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WinGD's ammonia engine technology for the new X-DF-A family

New Engine Concepts & Systems

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ABSTRACT

The maritime industry is undergoing a transformation to meet the International Maritime Organization's (IMO) greenhouse gas (GHG) reduction targets, which call for a 30% decrease in well-to-wake emissions by 2030, an 80% reduction by 2040, and net-zero emissions by 2050, compared to 2008 levels. Ammonia, as a carbon- and sulfur-free fuel, offers a promising pathway to maritime decarbonization. However, its implementation in marine engines presents challenges related to combustion characteristics, emissions control, safety, and infrastructure adaptation.

This paper outlines the development and validation of WinGD's X-DF-A ammonia-fueled engine technology, which incorporates an advanced ammonia injection and combustion system with integrated safety measures to mitigate toxicity and flammability risks. Key safety principles include: (1) a gas-safe machinery space concept that ensures no ammonia release in the event of a malfunction; (2) a double-wall piping system that provides secondary containment and early leakage detection; and (3) a purging concept for safe removal of ammonia during fuel changeovers, in case of leakages and during maintenance. These principles led to built-in safety measures such as a leakages containment and detection system in the fuel injection system, the elimination of ammonia recirculation to the fuel supply system during normal operation, and an ammonia monitoring system to prevent crankcase contamination through an improved gland box sealing concept. A continuous risk assessment process, including system risk evaluation, failure mode analysis, and technical design reviews, ensured safety throughout all stages of engine development. This resulted in the world's first Approval in Principle from Lloyd's Register in September 2023, followed by approvals from China Classification Society and Bureau Veritas.

The X-DF-A engine technology underwent a structured validation process, including component and engine testing. The ammonia injector was first tested on a hydraulic rig, confirming its reliability and accuracy. The combustion concept was then validated in a spray combustion chamber, where stable combustion was achieved with a diesel pilot injection, allowing for in-depth combustion characterization using optical diagnostics. Single-cylinder engine tests demonstrated additional tuning flexibility with ammonia compared to diesel operation, achieving lower NO_X emissions in Tier II despite increased peak firing pressures. At 100% engine load, NH_3 slip remained below 10 ppm, N_2O below 3 ppm, and a pilot fuel share ratio as low as 5% was achieved. The X-DF-A technology is now being implemented in the world's first commercial large-bore ammonia engine, currently in final assembly, with its factory acceptance test scheduled for the second quarter of 2025.

1 INTRODUCTION

The maritime sector serves as the backbone of international trade, facilitating the transportation of nearly 90% of global goods. However, this pivotal industry is also a significant source of Green-House Gas (GHG) emissions, contributing approximately 3% of global Carbon dioxide (CO_2) emissions.

As climate change continues to pose existential risks, the decarbonization of the maritime sector has emerged as an indispensable objective for policymakers, industry leaders and environmental advocates. Achieving a substantial reduction in shipping emissions is not only a moral imperative but also critical to fulfilling global climate commitments, including the Paris Agreement's ambitious goal of limiting temperature rise to 1.5°C above pre-industrial level [1].

The regulatory landscape governing the maritime industry has evolved rapidly to address the pressing challenge of climate change. The International Maritime Organization (IMO) has set forth stringent objectives, including the uptake of zero or near-zero GHG emission technologies, fuels and/or energy sources to represent at least 5%, striving for 10% of the energy used by international shipping by 2030. Additionally, the IMO targets achieving net-zero emissions by 2050 [2]. These benchmarks underscore the urgent need for transformative innovations and systemic shifts away from traditional fossil fuels. Beyond regulatory pressures, societal demands for cleaner technologies and sustainable practices are reshaping the priorities of maritime operators, driven by mounting expectations from stakeholders such as investors, customers, and global supply chains.

Despite the apparent necessity, transitioning to sustainable fuel solutions entails formidable challenges. Economic considerations, including high capital and operational costs, remain a significant barrier. The limited global availability of alternative fuels and the necessity for substantial infrastructure upgrades further complicate the adoption process [3].

Moreover, the operational demands of deep-sea shipping — characterized by long voyages and high energy requirements — render many renewable energy options insufficient. Addressing these multi-dimensional challenges demands advanced, scalable solutions tailored specifically to the maritime context.

Ammonia has garnered attention as a promising candidate for low-carbon maritime fuel, particularly for long-haul, deep-sea vessels. While it possesses a lower energy density compared to traditional fossil fuels and Liquefied Natural Gas (LNG), its advantages are profound.

Ammonia combustion produces no CO_2, and its synthesis can be achieved using renewable energy sources, offering a pathway to carbon-neutral fuel production [3]. Technological advancements aim to mitigate concerns regarding ammonia's toxicity and handling, further enhancing its feasibility. Additionally, with the currently established world grid of ammonia terminals and storage, a bunkering grid could be established quickly and cost-efficiently [4] presenting a logistical advantage that bolsters its potential for widespread adoption in the shipping industry.

The X-DF-A ammonia engine by WinGD represents a significant advancement in sustainable maritime propulsion. Developed in close collaboration with classification societies, universities and industry partners, this technology integrates advanced engineering solutions to enable the safe and efficient utilization of ammonia as a primary fuel.

To address the technical and regulatory challenges associated with ammonia combustion, WinGD formed joint development agreements in 2022 with key stakeholders, including shipowners, engine manufacturers, and fuel system suppliers. The resulting engine architecture not only ensures compliance with evolving regulatory frameworks but also enhances operational viability, positioning ammonia as a feasible zero-carbon fuel alternative.

