related to the engine. The required purging length depends on the position of knockout drum and ammonia nitrogen separator. The design of nitrogen purging piping system is a function of the final design layout to minimise the total installation cost by optimising one integrated ammonia/ nitrogen vapor capture system. Nitrogen purging length and time is kept on the top contributor list mostly for monitoring.

### 3.6.2 Un-Reliability Curve, MTTF, Failure Rate Prediction

In this section, the result of the analysis is summarised in Table 10 by the ammonia-fuelled ship system and subsystems (FTA 1- FTA8). The MTTF and failure rate values are calculated from the Windchill Risk and Reliability/ Fault Tree Analysis. The failure rate and MTTF have the following relationship.

$$MTTF = \frac{10^6}{Failure\ Rate}, \text{ in hours.}$$

The Mean Time To Failure (MTTF) for the total system is 4,590 hours. On the breakdown list FTA 1 to FTA 8, each subsystem is also analysed with their corresponding subsystem MTTF. FTA 6 (9,406 hours), FTA 5 (27,248 hours), FTA 7 (35,537 hours) and FTA 8 (50,000 hours) have shorter MTTF compared to other subsystems.

Out of the 8 subsystems, FTA 6 (the fuel supply system has the shortest MTTF as it is a more complex system, which has more failure modes contributing to a higher failure rate. Effort should be taken to plan for control measures and improving design failures analysed in the model, such as Manual valve/ESD/Non return valve leaking due to incorrect gasket material selection risk.

FTA 5 Hydraulic and sealing oil systems has a shorter MTTF compared to other subsystems due to its operation complexity to control sealing oil pressure higher than the ammonia fuel or pump failure. For instance, excessive vibration pump or overheated hydraulic oil can lead to pump bearing failure. Sealing oil failure cannot prevent ammonia backflow leading to ammonia contamination in the equipment. Ammonia contamination could be in sealing oil or hydraulic oil.

FTA 7 Bunkering system has a shorter MTTF compared to other subsystem due to design failure. Manual valve, ESD, or return valve could be leaking due to incorrect gasket material selection and causes fuel spill during bunkering operation. Bunkering hose leaking due to wear and tear should be mitigation by following OEM recommendation and inspection plan.

FTA 8 Reliquefaction system has a shorter MTTF due to the compressor design life. Despite the compressor used in conventional fuel is reliable, the compressor to process the boil-off gas (BOG) for the ammonia fuel reliquefaction system requires a higher speed type due to alternative fuel material properties. The conventional BOG compressor is typically designed to align with a ship's design life that does not require replacement. The BOG compressor used for ammonia fuel application would require further development to meet the reliquefaction system requirements.

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[19] OREDA Offshore Reliability Handbook

Table 10: Ammonia-fuelled propulsion system lifetime estimation summary

| System Identifier | MTTF Hours | Failure Rate Per million hours |
|---|---|---|
| **Ammonia Fueled Propulsion System** | 4,590 | 218 |
| FTA 1 & 2: Dual Fuel Engine System | 54,475 | 18 |
| FTA 3: Common Engine Component | 119,971 | 8 |
| FTA 4: Auxiliary Systems | 500,000 | 2 |
| FTA 5: Hydraulic & Sealing Oil Systems | 27,248 | 37 |
| FTA 6: Fuel Supply System | 9,406 | 106 |
| FTA 7: Bunkering System | 35,537 | 28 |
| FTA 8 Reliquefaction System | 50,000 | 20 |

The unreliability curve for the ammonia-fuelled propulsion system (the total system) is in Figure 27 and unreliability numerical results in Table 11.

Table 11: Unreliability table: ammonia fuel for ship system

| Time | Unavailability (Total System) |
|---|---|
| 0 | 0.01618 |
| 3000 | 0.46296 |
| 6000 | 0.71005 |
| 9000 | 0.84480 |
| 12000 | 0.91749 |
| 15000 | 0.95638 |
| 18000 | 0.97704 |
| 21000 | 0.98796 |
| 24000 | 0.99370 |
| 27000 | 0.99672 |
| 30000 | 0.99829 |

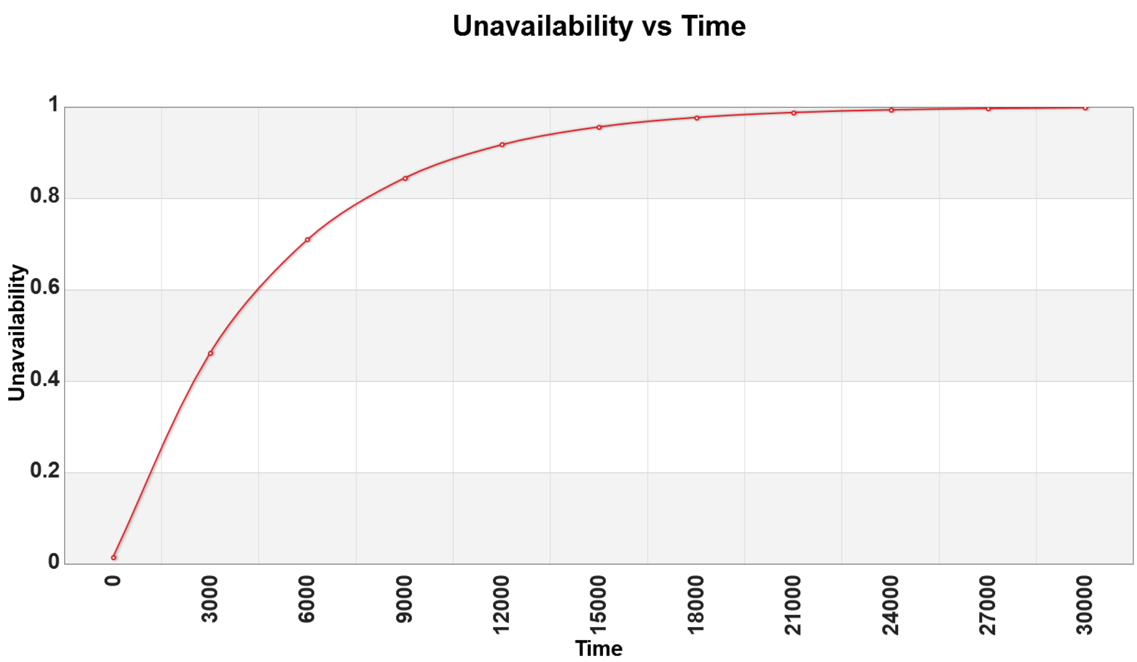



Figure 27: Unreliability curve: ammonia fuel for ship system

**Reliability** is a time-based probability value between 0 and 1. A value of 0 means the system is never functioning, and a value of 1 means it is always operating.

**Reliability** vs Time Shows the reliability function, R(t). This plot reports the reliability of the product at a given point in time according to the distribution. It is the complement of the cumulative distribution function, F(t), displayed on the Unreliability vs. Time plot.

**Unreliability** vs Time Shows the unreliability function, F(t) or Q(t). This plot reports the unreliability of the product at a given point in time according to the distribution.

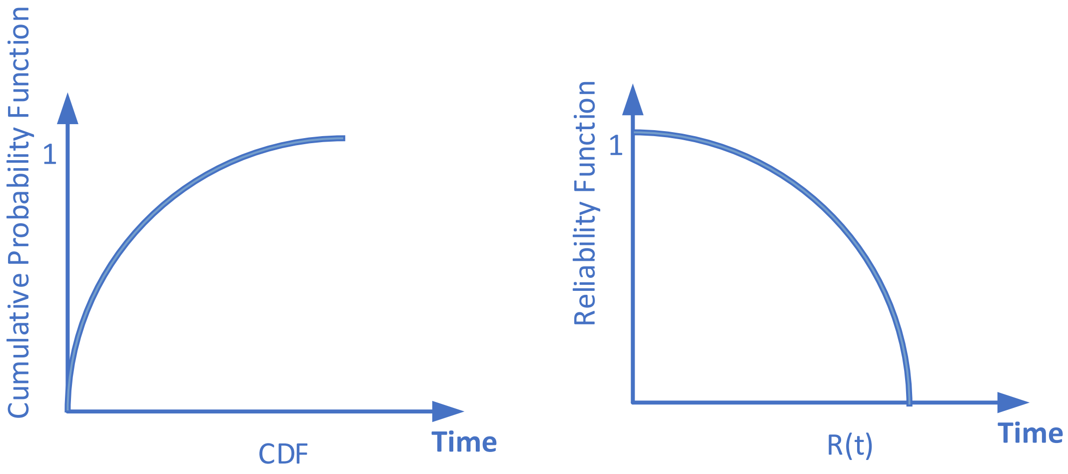
$$\text{Unreliabilty (t)} \; = \; 1 - \text{Reliability (t)}, \text{where t is time.}$$

**CDF**, **Cumulative Distribution Function**, vs Time is complement of reliability function.

$R(t) = 1 - F(t)$,

where R(t) is reliability function and F(t) is cumulative distribution function.

In graphical form, R (t) and F(t) are illustrated below –




**Mean Time To Failure** or **MTTF:** Another performance metric, Mean Time To Failure (MTTF), is derived from the reliability curve. By definition, MTTF is the cumulative time when half of the population fail. For instance, in the case of 100 products in a testing, as time progresses, the first unit fails, a failure time is recorded. As the 50th product fails, the failure time is recorded. The time when half of the population have failed is defined as Mean Time To Failure or average time it takes for the product to fail. In the reliability curve, when $R(t) = 0.5$, it means half of the population are expected to fail at time t, which is the definition of MTTF.

**Availability vs. Time** shows the availability function as a function of time.

The availability of a single unit having exponential failure and repair distributions that correspond to the constant failure and repair rates is calculated at each time point with the following equation:

$$A(t) = \frac{\mu}{\lambda + \mu} + \frac{\lambda}{\lambda + \mu} e^{-(\lambda+\mu)t}$$

Where:

A(t) =The availability of the unit at time t.

λ = The constant failure rate.

μ = The constant repair rate.

In the ammonia-fuelled propulsion system, repair time is not considered in the FTA model (i.e., $\mu = 0$)

As a result,

$$A(t) = \frac{0}{\lambda + 0} + \frac{\lambda}{\lambda + 0} e^{-(\lambda+0)t} \; = \; e^{-\lambda t}$$

$R(t) = e^{-\lambda t}$ for exponential distribution.

$$A(t) = R(t)$$

### 3.6.3 Sensitivity Analysis (What-If Analysis)

FTA 6 fuel supply system, FTA 7 bunkering system and FTA 8 reliquefaction system are selected for further sensitivity/what-if analysis due to the complexity of the system.

In FTA 1 and FTA 2, the following failure mode has been selected to demonstrate how its MTTF would impact the overall ammonia fuel system reliability.

The following sensitivity analysis for the ammonia-fuelled propulsion system has been selected to investigate further.

- Operation on ammonia fuel – a stop of ammonia operation and a seamless switch to diesel mode

  Failure in the ammonia system leads to a stop of ammonia operation and a seamless changeover to diesel mode. This is modelled as redundancy in engine fuel system (FTA 1 and FTA 2).

  - Dual Fuel Redundancy Concept Design: MTTF = 4,590 hours for ammonia-fuelled propulsion system.
  - Ammonia Fuel Engine Design Without Redundancy Design: MTTF = 3,822 hours for ammonia-fuelled propulsion system.

  As indicated in the unreliability curve (F(t): cumulative distribution function, $F(t) = 1 - R(t)$), the ammonia fuel design without redundancy concept increases more rapidly than the dual fuel redundancy concept design as shown in Figure 28.

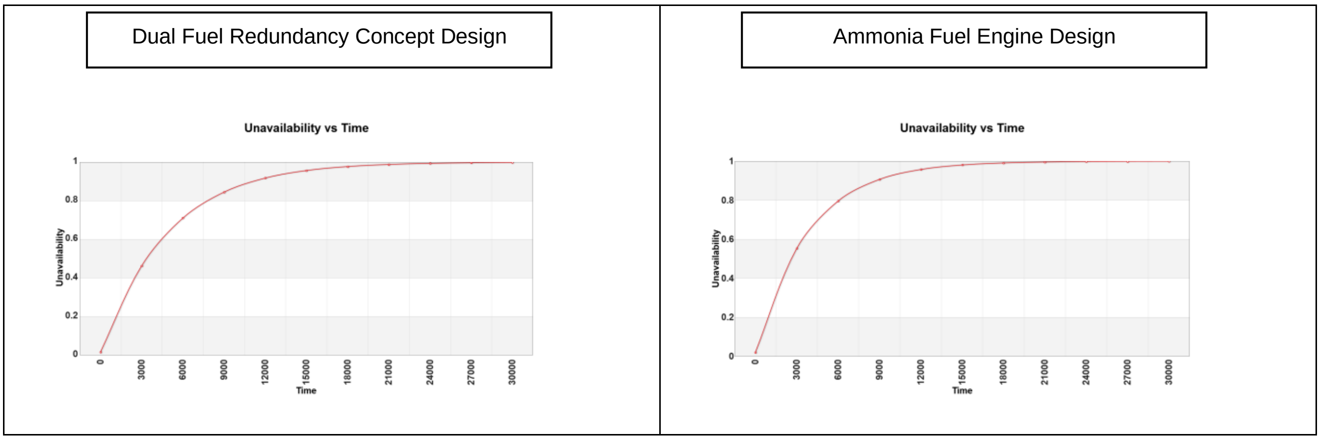



Figure 28: Unreliability curve comparison for dual fuel redundancy design vs. without redundancy

The following scenarios have been selected for further analysis to provide guidance in increasing system reliability or MTTF. Upon receiving equipment MTTF for fuel supply system, bunkering system and reliquefaction system, results have been compared for opportunity of improvement.[20] Depending on the equipment operational and maintenance philosophy, system reliability can be improved by increasing a unit design life or making a redundancy system when applicable. For instance, boil off gas (BOG) system can be paired with multiple compressors to increase the reliability and current technology can program the control system to operate BOG compressor.

