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Auxiliary systems and safety concepts for two-stroke ammonia burning engines

New Engine Concepts & Systems

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ABSTRACT

Paving the way for decarbonization of shipping in order to meet global greenhouse gas (GHG) reduction targets requires new alternative fuels such as ammonia to be burned in two-stroke marine engines in large merchant vessels instead of fossil fuels. Combusting ammonia emits only H2O and N2 hence it is a strong CO2 reducing enabler in shipping. When the green ammonia is ready in large quantities it will support decarbonisation of shipping significantly.

Ammonia is a well known product widely used in the farming segment as a fertilizer and shipped around the world on a daily basis by ammonia carriers distributing ammonia in a subcooled liquid state. Ammonia is a toxic substance with a pungent odour, hence it is important to take the necessary precautions when dealing with bunkering, storage, pumping and venting of ammonia used in marine engines.

In this paper, we will report the work related to preparing the auxiliary systems such as tank, bunkering station, supply system, fuel valve train, ammonia catch system, venting systems etc. as enabler of operation of a commercial two-stroke marine engine on engine builders shop test facility. One of the most important levers for development of both the first MAN B&W two-stroke ammonia engine and the Mitsui E&S auxiliary systems upstreams and downstreams the engine, is to test the combined ammonia engine and auxiliary system together, before implementation in commercial vessels.

Safety is a key factor when dealing with the toxic ammonia as fuel and a big part of the work for preparing for engine operation on ammonia has been focussing on how to deal with purging and venting as well as mitigating ammonia leakages scenarios. Different mitigation strategies have been investigated and implemented and dedicated emergency plans have been created.

1 INTRODUCTION

A lower impact on climate change is a critical concern for the shipping industry in the efforts to achieve global climate targets. Currently, marine transport accounts for approximately 3% of global greenhouse gas (GHG) emissions. To address this, the International Maritime Organization (IMO) has set a target to reduce CO_2 emissions by 50% by 2050 [1]. In response, MAN Energy Solutions (MAN ES) has been developing a dual-fuel two-stroke engine capable of operating on ammonia, aiming for a GHG emission reduction of more than 90% [2] [3].

A test platform for ammonia engine development has been established at the MAN Energy Solutions Research Centre in Copenhagen (RCC), featuring the 6.2 MW MAN B&W 4T50ME-X engine with an ammonia fuel supply system developed in cooperation between MAN ES and Eltronic Fueltech [2]. Additionally, a second test possibility has been set up at the Mitsui Engineering & Shipbuilding (Mitsui E&S) shop test facility in Tamano (Okayama) with a commercial 13.2 MW MAN B&W 7S60ME-C10.5-LGIA engine, and a fuel supply system developed by Mitsui E&S. The test engine at RCC has been operating on ammonia using one cylinder out of four since July 2023. A large rebuild in 2024 made it possible to operate the entire engine on ammonia at full load in December 2024. Hult et al. will present the results of the 4T50ME-X engine testing, including combustion performance and emissions [3]. The objective of this paper is to describe the ammonia fuel supply system, detailing the general process architecture and specific aspects of its implementation in land-based R&D and shop test facilities. Special emphasis is placed on the characteristics that differentiate ammonia from other fuels and their implications for plant design, particularly regarding safety and release mitigation.

2 AMMONIA ENGINE INJECTION CONCEPT

The injection concept determines the majority of the on-engine ammonia components. The gas block along with the fuel booster injection valve (FBIV) are responsible for the delivery and timely injection of the ammonia into the combustion chamber. The new FBIVA (A for ammonia) is a further development and redesign of the FBIVM and FBIVP, seen in ME-LGIM and ME-LGIP dual-fuel engines from MAN ES (operating on methanol and LPG, respectively), to handle the requirements associated with ammonia as a fuel.

The purpose of the FBIVA is to inject liquid ammonia into the combustion chamber. It is designed to pressurise the ammonia to the desired injection pressure, as well as to ensure the correct timing and duration of the ammonia injection. The FBIVA shown in Figure 1 combines a hydraulically actuated plunger pump with an injection needle valve. The ammonia injection pressure can be tuned by changing the hydraulic pressure or completely altered by changing the geometrical pressure ratio across the plunger in the FBIVA. For testing, a wide injection pressure range gives the engine the flexibility needed to optimise the ammonia combustion process.

The liquid ammonia supplied to the engine gas block should meet the conditions specified in Table 1 (these correspond to stream (5) in Figure 2).

Table 1. Fuel supply specifications.

Second fuel	Anhydrous ammonia (NH_3)
Water concentration	0.1–0.5%w
Fuel supply pressure	80 barg ±2 bar
Fuel supply temperature	25°C–45°C

On each cylinder gas block, the ammonia is distributed to the hydraulically actuated FBIVA valves at a pressure of 80 barg. The chamber in the FBIV is filled as the hydraulic plunger moves to the top position. The plunger's geometry is designed so that high-pressure hydraulic oil applied to the top of the plunger at 300 barg increases the ammonia pressure to 600–700 barg (stream (6) in Figure 2). The pressurised liquid ammonia then lifts the spindle from the valve seat, giving a direct injection of ammonia into the top of the combustion chamber. The ammonia is ignited using a small fuel pilot injection from the main diesel fuel injectors, similar to that seen in other dual-fuel engines from MAN ES.

The 80 barg pressure requirement at the FBIV suction, is necessary to prevent boiling and cavitation inside the booster, which could reduce the capacity and jeopardise the performance and, ultimately, damage the equipment.

To prevent ammonia vapour accumulation in the booster valves, a small fraction of the NH_3 fuel is continuously recirculated to the supply system. The circulation channels collect fuel from around the plunger as well as along the spindle clearance.

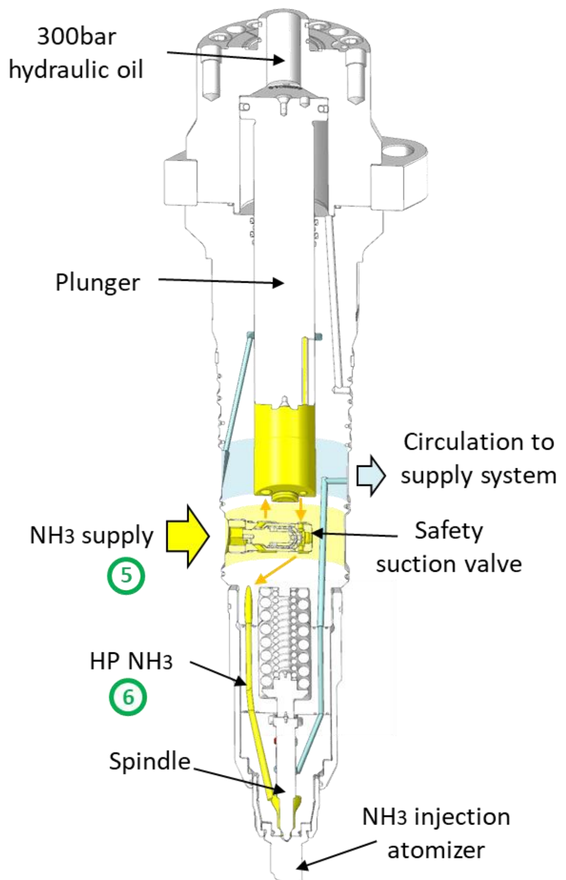

Figure 1. FBIVA cross section, showing the NH_3 supply to the nozzle and the circulation channels. Different cross-sectional views have been combined to show channels belonging to different planes.