2 X-DF-A DESIGN

The innovative design in WinGD's X-DF-A engines, coupled with critical safety features to mitigate the hazards associated with ammonia's toxicity and flammability, is essential for this state-of-the-art compression ignition engine.

2.1 X-DF-A Combustion Concept

The key development targets guiding the selection of the X-DF-A engine's combustion concept are outlined below.

2.1.1 Concept Selection Criteria

Table 1 compares key properties of ammonia (NH_3) with other fuels used in the maritime sector. At standard conditions, ammonia is a gas with a carbon- and sulfur-free molecular structure. Its high liquid density and ease of liquefaction make it well-suited for liquid fuel admission in combustion engines. Owing to its high auto-ignition temperature (T_{ai}) and low Flammability Limit (FL) in air, ammonia presents a lower flammability hazard compared to LNG and especially hydrogen (H_2).

Table 1. Maritime fuels key properties.

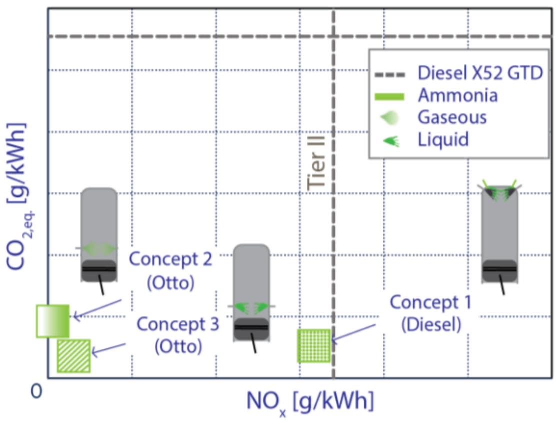
Property	Unit	NH_3	H_2	CH_3OH	LNG	MGO
ρ_l	kg/m3	600	71	798	467.3	900
LHV	MJ/kg	18.6	120	19.9	~50	42.7
T_{ai}	°C	651	571	444	499.8	230
H_v	kJ/kg	1371	-	37.34	511	353
MN	-	~0	0	-	> 65	-
CI	-	< 10	0	5	-	35
RON	-	110	~130	109	107	-
FL	%	14 - 27	4 - 75	6 – 36.5	5 – 15	1 - 6
T_{fp}	°C	132	-252	12	-188	60
$T_{b@\,1bar}$	°C	-33.6	-252	64.6	-161	-
T_c	°C	132.3	-	259	-82	-
p_c	bar	113	-	81	45	-

In terms of Lower Heating Value (LHV), ammonia has a lower energy density than Marine Gas Oil (MGO), similar to the other alternative fuels, but comparable to methanol (CH_3OH). Additionally, ammonia's high octane number and low self-ignition tendency make it ideal for pre-mixed combustion.

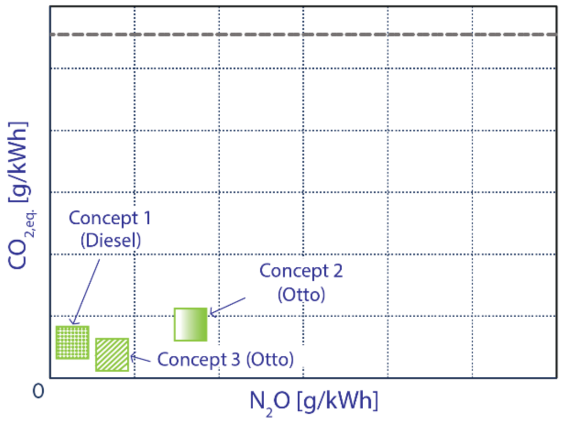
Various combustion concepts were initially evaluated by computational fluid dynamic, to find the thermodynamic cycle minimizing Nitrogen Oxide (NO_x), and GHG emissions. Focus was given on reducing Dinitrogen monoxide (N_2O) — also known as laughing gas — as it has a global warming potential 273 times higher than CO_2 over a 100-year period [3]. The CO_2-equivalent ($CO_{2,eq.}$) emissions of the three most promising combustion concepts were used as key selection criteria.

Figure 1 summarizes the emissions and benchmarks them against WinGD’s official diesel engine data in Tier II mode at 50% R1 rating. These results are representative for the whole load range. Here, Concept 1 refers to a liquid admission of ammonia in a Diesel-cycle, while Concept 2 and Concept 3 refer to an Otto-cycle with gaseous and liquid ammonia admission, respectively. Liquid ammonia injection demonstrated the greatest potential for $CO_{2,eq}$. reduction compared to gaseous admission (see Figure 1-a). While the Diesel thermodynamic cycle achieved $CO_{2,eq}$. levels comparable to the Otto-cycle, it was ultimately selected for its superior ability to minimize N_2O emissions (see Figure 1-b) while maintaining slightly lower NO_x levels than an equivalent marine diesel engine.

The simplicity of the Emissions Abatement System (EAS) also was a key factor in the concept selection process. Since no off-the-shelf N_2O catalyst solutions exist for two-stroke engines, minimizing N_2O emissions was prioritized. Although the Otto-cycle offered greater NO_x reduction, it posed a higher risk of NH_3 slip, requiring a more complex EAS, including a large ammonia slip catalyst and a bypass mode for diesel operation.