- Fuel Supply System (FTA 6 Model)
  1. **Rotating equipment pumps motor driven pressure centrifugal MTTF = 8,000 hours vs. Redundancy Multiple Pumps**
  2. **Mechanical seals in pumps MTTF = 25,000 hours vs. 50,000 hours**
  3. Protection systems relief valve spring loaded MTTF = 595,238 hours - Not selected

In the case FTA 6, where rotating equipment pump motor MTTF = 8,000 hours vs. two (2) redundancy pumps, the WRR results were compared in the following graph. The pump design life is not long enough to prolong FTA 6 fuel supply system MTTF by much.

[20] Guidelines for Process Equipment Reliability Data with Data Tables from American Institute of Chemical Engineers.

Figure 29 indicates the FTA 6 fuel supply system with single pump configuration $MTTF_{System} = 4{,}323\ hours$,
The FTA 6 fuel supply system with redundancy pumps (x2) $MTTF_{System} = 4{,}351\ hours$.

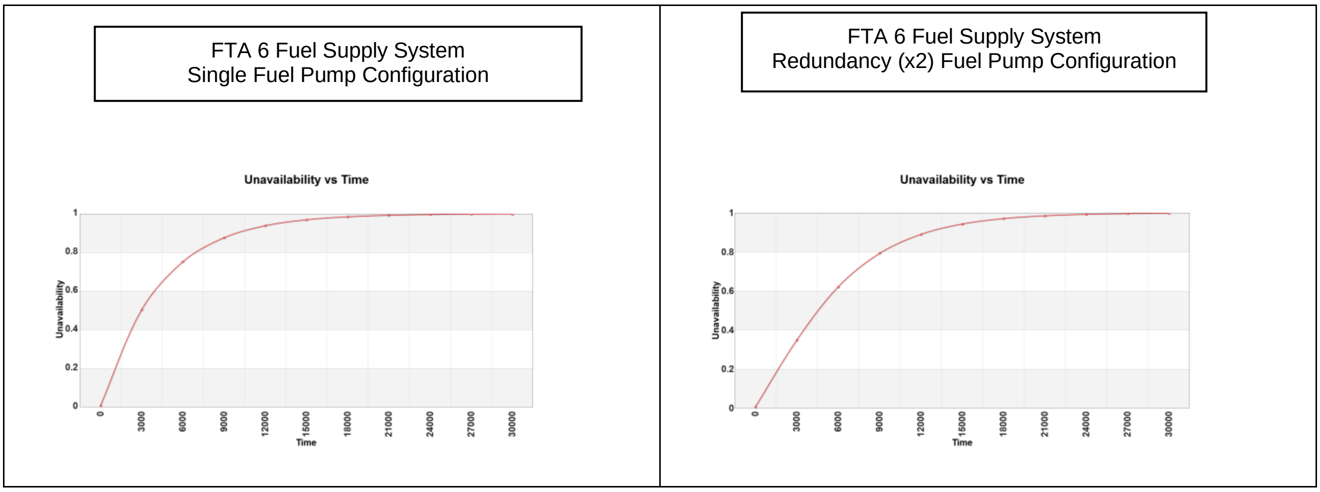



Figure 29: Unreliability curve comparison for FTA 6 fuel supply system single fuel pump configuration vs. redundancy fuel pump configuration

In the fuel pump, for mechanical seal MTTF = 25,000 hours, the sensitivity analysis is compared to the case where MTTF to be increased to 50,000 hours. The FTA 6 fuel supply system MTTF will be increased from 6,834 hours to 7,916 hours.

Figure 30 indicates:
the FTA 6 fuel supply system with mechanical seal MTTF=25,000 hours, the predicted $MTTF_{System} = 6{,}834\ hours$, and
the FTA 6 fuel supply system with mechanical seal MTTF=50,000 hours, the predicted $MTTF_{System} = 7{,}916\ hours$.

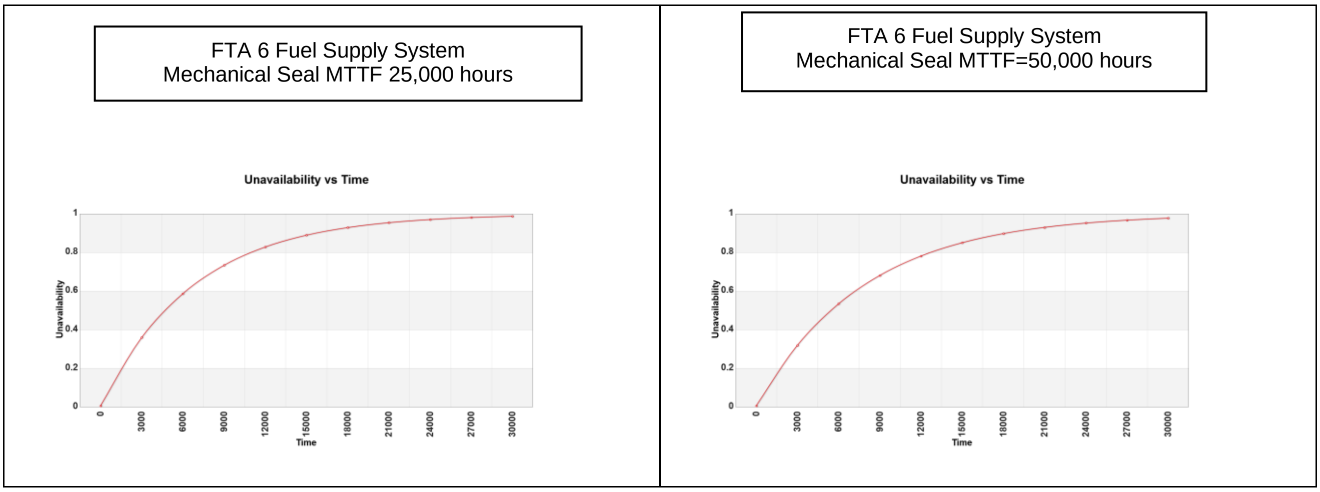



Figure 30: Unreliability curve comparison for FTA 6 fuel supply system mechanical seal MTTF 25,000 hours vs. 50,000 hours

After one time usage of the high-pressure relief valve, typically the valve needs maintenance or replacement of sealing. In the lifetime of the vessel, pressure relief valve is not expected to be used onboard the vessel for a highly reliable and mature control system.

- Bunkering System (FTA 7 Model)
  1. **Solenoid valve not open or close per command MTTF = 20,000 hours vs. 40,000 hours**
  2. Quick release coupling or ERC (Emergency release coupling) MTTF = 992,000 hours - Not selected
  3. Bunker hose MTTF = 1,754,386 hours – Not selected

In the case, where solenoid operated valves not open or closed per command MTTF = 20,000 hours, the FTA 7 model system $MTTF_{System} = 13{,}363\ hours$. If the solenoid valve MTTF is increased by double, the FTA 7 bunkering system $MTTF_{System} = 25{,}575\ hours$.

Figure 31 indicates the FTA 7 bunkering system unreliability curve; a comparison has been made if the solenoid valve not open or close per command is increased from 20,000 hours to 40,000 hours. The results indicate an improvement in reliability for the longer MTTF.

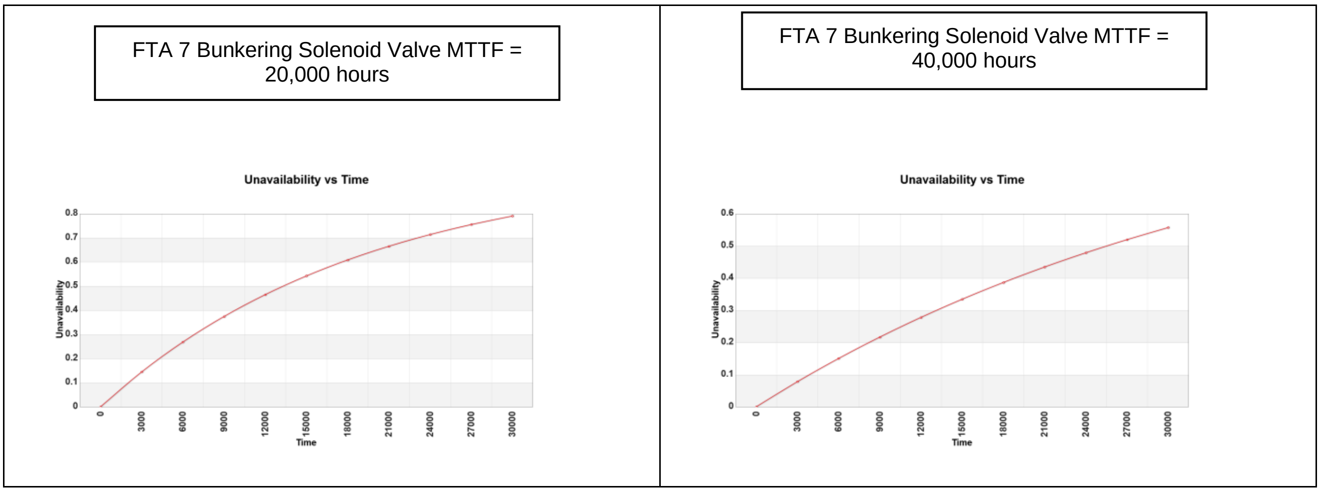



Figure 31: Unreliability curve comparison for FTA 7 bunkering system solenoid valve MTTF 20,000 hours vs. 40,000 hours

- Reliquefaction System (FTA 8 Model)
  - **Single Compressor MTTF = 700 hours vs. Redundancy Multiple Compressors**

The rotating equipment ammonia reliquefaction compressor has a more spread of reliability lifetime data. Vendor assessment has as long as the vessel design life and as short as MTTF = 700 hours. Conventional compressor has longer MTTF. However, a shorter MTTF high speed ammonia reliquefaction compressor is under development (current technology is 500 rpm, future technology over 1000 rpm is expected). The intention is to evaluate the case with the short compressor life when used in the FTA 8 reliquefaction system. FTA demonstrates the impact to choose multiple compressor redundancy (3 compressors are used) or improved MTTF by 10 times (i.e., 7,000 hours). The unreliability curves in Figure 32 are outlined below for comparison. With such a short MTTF, even if the equipment is configurated to have 2 other standby compressors, the reliquefaction system is not improved by much. However, if MTTF is increased by 10 times, the system reliability is increased significantly $MTTF_{System} = 5{,}008\ hours$.

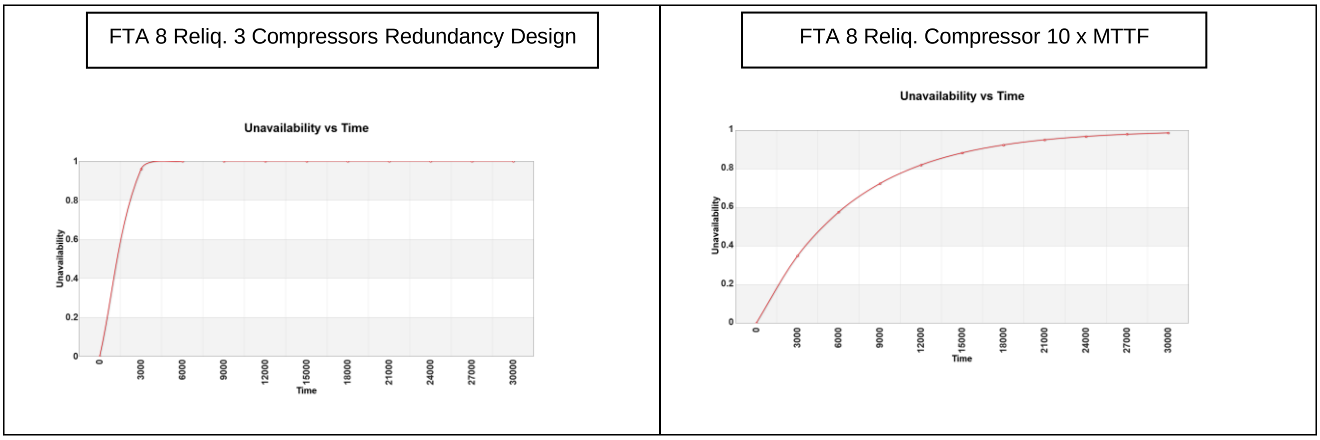



Figure 32: Unreliability curve comparison for FTA 8 reliquefaction system compressor redundancy design vs. 10 times MTTF

### 3.6.4 OREDA (Offshore Reliability Data)

#### 3.6.4.1 Combustion Engine Option

OREDA is a database containing failure rates related to subsea equipment for offshore application. In the qualitative FTA, each failure scenario ends with a basic event. OREDA (Offshore Reliability Data) has machinery failure rate data primarily for offshore equipment. Applicability of the data sets has been evaluated for the ammonia-fuelled propulsion ship system application. Particularly, the following asset structure is potentially relevant to some equipment. The OREDA equipment is often exposed to a sea/air environment. OREDA considers both the item (e.g., diesel engine – main power) and its support (starting system, lubrication system, and cooling system).

