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# Ammonia-powered future: introducing Wärtsilä 25

New Engine Concepts & Systems


## Tobias Krook, Wärtsilä

Robert Engsbo, Wärtsilä
Jan Torrkulla, Wärtsilä
Christer Hattar, Wärtsilä

## ABSTRACT

The shipping industry is exploring the use of ammonia (NH3) as fuel in order to reduce emissions and move towards a decarbonised future. Unlike many other fuels, ammonia emits no carbon dioxide (CO2) when combusted making it a compelling option for reducing greenhouse (GHG) gas emissions.

Ammonia introduces new challenges compared to conventional fuels, including toxicity and corrosivity, and these challenges need to be carefully addressed. The foremost concern is the toxicity of ammonia, which requires gas safe designs and the implementation of various safety measures during fuel handling.

The Wärtsilä 25 ammonia solution is an extension of the liquid natural gas (LNG) dual-fuel (DF) solution, benefiting from vast safety and operational experience gained with LNG fuelled ships. With a comprehensive solution including the engine, fuel supply system, ammonia release mitigation handling systems (ARMS), exhaust gas aftertreatment and hybrid electric battery system, safety and overall efficiency can be improved. Critical features of Wärtsila's integrated ammonia solution have been tested in laboratory facilities before being deployed in real-world operating environments

Ammonia is a good fuel for internal combustion engines. Testing of the Wärtsilä 25DF low pressure ammonia engine shows that combustion is robust, and in some regards even easier than in a typical LNG engine. Thanks to the built-in flexibility of the newly developed Wärtsilä 25DF engine, the inherent slow combustion speed of ammonia can be mitigated. The Wärtsilä 25DF ammonia engine fuel efficiency is equal to or even better than that of existing engines of same size, and better than the high-pressure liquid ammonia concept that has also been tested.

Although ammonia releases no carbon dioxide when combusted, it does generate a small fraction of nitrous oxide (N2O) emissions. These can be reduced to very low levels with the help of engine controls. Further reduction of the already low N2O emissions is possible by adding an N2O catalyst to the exhaust aftertreatment.

Another important aspect is ammonia slip, which refers to the small fraction of ammonia that passes unburnt to the exhaust. This amount matches well with the NOx level, ensuring that both are efficiently mitigated within the selective catalytic reduction (SCR) system.

This article aims to showcase how ammonia can be safely and efficiently used as fuel in marine engines, highlighting its potential to drive the shipping industry towards a decarbonised future.

## 1 INTRODUCTION

Driven by incentives and emission legislation changes, shipowners are actively seeking alternative $CO_2$ reduction methods to remain competitive and compliant with regulations throughout their ships' lifecycle. As a result, an increasing number of ships are being specified for zero-emission and carbon-neutral fuels.

Unlike many other fuels, ammonia ($NH_3$) emits no carbon dioxide ($CO_2$) when combusted, making it a compelling option for reducing greenhouse gas emissions. Despite the absence of $CO_2$ emissions, the overall greenhouse gas reduction potential of ammonia depends on the manufacturing method of the fuel. During the production phase of fuels, including ammonia, various steps in the process can cause emissions of different magnitude. These emissions are commonly referred to as well-to-tank emissions. The term well-to-tank refers to the total emissions generated from the initial extraction of raw materials to the final delivery of the fuel to the end user.

The term 'green ammonia' refers to ammonia produced from water and air, in a process where the hydrogen component is produced through electrolysis using renewable electricity. This method results in the lowest well-to-tank emissions compared to other ammonia production pathways. With traditional methods, which typically use natural gas as the raw material, the environmental footprint depends on the extent to which carbon capture is utilised[1].

Green ammonia is estimated to have well-to-tank emissions ranging from 2 to 19 gCO2-eq/MJfuel whereas grey ammonia, produced from natural gas without carbon capture can have emissions as high as 164 gCO2-eq/MJfuel according to Sphera [1].

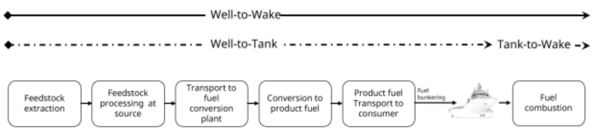


*Figure 1 The fuel supply value chain simplified based on IMO LCA guidelines [2].*

The infrastructure for ammonia is extensive, with millions of tons produced annually. Ammonia is used as a chemical and commonly transported by sea. However, using ammonia as fuel for internal combustion engines represents a new application. This application requires both technical adaptations to engine technologies and the adoption of robust safety protocols and systems to protect the people working with the ammonia powered ships.