(a) $CO_{2,eq.}$ vs. NO_X



(b) $CO_{2,eq}$. vs. N_2O

Figure 1. Selection criteria for the combustion concept in Tier II mode at 50% R1 rating.

2.1.2 X-DF-A Product Development Targets

Following the selection of the combustion concept, the main parameters of the X-DF-A portfolio engines (i.e., at the time of writing, X52DF-A-1.0, X62DF-A-1.0 and X72DF-A-1.0) were defined using a model-based design approach.

Similar to the procedure described in [5], each X - DF-A engine in the portfolio was simulated in 1D, confirming that in ammonia mode, the same Brake Specific Energy Consumption (BSEC) could be achieved as in diesel mode while the exhaust temperature is lower than in diesel mode. The performance values based on these 1D simulations were officially released in General Technical Data (GTD) [6]. In Figure 2, the BSEC and Exhaust temperature before Turbine (tEbT) overpower are provided for a 6X52DF-A-1.0 and 6X52-1.1 diesel engine of equivalent configuration, showing the same BSEC but lower tEbT for the ammonia mode.

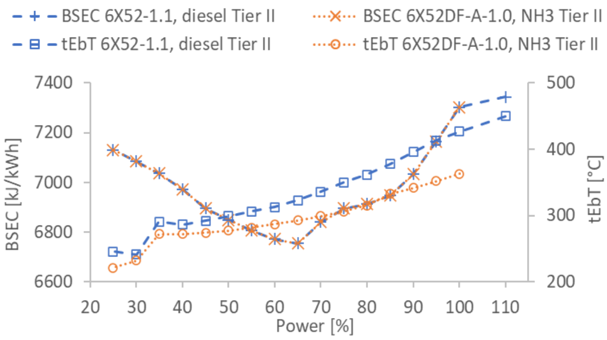


Figure 2. BSEC and tEbT overpower for 6X52DF-A-1.0 and 6X52-1.1 with rating 1810 kW/cyl at 105 rpm, based on GTD release 2.25.0.0.

2.2 Ammonia Injection System

Figure 3 and Table 2 outline key components of the X-DF-A engines, with the Fuel Injection System (FIS) at the core. The system enables optimized liquid ammonia injection using a pressure amplification mechanism powered by actuation oil.

The actuation oil supply unit pressurizes hydraulic oil to a level up to 300 bar, regulated by the engine control system. The oil is stored in a rail, allowing the Actuation Control Unit (ACU) to control ammonia injection timing and quantity. The ACU controls the individual ammonia injectors. Ammonia, pressurized up to 85 bar, is fed into an injector chamber, where an integrated pressure amplifier boosts it to injection pressures of up to 600 bar.

The X-DF-A engines feature an Ammonia Injector Cooling Water System (AICWS) that is used to cool the injector during diesel mode operation.

An example of the FIS integration on the X-72DF- A engine platform is provided in Figure 4.

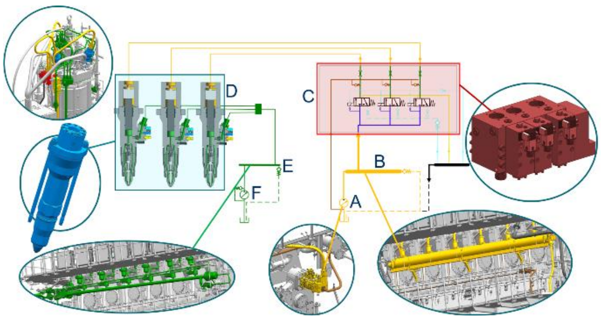


Figure 3. High level schematics of the X-DF-A FIS.

Table 2: X-DF-A FIS main components.

Marking	Component Name
A	Actuation Oil Pump(s)
B	Actuation Oil Rail
C	Actuation Control Unit
D	Ammonia Injection Valve
E	Ammonia Distribution System
F	Ammonia Supply System

2.2.1 Actuation Oil System

The actuation oil system is a distinct yet analogous counterpart to the exhaust valve servo oil system commonly found in most WinGD engines. Supplied by the common bearing oil system, additional actuation oil pumps utilize engine power via the crankshaft powertrain to pressurize hydraulic oil for the ammonia injection system. The pressurized oil is stored in the common oil rail.

The ammonia injection parameters directly influence oil pressure levels and flow. At each engine load, oil pressure is electronically controlled to the optimal level for combustion performance, up to 300 bar. Due to the relatively low volumetric energy density of ammonia compared to diesel fuel, larger injection quantities are required to achieve equivalent cylinder power, leading to high actuation oil flows. Consequently, a relatively large actuation oil rail volume is necessary. High-Pressure (HP) Double-Wall (DW) oil pipes connect the oil rail to the actuation control unit providing necessary safety as according to SOLAS requirements [7] and Classification Societies' Rules [8].