To prevent ammonia from entering the hydraulic oil, a sealing oil barrier separates the two systems in the FBIVA. The design concept applies sealing oil with a pressure of 100–110 bar to separate the ammonia supply from the hydraulic oil system.

The sealing oil system is designed as a standalone system, separated from the rest of the engine hydraulic systems. A small amount of sealing oil is consumed as it leaks into the NH_3 fuel channels in the FBIVA. From there, it is partly injected into the combustion chamber and partly recirculated to the supply system. Some of the sealing oil is drained from the FBIVA back to the sealing oil tank.

The electronic engine control system (ECS) controls the FBIVA as well as the diesel injection valve. The engine safety system monitors the combustion to ensure that the engine is changed over to diesel operation immediately, if any problems or alarms occur.
Furthermore, the finite volume of the FBIV pump restricts the maximum amount of ammonia that can be injected into the combustion chamber.

If a second fuel stop is initiated, either a planned stop or an emergency shutdown, the FBIV is emptied and purged using pressurised nitrogen.

All pipes and volumes containing ammonia in the engine room, including the gas block and the FBIVA, are designed with double-wall barriers with dedicated ventilation and leakage detection. Any ammonia leakage from damaged components is contained in the outer pipe and ventilated to avoid the risk of leakage to the engine room. Gas detectors monitor for leakages, and if an ammonia leakage is detected, an alarm is raised, which will result in a changeover to fuel oil mode.

The injection system and the desired combustion conditions set the requirements for the ammonia delivered to the engine regarding pressure, temperature and composition. These requirements and the boundary conditions are used for designing the ammonia auxiliary systems, such as the tank, supply and recirculation system, fuel valve train, knock-out drum, and ammonia release mitigation system.

3 GENERAL HAZARDS RELATED TO AMMONIA

Although anhydrous ammonia is widely used in the chemical industry, it is relatively uncommon in the shipping industry. This chapter highlights the characteristic hazards and behaviour of anhydrous ammonia compared to other liquid and gaseous fuels more common in the shipping industry.

3.1 Flammability and toxicity

Anhydrous ammonia is a gas at ambient temperature and pressure, with relatively high toxicity and rather poor flammability. Ammonia combustion in the open atmosphere is characterised by:

- Narrow flammability range (15–33%)
- High autoignition temperature (651°C)
- High ignition energy
- Low flame speed.

Because of these properties, the likelihood and potential consequences of an ammonia combustion, or explosion event are relatively low compared to other flammable fuels [4] [5].

However, even small amounts of anhydrous ammonia can cause moderate to severe health effects on exposed humans. In the event of an accidental release, the area affected by toxicity is much larger than the area impacted by a potential risk of fire or ammonia explosion. This paper shows that mitigating the toxicity hazard for both operators and the general public is a crucial aspect of designing an ammonia engine and fuel supply system.

3.2 Liquid hammer

When designing and operating liquid ammonia systems, it is important to consider the hazard of rapid pressure transients. Sudden changes in liquid velocity may lead to rapid pressure surges that can damage piping and components. This can happen in a number of scenarios, such as during quick valve closing (conventional liquid hammer), or the rapid collapse of a vapour volume (e.g., when subcooled liquid and vapour ammonia come in contact). The latter is known as condensation-induced liquid hammer, also referred to as “rapid phase transition” or “hydraulic shock”. This phenomenon is well-documented for steam-condensate systems (condensation-induced water hammer) and has also been observed in anhydrous ammonia refrigeration systems, where it has caused piping failure and significant ammonia releases [6] [7] [8] [9] [10].

Except for the fuel storage tank where the liquid is saturated, the entire ME-LGIA supply system operates in the subcooled liquid state. However, during process transients like startup or shutdown, pressure reductions can potentially lead to the formation of a saturated vapour phase. In these scenarios, it is crucial to control any transition back to a subcooled liquid state to prevent the rapid collapse of the vapour phase and consequent condensation-induced liquid hammer. This can be achieved through a combination of flow restrictions (to avoid high liquid velocities during transients) and purging/prefilling with incondensable gas (e.g., purging the piping with nitrogen before filling with liquid NH_3). Pressure surges, which can be explained by a liquid hammer, have been observed in double-block and bleed valve arrangements. It has been proven that prefilling the double-block and bleed volume with pressurised nitrogen can reduce the amplitude of the pressure overshoot significantly when pressurising the volume.

3.3 Evaporation and subcooling

Another relevant fluid behaviour is ammonia evaporation. When ammonia liquid gets in contact with a gas mixture with a low NH_3 partial pressure, the liquid will start evaporating to establish an equilibrium concentration in the vapour phase. Evaporation is an endothermic process, which uses the heat available. If the heat transfer from the surroundings is insufficient to support the evaporation, the liquid will use its own internal energy and the temperature will start dropping, potentially below the boiling point. This means that the liquid NH_3 temperature can go well below –33°C at atmospheric pressure, the theoretical minimum liquid temperature is given by the freezing point of –78°C.

Ammonia liquid in an open environment can easily be subcooled below the boiling point, this has been observed in liquid puddles on floors, drip trays, or open containers, as well as splashes on clothes or skin.

In closed geometries, this behaviour is less likely, but possible when another gas comes into contact with the ammonia liquid, for example:

- Ammonia liquid purged by nitrogen gas in a knock-out drum or vent line.
- Ammonia liquid leaking to a ventilated outer pipe in a double-wall piping system.

This behaviour must be considered when determining the proper equipment and piping design temperature, and when calculating thermal stresses.

3.4 Oil in ammonia

As detailed in chapter 2, the sealing oil system concept necessarily involves the leakage of a small oil amount into the ammonia fuel, which is partly injected into the combustion chamber with ammonia and partly recirculated to the supply system. The presence of oil in ammonia can have several practical implications:

- Media compatibility: the sealing oil may not react or degrade when in contact with ammonia.
- Material compatibility: metal components, sealing elements, and membranes may not degrade or swell in contact with either ammonia or sealing oil.
- Miscibility and two-phase behaviour: usually refrigeration oils, aimed for NH_3-applications, are immiscible with NH_3 and separate by gravity, however, small amounts of ammonia can be dissolved in also these oils at the process conditions [11].
- Explosion limit: the presence of an oil mist can potentially decrease the lower explosion limit (LEL) of NH_3 in air [12].

A synthetic refrigeration oil has been chosen for the ammonia testing at the RCC [2]. The selected oil has shown excellent performance in the system, with no reported sludge formation, deposit build-up or clogging issues. The sealing oil which is drained from the supply system after being in contact with NH_3 is safely handled and disposed considering the miscibility of NH_3 in oil and its desorption at ambient conditions.