The toxicity of ammonia is one of the key differences compared to LNG. Using ammonia as fuel has safety implications for ship's crew and owners. Acquiring critical competences is crucial. Crews working on board ammonia-fuelled ships need to be able to both operate systems safely and recognise risks. Operating ammonia fuelled machinery will require adjustments in routines and procedures. These aspects have been thoroughly considered in the development of the new Wärtsilä 25 ammonia solution, for example through a holistic solution approach, development of training programmes and development of competence guidelines together with classification societies and other key industry stakeholders.

The Wärtsilä 25 dual-fuel ammonia engine has been developed based on Wärtsilä's vast safety and operational experience gained from low pressure dual-fuel (DF) engines running on LNG. Additional safety features to address the unique properties of ammonia have been added to enhance this proven dual-fuel engine technology.


*Figure 2 A Wärtsilä 6L25DF ammonia engine at the engine laboratory in Vaasa Finland.*

Although combusting ammonia does not produce $CO_2$ emissions, small amounts of nitrous oxides ($N_2O$) are emitted. Even if the amount of $N_2O$ emitted during combustion is small, these emissions can have a significant impact on the total $CO_2$ equivalent emission level from ammonia. This is primarily because 1 g of $N_2O$ emissions is equivalent to 265 g of $CO_2$ emissions [2]. Minimising $N_2O$ emissions is therefore a top priority in engine design and tuning.

The Wärtsilä 25 ammonia solution is much more than just the engine. The W25 ammonia solution comprises the engine, fuel supply system, ammonia release mitigation handling system, exhaust gas aftertreatment system and the hybrid electric battery system.

Critical features of the Wärtsilä 25 ammonia solution can be tested in laboratory facilities before being deployed in real-world operating environments. This approach enhances safety, reliability, and the overall efficiency of the solution.

Introducing a new fuel to the market requires close collaboration with customers and ship operators. Real operating environment experience and gathering feedback back to support product development helps in improving the maturity of the solution.

Because ammonia is a new fuel for the marine industry, and has not been extensively tested in real world situations, it is crucial to use all possible means to support its introduction. For example remote monitoring allows proactive measures to be taken in case of deviations in engine performance. This approach enables early detection of potential issues, enhancing ship safety and reducing downtime.

## 2 NEXT-GENERATION DUAL-FUEL ENGINE TECHNOLOGY ADAPTED FOR AMMONIA COMBUSTION

The Wärtsilä 25 engine is available in 6- to 9L cylinder configurations with an output ranging from 1.7 to 3.4MW. In addition to ammonia, the Wärtsilä 25 engine can operate on a variety of other fuels, including light fuel oil, biofuels and LNG.

When it comes to emissions and fuel economy the Wärtsilä 25 platform is based on Wärtsilä's next generation dual-fuel engine technology (NextDF), introduced with the Wärtsilä 31 engine.

The Wärtsilä 25DF engine is optimised to operate on gaseous ammonia but can also use liquid diesel fuel. In gas mode the engine runs as a lean-burn engine, where the ignition is initiated by a small amount of liquid fuel that acts as the pilot for combustion.

The type-approved power of the ammonia version of the Wärtsilä 25DF will equal to that of the LNG DF variant, 345 kW/cylinder at 1000 rpm and 315 kW/cylinder at 900 rpm. The power is same in diesel mode as in ammonia gas mode. The nominal power of engines delivered during piloting phase may be different compared to what is stated in type approval certificate.

### 2.1 The Wärtsilä 25DF design

The Wärtsilä 25 ammonia engine is designed according to gas-safe principles, based on the proven LNG DF engine. Following the design principle that a single failure cannot cause ammonia fuel leak into the engine room.

Ammonia is supplied at low pressure through a double-wall pipe routed along the engine branching into individual feed pipes to each cylinder. The gas manifold and de-gassing pipe is of double wall design, where a leakage/failure of the inner pipe can be safely contained and detected.

The electronically controlled gas admission valve adjusts the amount of gaseous ammonia fed into the cylinders. The gaseous ammonia is mixed with combustion air in the intake channel of the cylinder head during the intake stroke.