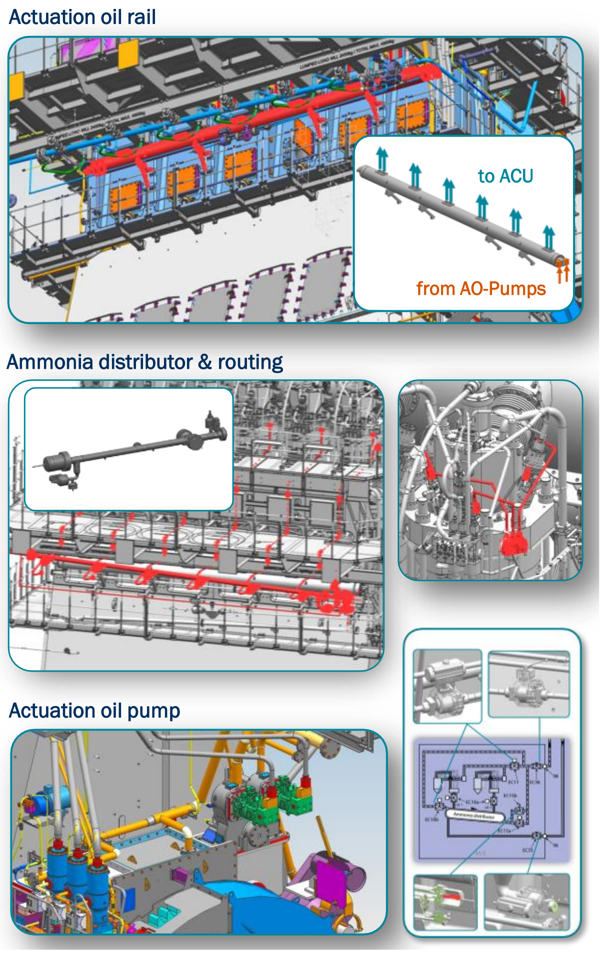


Figure 4. Example of X-DF-A design for a 72 bore engine platform.

2.2.2 Actuation Control Unit

The Actuation Control Unit (ACU) functions and the control elements for the ammonia injection process are presented in Figure 5. Each engine cylinder is equipped with one ACU, which contains an Oil Control Valve (OCV) for each injector, resulting in a total of three OCVs per ACU. This configuration enables individual control of each injection valve.

Injection control regulates the pressurized oil flow to the ammonia injection valve, with the OCV opening duration determining injection quantity. When energized, the electro-hydraulic OCV moves a sliding element, directing oil to the injector. De-energizing closes the OCV, redirecting oil to depressurize the injection valve. DW pipe diameter and quantity vary with engine bore size and oil flow rates.

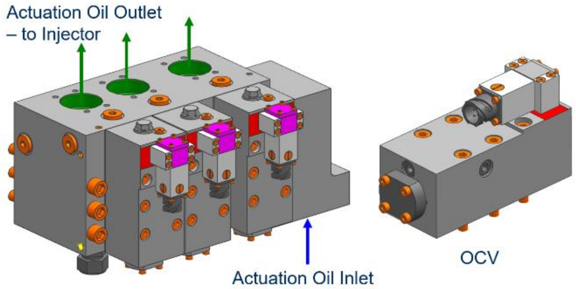


Figure 5. X52DF-A ACU and OCV.

2.2.3 Ammonia Injection Valve

The ammonia injection valve, shown in Figure 6, integrates a pressure amplifier and a spring-loaded injection needle. When oil is pressurized, the 85 bar ammonia in the injection chamber is compressed to the injection pressure (up to ~600 bar), which is determined by the actuation oil pressure and the amplifier piston geometry.

Beyond injection, the valve facilitates ammonia purging and injector cooling during diesel operation. Oil contamination is prevented by sealing rings, low-pressure leakage grooves, and wipers, with leak monitoring in place. Ammonia slip is minimized by reducing the sac volume at the nozzle tip.

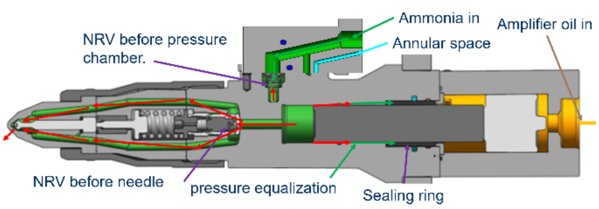


Figure 6. Ammonia injection valve cross-section.

2.3 Cylinder Cover

Compared to our diesel portfolio engines, the X-DF-A features a new cylinder cover that allows three additional ammonia injectors. The standard diesel Fuel Injection System (FIS) is used to perform a pilot injection to support the ammonia spray ignition.

The cylinder cover has also been equipped with dedicated channels integrated to the engine annular spaces concept (see next Section 2.4) allowing an extra safety feature in case of injector failure during operation. An exemplary cover design for X-DF-A is provided in Figure 7.

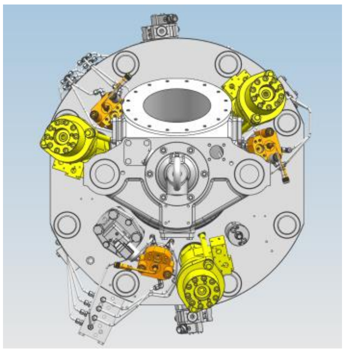


Figure 7. Example of X-DF-A cylinder cover design.

2.4 Safety by Design

Safety has been at the core of the ammonia engine development. The X-DF-A engine is designed to operate on ammonia at the same safety level as when using diesel fuel. The Safety Concept [9] emphasizes early detection of hazards, triggering immediate preventive actions. It is based on the following key aspects:

- Gas safe machinery space principle, which ensures that a single failure in the ammonia system cannot lead to any ammonia release into Engine Room (ER).
- DW piping concept to ensure secondary containment and automated early detection of any ammonia leakage.
- A purging strategy that ensures meeting the safety requirements during the fuel changeover, in case of leakages as well as in preparation of maintenance work.