The following asset structure, taken from OREDA showing 1) the combustion engine options with "main power" underlined as selected as the most relevant option regarding dual fuel engine operations, 2) list of failure modes (Table 12), 3) the combustion engines boundary definition (Figure 33), 4) the combustion engine subdivision in maintainable items (Table 13: OREDA subdivision in maintainable items for combustion engines (©OREDA) Table 13) and 5) failure rate table (Table 14).

Combustion Engine Options (©OREDA)

- Combustion Engine – Aggregate
- Diesel Engine
  - Aggregate
  - Compressed Air
  - Emergency Air
  - **Main Power**
  - Process Shutdown and ESD
  - Water Fire Fighting

- Gas Engine
  - Crude Oil Handling
  - Emergency Power
  - Main Power

Table 12: OREDA list of failure modes for combustion engines (©OREDA)

| List of failure modes | |
|---|---|
| AIR | Abnormal instrument reading |
| BRD | Breakdown |
| ERO | Erratic output |
| ELF | External leakage - Fuel |
| ELU | External leakage - Utility medium |
| FTS | Fail to start on demand |
| STP | Fail to stop on demand |
| HIO | High output |
| INL | Internal leakage |
| LOO | Low output |
| SER | Monitor in-service problems |
| NOI | Noise |
| OTH | Other |
| OHE | Overheating |
| PDE | Parameter deviation |
| UST | Spurious stop |
| STD | Structural deficiency |
| UNK | Unknown |
| VIB | Vibration |
| Source ©OREDA | |

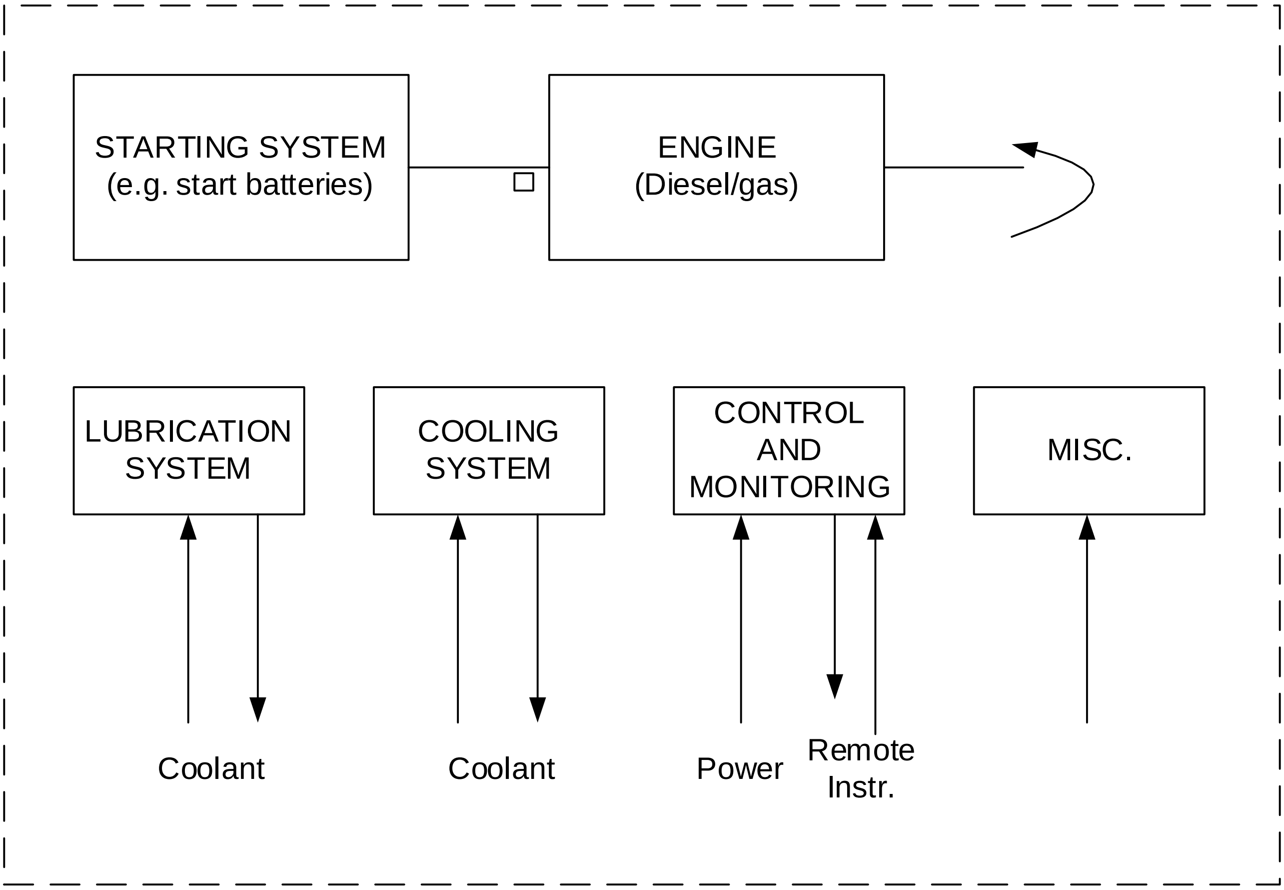



Figure 33: OREDA boundary definition for combustion engines (©OREDA)

Table 13: OREDA subdivision in maintainable items for combustion engines (©OREDA)

| COMBUSTION ENGINE | | | | | |
|---|---|---|---|---|---|
| **Starting system** | **Engine** | **Control & Monitoring** | **Lubrication system** | **Cooling system** | **Miscellaneous** |
| • Instruments<br>• Start control<br>• Start energy (battery, air)<br>• Starting unit | • Air inlet<br>• Camshaft<br>• Cylinders<br>• Exhaust<br>• Filter<br>• Pump<br>• Injections<br>• Instruments<br>• Piping<br>• Piston<br>• Radial bearing<br>• Seals<br>• Shaft<br>• Super charger<br>• Thrust bearing<br>• Timing chain/V-belt<br>• Valves | • Actuating device<br>• Cabling & junction boxes<br>• Control unit<br>• Instruments<br>• Internal power supply<br>• Monitoring<br>• Valves | • Reservoir<br>• Pump w/motor<br>• Filter<br>• Cooler<br>• Valves & piping<br>• Oil<br>• Instrument<br>• Seals | • Heat exchanger<br>• Fan w/motor<br>• Filter<br>• Valves & piping<br>• Pump<br>• Instruments | • Hood<br>• Heater |

Table 16 taxonomy no. 1.4.1.3 covers failure rate information for Item Machinery/Combustion Engines/Diesel Engine/Main Power.

***Example****: For Taxonomy no. 1.4.1.3 what is the probability of failure due to vibration that causes critical failure, on the operational time scale?*

*Answer: Select the critical failure and vibration. Choose the operational scale, Mean is 52.52 failures per $10^6$ hours, which is 19,040 hours MTTF.*

The various entries of the data table are explained in the following:

**Taxonomy number and Item**

The taxonomy number is a numerical identification of the item. The description of the item is given in a hierarchical structure. Only data from items of this generic category of components/equipment are input to the estimates presented in the quantitative part of the data table.

**Population**

Total number of items forming the basis for the estimates.

**Installations**

Total number of installations (platforms) covered by the data surveillance for the item in question.

**Aggregated time in service**

Two types of time scales are presented as the basis for the failure rate estimates; calendar time and operational time. The aggregated time in service for the total population is given for both time scales. Note that while the calendar time is given with high certainty, the operational time has in many cases to be based on estimates (by the data collector).

**Number of demands**

The accumulated number of demands/cycles for the total population is given when available. In several cases these numbers are based on estimates and not accurate measurements.

**Failure mode**

This column contains a brief description of the manner in which the failure occurred, when such information is available.

**Number of failures**

The total number of failure events is presented for each failure mode. The accumulated number of failures is presented as "All modes".

**Failure rate**

The failure rate columns present estimates of the failure rate for each failure mode. Results are given both under the "multi-sample" assumption, and under the assumption of homogeneous data sets. In the multi-sample situation, the failure rate is assumed to vary between installations (platforms), and each platform represents one sample. The following entries are included:

*Mean* — An estimate of the "average" failure rate with respect to the specified failure mode, obtained by using the OREDA estimator.

*(Lower, Upper)* — A 90% uncertainty interval for the failure rate.

*SD* — A standard deviation indicating the variation between the multiple samples.

$n/\tau$ — The total number of failures divided by the total time in service, i.e., the estimate of the failure rate we would use for a homogeneous sample.

All the entries are measured per $10^6$ hours and refer either to calendar time (marked *) or operational time (marked t).

**Calendar Time**

The interval of time between the start and end of data surveillance for a particular time.

**Operational Time**

The period of time during which a particular item performs its required function(s), between the start and end of data surveillance.

**Severity Class Types (C)**

**CRITICAL FAILURE**: A failure which causes immediate and complete loss of a system's capability of providing its output.

**DEGRADED FAILURE**: A failure which is not critical, but which prevents the system from providing its output within specifications. Such a failure would usually, but not necessarily, be gradual or partial, and may develop into a critical failure in time.

**INCIPIENT FAILURE**: A failure which does not immediately cause loss of a system's capability of providing its output, but which, if not attended to, could result in a critical or degraded failure in the near future.

The failure rate function tells us how likely it is that an item that has survived up to time (*t*), will fail during the next unit of time. The following is a mathematical definition of the failure rate function:

$$\lambda(t).\Delta t = \Pr(t < T < t + \Delta t \mid T > t)$$

The right-hand side of this equation denotes the probability that the item will fail in the time interval $(t, t + \Delta t)$, when the item is still function at time ($t$).

The failure rate estimates presented in OREDA assume that the failure rate is constant and independent of time, in which case $\lambda(t) = \lambda$.

The mean time to failure, MTTF, may be calculated as:

$$MTTF = \frac{1}{\lambda}$$

Table 14: OREDA failure data table for main power diesel engines (©OREDA)

| **Taxonomy no**<br>1.4.1.3 | | **Item**<br>Machinery<br>Combustion Engines<br>Diesel engine<br>Main power | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Population**<br>6 | **Installations**<br>2 | **Aggregated time in service (106 hours)** | | | | | **No of demands**<br>800 | | | |
| | | **Calendar time •**<br>0.1761 | | | **Operational time ᵗ**<br>0.0487 | | | | | |
| **Failure mode** | **No of failures** | **Failure rate (per 10^6 hours).** | | | | | **Active rep.hrs** | **Repair (manhours)** | | |
| | | **Lower** | **Mean** | **Upper** | **SD** | $n/\tau$ | | **Min** | **Mean** | **Max** |
| **Critical** | **23'** | **2.84** | **90.12** | **273.49** | **94.20** | **130.63** | **78.8** | **1.0** | **168.5** | **2730.0** |
| | **23ᵗ** | **7.78** | **324.68** | **997.26** | **349.29** | **472.18** | | | | |
| Fail to start on demand | 12' | 7.69 | 53.39 | 133.46 | 41.07 | 68.16 | 10.5 | 1.0 | 21.0 | 52.0 |
| | 12ᵗ | 22.10 | 190.24 | 495.81 | 155.62 | 246.36 | | | | |
| Overheating | 2' | 0.78 | 10.14 | 28.79 | 9.44 | 11.36 | 42.5 | 50.0 | 85.0 | 120.0 |
| | 2ᵗ | 2.57 | 36.47 | 104.88 | 34.57 | 41.06 | | | | |
| Spurious stop | 6* | 12.36 | 31.23 | 57.07 | 13.91 | 34.08 | 8.7 | 4.0 | 17.3 | 40.0 |
| | 6ᵗ | 44.45 | 112.61 | 206.04 | 50.29 | 123.18 | | | | |
| Vibration | 3' | 0.91 | 14.62 | 42.73 | 14.16 | 17.04 | 516.7 | 140.0 | 1116.7 | 2730.0 |
| | 3ᵗ | 2.89 | 52.52 | 155.74 | 51.85 | 61.59 | | | | |
| **Degraded** | **30'** | **25.74** | **132.99** | **309.07** | **91.12** | **170.39** | **11.9** | **3.0** | **23.7** | **80.0** |
| | **30ᵗ** | **76.78** | **473.57** | **1151.17** | **348.68** | **615.89** | | | | |
| Abnormal instrument reading | 1· | 0.11 | 5.21 | 16.10 | 5.68 | 5.68 | 1.5 | 3.0 | 3.0 | 3.0 |
| | 1ᵗ | 0.39 | 18.77 | 58.12 | 20.53 | 20.53 | | | | |
| Erratic output | 1' | 0.11 | 5.21 | 16.10 | 5.68 | 5.68 | 30.0 | 60.0 | 60.0 | 60.0 |
| | 1ᵗ | 0.39 | 18.77 | 58.12 | 20.53 | 20.53 | | | | |
| External leakage • Utility medium | 11' | 31.06 | 60.17 | 97.05 | 20.33 | 62.48 | 14.0 | 6.0 | 27.5 | 60.0 |
| | 11ᵗ | 99.59 | 214.70 | 365.21 | 82.19 | 225.83 | | | | |
| Internal leakage | 5' | 0.84 | 22.93 | 69.21 | 23.61 | 28.40 | 25.2 | 12.0 | 50.4 | 80.0 |
| | 5 | 2.50 | 82.38 | 250.34 | 86.42 | 102.65 | | | | |
| Low output | 1* | 0.11 | 5.21 | 16.10 | 5.68 | 5.68 | 7.0 | 14.0 | 14.0 | 14.0 |
| | 1ᵗ | 0.39 | 18.77 | 58.12 | 20.53 | 20.53 | | | | |
| Other | 3' | 0.91 | 14.62 | 42.73 | 14.16 | 17 04 | 4.0 | 6.0 | 8.0 | 12.0 |
| | 3ᵗ | 2.89 | 52.52 | 155.74 | 51.85 | 61.59 | | | | |
| Overheating | 7* | 15.71 | 36.44 | 64.16 | 15.03 | 39.76 | 3.0 | 4.0 | 6.0 | 12.0 |
| | 7ᵗ | 48.07 | 129.13 | 242.16 | 60.58 | 143.71 | | | | |
| Structural deficiency | 1· | 0.11 | 5.21 | 16.10 | 5.68 | 5.68 | 6.0 | 12.0 | 12.0 | 12.0 |
| | 1t | 0.39 | 18.77 | 58.12 | 20.53 | 20.53 | | | | |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Incipient** | **77'** | **1.66** | **270.41** | **947.72** | **349.86** | **437.34** | **6.3** | **1.0** | **12.3** | **110.0** |
| | **$77^t$** | **5.76** | **984.66** | **3478.6** | **1284.7** | **1580.7** | | | | |
| Abnormal instrument reading | 34• | 1.67 | 126.84 | 405.58 | 146.48 | 193.11 | 3.0 | 1.0 | 5.9 | 40.0 |
| | $34^t$ | 5.23 | 459.12 | 1487.62 | 540.45 | 698.01 | | | | |
| External leakage - Utility medium | $8^*$ | 13.43 | 40.04 | 78.15 | 20.28 | 45.44 | 11.9 | 4.0 | 23.8 | 100.0 |
| | $8^t$ | 39.04 | 141.35 | 295.61 | 81.15 | 164.24 | | | | |
| Internal leakage | 4' | 0.93 | 18.85 | 56.49 | 18.89 | 22.72 | 25.8 | 6.0 | 51.5 | 110.0 |
| | $4^t$ | 2.72 | 67.74 | 203.95 | 69.14 | 82.12 | | | | |
| Minor in-service problems | $22^*$ | 3.15 | 86.78 | 262.06 | 89.43 | 124.95 | 4.8 | 1.0 | 9.5 | 40.0 |
| | $22^t$ | 8.44 | 312.46 | 954.27 | 331.85 | 451.65 | | | | |
| Other | $8^*$ | 13.43 | 40.04 | 78.15 | 20.28 | 45.44 | 7.8 | 2.5 | 15.7 | 44.0 |
| | $8^t$ | 39.04 | 141.35 | 295.61 | 81.15 | 164.24 | | | | |