4 AMMONIA AUXILIARY OVERVIEW

The MAN B&W ME-LGIA engine requires auxiliary systems that are designed to handle both ammonia supply and return from the engine. The ammonia auxiliary systems include: tank, supply and recirculation system, fuel valve train, knock-out drum, recovery tank, ammonia release mitigation systems and outer pipe, and scrubber systems.

The architecture of the process is illustrated in Figure 3, in the form of a block flow diagram. The operating conditions of the most relevant process sections are numbered and visualised in the pressure-enthalpy diagram in Figure 2. The numbers from (1) to (10) in round brackets in the text refer to states and process streams in Figures 2 and 3.

4.1 Fuel tank

Ammonia fuel is stored in a fuel tank, which can be either pressurised at ambient temperature (Figure 2, state 1), semi refrigerated or fully refrigerated (-33°C, 0 barg) (1'). While the refrigerated storage option might be more complex, it offers significant safety improvements in case of loss of containment as the ammonia is kept at ambient pressure [4] [13].

The tank size capacity is a decisive factor when considering the trade-off between a fully refrigerated setup, including a reliquefaction system, and a system with a pressurised tank.
At the RCC, the ammonia fuel tank is a pressurised tank, kept at ambient temperature, with a design pressure of 18 barg. The ammonia tank pressure ranges between 5–15 barg depending on the tank temperature. Given the frequent bunkering operations, and the absence of a reliquefaction system, it is difficult to completely prevent oxygen contamination of the ammonia. The tank has therefore been made of stainless steel to minimise the risk of stress corrosion cracking [14] [15].

Furthermore, the fuel tank includes a low-pressure (LP) pump, which is installed as a deep well pump. The LP pump supplies and raises the ammonia pressure from the tank pressure to approximately 30 bar (Figure 2, state 1→2) before the ammonia enters the mixing tank in the supply and recirculation system (3).

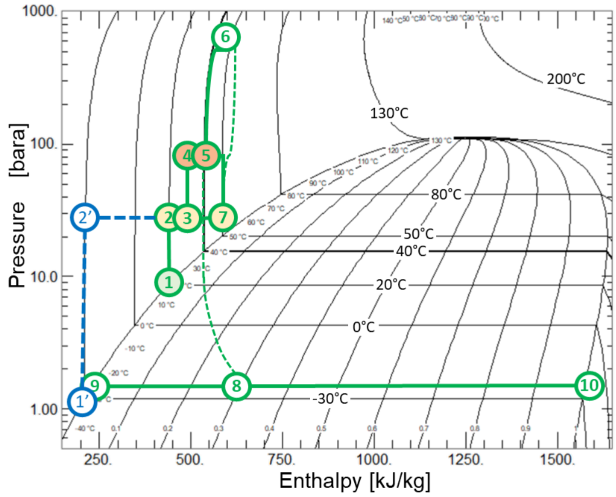

Figure 2. Ammonia states in the fuel supply system across the pressure – enthalpy diagram for pure NH_3. The numbers correspond to the streams in Figure 3 and are referred to in round brackets in this paper.

The fuel tank is equipped with a relief valve to handle overpressure and to protect the tank. If overpressure occurs in the tank, the relief valve will relieve to a dedicated water-filled catch tank. The tank is located in the enclosed tank yard and therefore not directly exposed to sunlight or large temperature fluctuations. The safety measures implemented in the tank yard are described in further detail in Chapter 6.

4.2 Ammonia supply and recirculation system

The ammonia supply and recirculation system has the function of conditioning and delivering ammonia according to the main engine inlet requirements regarding pressure, temperature and composition. Furthermore, it must be able to handle the ammonia returned and recirculated from the engine. This covers both returned ammonia from planned stops, unplanned shutdowns, and the recirculation during operation.

The supply and recirculation system consists of mixing tank (3), high-pressure (HP) pump, heat exchanger, and duplex filter in the supply line to meet the engine inlet requirements. A nitrogen separator in the return line handles the returned ammonia-nitrogen mixture when operation is stopped.

Most of the components will be in direct contact with ammonia, sealing oil, and nitrogen, and the material choice is therefore important and must comply with the relevant specifications. The unit is designed in stainless steel, and sealings and O-rings must be of an ammonia compatible material.

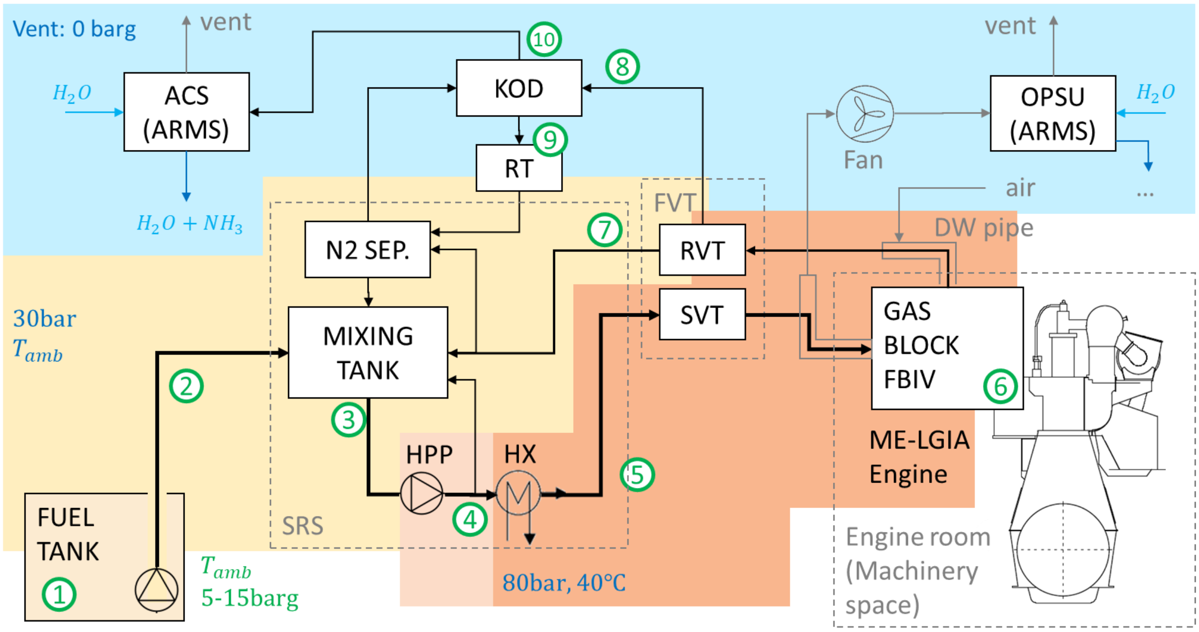

Figure 3. Simplified block flow diagram of the ME-LGIA ammonia auxiliary system. The numbers correspond to the states in Figure 2 and are referred to in round brackets in this paper.

The ammonia is supplied via an LP pump (Figure 2, state 1→2) to the fuel supply system mixing tank, at an intermediate pressure of around 30 bar. The mixing tank allows the LP pump supply stream (2) to mix with the recirculated stream from the engine that is at a higher temperature (7), resulting in an intermediate state in the mixing tank (3).