Referring to the properties listed in Table 1, the risk of an ammonia fire is lower compared to other fuel oils or gases. However, fire and explosion risks have been assessed, with mitigation measures detailed in the X-DF-A Safety Concept [9].

The main safety concern in relation to ammonia is associated with its toxicity and gas-dispersion properties. Based on Acute Exposure Guideline Levels (AEGL) for airborne chemicals defined by the Environmental Protection Agency (EPA) US, the limits to ammonia exposure can be identified as shown in the following Table 3 [10]. Due to its toxicity, ammonia release into the air must be limited to the lowest practicable level.

Direct venting of ammonia to the atmosphere is prohibited under normal operation, including for pressure control in storage tanks, except in failure conditions where it does not create hazardous concentrations. To ensure compliance with safety standards, an Ammonia Vapor Processing System (AVPS) has been considered to collect and treat all ammonia vapors from the engine and the fuel system before release to atmosphere (see Figure 8).

Core of the X-DF-A Safety Concept is the purging procedure. It is based on a two-phase approach, designed to enhance crew safety in the event of ammonia leakage or during maintenance.

- Initial purging: All liquid ammonia in the engine and fuel system piping is purged using pressurized inert gas (e.g., N_2) into a dedicated tank (see Figure 8). The inert gas is supplied via an inert gas supply system.
- Residual ammonia vapor removal: The Ammonia Injector Cooling Water System (AICWS) is then activated. This system ensures not only the injector cooling but as well as absorption, flushing, and collection of any remaining ammonia (e.g., the wet surface on the piping), including surface residues, into an AICWS-dedicated tank (see Figure 9).

Both systems connect via the Fuel Valve Unit (FVU), which houses a series of fuel control valves and interfaces the engine and ancillary systems.

As aforementioned, in the ER the gas safe machinery space principle ensures that a single failure cannot result in ammonia release and thus all ammonia containing piping is DW.

Table 3. EPA Acute Exposure Guideline Levels.

Guideline	10 min	30 min	1 h	4 h	8 h
AEGL-1 / ppm	30	30	30	30	30
AEGL-2 / ppm	220	220	160	110	110
AEGL-3 / ppm	2,700	1,600	1,100	550	390

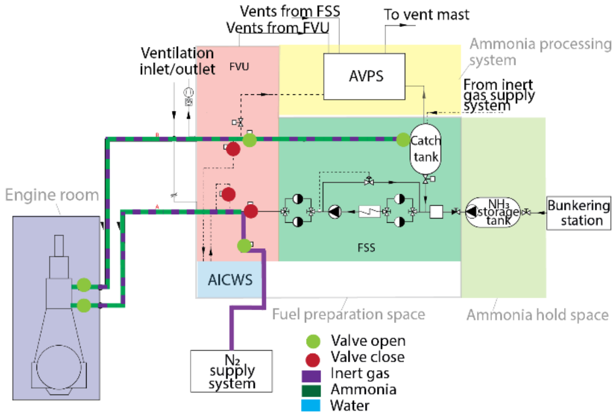


Figure 8. Ammonia fuel system purging: liquid ammonia removal

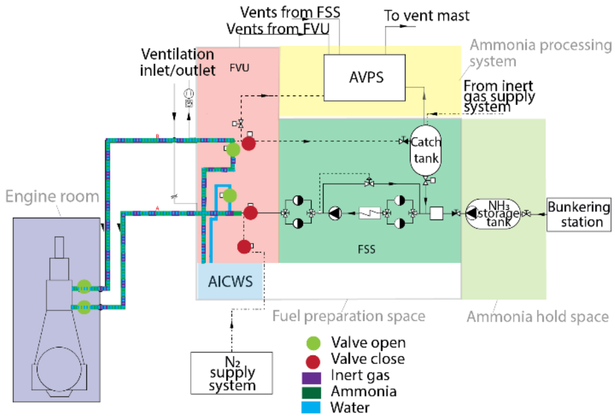


Figure 9. Ammonia fuel system purging: AICWS activation.

The annular space between the pipes is mechanically ventilated with a slight under pressure, refreshing the air 30 times per hour under normal conditions.

Ammonia detectors are strategically placed in the annular space ventilation, piston underside, and engine exhaust system for early leakage detection. In case of leakage, the engine trips to safe mode, triggering the purging process to ensure safe crew inspection.

Fuel piping and ammonia-containing components are designed to minimize mechanical damage risks during ship operations. Beyond design measures for ammonia's toxicity, operational precautions (i.e., adequate personal protection equipment and inherent procedures) for the crew during ammonia mode operation and dedicated crew training are essential.

During ammonia mode, or if the fuel system is pressurized (e.g., standby stop), crane operations near ammonia components should be prohibited to prevent damage. Additionally, components storage in the engine room should be minimized, and any spares must be securely fastened to prevent movement (e.g., lashing).

Following all the above considerations, built-in safety for the X-DF-A engine design was assured, resulting in the below aspects:

- Built-in leakage containment and detection system within the FIS, to mitigate risks in case of component failure.
- No recirculation of ammonia to the fuel supply system (FSS) during normal operation.
- An ammonia monitoring system for the piston underside and an updated gland box sealing concept to prevent crankcase contamination.