The common rail diesel fuel oil system consists of one or two electronically controlled engine-driven high-pressure pumps and double-wall jumper rails. Each cylinder has an electronically controlled injector. The same injectors and high-pressure pumps are used in diesel mode as for pilot fuel injection in ammonia gas mode, meaning there is no need for a separate pilot fuel injection system.

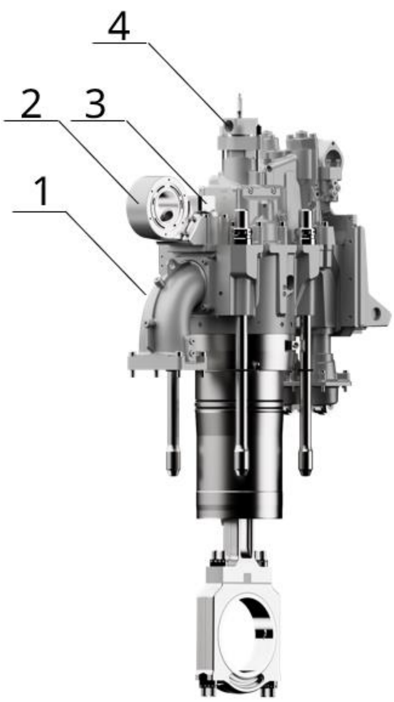


*Figure 3 Wärtsilä 25DF power pack showing the charge air riser pipe (1), gas manifold (2), gas admission valve (3) and liquid fuel injector for diesel mode and pilot fuel injection (4).*

To prevent condensation of ammonia, the gas inlet pipe temperature is continuously monitored. The temperature of the gaseous ammonia and the gas supply piping is maintained so that it is always higher than the dew point. In case the gas or the gas piping is too cold, engine automation system will initiate necessary machinery protection.

The engine machinery protection is developed based on the dual-fuel LNG engine. In case of deviation in engine operating parameters when running in gas mode, engine will transfer to diesel mode automatically, commonly referred to as a gas trip. The Wärtsilä 25DF engine can have a full engine trip to diesel mode or a cylinder wise trip to diesel, in case of a disturbance isolated to a single cylinder. The cylinder wise trip functionality makes the gas mode more robust without sacrificing safety.

### 2.2 Development timeline

Wärtsilä has experience of both low-pressure and high-pressure technology for LNG. The low-pressure Otto concept relies on the technologies and safety concepts used for LNG engines in the marine industry over the last 20 years. Using existing safety concepts and technologies means that the maturity level in certain aspects is good, even though the fuel is different.

The decision on what ammonia technology to choose for the Wärtsilä 25 engine platform was made following full-scale testing on ammonia for both the gaseous Otto concept and the high-pressure liquid concept. The test results were carefully analysed and resulted in decision to go for the gaseous Otto concept. Key factors influencing the decision-making included safety, efficiency and, overall potential for greenhouse gas reduction among several other parameters.

Testing and validation of the Wärtsilä 25DF ammonia engine are ongoing across several different engine platforms and rigs. The Wärtsilä 25DF ammonia engine testing was first started on a 1L25DF engine and later continued on a full-scale 6L25DF engine. Additionally, a 6L34DF ammonia research engine is providing further valuable input for developing the platform.

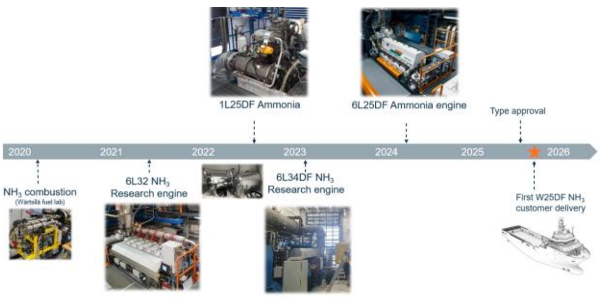


*Figure 4 Testing on various platforms, rigs, single cylinder engine and full-scale multi cylinder engines.*

The data gathered from these various test platforms will contribute to further optimisation of the engine and the complete ammonia solution. This data is crucial for thoroughly assessing the safety, efficiency, and reliability of the Wärtsilä 25 ammonia solution.

### 2.3 Testing and validation in engine laboratory

The operation and maintenance of the Wärtsilä 25DF ammonia engine is not that different to the dual-fuel LNG variant. However, there are a few key differences to consider. The toxicity of ammonia requires specific handling and safety measures. Additionally, the corrosive nature of ammonia imposes material changes to certain engine components that are in contact with ammonia.