### 3.6.4.2 Control System

Offshore reliability data (OREDA) categorises process sensors and valves failure rates. Figure 34 contains isolation valves (block valves) and associated piping. Table 15 indicates process sensors in maintainable items.

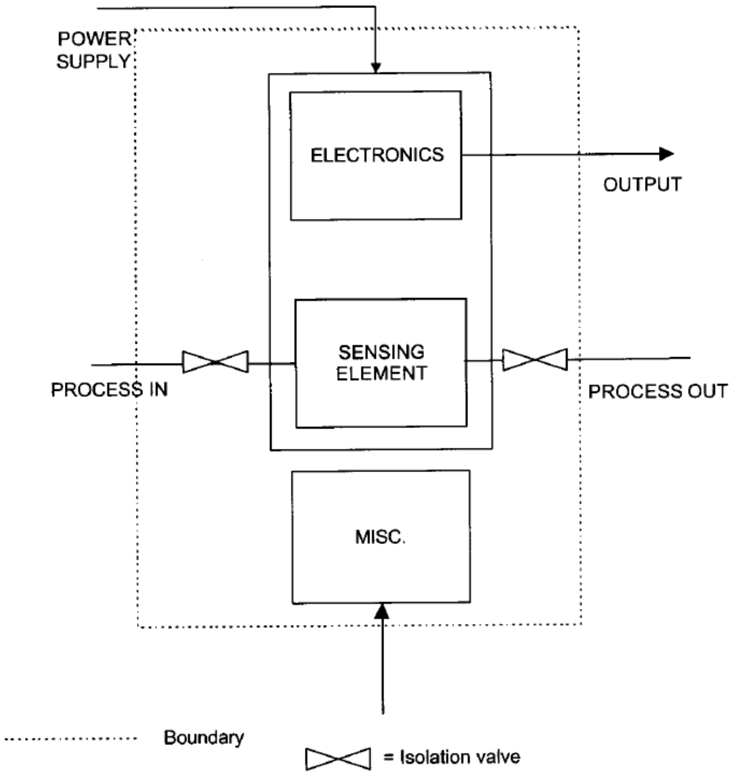



Figure 34: Process, Sensors, Boundary Definition (©OREDA)

Table 15: Process Sensors, Subdivision in Maintainable Items (©OREDA)

| Process Sensor | |
|---|---|
| **Sensor & Electronics** | **Miscellaneous** |
| ■ Sensing element<br>■ Electronics | ■ Isolation valve<br>■ Piping |

List of failure modes includes:

| | |
|---|---|
| FRO | Erratic output |
| FTF | Failure to function on demand |
| HIO | High output |
| LOO | Low output |
| SER | Minor in-service problems |
| OTH | Other |
| SPO | Spurious operation |

### 3.6.5 Uncertainties and Assumptions

The use of data that is not system specific often raises the question “are the failure data directly applicable to this situation?” Unfortunately, the answer in most cases is no. Subtle differences in installations, service conditions, and maintenance practices can cause notable differences in failure characteristics. When using fault tree analysis, the limitation is the data may not be direct comparison. To overcome this drawback, subject matter opinions and closely related application testing can be used to adjust the accuracy of the model. For instance, the principle of LPG or LNG fuel application is the same as ammonia fuel. In this case, MTTF/failure rate can be used.

As an example, ammonia fueled engines are yet available in the market, so the available failure modes of the liquified petroleum gas (LPG) engines are selected to be used as a reference for the preparation of the fault tree analysis of the ammonia fueled engines in this report considering the similarities of both fuels (e.g. vapor pressure, storage conditions, etc.) but also the similar design principles applied on the production of LPG and ammonia-fuelled engines. LPG fuelled engines have been on the market for some time now, so the experience gained, and lessons learnt have been used while analysing the fault trees with consideration also the different properties and characteristics of each fuel, such as LPG is much more flammable than ammonia, while ammonia is more prone to corrosion compared with LPG.

In addition, knowing the sample size, variability of the sample, and the quality of the data will help you understand the uncertainty in the data and whether the uncertainty will affect the decision sought. A sample in the statistical analysis is referred to as the ammonia-fuelled propulsion system or equipment subsystem under testing. In FTA methodology, when the probability of ammonia fuel valve sealing leaking in the fuel supply system is used in the model inputs, the sample is the fuel valve sealing. Depending on how many sample units were used to establish MTTF for sealing, the variability changes. When sample size is increased, the variability of MTTF decreases.

The probability of failure estimation is based on the following assumptions:

- Vendor assessment based on experience or test results (Table 16),
- Industry data / standards (Offshore Sector, Chemical Industry, Shipping Industry, Aerospace),
- Human Error (operator related error in installation, manufacturing defects and operational tasks).

Vendors of industrial machines, tools, and other products publish reliability related data for the product they sell. To meet this requirement, vendors are having to perform reliability analyses to predict their product performance. The use of reliability data by vendors is also preparing for warranty policy determination knowing what design life is and how much warranty cost it should be for economic evaluation. This study references LPG and methanol engines and the vendor component design life in Table 16. This is publicly available data. Expected service life is used in the simulation.

Table 16: Expected Service Life (Vendor Published Data) for Engines

| Component | Expected service life (hours) |
|---|---|
| Cylinder liner<br>(Bore sizes 60-50) | 60,000 |
| Piston rings | 24,000 |
| Exhaust actuator<br>Non-return valve | 64,000<br>12,000 |
| Valve nozzle | 8,000 |
| Fuel pump seals | 32,000 |
| Main bearing<br>Crank bearings<br>Thrust bearings | 96,000<br>96,000<br>96,000 |
| Accumulators | Engine lifetime |
| Fuel oil valve design | Spring 32,000 |
| Fuel oil pressure booster | 64,000 |
| Hydraulic start-up pump | 96,000 |

The probability of human error is to be expected at a more frequent event with a layer of protection set in place to reduce the probability from 1E-3 to 1E-4. The reference NUREG/CR-1278 (Table 20-10) Human Error Probability (HEP) provides a detailed study on this subject. In the FTA model, there are many events related to human error, therefore, when reporting the top contributor failure mode, it is being compared with the human error probability. If the basic event is lower probability than human error, it is most likely will not appear on the top contributor list.

OREDA in Table 17 and Table 18 are used in the model for equipment failure modes as appropriate.

Table 17: Control and Safety Equipment Failure Rate (©OREDA)

| Failure Mode | Mean (SD) 1E-6 | Failure Mode | Mean (SD) 1E-6 |
|---|---|---|---|
| External Leakage | 0.24 (0.3) | Spurious Operation | 0.61 (1.25) |
| Valve leakage in closed position | 0.25 (0.21) | Abnormal instrument reading | 0.0 (0.99) |
| Vibration | 14.62 (14.16) | Overheating | 10.14 (9.44) |
| No Output (Communication loss) | 0.3 (0.8) | Failure to regulate | 0.55 (3.05) |

Table 18: Mechanical Equipment Failure Rates (©OREDA)

| Failure Mode | Mean (SD) 1E-6 | Failure Mode | Mean (SD) 1E-6 |
|---|---|---|---|
| External Leaking | 5.14 (6.76) | Internal leakage | 1.0 (0.67) |
| Insufficient Heat Transfer | 1.0 (1.58) | | |

How does a failure rate per $10^6$ hours translate to the number of failures per year? The following example uses bearing failure to provide insight on the conversion. Table 19 contains failure rates for individual bearings in commercial and military applications. As expected, the military has a more stringent requirement resulting in lower failure rates. However, even the highest failure rate of 20 failures per $10^6$ hours, allowed in commercial applications, is equivalent to 0.58 failure per year. 0.58 failure per year means having less than one failure per year, which is a relatively low failure rate.

$$\frac{20}{1000000\ hours} \times \frac{8\ hours}{day} \times \frac{365\ days}{year} = 0.58\ failure\ per\ year$$

Table 19: Failure Rates for Individual Bearings

| Source | Type | Failure Rate (per $10^6$ hours) |
|---|---|---|
| Bearing, heavy duty (general industry) | Commercial | 20.0 |
| Bearing, light duty (general industry) | Commercial | 10.0 |
| Bearing, commercial quality (airborne uninhabited transport) | Military | 11.5 |
| Bearing, commercial quality (ground fixed, standard environment) | Military | 4.1 |
| Bearing, commercial quality (ground benign, clean laboratory environment) | Military | 0.03 |

The fuel injection system has a complex operation profile, which provides design redundancy with ammonia and pilot fuel injection systems, resulting in higher reliability. Primary ammonia fuel and the secondary pilot fuel are both required in the combustion process. However, if the primary ammonia fuel fails, the engine is designed to switch to fuel oil operation (diesel mode) and can continue the combustion process independently. In the reliability analysis, the complex operation is simplified in this study. It is assumed the ammonia fuel system has a parallel redundancy via the fuel oil system.

The unreliability curves in the analysis should be treated as a comparison of different failure scenarios and their impact on its design life. With that information, FTA is a decision-making tool designed for weak component screening purposes and reliability evaluation for resource allocation.

# 4. Conclusions and Recommendations

In conclusion, an in-depth fault tree analysis has been completed for a new alternative fuel technology. As part of the decarbonisation journey to achieve 2050 target set by IMO, ammonia fuel is one of the most promising technologies to be used onboard ships. Due to the lack of equipment data and testing, it is difficult to obtain an estimated ship life. It is necessary to use a logical structure approach in evaluating failure modes when developing a new technology. More often than it should, resources are not well utilised to achieve the highest reliability gain. To bridge the gap, FTA is sought after to identify failure modes, possible causes and estimation of probability of occurrence for each failure scenario.

The ammonia-fuelled ship system is estimated 4,590 hours analysed by 8 FTA models based on the hierarchy equipment structure. Out of the 8 subsystems, FTA 6 Fuel supply system has the shortest MTTF (9,406 hours) as it is a more complex system, which has more failure modes contributing to a higher failure rate. FTA 5 Hydraulic and sealing oil systems has a shorter MTTF (27,248 hours) compared to other subsystems due to its operation complexity to control sealing oil pressure higher than the ammonia fuel or pump failure. FTA 7 Bunkering system has a shorter MTTF (35,537 hours) compared to other subsystem due to design failure. FTA 8 Reliquefaction system has a shorter MTTF (50,000 hours) due to the high-speed type of compressor design life that requires further root cause analysis.