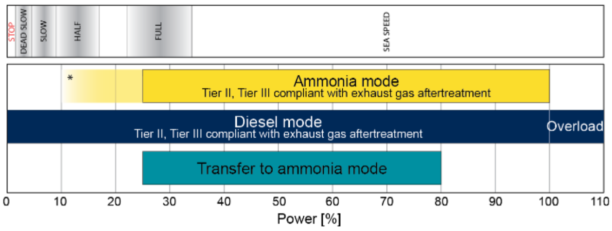
3 ENGINE MODES

The X-DF-A engine operates continuously on ammonia or diesel, with mode options across specific power ranges. Ammonia mode is available between 25% and 100% load, while diesel from 0% up to 100% load, as shown in Figure 10.

Changeover refers to switching between fuel modes. If the changeover introduces ammonia fuel, it is called a transfer. If the changeover between operating modes stops the use of ammonia fuel, thus, defaulting to diesel mode, then it is called an Ammonia Trip (AT). An AT happens immediately and can be either automatic (failure mode) or manually initiated by the operator. A transfer takes a few minutes to complete the necessary steps (as described next) and can only by initiated by the operator. The fuel split ranges are shown in Figure 10.

The engine starts in diesel mode, available from 0–110% Contracted Maximum Continuous Rating (CMCR) power (see Figure 10). In diesel mode, the main fuel injectors supply fuel, while the AICWS circulates water through the ammonia injectors, as aforementioned. At 25% CMCR power, a transfer to ammonia mode becomes available, as shown in Figure 10. During the transfer, injector cooling water is purged, preparing the engine for ammonia operation. The ammonia mode is currently available from 25 to 100% CMCR. However, it is the target to further extend the lower limit as shown in Figure 10.

Different operational steps are available for the X - DF-A engine. When starting ammonia mode, the FSS and engine are filled in a specific sequence.



* Ammonia mode is currently available from 25% to 100% CMCR power.
An extension of the operating range to a lower CMCR power is under development.

Figure 10. Available engine modes.

Table 4. Approximate fuel split (energy-based) for different operating modes.

Engine mode	Fuel split
Ammonia mode	5% MGO/MDO as pilot
	95 % ammonia fuel
Diesel mode	100% MGO/MDO/HFO

Liquid ammonia is pumped from the storage system to the engine via a Low-Pressure (LP) and a HP pump. During filling, excess ammonia recirculates to the catch tank until the return is cut-off and pressure is built up to the supply pressure.

During normal operation, ammonia is supplied by LP and HP pumps. All the fuel supplied to the engine is fully consumed, with no recirculation to the ammonia supply system. This greatly simplifies the system on the engine and on the FSS side.

If power is reduced below 25% CMCR (e.g., during maneuvering or pilot boarding), it is possible to have a stand-by stop of the ammonia mode for a defined period. Here, ammonia is still supplied to the engine but not injected, while the engine runs on diesel, ensuring a quick restart when needed.

If the stand-by stop exceeds the defined period, or in case of safety system activation, or in case of a specific request by the operator, the ammonia system is stopped and purged. Liquid ammonia is removed using inert gas, the AICWS activates, and the engine switches to diesel mode.

4 TESTING FACILITIES

WinGD's global testing network, with facilities in Switzerland, and in China, enables optimized resource use during product development [16]. This integrated system ensures rigorous testing aligned with WinGD's quality standards.

Testing begins with a Spray Combustion Chamber (SCC) — presented in Figure 11 — for detailed analysis of spray patterns, ignition, combustion, and emissions. Further evaluation takes place on various global test rigs, including dedicated fuel injection system test rigs (see Figure 12), where fuel injection components are meticulously analyzed. The final phase involves engine testing on two platforms: the Single Cylinder Engine (SCE52) in Winterthur, upgraded for X-DF-A experiments, and the RTX-8 in Shanghai, a multi-cylinder engine reproducing full-scale commercial operation.

A key objective of this framework is to leverage a two-tier testing strategy, utilizing the SCE52 for rapid setup changes and experimentation, alongside a multi-cylinder engine that closely replicates commercial engine configurations. This approach enables faster iteration and detailed validation at both conceptual and operational levels, maximizing testing efficiency and development effectiveness.

4.1 Spray Combustion Chamber

The SCC is a unique test facility providing the capability to investigate injection behaviour and spray/fuel admission characteristics, as well as ignition/combustion behaviour and subsequent emission formation. The versatile set-up allows experiments to be carried out under engine-like conditions (i.e., peak combustion pressure up to 20 MPa) relevant to large marine engine combustion systems. At the start of fuel injection/admission, realistic pressure, temperature, and flow (swirl) conditions can be achieved due to a sophisticated pressure vessel/heat regeneration system which supplies heated and pressurised process gas (air, N_2) and exhaust gas recirculation mixtures to the combustion chamber [11]-[14].

This essential R&D tool enabled detailed investigations of key components and parameters early in the ammonia technology development phase, even when using a prior version of the injection hardware [15]-[17]. Later, the fuel injection system of the SCC has been adapted to operate with the actual X-DF-A design incl. ACU as well as newly developed ammonia injection valve (see Figures 5 and 6).

For pilot ignition, an upstream injector delivers a small amount of diesel to initiate and enhance the subsequent combustion of the downstream main injection. Optical accessibility is provided by sapphire windows and allows the application of various (laser) optical and advanced measurement techniques to investigate the processes and underlying phenomena of ammonia fuel injection, ignition and subsequent combustion and emission formation.