The mixed stream is fed to the HP pump, which increases the ammonia pressure to 83 bar (3→4). This compensates for downstream pressure losses and meets engine inlet requirements of 80 barg with a tolerance of ±2 bar. It is important to keep a constant engine inlet pressure regardless of the varying fuel flow. The pressure is monitored downstream and if it deviates from the given tolerances, the engine control system will initiate a change-over and stop second fuel operation and return to diesel operation.

Downstream the HP pump, the ammonia is heated to meet the main engine fuel supply temperature requirements of 25–45°C (5). Heat tracing and insulation can be required to compensate line heat loss.

Furthermore, the ammonia passes through a duplex filter with a 10 µm mesh meeting the ammonia injection systems particle requirements before entering the fuel valve train (FVT).

The ammonia in the engine's return line flows towards the return valve train (RVT) and, depending on the operational state of the system, follows one of three paths:

A. During normal operation, ammonia recirculates to the mixing tank (Figure 4, path A).
B. During planned stops, ammonia is purged to the nitrogen separator and recovered for re-use in the next startup of ammonia operation (Figure 4, path B).
C. During unplanned stops, ammonia is purged from the RVT directly to the knock-out drum (Figure 4, path C).

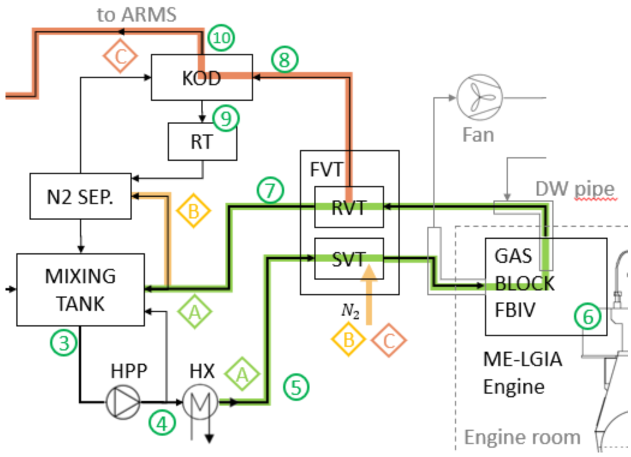

Figure 4. Comparison of ammonia operating modes: (A) second fuel operation, (B) second fuel stop, (C) second fuel shutdown.

The supply and recirculation system is commonly a single-walled piping system. At the RCC it is a skid-mounted unit in a ventilated enclosure placed outdoors and enclosed by concrete walls.

In a vessel installation, the system would likely be placed in an ATEX zone inside the fuel preparation room, with ventilation and ammonia detection.

4.3 Fuel valve train

The FVT has several purposes combining both safety and operability, such as:

- Separating the consumer (engine) from the high-pressure supply according to the IGF and IGC Codes.
- Ensuring purging and pressure testing capabilities for startup of engine second fuel operation (including nitrogen connection.
- Managing ammonia start and stop sequences, including monitoring, testing and controlling the ammonia through the valve configuration and components.
- Ensuring correct recirculation flow.

The FVT consists of a supply valve train (SVT) and a return valve train (RVT), handling both the supply line to the engine and the return line from the engine.
The FVT is designed to completely separate and depressurise the ammonia systems in the engine room using a double-block and bleed valve configuration. This accounts for ammonia as well as nitrogen lines. The FVT is designed so that the valve closest to the HP supply systems in the ammonia double-block and bleed valve configuration can be applied as a master valve.

The nitrogen double-block and bleed connection enables purging. An assembly test, or verification test, using nitrogen is run at every startup to test the integrity of the components in the FVT and on the engine before switching to ammonia operation.

The ECS designed by MAN ES controls and monitors the FVT, which is therefore integrated in the risk assessment of the main engine.

At the RCC, the FVT is placed next to the engine room. This minimises the piping length to the engine and reduces the ammonia volume that needs to be handled during a second fuel stop or shutdown. The distance between the FVT and the engine has direct impact on the sizing of other auxiliary components, such as the knock-out drum, recovery tank, ammonia release mitigation system, nitrogen separator, and nitrogen buffer capacity.

The supply and recirculation system supplies the conditioned ammonia (5) through the SVT to the gas block on each cylinder. The ECS monitors the FVT, which includes pressure, temperature and level transmitters. This ensures safe operability of the engine on ammonia and during planned stops or shutdowns.

Similarly to the supply and recirculation system, the FVT is a single-walled piping system. In RCC, the unit is encapsulated by steel sheets with a duct and ventilator, as described in Chapter 6. In a vessel configuration, it would often be placed with the supply and recirculation system in a dedicated fuel preparation room with ventilation and detection.

4.4 Knock-out drum and recovery tank

It is a part of the engine safety concept that the second fuel is removed from the engine as quickly as possible during an emergency shutdown on the engine. This requires depressurisation and purging of the second fuel equipment on the engine into a non-pressurised (read atmospheric) KO drum.

In planned stops, the ammonia will be returned and purged to the nitrogen separator (7). However, in unplanned stops, where the ammonia cannot be sent to the supply and recirculation system, the ammonia is purged to the KO drum (8) through the RVT.

The purpose of the knock-out (KO) drum is to separate (knock out) ammonia liquid, including droplets, during gas venting at maximum gas flow in blow-off condition. Additionally, it must be able to contain the full volume and mass of ammonia contained in the piping that is vented in a worst-case shutdown scenario. It should safely hold and depressurise the ammonia and ensure that only ammonia vapour is emitted to the ammonia release mitigation system (ARMS).

The purpose of the recovery tank is to recover as much liquid ammonia as possible from the purged mixture to the KO drum. The concept of recovery is introduced to reuse the fuel in the next startup, but also to minimise the load on the ARMS.

At the RCC, the KO drum and recovery tank are installed next to the supply and recirculation system within the concrete wall enclosure. The KO drum is placed above the recovery tank, and they are integrated with a valve configuration ensuring the recovery of liquid ammonia from the KO drum to the recovery tank (9) by gravitational flow. In order to recover as much as possible, it is important that the KO drum and recovery tank, and the integration of them, are designed with adequate piping and valve dimensions to ensure a swift recovery. The recovery tank is a pressurised vessel using pressurised nitrogen. The pressurised nitrogen is applied to push out the ammonia when emptying the recovery tank to the nitrogen separator. Ultimately, it is to be reinjected at the next ammonia startup.

The fraction of ammonia vapour that boils off (10) during purging through the KO drum, before recovery in the recovery tank, is handled in the ARMS by means of water absorption.

4.5 Nitrogen system

Nitrogen is required before, during, and after ammonia running, and it is essential for safe operation. It is specifically used for:

- The assembly test, which is made before every startup by pressurizing the FVT and engine, to ensure integrity and tightness of valves and components before allowing ammonia to enter the system.
- Liquid freeing and purging after ammonia operation to ensure that all ammonia has been removed from the engine and pipes in the engine room.
- Gas freeing prior to maintenance.
- Tightness testing of components and system after any maintenance.
- Nitrogen padding, pressure control and emptying of tanks.

The availability of nitrogen according to engine and system requirements is important for the reasons listed above. It is in line with the safety philosophy that it must be possible to depressurise, empty, and inert the engine at every stop. A nitrogen system, including storage of pressurised nitrogen at the correct pressure and capacity for the mentioned purposes, is required.