Due to the toxicity of ammonia, test personnel are provided with handheld ammonia detectors, and breathing masks are easily accessible. In addition, the engine room is effectively ventilated, and gas detection systems are installed at various locations within the test cell.

Before a maintenance work starts, it is important to make sure systems that may contain ammonia fuel or ammonia vapours are purged properly, for example before opening the gas piping or the crankcase.

*Figure 5 A Wärtsilä 6L34DF ammonia research engine at Sustainable Energy Katapult center testing facility in Norway.*

Testing experience shows that there is no smell of ammonia in the engine room after the engine is stopped, nor is there any ammonia present in the engine room during normal operation. Small amounts of ammonia are absorbed into the lubrication oil, which is in line with our initial expectations. Consequently, material selections in the engine have been made considering the presence of ammonia in the lubrication oil.

Considering the low-pressure Otto concept there are no identified scenarios that would significantly increase the amount of ammonia in the lubrication oil. Based on Wärtsilä's testing, the high-pressure liquid concept typically has an even lower amount of ammonia during normal operation but may be subject to failure scenarios that result in a sudden increase of ammonia in lubrication oil. In other words, both the high-pressure liquid concept and the low-pressure ammonia concept have their respective advantages and disadvantages.

As with all 4-stroke internal combustion engines, the crankcase gas contains fuel gas vapours originating from cylinders blow-by diluted by air from the turbocharger. The amount of ammonia in the crankcase is comparable to the amount of methane in a typical dual-fuel LNG DF engine, running according to the Otto principle.

The Wärtsilä 25DF ammonia engine crankcase is subject to a slight under-pressure maintained by an extraction fan. This is an additional safety and odour avoidance precaution for ammonia engines. The total crankcase vent is typically <0.5% of the total engine exhaust flow.

## 3 THE WÄRTSILÄ 25DF AMMONIA ENGINE PERFORMANCE

Throughout testing on several platforms, the efficiency of the low-pressure Otto concept has been consistent with and equal to that of dual-fuel LNG engines, and typically better than that of a diesel engine (i.e. ~46%). In Wärtsilä tests ammonia has proved to be a good fuel for the low-pressure Otto concept. It is highly knock resistant, and the combustion is robust across a wide range of engine settings. Thanks to the built-in flexibility of the newly developed Wärtsilä 25DF engine, the inherent slow combustion speed of ammonia can be mitigated.

Ammonia is ignited by a small amount of pilot diesel as in Wärtsilä dual-fuel LNG engines. The energy share of ammonia is ~95% across a wide load range, as can be seen from the engine testing data shown in figure 6.

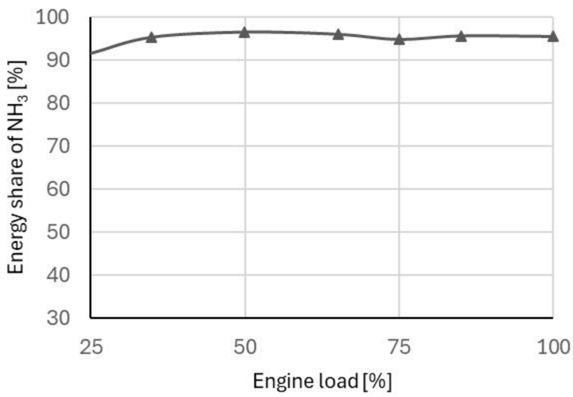


*Figure 6 Typical energy share of ammonia during engine tests on a 6L25DF Wärtsilä engine.*

Engine test results show that when using fossil-diesel as pilot the Wärtsilä 25DF ammonia engine achieves GHG emissions below 50 g/kWh $CO_2$eq, tank-to-wake (see figure 7). In terms of well-to-wake emissions, which are relevant in terms of global warming and FuelEU Maritime regulations, the Wärtsilä 25DF ammonia engine achieves an emission level of less than 11 gCO2eq/MJfuel with the greenest available ammonia according to SPHERA [1]. This represents a reduction of 89% compared to the FuelEU Maritime reference level. Using biodiesel as the pilot fuel reduces total $CO_2$ emissions even further.