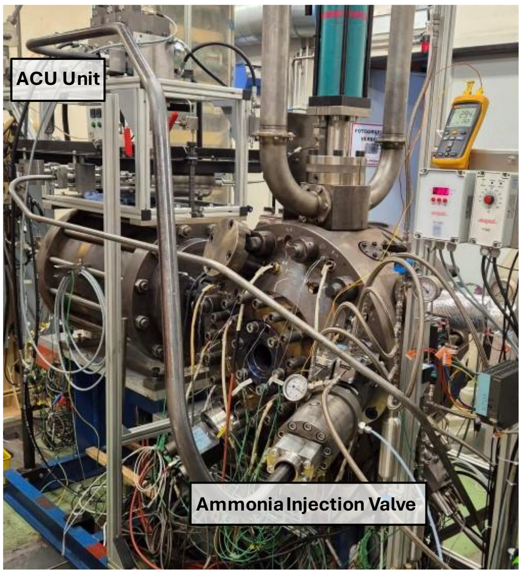


Figure 11. WinGD's spray combustion chamber with ammonia fuel injection system setup.

4.2 Hydraulic Rig

The ammonia and methanol fuel injection rigs available in Shanghai and Winterthur (see Figure 12) are key component test facilities, designed for versatility across all available X-DF-A bore sizes. To accurately replicate on-site conditions, the rigs' injection systems are built identically to those on the engines.

These rigs facilitate the validation of injection systems and hydraulic designs through performance and functional testing. Hydraulic performance tests include shot-to-shot dispersion analysis for consecutive injections and across different injectors, endurance testing, and the creation of injection maps for the engine control system. Functional tests also verify the various procedures of the injection system (fuel purging, filling, changeover to water and ammonia). Additionally, they assess the engine's safety features, such as the annular space venting system.

Safety and compliance are paramount at these facilities. The control system includes alarm monitoring, ensuring prompt detection and response to anomalies. Specifically for ammonia, the facilities include storage for pressurized liquefied gas and a vent treatment system to neutralize any collected ammonia vapor, ensuring safe handling and testing of ammonia fuel.

Figure 12: Fuel injection rig.

4.3 Single Cylinder Engine

The SCE52 is a test engine based on the X52 platform and fully upgraded with X-DF-A features, as seen in Figure 13.

The key specifications of the SCE52 are presented in Table 5. While featuring only one cylinder, the crankcase and crankshaft are designed for three cylinders to keep vibrations acceptably low. To replicate air and exhaust flow dynamics similarly to those of a multi-cylinder engine, the intake and the exhaust piping volumes are deliberately oversized.

The engine is equipped with a turbocharger commonly used in four-stroke engines. To emulate the turbine flow area and turbocharger efficiency characteristics of two-stroke engines, the turbocharging system incorporates additional features. A high-capacity electric blower is installed upstream of the turbocharger compressor, complemented by a large wastegate.

The SCE52 is equipped with fully instrumented combustion chamber components for wall temperature measurement (piston, liner, cover, and exhaust valve), fast data acquisition for dynamic measurements and extensive low-frequency data acquisition integrated with advanced emission measurement devices.

This setup allows WinGD experts to analyze the impact of all tuning parameters and hardware changes on critical engine components and engine performance characteristics.

Figure 13 The SCE52 engine in Winterthur.

Table 5. Single Cylinder Engine - SCE52.

Characteristic	Unit	Value
Number of cylinders	-	1
Bore	m	0.520
Stroke	m	2.315
Bore/Stroke	-	4.45
Displacement / Cylinder	m3	0.492
Rated power / Cylinder	kW	1807
Rated speed	RPM	105

*Revolution Per Minute (RPM).

4.4 Multi-Cylinder Engine

Full-scale testing is currently being conducted on the RTX-8 test engine, located in Shanghai. The RTX-8 is a four-cylinder hybrid engine, integrating features from the WinGD X52 and X62 engine platforms. Specifically, it combines the bore size of the X52 with the structural framework of the X62 frame size. This configuration facilitates enhanced operational limits, particularly regarding maximum firing pressures and engine torque. Initially designed for operation with diesel fuel, it was enhanced with X-DF-A features. The main characteristics of the RTX-8 are summarized in Table 6.

Table 6. Multi-cylinder test engine RTX-8.

Characteristic	Unit	Value
Number of cylinders	-	4
Bore	m	0.520
Stroke	m	2.658
Bore/Stroke	-	5.11
Displacement / Cylinder	m3	0.564
Rated power / Cylinder	kW	2520
Rated speed	RPM	103

5 ENGINE CONCEPT APPROVAL IN PRINCIPLE

Since the initial development and conceptualization began in late 2021 — when a consolidated regulatory framework for ammonia as a marine fuel was yet to be established — preliminary rules from Classification Societies were closely monitored (i.e., see [8],[18] [19]). Additionally, expertise from other industrial sectors was incorporated to guide the process [20]. Since the challenges with ammonia being used as fuel are completely novel, it was necessary to chart an own course to receive an official Approval in Principle (AiP) with the marine Classification Societies, along with the key stakeholders of first pilot projects (see Introduction). This allowed to fully address safety while proceeding with the X-DF-A technology development.

A continuous risk assessment was conducted along the development stages, ranging from system risk assessment, detailed hardware failure mode analysis and technical design reviews. Overall, the goal was to safely develop a new engine concept while engaging with Classification Societies towards a first AiP.