At the RCC, this is handled by using nitrogen bottle banks due to the small scale of the test engine.

In a vessel configuration, to avoid downtime on ammonia, it is necessary to install a nitrogen generator, booster, and buffer tank to recharge the nitrogen storage capacity independently.

The purging strategy applied for the ME-LGIA engine consists of two different methods in sequence:

Flow purging is applied by liquid freeing and pushing the ammonia to the nitrogen separator in planned stops (path B in Figure 4), or to the KO drum in unplanned stops (path C). Flow purging is performed with constant flow capacity and pressure. Flow purging is the first stage in a purging sequence where the majority of the liquid ammonia in the supply and return pipe as well as on the engine is pushed back to the supply system. A level switch in the RVT informs the ECS of when the liquid has been removed. Once the free flowing liquid ammonia has been removed, most of the remaining ammonia will be in the vapour phase.

The ECS then initiates pulse purging, which dilutes the remaining ammonia vapour by pressurising the closed system from the SVT through the engine to the RVT. Once pressurised, the gas mixture is released through the vent valves towards the KO drum, thereby diluting the concentration of the ammonia in the system in steps. This procedure is done several times to reach a fully purged state. In conclusion, the system is left depressurised with the vent valves open to the KO drum.

To ensure proper liquid freeing and purging through horizontal and vertical pipes, it is important that the nitrogen pushes the liquid column without flowing through or above the liquid. To avoid this phenomenon, it is important to follow the nitrogen specifications in regards to capacity and pressure as well as the supply and return pipe specification.

5 MITIGATION OF EXPECTED AMMONIA RELEASES

Releases of ammonia to the atmosphere can be divided into two categories [4]: “Expected releases”, such as releases from safety or blow-off valves, and “unexpected releases”, which includes leaks and spills caused by failure of process equipment, flanges, and piping.

As described in Figure 3, there are at least two systems designed to process the expected releases in the fuel supply system:

- Ammonia catch system (ACS)
- Outer pipe scrubber unit (OPSU)

Both systems fall within the category of ammonia release mitigation systems (ARMS) defined by the IMO preliminary guidelines.

5.1 Ammonia catch system (ACS)

The toxicity of ammonia and the scale of an ammonia release related to an engine stop or shutdown require a handling system to minimise the release of ammonia to the atmosphere.

Water absorption has previously been used to contain and mitigate ammonia releases in the ammonia refrigeration industry [16] [17] [10]. The solution implemented at the RCC consists of a water absorption based ACS, consisting of multiple absorption tanks connected in series to enhance the efficiency of the ammonia capture.
The fraction of ammonia that evaporates during purging to the KO drum, before recovery in the recovery tank, is handled in the ACS (10). Ammonia detectors are placed at the outlet to monitor the slip to the atmosphere. Liquid density measurement and electrical conductivity sensors can be used to estimate how much ammonia has been captured by the water. The catch system

dilutes the last stage with freshwater when the capture efficiency of ammonia drops. In planned stops most of the ammonia will be returned and purged to the nitrogen separator (7), and a small amount will be purged to the KO drum. During unplanned stops (second fuel shutdown), the entire piping, and engine liquid ammonia inventory is purged to the knock-out drum (8). The recovery tank is designed to capture most of the liquid ammonia. However, the ACS must be designed for the worst-case scenario, being that the full liquid inventory of ammonia is evaporated and absorbed in the ACS.

The ACS at the RCC can handle engine stops and shutdowns while keeping atmospheric emissions within safe limits. The ammonia-water mixture generated by the catch system must be stored and disposed of correctly.

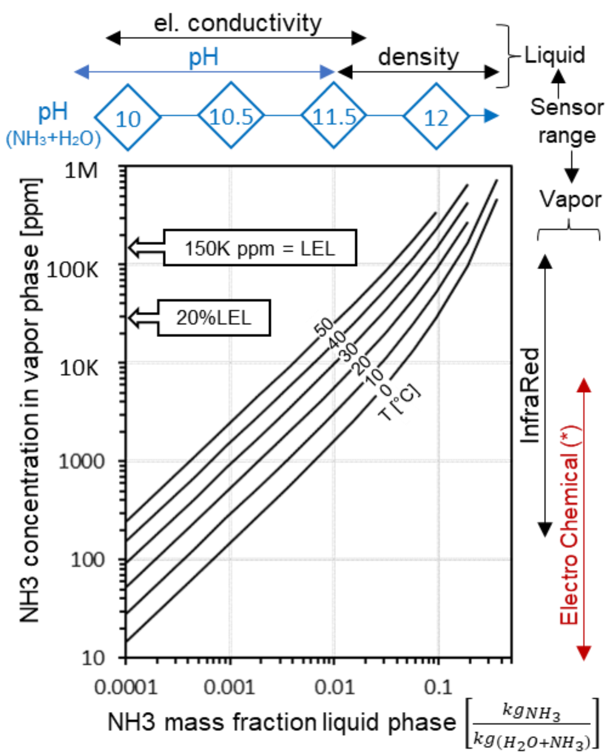

Figure 5. Vapour liquid equilibrium (VLE) for the binary NH_3-H_2O mixture. Diluent is assumed to be an inert gas at atmospheric pressure (air). The effect of CO_2 absorption in the liquid phase is neglected. Generated with NIST REFPROP 10.0®. Typical measurement ranges for different sensor technologies are shown on each axis.

Testing at RCC has shown that ammonia-water solutions exposed to air tend to absorb atmospheric CO_2. The progressive increase of CO_2 content in the mixture can introduce a deviation from the binary VLE in Figure 5 by lowering the solution pH and, thereby, the NH_3 vapour pressure. The presence of CO_2 can lead to salt precipitation and deposition on metal surfaces, which can affect the accuracy of some instruments, such as vibrating fork densimeters or conductivity sensors.

5.2 Outer pipe and scrubber unit (OPSU)

The double-wall system concept is well-known and established for all dual-fuel engine technologies from MAN ES. It consists of a ventilated double-walled pipe installation where the outer pipe (the secondary enclosure in the IMO nomenclature) encapsulates the fuel supply line (inner pipe) in the engine room (machinery space).

As illustrated in Figure 3, the double-wall piping starts downstream the FVT, is routed through the engine room, and ends upstream the RVT while the rest of the installation outside the engine room is single-walled. The function of the outer pipe is to contain a potential leakage and release it to a safe location outside the machinery space, while enabling rapid and reliable detection of the leakage. Figure 6 illustrates the functionality of the double-walled piping system in a bowtie diagram, where the main failure is identified as a fuel leakage (NH_3) from the inner pipe to the outer pipe. Some of the possible causes are listed to the left, and the potential consequences are listed to the right. A number of preventive and mitigating barriers are placed according to their mitigating effects. In addition to the conventional features from other dual-fuel engines (such as assembly test for both inner and outer pipe, and gas detection), the LGIA ammonia system design includes a release mitigation system to limit the atmospheric release of NH_3, hereby called outer pipe and scrubber unit (OPSU).