Based on the results of the FTA assessment, FTA 5 – FTA 8 seem to be the most critical components that would need to be further investigated as newer technology development information becomes available:

FTA 5: Hydraulic Oil/Sealing Oil System
FTA 6: Fuel Supply System
FTA 7: Bunkering System
FTA 8: Reliquefaction System

Table 20 summarises significant findings from the FTA assessment, which is structured based on the product lifecycle, when potential failures could be introduced in the product lifetime. There are 143 failures found in the 8 subsystems. Each failure mode and causes are described in the Fault Tree in section 3.5 FTA interview workshop documentation. Task 3 HAZOP and FMECA workshop should reference this report and use this as input for further development. Task 2 focuses on machinery equipment failures and probability estimation. Personnel safety and environmental impact have NOT been considered in Task 2 and are expected to be analysed in Task 3.

Table 20: Signiant Findings for Ammonia-fuelled Propulsion System

| Significant Findings | | |
|---|---|---|
| **Lifecycle** | **Top Contributors** | **Total # Findings:** 143 |
| **Design** | **FTA 1 - Ammonia Engine Fuel System**<br>■ Ammonia leak in the ammonia fuel injector valve,<br>■ Ammonia nozzle is damaged from cyclical stress, injection pressure or cyclical thermal load coming from the heat of the combustion,<br>■ Ammonia nozzle is damaged from high heat,<br>■ Ammonia fuel injector valve cannot open fully, and, but not limited to,<br>■ Leak in the fuel filter. | 5 |
| | **FTA 2 - Engine Fuel Oil System**<br>■ Fuel leak in injector valve and fuel filter<br>■ Valve is not open fully | 2 |
| | **FTA 3 - Common Engine Equipment**<br>■ Piston failure<br>■ Cylinder liner failure<br>■ Common rail fuel oil line system (HP fuel pump fails or incorrect material selection)<br>■ Cylinder cover leaks | 4 |
| | **FTA 4 - Engine Auxiliary Systems**<br>■ Design failure high temperature freshwater cooling contaminated with ammonia,<br>■ Cylinder lube oil contaminated by ammonia,<br>■ Leak in lube oil filter (piston and cylinder). | 3 |
| | **FTA 5 - Hydraulic and Sealing Oil System**<br>■ Hydraulic pump failure,<br>■ Hydraulic accumulator failure,<br>■ Hydraulic control unit failure. | 3 |
| | **FTA 6 - Fuel Supply System**<br>■ Ammonia components stress or fatigue load is exceeded,<br>■ HP ammonia fuel pump leaking,<br>■ Ammonia fuel buffer tank leaking,<br>■ Fuel system piping pressure loss greater than expected,<br>■ Corrosion allowance for piping may be exceeded,<br>■ Damaged of valve sealings/gaskets,<br>■ Liquid ammonia in KOD during disassembly causing personal injury,<br>■ Vapor ammonia in KOD during maintenance of return system and engine,<br>■ In the ventilation system, corrosion of double wall pipes and ventilation fan, and,<br>■ Ammonia vapor/liquid at ventilation outlet. | 10 |
| | **FTA 7 - Bunkering System**<br>■ Height difference between manifold and tank made it unable to drain ammonia inventory | 4 |

| | | |
|---|---|---|
| | ■ Fuel spills from QRC/ERC/flange,<br>■ Fuel spills from manual valve/ESD valve/ non-return valve,<br>■ Fuel spills from bunkering hose. | |
| | **FTA 8 - Reliquefaction System**<br>■ Cold liquid ammonia in the separator tank exacerbates corrosion issue leading to higher corrosion wall loss than allowance leading to liquid separator leaking ammonia,<br>■ Incorrect sizing of compressor/condenser/expansion valve leading to ammonia fuel tank overpressure/excessive BOG. | 2 |
| **Manufacturing** | **FTA 1 - Ammonia Engine Fuel System**<br>■ Failed threaded connection in ammonia fuel injector valve,<br>■ Forging/machining failure in ammonia fuel injector valve. | 2 |
| | **FTA 2 - Engine Fuel Oil System**<br>■ Forging defects in the valve body,<br>■ Threaded connection failure. | 2 |
| | **FTA 3 - Common Engine Equipment**<br>■ Common rail fuel oil line. | 1 |
| | **FTA 4 - Engine Auxiliary Systems**<br>■ Pump manufacturing defect,<br>■ Valve manufacturing defect. | 2 |
| | **FTA 5 - Hydraulic and Sealing Oil System**<br>■ Hydraulic/sealing pump defects,<br>■ Hydraulic/Sealing control unit manufacturing defects,<br>■ Hydraulic/Sealing oil electric motor low resistance failure. | 3 |
| | **FTA 6 - Fuel Supply System**<br>■ HP ammonia fuel pump manufacturing defects,<br>■ Valves manufacturing defects,<br>■ Air compressor manufacturing defects. | 3 |
| | **FTA 7 - Bunkering System**<br>■ Bunker hose manufacturing defects,<br>■ Manual/ ESD/ Non-return valve manufacturing defects,<br>■ Coupling manufacturing defects | 3 |
| | **FTA 8 - Reliquefaction System**<br>■ HP pump manufacturing defects,<br>■ Compressor manufacturing defects. | 2 |
| **Installation** | **FTA 1 - Ammonia Engine Fuel System**<br>■ Ammonia fuel injector valve is installed incorrectly,<br>■ Leakage of nitrogen into engine room during pressure testing. | 2 |
| | **FTA 2- Engine Fuel Oil System**<br>■ Valve installation procedure is not followed. | 1 |
| | **FTA 3- Common Engine Equipment**<br>■ Piston jams and piston ring scrapping failure. | 1 |
| | **FTA 4- Engine Auxiliary Systems**<br>■ Low lube oil pressure after cylinder lube oil booster injector replacement due to incorrect injector installation,<br>■ Lube oil filter leak (cylinder and piston) due to filter change procedure not followed correctly. | 2 |
| | **FTA 5- Hydraulic and Sealing Oil System**<br>■ Hydraulic/Sealing oil pump leaks,<br>■ Hydraulic accumulator leaks,<br>■ Hydraulic /Sealing oil gasket is leaking,<br>■ Sealing oil supply line between ammonia control block and fuel injector is blocked. | 4 |
| | **FTA 6- Fuel Supply System**<br>■ Wrong installation of inner pipe leading to leakage from inner pipe to outer pipe,<br>■ Wrong installation of outer pipe leading to leakage from outer pipe to engine room, | 4 |

| | | |
|---|---|---|
| | ■ Water/particles in compressed air during leak test leading to corrosion of double wall pipes,<br>■ Operator not following ammonia fuel injector procedure leading to damaged seal between SO and outer pipe and allows SO leaking into double wall pipes. | |
| | **FTA 7 - Bunkering System**<br>■ Bunkering hose leaking due to operator not following bunkering procedure leading to bunker make up incorrectly<br>■ Manual/ ESD/ Non-return valve leaking due to incorrect valve installation,<br>■ Coupling leaking due to Improper coupling connection prior to bunker operation. | 3 |
| | **FTA 8 - Reliquefaction System**<br>■ Compressor installed incorrectly. | 1 |
| **Operations** | **FTA 1 - Ammonia Engine Fuel System**<br>■ Leakage of nitrogen into engine room via double wall pipe connection during purging and testing of valves and connections,<br>■ Fuel transfer pump fails,<br>■ Ammonia fuel leak in ammonia fuel injector valve,<br>■ Ammonia injector valve fails to open or close as commanded,<br>■ Low ammonia fuel supply pressure,<br>■ Ammonia nozzle not injecting fuel,<br>■ Ammonia fuel injector is clogged,<br>■ Leak in fuel filter,<br>■ Too early injection of ammonia fuel injector valve,<br>■ Too much amount of ammonia injected,<br>■ High temperature of ammonia due to less circulation flow,<br>■ Fuel booster pressure is too high,<br>■ Excessive flow to combustion chamber, and, but not limited to,<br>■ Excessive pilot fuel injection at high load in addition to ammonia fuel that lifts cylinder cover, leading to unburned ammonia and exhaust in the engine room. | 14 |
| | **FTA 2 - Engine Fuel Oil System**<br>■ Fuel pump fails<br>■ Fuel leak in injector valve<br>■ Injector valve not open or close as commanded<br>■ Low fuel supply pressure<br>■ Nozzle not injecting fuel or clogged<br>■ Leaking in fuel filter or heat exchanger | 6 |
| | **FTA 3 - Common Engine Equipment**<br>■ Cylinder liner failure<br>■ Piston and piston ring failure (piston blow by, low level lube oil, wear and tear, wrong dozing of lube oil)<br>■ Turbocharger bearing housing overheating<br>■ Turbocharger clearance b/t shaft and bearing or bearing and housing is out of spec<br>■ Turbocharger vibration increased<br>■ Exhaust valve failure (overheating) | 6 |
| | **FTA 4 - Engine Auxiliary Systems**<br>■ Lube oil heat exchanger leaks,<br>■ Leak in lube oil filter,<br>■ Lube oil accumulator leaking,<br>■ Lube oil pump fails,<br>■ HT freshwater cooling contaminated with Ammonia,<br>■ Secondary fuel (SF) in scavenging receiver explosion,<br>■ SF in exhaust receiver/funnel explosion,<br>■ Low pressure in lube oil system,<br>■ Cylinder liner high temperature alarm/ lube oil overheating,<br>■ Lube oil pump bearing damage,<br>■ Exhaust gas leaking into Ammonia and sealing oil,<br>■ Cylinder liner damage due to cylinder lube oil failure. | 12 |

| | | |
|---|---|---|
| | **FTA 5 - Hydraulic and Sealing Oil System**<br>■ Hydraulic and sealing oil pump failure,<br>■ Low pressure in hydraulic/sealing oil system leading to contamination by ammonia,<br>■ Sealing oil failure cannot prevent ammonia backflow,<br>■ Sealing oil leaking into ammonia equipment,<br>■ Loss of hydraulic and sealing oil,<br>■ Ammonia contamination in sealing oil,<br>■ Ammonia contamination in hydraulic oil,<br>■ Hydraulic/Sealing oil gasket is leaking,<br>■ $N_2$ accumulator leaking into hydraulic/sealing oil,<br>■ Ammonia entrapped in injection valve and fails to inject ammonia,<br>■ Ammonia inlet pipe rupture. | 11 |
| | **FTA 6 - Fuel Supply System**<br>■ Overfilled nitrogen separator with ammonia,<br>■ No ammonia fuel to engine,<br>■ MFV+ DBBV leaking,<br>■ No or reduced ammonia in the supply line to engine,<br>■ Leaking valve on the supply line,<br>■ No ammonia in the supply line,<br>■ Knock-out drum failures,<br>■ Pump failure,<br>■ Bleed valve stuck in closed position,<br>■ Insufficient purging,<br>■ Ammonia in nitrogen vent,<br>■ Ventilation is too low,<br>■ Pressure regulating valve failure. | 13 |
| | **FTA 7 - Bunkering System**<br>■ Overfilled ammonia tank,<br>■ Overpressure of bunkering manifold,<br>■ Quick release coupling/flange/ERC/Non-return valve leak,<br>■ Bunker hose leaking. | 4 |
| | **FTA 8 - Reliquefaction System**<br>■ Liquid separator leaking ammonia,<br>■ Ammonia fuel tank overpressure,<br>■ Leaking ammonia in the compressor room via sealing/pipe connection,<br>■ Compressor failure:<br>o Excessive ammonia vaporisation in economiser could cause ammonia to backflow into compressor leading to compressor shutdown.<br>o Excessive vibration level on ammonia reliquefaction compressor crankgear is detected and leading to compressor shut down. Incorrect damper design or loose screw on balancing weight could lead to excessive vibration.<br>o Ammonia reliquefaction compressor piston seizure due to local high heat impact and piston rod deformation.<br>■ LP ammonia pump failure due to suction of contaminated ammonia,<br>■ Condenser leaking failure,<br>■ Reliquefaction coolant system shutdown,<br>■ Pressure drop in the ammonia reliquefaction system. | 8 |

In conclusion, Phase II FTA results were summarised for each subsystem. FTA 6, the fuel supply system has the shortest MTTF 9,406 hours as it is a more complex system, which has more failure modes contributing to a higher failure rate. FTA 5 hydraulic and sealing oil systems have a shorter MTTF 27,248 hours compared to other subsystems due to its operation complexity to control sealing oil pressure higher than the ammonia fuel or pump failure. FTA 7 Bunkering system has a shorter MTTF 35,537 hours compared to other subsystem due to design failure (incorrect material selection of a solenoid operated valve / ESD) leading to fuel a spill. FTA 8 Reliquefaction system has a shorter MTTF 50,000 hours due to the ammonia reliquefaction compressor design life (high speed type: piston rod deformation and crank gear vibration issues).

In conclusion, sensitivity analysis for the ammonia-fuelled ship system has been investigated and are here summarised:

- Operation on ammonia fuel – a stop of ammonia operation and a seamless switch to diesel mode
    - Dual Fuel Redundancy Concept Design: MTTF = 4,590 hours for ammonia-fuelled ship system.
    - Ammonia Fuel Engine Design Without Redundancy Design: MTTF = 3,822 hours for ammonia-fuelled ship system.

  Dual fuel design concept provides a redundancy in operation, which increases the engine's design life MTTF.