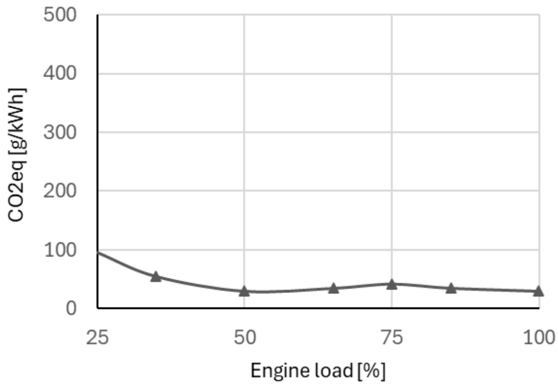


*Figure 7 Typical tank-to-wake GHG emissions over the load range during engine tests on a Wärtsilä 6L25DF engine. CO2eq emissions are reduced by >90% compared to a diesel engine using LFO.*

A small amount of ammonia passes unburnt to the exhaust. This amount matches well with the NOx level so that both are mitigated in the SCR to desired level.

## 4 THE AMMONIA ENGINE OPTIMISED AFTERTREATMENT SYSTEM

The development of the Wärtsilä 25DF ammonia aftertreatment system has been closely integrated with the development of the engine's performance.

As a first step in the development process, catalyst elements were screened in a laboratory-scale microreactor. The emission matrix of an engine operating on ammonia can be significantly different from traditional fuels. Therefore, there are no readily available and tested catalysts and solutions for the emission control needs of ammonia engines.

The tests identified the criticality both of selecting suitable catalysts and also the strong link between engine performance parameters and the performance of the elements. While it is possible to reach very good emission performance in a certain setup, selecting the wrong ammonia slip catalysts for example, may lead to a significant increase in $N_2O$ emissions.

Based on the experience from small-scale laboratory testing, a full-scale system for operating on ammonia has been developed, using the proven

Wärtsilä NOR platform as a basis. This system has operated on both the Wärtsilä 34DF ammonia research engine and the Wärtsilä 25DF ammonia engine.

The results from the tests have verified the good emission performance of the integrated engine and SCR system. Tier III NOx performance can be maintained in both ammonia and diesel mode. Ammonia slip is also maintained at low levels during operation and is not a concern for the overall environmental footprint of the solution or the safety. In the tests, ammonia slip has been below 50 ppm.

The performance of the catalysts has been tested in a wide range of conditions as has the ability of the control system to keep the reagent dosing at the correct level.

Having a full-scale SCR system in operation during engine tuning and testing has enabled careful selection of the operating parameters to achieve the best possible overall performance.

The greenhouse gas footprint of the total solution is the key driver for selecting an engine that operates on ammonia. Therefore, during the development Wärtsilä has placed particular emphasis on both minimising the $N_2O$ emissions from the engine and on developing an aftertreatment system that enables further emission reductions. The tests have shown that by selecting the correct operating conditions a $N_2O$ reduction well above 50% can be achieved in the aftertreatment, if there is a driver to further reduce the already low $N_2O$ emissions after the engine. One enabler for the good $N_2O$ removal performance is the relatively high temperature of the engine exhaust.

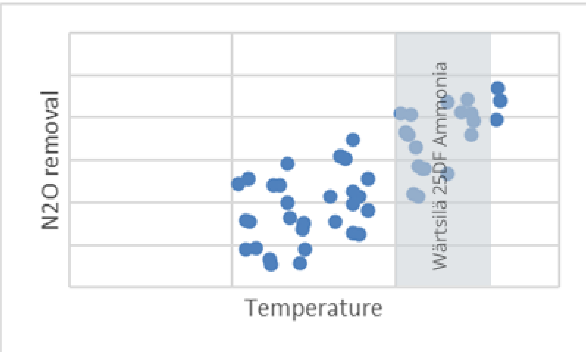


*Figure 8 $N_2O$ removal as a function of temperature. The Wärtsilä 25DF exhaust composition and temperature is good for efficient use of $N_2O$ catalyst.*

From a SCR control point of view, one of the main differences compared to a standard diesel engine is that, in addition to NOx, any unburned ammonia in the exhaust will act as a reagent in the SCR system and the external feed of reagent needs to be adjusted accordingly. The Wärtsilä 25DF ammonia aftertreatment is equipped with sensors and analysers supported by advanced combustion balance calculations to determine the correct reagent dosing level.