The OPSU design at the RCC and MES E&S follows the principle of water absorption of ammonia, like the ACS. The difference is that the OPSU inlet stream is a very diluted air stream with a low and unsteady concentration of NH_3 gas. At the RCC, the system has been designed as a water scrubber, continuously circulating water through a random packing section in a counterflow arrangement with the air flow. The scrubbing medium can be either freshwater, or a solution of water and acid. If freshwater is used, the NH_3 vapour fraction at the outlet will correlate with the NH_3 fraction in the liquid phase, according to the VLE (see Figure 5).

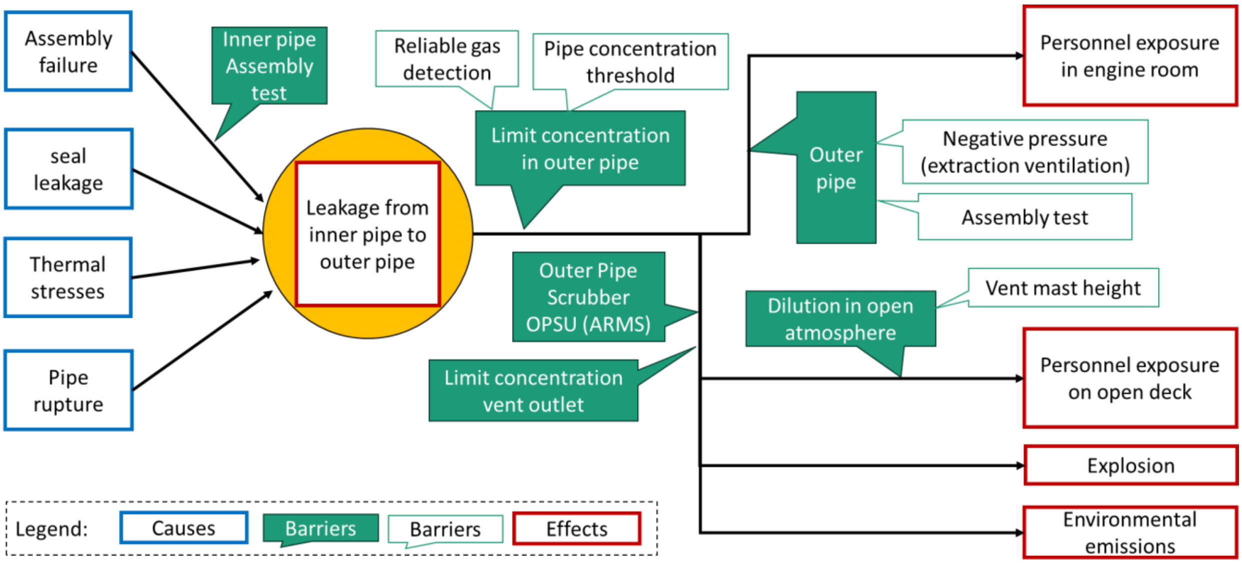

Figure 6. Bowtie analysis explaining the functions of the outer pipe in the engine room, showing causes to the left, consequences to the right, and preventive and mitigating barriers.

For example, to keep the NH_3 vapour concentration below 1000 ppm at the OPSU outlet with a water temperature of 20°C, the liquid concentration must not exceed 0.002% (i.e., 2000 ppm weight). This will require a frequent water exchange, and the handling and disposal of large amounts of very diluted ammonia water solutions. If the alkaline solution is circulated for a long time, it is expected that atmospheric CO_2 will be absorbed in the liquid resulting in a deviation from the binary VLE (Figure 5) by lowering the pH and the NH_3 vapour pressure.

The progressive addition of diluted sulphuric acid (H_2SO_4) to the water has been successfully tested in RCC, enabling the absorption of a larger amount of ammonia without building up a vapour pressure, and thereby reducing water replacement. The disadvantage of adding acid is that, while ammonia can be easily distilled out of the binary ammonia-water solution, such a process is not possible with a ternary NH_3-H_2O-H_2SO_4 solution, which instead needs to be stored.

6 EMERGENCY RESPONSE AND MITIGATION OF UNEXPECTED LEAKAGES

Unexpected process releases are defined as leakages and spills caused by failure of sealing elements, rupture or disassembly of piping, tubing and equipment, or incorrect manual operation (including deliberate disassembly associated to theft attempts [18] [19]). For conventional gaseous fuels, such as methane or LPG, such releases pose explosion hazards and must be quantified and handled in relation to the ATEX regulations. For ammonia, the combined flammability and toxicity hazards require careful estimation of the leakage scenarios, with particular emphasis on the high inventory loss cases.

The LGIA fuel supply system operates under subcooled liquid conditions, therefore most leakage scenarios involve pressurised liquid NH_3 flashing through an opening and generating a two-phase cloud of air, NH_3 vapours, and liquid aerosols (the initial isenthalpic flash can be approximated by point 8 in Figure 2). The cloud can be either heavier than air or buoyant, depending on the aerosol fraction and gas temperature, and the atmospheric conditions [20] [21] [22].

At the RCC, specific mitigation measures have been implemented for each plant section based on the NH_3 inventory:

- Large inventory, outdoor (fuel tank, bunker truck)
- Medium inventory, outdoor (SRS, FVT)
- Medium inventory, indoor (engine)

The only indoor NH_3 inventory is the content of the piping in the engine room during second fuel operation. The double-walled piping system provides a sufficient level of safety and no further measures have been deemed necessary.

The large inventory scenario applies to the fuel tank (4 tonnes) and bunker truck (up to 20 tonnes). Despite the low likelihood, the severity of a loss of containment scenario for such systems is high enough to require additional countermeasures.

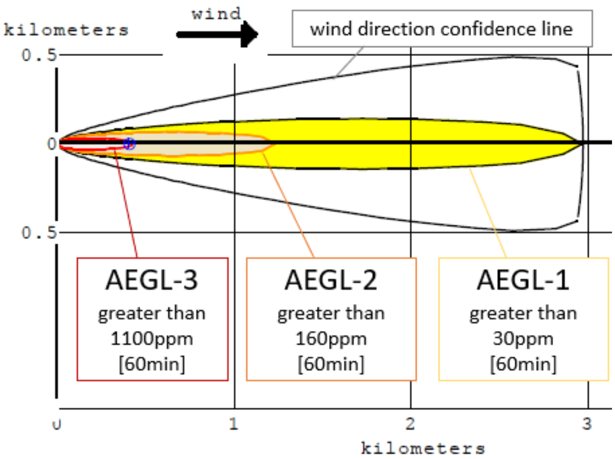

Figure 7. Example of toxic threat zone estimated by ALOHA® for a scenario of unmitigated loss of containment, with 4.2 tonnes of pressurised NH_3 liquid released in 12 minutes.

Based on the literature on the topic and the experience of other companies (RelyOn Nutech, Yara, Give Sværgods), the following mitigation strategy was implemented for the tank yard and the bunker yard in RCC:

- Contain potential liquid NH_3 spillage via drip trays to delay evaporation of the spilled liquid [23].
- Provide obstacles to wind, direct jet, or vapour cloud migration (walls, roofs, partial enclosures) [23] [24] [25].
- Use water curtains and water sprays to absorb NH_3 vapours [26] [22].
- Drain and collect the contaminated waste water (while avoiding water contact with the liquid NH_3 puddle).