- Fuel Supply System ( FTA 6 Model)
    - Rotating equipment pumps motor driven pressure centrifugal MTTF = 8,000 hours vs. Redundancy Multiple Pumps
    - Rotating equipment pump motor MTTF = 8,000 hours vs. two (2) redundancy pumps - The pump design life is not long enough to prolong FTA 6 fuel supply system MTTF by much from 4,323 hours to 4,351 hours within the error bar.
    - In the fuel pump, for mechanical seal MTTF = 25,000 hours, Mechanical seal MTTF increased to 50,000 hours.

  The FTA 6 fuel supply system MTTF will be increased from 6,834 hours to 7,916 hours.

- Bunkering System ( FTA 7 Model)
    - Solenoid valve not open or close on demand MTTF = 20,000 hours vs. Solenoid operated valve MTTF = 40,000 hours

  In the case, where solenoid operated valves not open or closed on demand MTTF = 20,000 hours, the FTA 7 model system $MTTF_{System} = 13{,}363\ hours$. If the solenoid valve MTTF is increased by double, the FTA 7 bunkering system $MTTF_{System} = 25{,}575\ hours$. The results indicate an improvement in reliability for the longer MTTF.

- Reliquefaction System ( FTA 8 Model)
- Single Compressor MTTF = 700 hours vs. Redundancy Multiple Compressors

  A shorter MTTF high speed ammonia reliquefaction compressor is under development (current technology is 500 rpm, future technology over 1000 rpm is expected). FTA has demonstrated the impact of choosing multiple compressor redundancy (3 compressors are used) does not improve the reliquefaction system by much (under 1,000 hours). However, if MTTF is increased by 10 times (MTTF 7,000 hours), the system for FTA 8 reliability is increased significantly $MTTF_{System} = 5{,}008\ hours$.

**Recommendations**

Fault Tree Analysis is developed based on the four project lifecycles, which provides guidance on what control measures are effective in mitigating the potential failure modes. Examples provided in this report are to be understood as a general assessment guidance on how to use the FTA information.

The failure modes are categorised by the product lifecycle in

Table 21, which indicates how these failures can be mitigated in the following paragraphs, such as mitigating design failures involves design calculation and installation failure involves procedure development to control human error. The Table shows that more than half of the failures are in the operation phase. However, design failure takes up about a quarter of the failures where the consequence of the design failure is usually much higher, and therefore should not be underestimated. For instance, the ammonia reliquefaction compressor, if not designed properly, can lead to piston rod deformation, which could lead to piston seizures that would lead to a compressor shutdown.

Table 21: Summary of Findings by Category

| | Number of Findings | Percentage |
|---|---|---|
| **Design** | 33 | 23% |
| **Manufacturing** | 18 | 13% |
| **Installation** | 18 | 13% |
| **Operations** | 74 | 52% |

**Design Failure**

Generally, failure modes in the design phase involves analytical design calculation with safety factors. For instance, ammonia fuel injector design to handle the ammonia injection requirement (heat shield spacing, injector geometry) will be possible in full only when further testing data is available, and FTA 1 model needs to be updated. Another example is ammonia reliquefaction compressor which is designed for high-speed service over 1000rpm; such compressor may experience excessive vibration that may led to loose screw and loose joint connection, leading to a deformed piston rod due to large heat impact. Monitor the corrective action in the root cause analysis and evaluate reliability improvement. Recommendation is to continue to work with OEM vendors closely on these design issues identified with a view to update the FTA assessment.

**Manufacturing Defects**

Failure modes in the manufacturing phase are mainly manufacturing defects that may not be the major concern. However, due to human operations involved in the manufacturing process such as heat treatment, welding defect, etc., require a standard operating procedure to maintain the manufacturing reliability on critical components . There are no specific manufacturing defects for components of the ammonia fuel system. The main manufacturing defect comes from new equipment development, where controlling the process parameters in the manufacturing process, such as HP ammonia fuel pump (PTFE diaphragm is replacement every 12,000 operating hours).

**Installation Failure**

Failure mode in the installation phase is primarily driven by human error. For every installation, it is important to have the installation procedure in place and the operator trained to follow the procedure. The human error probability is relatively high compared to other failure modes because it involves many human factors, such as psychological, mental, fatigue, following procedures, etc. For instance, common installation failures include installing the gasket, inner pipe, or outer pipe in the fuel supply system incorrectly, not following ammonia fuel injector procedure and damaged deal between sealing oil and outer pipe.

**Operations Failure**

Operations failure rate exhibits a more dynamic pattern where the operating profile requirement changes resulting in more room for error. Operating hydraulic and sealing oil, fuel supply system, bunkering system, and reliquefaction plant is dynamic due to multiple challenges faced in operating a ship, such as potential improper maintenance and inspection, equipment degradation challenges, operator not following procedure, skipped planned maintenance, overstressing the equipment, ammonia contamination issue in the equipment, valve malfunctioning, ammonia reliquefaction compressor and HP fuel pump reliability issues, ARMS leaking (ammonia release mitigation system, e.g., KO drum, ammonia catching system), etc. Maintenance strategy and sparing analysis is important to minimise the equipment downtime and maintenance cost during the operational phase.

**Note - FTA for Other Alternative Fuels**

FTA assessment for other alternative fuels should be evaluated case by case. There are similarities and differences for other alternative fuels, such as LPG, LNG or methanol. The ammonia fuel study has taken LPG FMECA study as an input and modified to fit ammonia application. In general, it has similarities due to the common equipment onboard the ship. However, due to material properties and operational profile, it may yield a different component design life among the different fuels. Aside from that one of the main differences is the ammonia catch system that is driven by regulatory requirement and safety concern from ammonia toxicity. Future recommendation is to use the ammonia fuel FTA models and follow the FTA process to revise for other alternative fuels. In addition, as future work concerning design details and operational testing data become available, the FTA model should be updated.

**Follow On Tasks**

The results of the FTA Phase I and Phase II have been summarised in Table 20. Together with the detailed analysis in Section 3 should be used as inputs for EMSA Ammonia Safety Task 3, i.e. FMECA/HAZOP. Each failure scenario (failure modes in cause/ effect relationship) and its associated probability of occurrence are in this report. These results are considered for Task 3 risk assessment (FMECA/HAZOP) to gather the consequences and mitigation control measures. FTA and FMECA/HAZOP go hand in hand and are often utilised for new technology development. Table 22 is intended to compare the two methodologies to standardise tasks in this project.

Table 22: Reliability Methodology Comparison FTA vs. FMECA

| **Methodology** | **FMECA** | **FTA** |
|---|---|---|
| **What** | ▪ Inductive reasoning approach that is best suited for reviews of mechanical and electrical hardware and systems. | ▪ Deductive analysis that can graphically model how logical relationships among equipment failures, human errors and external events can combine to cause an undesirable top event. |
| **Purpose** | ▪ Structured brainstorming of the failure modes for alternative fuel system | ▪ Qualitative assessment of logical cause and effect diagram.<br>▪ Quantitative estimates of failure frequencies. |

| | | |
|---|---|---|
| **Inputs** | ▪ Information about ammonia fuel system to be analysed for how it could fail and the consequences. FTA failure modes can be used as inputs.<br>▪ Historical field failures are the most valuable, if available. | ▪ FTA can use FMEA as its starting point to build cause and effect relationships.<br>▪ For quantitative assessment, failure rate / MTTF in the basic events are needed. |
| **Outputs** | ▪ Table summarising the failure modes, effect, causes and existing controls<br>▪ Summary of recommendations<br>▪ Lists of the recommended risk control measures to mitigate risk and the evaluation of the recommendations | ▪ Graphical representation of the fault tree demonstrating how the failure of the top event can occur<br>▪ The probability of failure of the top event<br>▪ Sensitivity analysis to evaluate options to improve reliability (how much system reliability is increased by increased component MTTF) |
| **Strengths** | ▪ Covers lifecycle failure modes<br>▪ Provides inputs to maintenance and monitoring program<br>▪ Circumvents the need for costly modification by identifying problems early in the design process. | ▪ Same as FMEA<br>▪ Candidate for new technology that requires critical thinking |
| **Limitations** | ▪ Unless adequately controlled and focused, the studies can be time-consuming and costly.<br>▪ Excel outputs can be challenging for implementation. | ▪ Unless well categorised, the results can be comprehensive.<br>▪ Summary of recommendations can mitigate this drawback. |

# 5. References

*ABS. (2023a). Requirements for Ammonia Fueled Vessels.*

*ABS. (2023b). Rules for Building and Classing Marine Vessel, Part 5C Specific Vessel Types (Chapters 8, 13).*

*ABS. (2024). Ammonia Bunkering Advisory- Technical and Operational Advisory.*

*Laursen, R., Barcarolo, D., Patel, H., Dowling, M., Penfold, M., Faber, J., . . . Pang, E. v. (2022). Potential of Ammonia as Fuel in Shipping.*

*EMSA. Energy Solutions. (2023, October). MAN B&W two-stroke engine operating on ammonia. Retrieved November 2023, from https://www.man-es.com/docs/default-source/marine/tools/man-b-w-two-stroke-engine-operating-on-ammonia.pdf*

*Energy Solutions. (2024). A new chapter – ammonia two-stroke engines. Retrieved from https://www.man-es.com/marine/products/two-stroke-engines/ammonia-engine*

*MMMCZCS. (2023). Managing Emissions from Ammonia-Fueled Vessels. Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping.*

*NTU. (2022). Ammonia as a marine fuel – Bunkering, Safety and Release Simulations. Singapore.*

*SGMF. (2023). Ammonia as a marine fuel, an introduction.*

*SIGTTO. (2016). Liquefied Gas Handling Principles on Ships and in Terminals (LGHP4), Fourth Edition. Witherby Publishing Group Ltd.*

*WinGD. (2024). X-DF-A Ammonia Engine Documentation. Retrieved from https://www.wingd.com/en/engines/engine-types/x-df-dual-fuel-ammonia/documentation/*

*The New Weibull Handbook, 5th ed., by Dr. Robert B. Abernethy*

*NUREG/CR-1278 (1985). A.D. Swain, H.E. Guttmann. Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications Final Reportssion.*

*Guidelines for Process Equipment Reliability Data, with Data Tables, American Institute for Chemical Engineers, February 1989.*

# Appendix A Fuel Cells

Fuel Cells: A Clean and Efficient Electrochemical Power Source

Fuel cells are electrochemical devices that convert chemical energy, often from hydrogen, directly into electricity through an oxidation reaction. This technology offers advantages over traditional combustion engines, including higher efficiency, less and cleaner emissions, and the potential for continuous power generation. This section explores the operating principles of fuel cells, their environmental benefits, and diverse applications, highlighting their potential as a sustainable and efficient power solution.

From Combustion Engines to Clean Energy: The Rise of Fuel Cells

The growing demand for clean and efficient energy solutions has propelled fuel cell technology to the forefront of innovation. First conceptualised in 1839 by William Grove (Larminie & Dicks), fuel cells offer a promising alternative to conventional methods of power generation. Unlike combustion engines that rely on burning fuel and releasing harmful emissions, fuel cells operate through an electrochemical process, directly converting chemical energy stored in a fuel (often hydrogen) and an oxidant (typically oxygen) into electricity, with water and heat as byproducts. This paper delves into the key aspects of fuel cells, including their operational principles, environmental advantages, and diverse applications, emphasising their potential as a sustainable and efficient approach to power generation.

Clean and Efficient: Mitigating Environmental Impact

Fuel cells function on the principle of electrochemical oxidation. Hydrogen fuel reacts with oxygen at the anode and cathode, generating electricity through the flow of electrons in an external circuit. This process is inherently clean, producing only water vapor as a byproduct, making fuel cells a valuable contributor to mitigating environmental impact by reducing greenhouse gas emissions and air pollution.

Surpassing Combustion Engines: The Efficiency Advantage

Fuel cells surpass traditional internal combustion engines in terms of efficiency. While combustion engines experience energy losses due to heat dissipation and friction, fuel cells can achieve thermal efficiencies reaching up to 60%, compared to smaller size genset engines the 33-35% range of internal combustion engines (International Energy Agency (IEA), 2004). This translates to increased power generation from the same amount of fuel, contributing to resource conservation and reduced emissions. Note that bigger gensets engines and two-stroke main engines have significantly higher efficiencies, in the range of 45-50%

Furthermore, fuel cells offer remarkable versatility in their applications. They have been a reliable source of power for spacecraft and satellites for decades, providing sustained energy for exploration and scientific missions. Additionally, fuel cells are finding increasing applications in:

- **Stationary power generation**: Contributing to the overall energy grid by providing primary or backup power for utilities, hospitals, schools, and office buildings.
- **Waste-to-energy systems**: Utilising methane gas from decomposing waste to generate electricity, promoting a circular economy approach.