## 5 THE AMMONIA FUEL SUPPLY SYSTEM

Wärtsilä recognised the need to develop a complete solution for ammonia powered vessels due to the lack of available solutions on the market, and the importance of being able to ensure the quality and safety of the whole system. The ammonia fuel supply system (Wärtsilä AmmoniaPac) needs to be well integrated into the rest of the vessel to ensure high operational reliability and to avoid compromising safety. The basis for the AmmoniaPac design is the Wärtsilä's proven LNGPac fuel gas supply system. The key requirements of the system are to safely store, handle and supply ammonia in the correct condition to the consumers. The overall energy efficiency of the system has been considered throughout the development process to ensure the competitiveness of the solution during the lifecycle of the vessel.

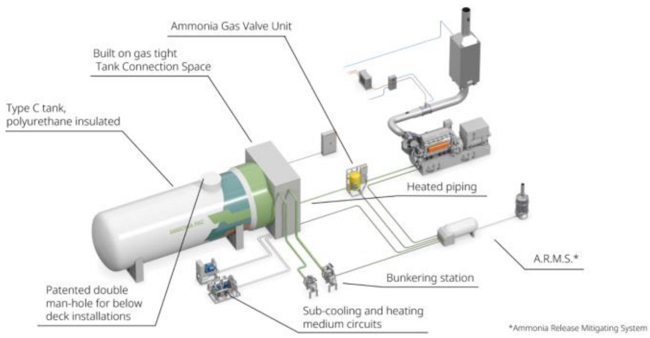


*Figure 9 Overview of the Wärtsilä AmmoniaPac fuel gas supply system.*

### 5.1 SYSTEM DESCRIPTION

The ammonia tank is filled from the bunkering station, which contains two interfaces towards the supplier, a liquid filling connection and a vapour return. The tank is a type - C polyurethane isolated tank with a built-in gastight tank connection space (TCS), designed to contain leakages. To enable bunkering of both refrigerated and ambient temperature ammonia, a high tank design pressure, up to 45 °C ammonia vapor pressure (around 18 barg) is considered an option until refrigerated ammonia is widely available.

If the tank cannot withstand unlimited holding time at 45 °C ammonia vapor pressure, additional equipment for managing the ammonia pressure and boil of gas (BOG) in the tank is needed.

Wärtsilä has developed a subcooling system that recirculates the liquid ammonia through a cooling system to the top spray line of the tank enabling both semi and fully refrigerated ammonia to be stored. In addition, to ensure redundancy in BOG management, the Wärtsilä ammonia release mitigation system (WARMS) can be used to consume BOG from the tank.

All interconnecting piping between hazardous areas (TCS, bunkering station) are double walled with an annular space that ensures leaks are contained and detected.

Inside the TCS there is an ammonia pump that raises the pressure according to the requirements of the consumers before an ammonia vaporiser that vaporises the ammonia and heats the ammonia gas to a temperature well above the dewpoint. Since ammonia requires more than twice as much energy to evaporate compared to LNG, the full system approach is important to ensure that there is available heat onboard the vessel. Due to the high temperature requirement, waste heat from the engine's high-temperature cooling water system is used.

Since ammonia gas can easily condensate if pressurised in ambient temperatures, all piping downstream from the vaporiser where ammonia is intended to be kept in gaseous form is heated and monitored. Wärtsilä's engine laboratory tests have demonstrated the importance of keeping the ammonia gas and piping warm enough to avoid condensation. A liquid trap is also arranged to ensure that a failure to maintain the ammonia in gaseous form does not result in ammonia droplets being fed to the consumers.

The gas valve unit (GVU) contains a double block and bleed (DBB) function and a regulating valve that adjusts the ammonia gas pressure, according to the demand from the engine, depending on the engine load. The GVU equipment is contained in a gas-tight enclosure and can be located close to the engine in a gas-safe engine room, to ensure good pressure regulation.

All process vent and relief lines are routed to a buffer tank that enables quick pressure relief from the process piping in case of an over-pressure event or other scenario. The buffer tank is sized according to the project-specific system specifications to ensure all relief scenarios are considered. After the initial release of ammonia, an ARMS is used to empty the buffer tank in a safe and controlled manner. This arrangement enables on/off operation of the ARMS to minimise unnecessary operation of the system. The WARMS is a compact gas combustion unit which safely and efficiently burns the ammonia and/or ammonia nitrogen mix that is released to the buffer tank in a failure scenario or during maintenance operations. This system ensures that emissions from the process are kept to a minimum and well within regulations.

### 5.2 ENSURING SAFE OPERATION AND MAINTENANCE

The Wärtsilä AmmoniaPac fuel gas system is remotely controlled with automated sequences that require limited operator input or manual action. This reduces the risk of human error leading to ammonia exposure.