The purpose of this approach is to limit and delay the release of NH_3 vapour and aerosols, and absorb as much of them as possible into water, thereby lowering the toxicity levels in the vicinity of the installation and reducing the size of the area affected.

Figure 8 and 9 show how this was implemented for the 4 tonnes NH_3 fuel tank at the RCC.

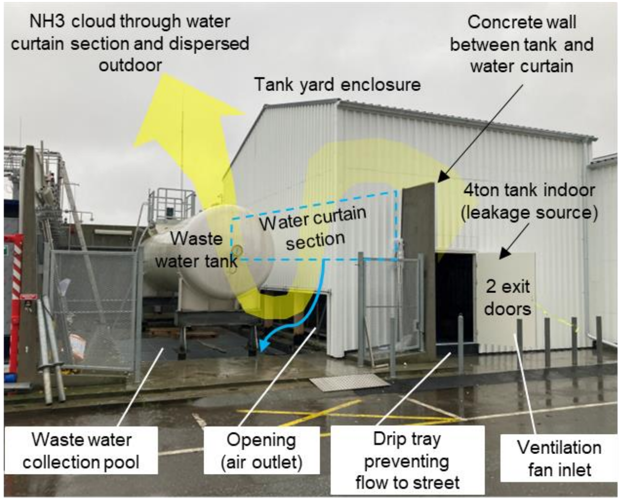

Figure 8. Tank yard and water curtain installed at the RCC. The yellow arrow shows the intended NH_3 vapour path from inside the enclosure, through the water curtain section and out to the open environment.

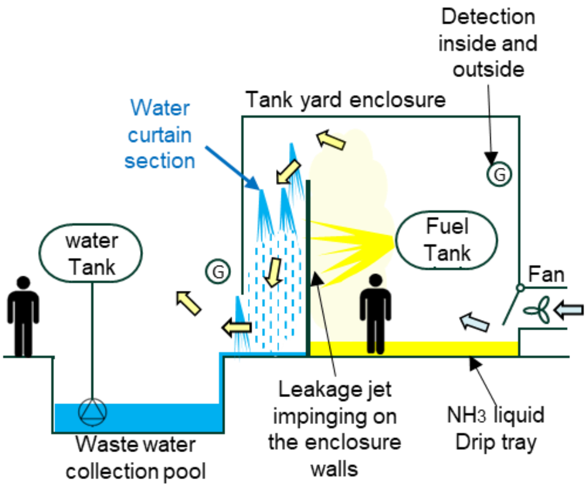

Figure 9. Schematic cross-sectional view of the tank yard and water curtain installed at RCC.

The enclosures (walls and roof in the tank yard) have the following main functions:

- Solid surface where the NH_3 droplets spraying from the leakage point can impinge and coalesce, thus draining to the floor [23].
- Guide the cloud to the water curtain in the opening and avoid bypassing the curtain.
- Reduce the wind speed around the leakage source, reducing the liquid puddle evaporation rate and the disturbance of the water curtain patterns.

The mitigation system is activated by a number of gas detectors installed, with redundancy, inside and outside of the enclosure. If the safety concentration threshold of ammonia is exceeded, the ventilation in the enclosure is stopped, and 700 l/min of seawater is supplied to the spray nozzles.

The water is drained by gravity outside of the enclosure to a dedicated collection pool. When designing the water curtain section and the draining system, it is critical to avoid contact between the sprayed water and the liquid NH_3 puddle, which might be resting in the drip tray section. That would promote even more ammonia evaporation and aggravate the incident [22] [10].

A similar concept is adopted for the bunker yard where the truck is parked during tank filling.

The rest of the plant is divided in sections with a much lower inventory (approx. 100–400 kg per section). The leakage hazard for these process sections is still considerable, but the impacted area for a loss of containment scenario is smaller compared to the fuel tank. Taking this into account, the leakage mitigation system adopted for the SRS and the FVT consisted in a ventilated enclosure design (Figure 10), which is based on the same concepts illustrated for the tank yard, with the following differences:

- The enclosure is made by covering the process skid with removable steel cover plates.
- Personnel cannot enter the enclosure unless the plates are removed.
- The scrubbing section in the vent line has a lower water supply capacity (only sufficient for small leakages).

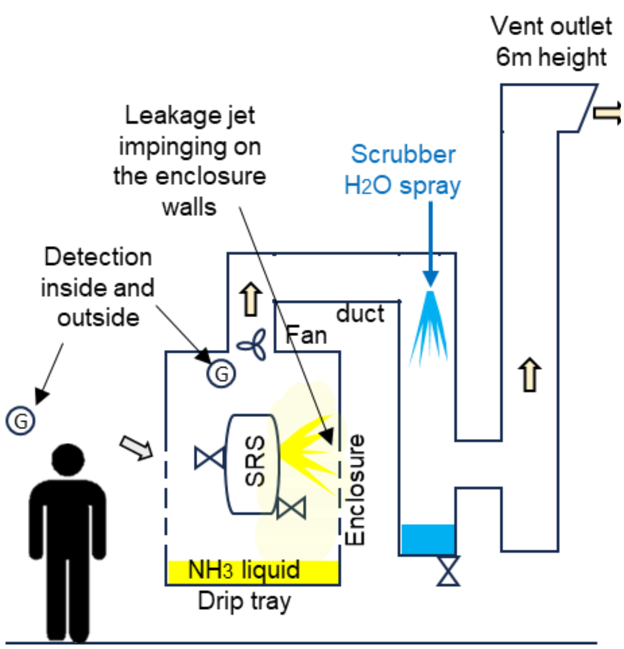

Figure 10. Concept of ventilated skid enclosures used for SRS and FVT at the RCC, illustrating the concepts of liquid containment, segregation between liquid NH_3 and water, and safe release location.

It is worth noting that all the systems described above can be considered a partial mitigation, but they are by no means sufficient to completely contain an ammonia release. Some of the ammonia vapour will pass through the spray section [22], and if the release rate is sufficiently high, the absorption capacity can be exceeded. Therefore, an emergency response plan will be necessary. Table 2 offers an overview of the safety measures in place at the RCC.

Table 2. Overview of mitigation measures for NH_3 leakage in RCC.

Personnel working inside hazardous locations	Personnel located in the test center premises
• PPE (personal protective equipment) • Emergency exits (two or more) • Emergency showers and eye rinse • Fire extinguisher on bunker truck • Remote shutdown of truck supply	• Fixed gas detectors • Ventilated enclosures and water curtains • Alarm system • Emergency response plan • Shelter locations in each building • Shutdown of building ventilation (where relevant) • Evacuation according to wind direction (evaluated for each case)

The emergency response to an uncontrolled large ammonia leakage must protect not only the operators but everyone present in the identified hazardous area. Gas detectors trigger the alarm system and, depending on the threshold, the emergency response plan is launched.