The Transportation Sector: Embracing Clean Mobility with Hydrogen Trains and Ferries

The transportation sector is witnessing a significant shift towards cleaner technologies, and fuel cells are playing a pivotal role in this transformation. One of the most promising advancements is the emergence of hydrogen trains, as exemplified by Germany's pioneering initiative with commercially operating hydrogen trains on a 100-kilometer route in Lower Saxony. The train is powered by Hydrogen Fuel Cells

Similarly, the maritime industry is also exploring the potential of fuel cells to decarbonise its operations. Pioneering projects are demonstrating the feasibility and benefits of fuel cells in various maritime applications:

- Ferries: The "MF Hydra," the world's first hydrogen-powered ferry, began operating in Norway in 2023. This pioneering vessel showcases the potential of fuel cells for short-distance, high-frequency routes, currently sailing the triangular route between Hjelmeland, Skipavik, and Nesvik in Norway. It boasts a capacity of 295 passengers, 8 crew members, and 80 vehicles. (Staten Vegvesen, 2023)

- Harbor tugs and workboats: US-based company Amogy, founded through a $220 million fundraising effort, is currently retrofitting the "$NH_3$ Kraken," a 32-meter tugboat built in 1957. Located in Feeney, approximately two hours north of New York City, the vessel is undergoing conversion to feature a novel ammonia-to-electric powertrain. (Stott, 2023)

While challenges remain regarding infrastructure development, cost reduction, and large-scale hydrogen production, the progress made in both the transportation and maritime sectors highlights the potential of fuel cells to revolutionise various industries and contribute to a cleaner and more sustainable future.

A Landscape of Fuel Cell Technologies: Comparing Performance and Characteristics

Fuel cells come in various types, each with distinct characteristics, advantages, and limitations. This section provides a comparative overview of six major fuel cell technologies (Table 23), including their operating principles, efficiencies, operating temperatures, applications, and key considerations.

Table 23: Different Fuel Cell Types

| Type | Efficiency (%) | Operating Temp (°C) | Applications | Advantages | Disadvantages | Comments |
|---|---|---|---|---|---|---|
| Polymer Electrolyte Membrane Fuel Cells (PEMFCs) | 50 - 60 | 50 - 80 | Electric vehicles, portable electronics, stationary power | Low weight, high power density, fast startup | Sensitive to CO poisoning, requires pure hydrogen | Most common type of fuel cell. Low weight, high power density |
| Phosphoric Acid Fuel Cells (PAFCs) | 40 - 45 | 150 - 200 | Stationary power (CHP) | Long lifespan, reliable, tolerant of impurities in Hydrogen | Slow startup, emission of phosphoric acid vapor. Requires good ventilation | First commercially available type |
| Alkaline Fuel Cells (AFCs) | 50 - 60 | 200 - 250 | Spacecraft, submarines | Highly efficient, operates on various fuels | Requires pure hydrogen, complex system | Used in niche applications due to high operating temperature |
| Solid Oxide Fuel Cells (SOFCs) | 40 - 60 | 600 - 1000 | Stationary power (CHP, micro-CHP) | High efficiency, internal reforming of fuels, tolerant to impurities | Slow startup, high operating temperature, Expensive ceramic construction, slow response to changes in electricity demand | Being developed for various applications |
| Molten Carbonate Fuel Cells (MCFCs) | 50 - 60 | 600 - 650 | Large-scale stationary power | High efficiency, good fuel flexibility | High operating temperature, requires special materials | Limited applications due to complexity |
| Reversible Fuel Cells | 50 - 60, 60 - 70 | 50 - 80 | Renewable energy integration, grid balancing | Energy storage and conversion, bidirectional operation | Still under development, limited commercial availability | Potential for future applications |

**Promising applications and technologies:**

Despite the challenges, pilots and demonstrations are showing promise for specific applications:

- **PEM Fuel Cells**: Smaller vessels operating within harbors, such as tugs and workboats, are potential candidates due to their shorter-range requirements and the possibility of shore-side hydrogen refuelling. However, it needs high purity of Hydrogen and that can be a challenge.
- **Solid Oxide Fuel Cells (SOFCs)**: Their ability to operate on various fuels, including methanol and ammonia, makes them attractive for larger vessels like ferries. However, their high operating temperature poses technical challenges. This is emerging as the dominant type of fuel cells for Marine Use. (Veldhuizen, 2023)

Ammonia to Electricity Via Fuel Cells

A typical process flow diagram for ammonia to electricity via fuel cells is shown in Figure 35 below.

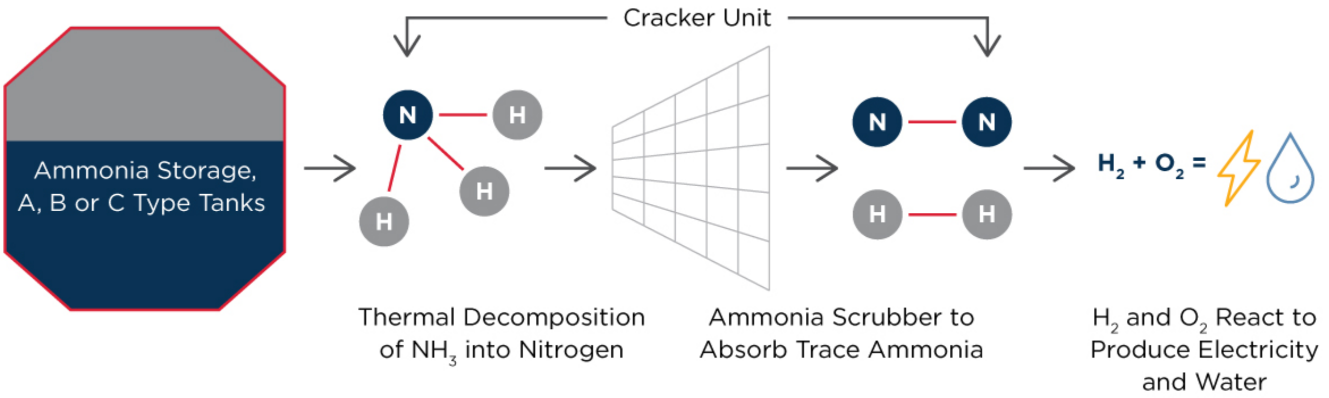



Figure 35: Ammonia to Electric Power

Ammonia-based SOFC

Solid Oxide Fuel Cells (SOFCs) are a highly researched and promising technology for clean and efficient power generation. Renowned for their remarkable energy conversion efficiency, SOFCs offer several advantages, including:

- High efficiency: SOFCs achieve exceptional efficiency exceeding 60%, operating at high temperatures (500°C - 1000°C) due to the electrochemical process involved. (Source: Neelima Mahato)
- Fuel flexibility: Unlike other fuel cell types, SOFCs can operate on various fuels, including hydrogen, natural gas, and even ammonia, broadening their application potential. (Source: A.Boudghene Stambouli, 2002)

This fuel flexibility, particularly their ability to utilise ammonia ($NH_3$), positions SOFCs as a significant contributor to the transition towards sustainable energy solutions.

1. Advantages of Ammonia Utilisation in SOFCs:

Ammonia presents several compelling advantages as a fuel for SOFCs:

- High hydrogen content: Ammonia consists of approximately 17.6% hydrogen by weight, making it a promising hydrogen carrier for fuel cell applications.
- Ease of storage and transportation: Compared to hydrogen gas, ammonia is easier and safer to store and transport due to its liquid state at relatively low pressure (around 10 bars at 25°C) or can be liquified through cooling (-33°C). It can be stored in readily available tanks made of carbon or chromium-nickel (molybdenum) steel. (Source: Pasman)

2. Ammonia Cracking Process:

In ammonia-fed SOFCs, the fuel undergoes an initial process known as ammonia cracking:

- High-temperature decomposition: At elevated temperatures (500°C-1000°C), ammonia molecules break down into nitrogen ($N_2$) and hydrogen ions ($H^+$) through the following reaction:

$$NH_3 \rightarrow N_2 + 3H^+ + 3e^-$$

3. Benefits of High-Temperature Operation:

The high operating temperatures in SOFCs offer several advantages when using ammonia:

- Process integration: Elevated temperatures enable the integration of ammonia cracking and electricity generation within a single system, simplifying the overall process and reducing complexity.
- Direct ammonia feeding: SOFCs can directly utilise ammonia without requiring extensive pre-treatment, minimising energy losses and system complexity.
- Cost savings: Eliminating the need for a separate ammonia cracking unit translates to reduced costs.
- Enhanced ionic conductivity: High temperatures enhance the ionic conductivity within the fuel cell, leading to lower ohmic losses and improved efficiency.

4. SOFC Categories Based on Electrolyte:

SOFCs can be categorised based on the type of electrolyte they employ:

- SOFC-O (Oxygen Anion Conducting): These cells use oxygen ions ($O^{2-}$) as the charge carriers through the electrolyte.
- SOFC-H (Proton Conducting): These cells utilise protons ($H^+$) as the charge carriers.

5. Comparison and Advantages of SOFC-H:

SOFC-H cells offer several advantages over SOFC-O cells when utilising ammonia:

- Lower operating temperature: SOFC-Hs operate at lower temperatures compared to SOFC-Os, enabling the use of a wider range of materials and minimising problems like catalyst sintering and thermal expansion mismatch, which can occur at higher temperatures.
- Reduced ohmic losses: Lower operating temperatures in SOFC-Os can lead to lower ionic conductivity, resulting in higher ohmic losses, which reduces overall efficiency. SOFC-Hs mitigate this issue.
- Water management: The water vapor produced at the cathode in SOFC-Hs doesn't dilute the ammonia fuel at the anode, simplifying water management.

<u>Overcoming Challenges: Addressing Limitations</u>

1. $NO_x$ Formation and Mitigation Strategies

- SOFC-O cells (steam supplied to the anode) typically generate $NO_x$ emissions.
- SOFC-H cells (steam produced at the cathode) eliminate $NO_x$ formation due to steam separation and recirculation not being required at the anode. This also eliminates the health and environmental risks associated with $NO_x$ emissions.

2. Preventing Ammonia Slip

- Unreacted ammonia can escape the cell, causing air pollution and potential health problems.
- Effective strategies by use of scrubbers and absorbers to prevent ammonia slip are essential.

3. Material degradation:

Various cell components experience degradation due to high temperatures and ammonia exposure:

- Electrolytes (YSZ): Nitridation, volatilisation, and reduced conductivity.
- Anodes (Ni-based cermet): Sintering, carburisation, and ammonia poisoning, leading to decreased active surface area and hindered catalytic activity.
- Cathodes (LSM): Sintering and chemical instability, leading to decreased active surface area and material loss.
- Seals and interconnects (metallic): Oxidation and nitridation, compromising gas tightness and mechanical integrity.

**Conclusion**

Fuel cells hold immense potential as a clean, efficient, and versatile power generation technology. Their ability to convert chemical energy directly into electricity, coupled with minimal emissions and the potential for diverse fuel utilisation, positions them as a frontrunner in the transition towards a sustainable energy future.

This report has explored the key aspects of fuel cells, including their:

- Operating principles: Explained the electrochemical process that generates electricity from the reaction between a fuel and an oxidant.
- Environmental advantages: Highlighted their role in mitigating climate change by reducing greenhouse gas emissions and air pollution compared to traditional combustion engines.
- Superior efficiency: Emphasised their ability to achieve higher efficiencies than combustion engines, leading to resource conservation and reduced emissions.
- Diverse applications: Showcased their potential in various sectors, including transportation, stationary power generation, and waste-to-energy systems.

While challenges regarding infrastructure development, cost reduction, and large-scale hydrogen production remain, significant advancements are being made in fuel cell technology. The increasing adoption of hydrogen-powered trains and ferries exemplifies the progress in the transportation sector. Additionally, ammonia-fed SOFCs present a promising avenue for further enhancing sustainability and fuel flexibility.

Looking ahead, ongoing research and innovation hold immense promise for overcoming existing limitations. Advancements in diverse areas like ammonia-fed SOFCs, high-temperature materials, and renewable hydrogen production are paving the way for a future powered by fuel cells. As research progresses and collaborations intensify, the potential for fuel cells to revolutionise the global energy landscape, decouple energy production from fossil fuels, and create a cleaner, more secure, and environmentally responsible energy future becomes increasingly realisable.