Most of the equipment for the AmmoniaPac system is arranged with double isolation valves towards the ammonia storage tank, to ensure operator safety when removing equipment from the system without the need to empty the tank.

Ventilation ducting inside the TCS, where most ammonia equipment is located, is arranged to ensure good airflow in all areas avoiding any undetected pockets of ammonia gas from forming. The system is designed with ease of maintenance and operability in mind to ensure the ammonia piping can be inerted and gas freed in a safe manner.

## 6 CONCLUSIONS

Ammonia was included early in the development process of the Wärtsilä 25 engine. Full-scale ammonia engine tests were performed in 2021, both for the high-pressure liquid concept and the gaseous Otto concept.

The W25 ammonia solution is very similar to a Wärtsilä LNG installation. Certain adaptations have been made due to the properties of ammonia. On a system level the main difference is the addition of an ammonia release management system.

Ammonia is a good fuel for internal combustion engines, specifically for an engine like W25 having the flexibility to optimise combustion parameters. High ammonia energy fuel shares close or equal to dual-fuel LNG engines are possible over a wide operating range. Ammonia combustion is robust, and in some regards even easier than combustion in a typical LNG engine. Fuel efficiency of the W25DF ammonia engine is equal or better than existing engines of same size and better than the liquid ammonia concept tested.

The engine performance and aftertreatment are optimised together. Nitrogen oxides and ammonia slip are mitigated in the SCR resulting in an IMO Tier III compliant solution.

The Wärtsilä 25 ammonia solution has high greenhouse gas reduction potential. With tank-to-wake emissions below 50 g/kWh $CO_2$eq reached in engine testing. The W25 ammonia solution is an enabler to meet the FuelEU Maritime targets set for 2050.

The toxicity of ammonia is a fact that all parties involved in ammonia-fuelled shipping must address. With a safety-first mindset, the introduction of ammonia can be done in a safe manner. Any incident, regardless of the technology chosen, or ammonia power solution provider, will have an impact on the public perception of ammonia. Therefore, if we are to increase the pace of the green transition in the marine industry and demonstrate the true potential of ammonia as a carbon-free fuel, safety must be at the core of everything we do.

# 7 ABBREVIATIONS

| | |
|---|---|
| ARMS | Ammonia Release Mitigation System |
| BOG | Boil Of Gas |
| DF | Dual-Fuel |
| GHG | GreenHouse Gas |
| LCA | Life Cycle Assesment |
| LFO | Light Fuel Oil |
| LNG | Liquified Natural Gas |
| NOR | Wärtsilä NOx Reducer |
| TCS | Tank Connection Space |
| WARMS | Wärtsilä Ammonia Release Mitigation System |

# 8 DEFINITIONS

| | |
|---|---|
| Ammonia Solution | In this article, referring to the solution comprising the engine, fuel supply system, ammonia release mitigation handling system, exhaust gas aftertreatment system and the hybrid electric battery system. |
| AmmoniaPac | The Wärtsilä ammonia fuel gas supply system. |
| Annular space | In this article, referring to the empty space between the inner and outer wall in the gas supply piping. |
| Diesel mode | DF engine operating mode using diesel fuel only. |
| Gas mode | In this article, DF engine operating mode where gaseous ammonia is fed into cylinders ignited by liquid pilot diesel. |
| Green ammonia | Ammonia produced by renewable energy from water and air. |
| Lean-burn | the burning of fuel with an excess of air in an internal combustion engine. |
| Liquid concept | In this article referring to high-pressure direct injection of liquid ammonia to the cylinder, following the diesel combustion process. |
| LNG DF | In this article referred to as a Wärtsilä low pressure Liquid Natural Gas engine working according to the Otto principle. |
| LNGPac | The Wärtsilä LNG fuel gas supply system. |
| NextDF | In this article referring to advanced engine technology introduced by Wärtsilä for lowering emissions and improving efficiency. |
| Otto principle | In this article referred to a combustion in which fuel and air are mixed before entering the combustion chamber. Ignited by pilot fuel. |
| Well-to-tank | All emissions from fuel production to the end consumer, are called well-to-tank emissions. |

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|---|---|
| Well-to-Wake | All emissions from extraction of raw materials and fuel production to combustion of the fuel. |

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## 10 ACKNOWLEDGMENTS

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## 11 CONTACT

For further information, contact details can be found from: [www.wartsila.com/contact](www.wartsila.com/contact)