Similarly to a fire event, all personnel in the target area must be warned. However, it is important that there is a clear distinction between a fire evacuation and an ammonia leakage response. While an emergency response to a fire generally consists of rapidly evacuating the buildings and assembling outdoors, an ammonia leakage from an outdoor system usually requires a "shelter in place" approach as a first step [27] [28] [29]. If evacuation from the shelter location is deemed necessary, it should be planned and executed considering the specific release characteristics and the wind conditions to avoid the risk of evacuating people towards a high concentration zone.

7 MITSUI E&S SYSTEM IMPLEMENTATION

The pilot project at Mitsui E&S (MES) was started as simultaneous developments for both the engine (i.e., 7S60ME-C-LGIA) and a newly designed low flashpoint supply system (LFSS) by MES aiming to deliver to commercial vessels.

The coupling test of the engine and LFSS conducted during the engine shop test can ensure the robustness of the whole system design concept and its performance.

As a basic study to develop the LFSS, 1D simulation is conducted to evaluate the pressure fluctuation, not only at the steady-state load condition, but also at the transient condition, such as fuel changeover and engine shutdown (see Figure 11).

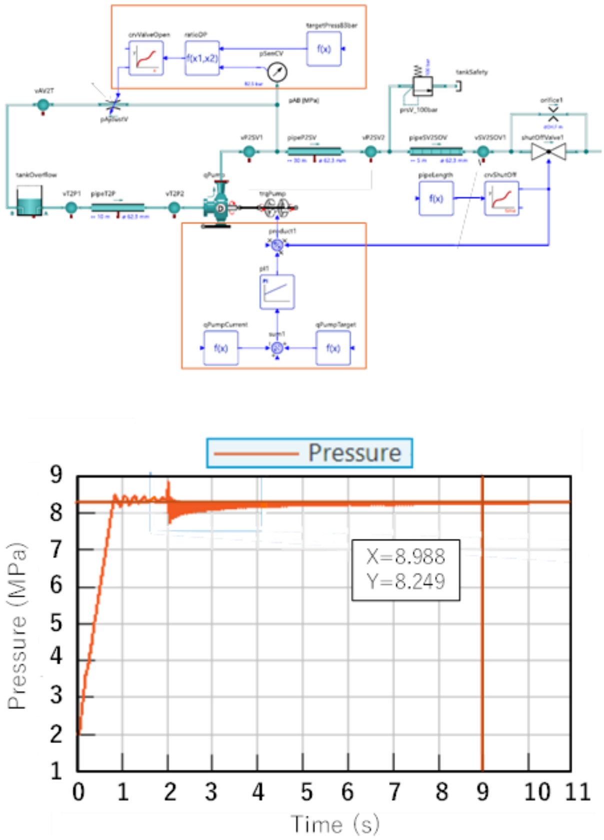

Figure 11. 1D-simulation.

The flexibility of the arrangement and the easy accessibility for maintenance are key elements of the unit configuration. Further, the optimum arrangement of LFSS units on a ship and in an engine facility is different.

The LFSS should be developed in accordance with the engine requirements and applicable rules, but those are subject to change as a result of R&D tests and international negotiations. So, additional design flexibility may be required, especially for the pilot project.

The LFSS unit configuration as shown below is decided accordingly:

- Recovery tank unit (*)
- High-pressure pump unit
- Supply valve train
- Return valve train
- Gas-liquid separator unit (*)
- NH_3 catch system
- Glycol water unit

(*) Note: there is a difference between the nomenclature used by MES and MAN ES.

There are two fundamental elements for achieving safety first, system robustness and safety management.

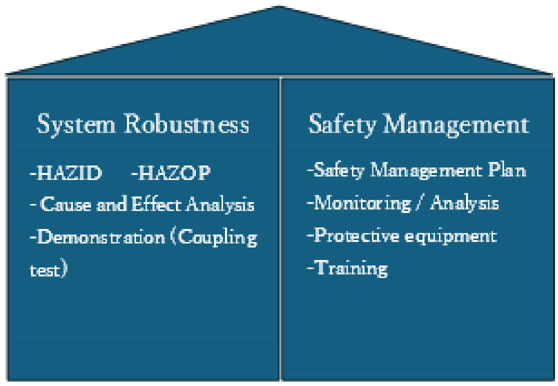

Figure 12. Safety first concept.

HAZID study for an ammonia-fuelled ship has been performed among the consortium members to AiP (approval in principle).

HAZOP study for an ammonia facility was also performed together with class NK.

After the system installation, all the system functionality with small injection to the cylinders has been confirmed using water instead of the ammonia.

For an NH_3 catching system, a three-step confirmation has been performed before the ammonia engine start (test using a small amount of ammonia gas, test using a small amount of liquid NH_3 and test using the full amount of liquid NH_3).

Safety regulations, including an evacuation procedure, have been developed to ensure the safety of all persons near the ammonia facility. Several ammonia sensors installed in the ammonia facility are connected to the alarm system in the MES factory in order to take evacuation immediately in case of ammonia leakage. Evacuation drills were also performed to take calm and safe action of evacuees.

Ammonia bunkering by lorry was started after a successful water injection test. Since then, MES has started 24 hours monitoring against the ammonia leakage.

At the time of writing, the LFSS system is being filled with ammonia, and final confirmation to start the ammonia engine is almost finished.

Figure 13. Ammonia test facility (tank and SFSS).

8 CONCLUSIONS

Preparing the shipping world for ammonia as a future decarbonising fuel by developing engine concepts with auxiliary system constructions dealing with the properties of ammonia, in particular the safety aspects, has shown to be a complex and comprehensive task to solve. To handle ammonia from bunkering in large tanks to supply and conditioning for engine injection as well as dealing with the residual ammonia when emptying and purging of engine and auxiliary systems requires new design of dedicated equipment which can contain, collect or absorb the ammonia so that people in surrounding areas are protected against exposure and the environment is protected against pollution.

MAN ES has designed, built and tested a complete site installation in the Research Centre Copenhagen for supply of ammonia to the 4T50ME-X research engine producing 6.2 MW power at full engine load. The installation includes the complete fuel supply system, from the fuel storage tank to the engine, including all the standard safety system for a ship's engine room installation as well as the additional specific safety features necessary for a land-based installation. The 4T50ME-X engine at RCC is currently successfully operated on ammonia providing the world's first full-scale two-stroke marine engine running at ammonia.

Mitsui has designed, build and installed a complete ammonia site installation accommodating shop test capability for MAN B&W ammonia engines based on MAN ES specification material and the first 7S60ME-LGIA engine is currently operated successfully on shop.

Emergency plans and drills have successfully been carried out taking the behaviour and properties of ammonia into account at both RCC in Copenhagen and at the Mitsui production site in Tamano.

9 ACRONYMS

The acronyms used in the article are listed below.

ACS	Ammonia catch system
ARMS	Ammonia release mitigation system
FBIVA	Fuel booster injection valve ammonia
KO	Knockout (drum)
LFSS	Low-flashpoint supply system
LGIA	Liquefied gas injection ammonia
MAN ES	MAN Energy Solutions
MES	Mitsui E&S
NH_3	Anhydrous ammonia (second fuel)
FVT	Fuel valve train
OPSU	Outer pipe scrubber unit
RCC	Research Centre Copenhagen
RT	Recovery tank
RVT	Return valve train
SRS	Supply and recirculation system
SVT	Supply valve train

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