# Appendix B Asset Structure in FTA for Ammonia-fuelled Propulsion System

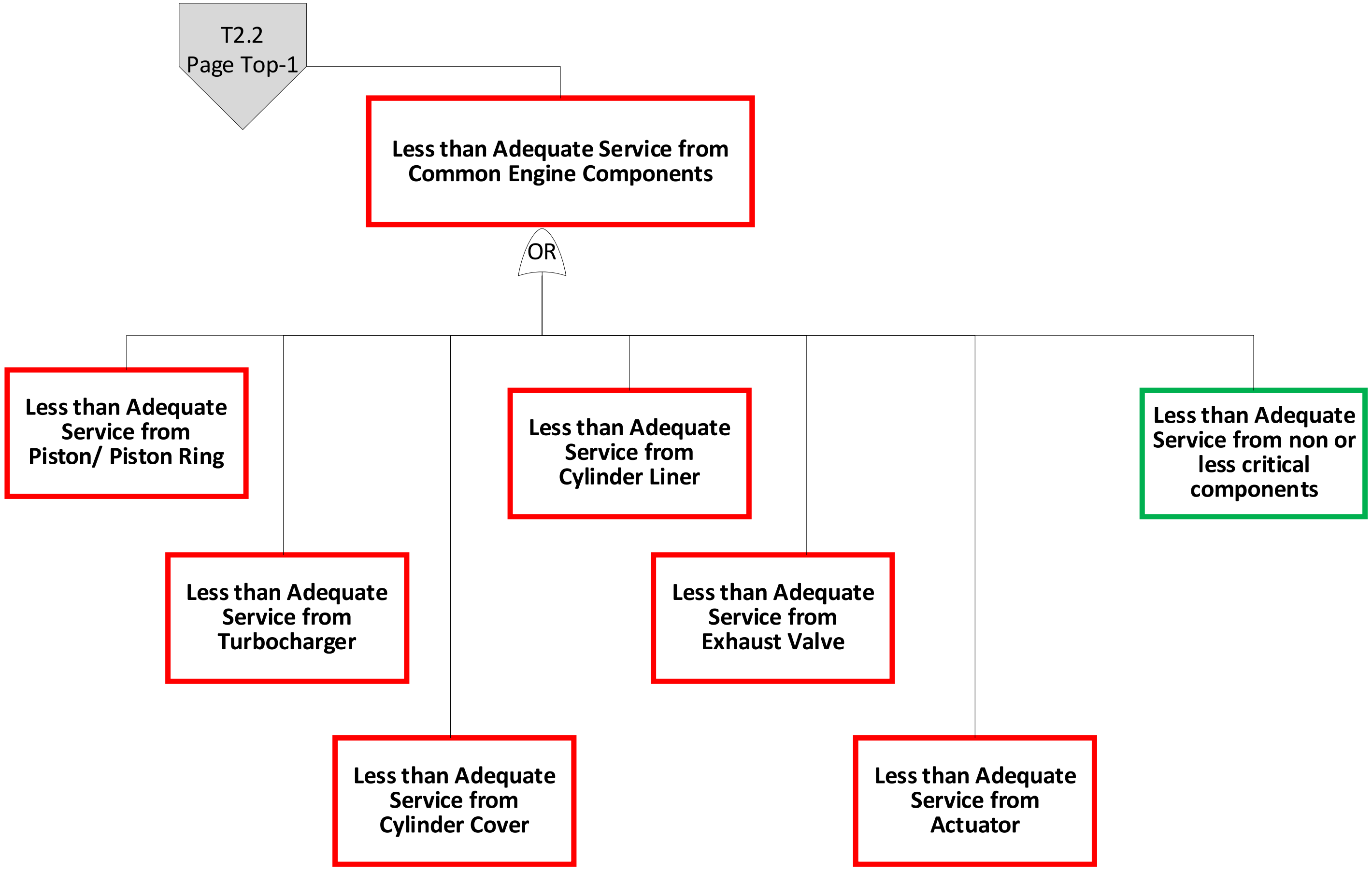



Figure 36: FTA Asset Structure T2.2 Common Engine Components

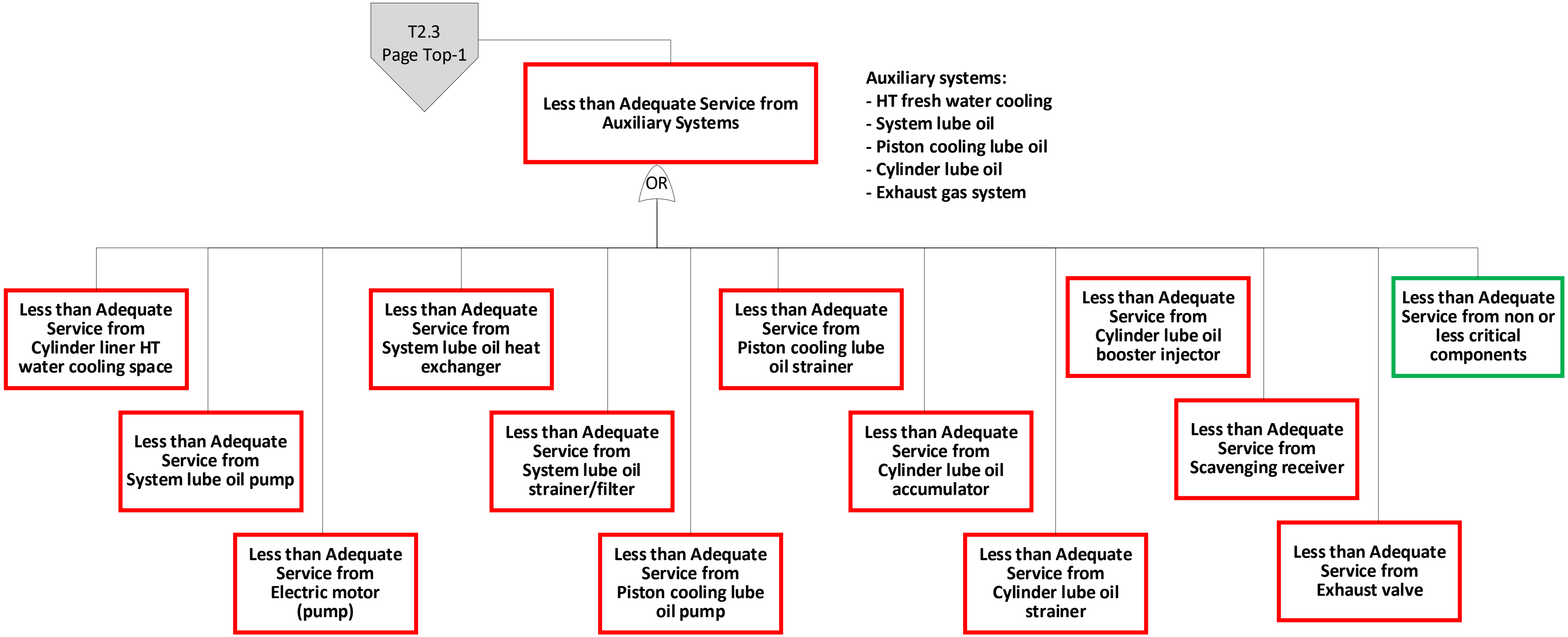



Figure 37: FTA Asset Structure T2.3- Auxiliary Systems

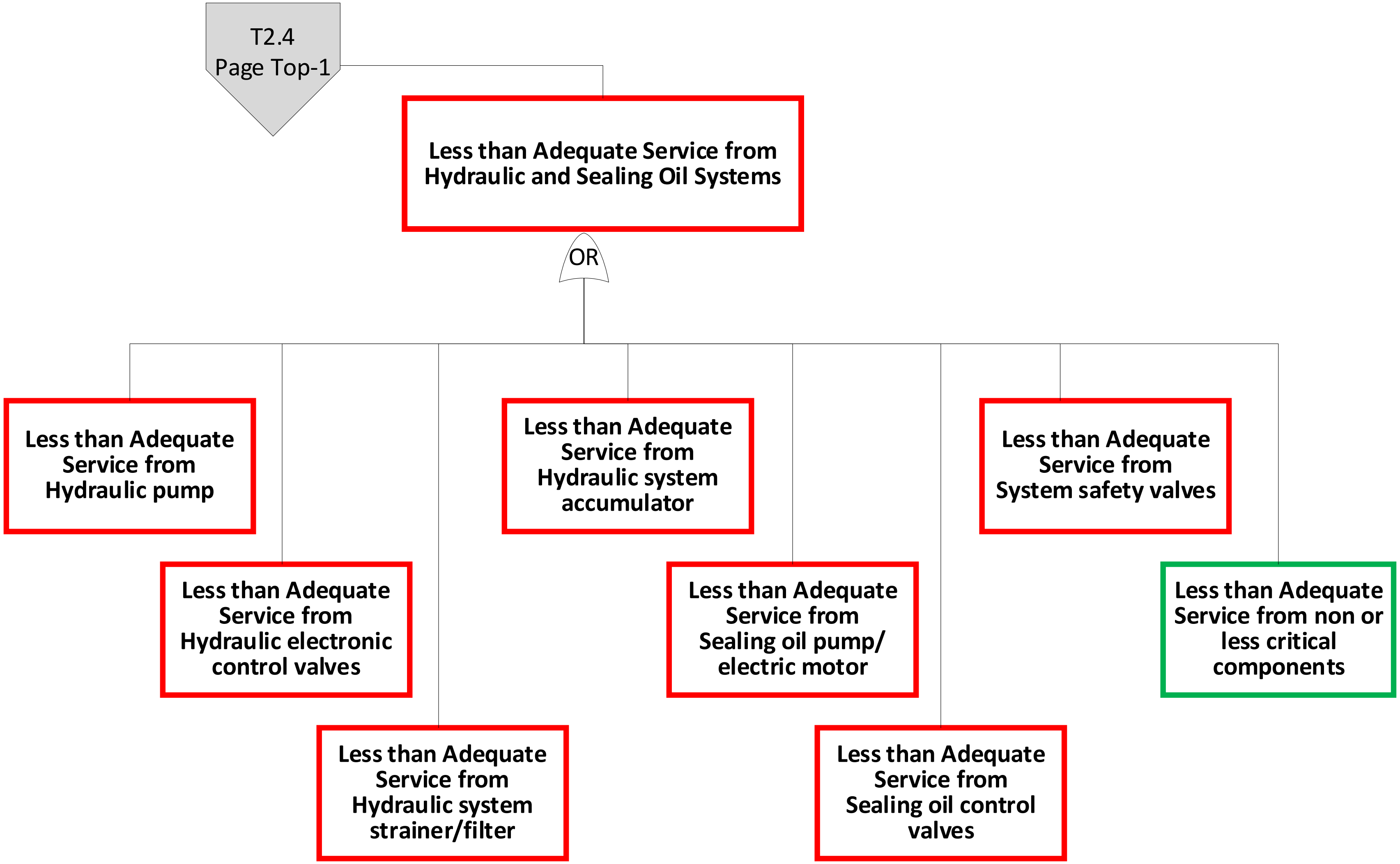



Figure 38: FTA Asset Structure T2.4 - Hydraulic and Sealing Oil Systems

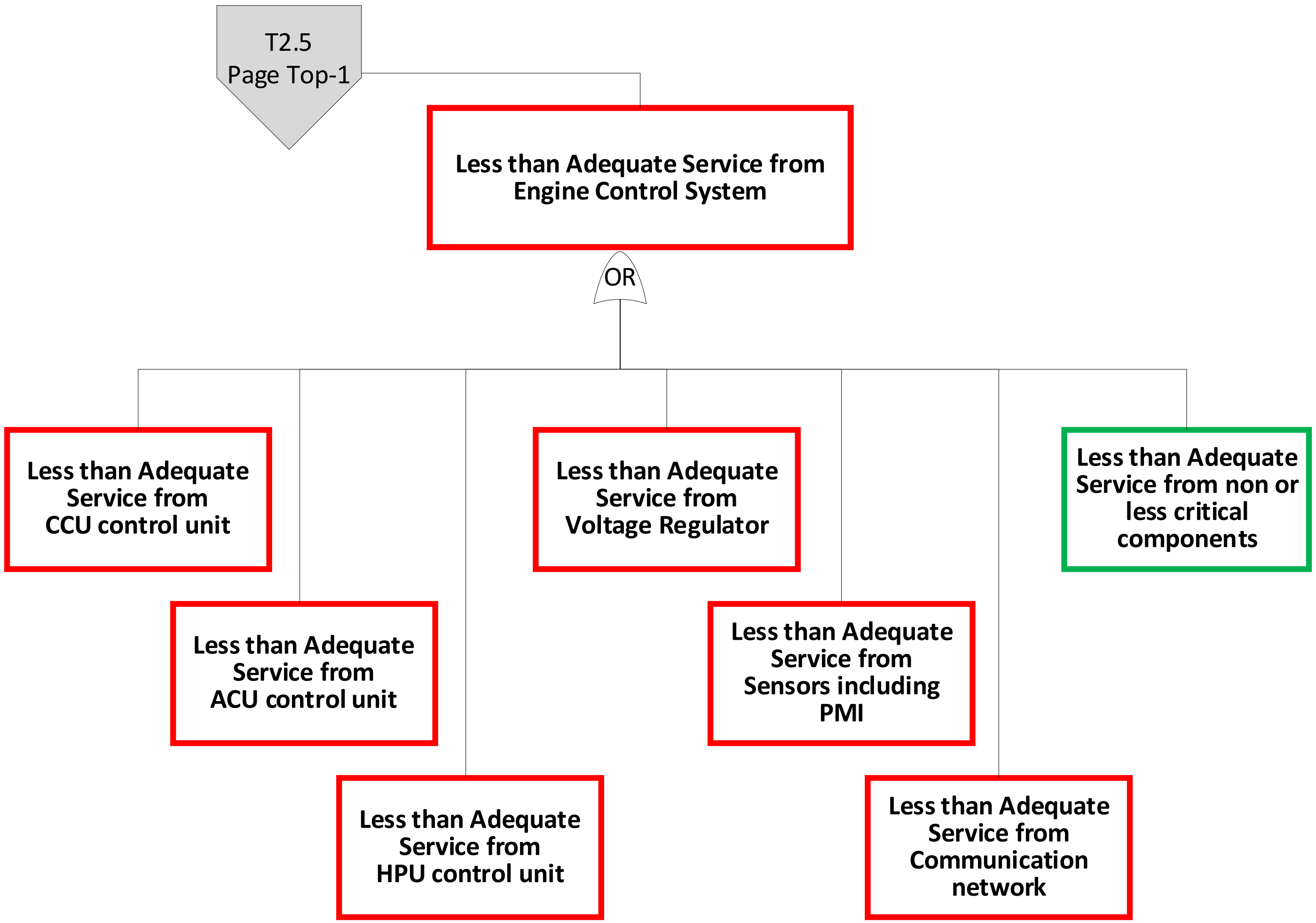



Figure 39: FTA Asset Structure T2.5 – Engine Control System

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