After the initial engine concept was developed, a comprehensive Hazard Identification (HAZID) exercise in a joint development pilot project was undertaken, to chart the concept against possible risks. While the HAZID focused mainly on the entire vessel, the fuel supply system and the engine played a vital role as the change to ammonia as a fuel affected these systems almost absolutely, and novel concepts had to be examined (see Figures 8 and 9). Therefore, under the able guidance of the Classification Societies, the risk assessment was performed diligently keeping safety and safe operation as the unconditional objectives.

As the full risk assessment is exceeding the scope in the present work, the major concerns and their mitigations addressed during the HAZID are summarized next for WinGD's engine safety concept.

5.1 Engine Room Safety

In this section the Machinery Space also referred herein as Engine Room (ER) is analyzed and the main HAZID points addressed in the X-DF-A safety concept are presented.

5.1.1 Gas Safe Machinery Space

A principal point in the HAZID was for the ER to remain a safe area for personnel, by ensuring no release of ammonia from the engine or leakages from the fuel piping. This includes all the fuel piping within the ER from fuel preparation space and the high-pressure supply piping part to the engine.

This HAZID point was primarily mitigated by a gas safe machinery space arrangement, which implies that a single failure within the fuel system shall not lead to an ammonia release into the machinery space. This is as explained in Par. 2.4 with a cleverly designed DW piping system with the annular space monitoring concept. The ammonia gas safe machinery space concept is fundamental to the ER remaining safe for personnel and a safe area during operation.

5.1.2 Material Compatibility

A next important HAZID risk identified was concerning material compatibility issues and corrosion risks to the components and fuel piping, to mitigate risks associated with loss of containment, leakages or other failures due to material degradation over time.

WinGD X-DF-A material selection involved comprehensive evaluation of the different compartments of the engine to check the components' material compatibility with ammonia. Suitable metals, polymers and coatings were carefully chosen based on the type of exposure to ammonia such as exposure to liquid anhydrous ammonia for fuel piping, vaporized or gaseous ammonia for combustion spaces, combustion products or condensates also for combustion spaces, and possible ammonia water mixtures for the exhaust gas drains.

For metals, materials that are not prone to stress-corrosion cracking were chosen. For the HP fuel supply part, all components which can be in contact with liquid anhydrous ammonia are made of stainless-steel grades and suitable sealing materials. Suitable coatings were applied wherever the components are hindered by the low self-lubricating property of ammonia. Thorough internal investigations have confirmed that risks due to material compatibility issues have been well mitigated.

5.1.3 Risk of Ammonia in Crankcase

The risk of unsafe levels of ammonia concentration in the crankcase prior to opening or before maintenance was addressed.

WinGD X-DF-A engine layout with its newly developed stuffing box (see Par. 2.4) design provides a gas tight separation of the piston underside area to the crankcase, resulting in no gaseous ammonia leaking to the crankcase. An ammonia detection arrangement is in place in the piston underside area, monitoring continuously for any ammonia concentrations. The implemented piston underside gas detection provides a higher level of safety compared to crankcase ammonia detection, preventing any possible ammonia ingress into the crankcase, and ensuring the space is safe for personnel before maintenance.

5.2 Safety outside the Engine Room

Since the ER is just one of the HAZID nodes, and safety outside it often depends on engine operations, key recommendations on the engine and its interfaces are briefly covered below.

5.2.1 Inerting and gas freeing of the Ammonia system

The HAZID identified is the risk of unsafe concentration levels of ammonia within the fuel piping to the engine before maintenance. The concern relates to operators not knowing or being able to determine when the fuel piping is safe for maintenance.

As explained in Par. 2.4, the X-DF-A purging strategy thoroughly addresses the hazard of clearing ammonia from the piping before any maintenance operation is performed. The purging strategy controls the ammonia purging to a level below the required 25 ppm which is considered as the threshold workspace exposure limit [10]. After the full purging sequence is executed, the system is rendered safe for maintenance and personnel.

5.2.2 Operational Releases of Ammonia

The HAZID point focuses on concerns related to high concentrations of ammonia released via the fuel supply system vent masts during normal operation, or in a foreseeable failure situation.

WinGD X-DF-A engine has no direct release of ammonia to the atmosphere during normal engine running conditions. However, during a transfer from ammonia to diesel, or when a safety relevant action is requested from the safety system, the main supply of ammonia must be stopped and purged out. Certain operations such as bleeding the lines from the double block and bleed arrangements, releases from pressure relief valves (safety release), resulting in a momentary release of ammonia are normally contained in the Ammonia Vapor Processing System (AVPS), ref. to Figures 8-9. The AVPS shall be capable of reducing the ammonia discharged to air from the abovementioned operations or during any failure situations to concentrations not exceeding specified threshold values via the vent masts.

Although the AVPS shall contain such releases, it must be noted that these are not continuous releases during normal operation but only instantaneous releases over a short period of time via the vent mast, which is then quickly diluted to safe levels without compromising safety of personnel. Therefore, regulations prescribed specific limit values aimed at continuous releases may result in higher complexities of the AVPS (to be designed to contain continuous releases) which may not be required from a safety perspective.

5.3 World’s first Ammonia Engine Approval in Principle

The HAZID recommendations and their mitigations played a key role in developing the WinGD 2-stroke ammonia engine Safety Concept, ensuring safe handling and operation [9]. In a final step, the X- DF-A concept documents, the risk assessment results and the engine safety concept, were instrumental in paving the way for the world’s first Approval in Principle for a 2-stroke marine dual fuel ammonia engine with the Classification Society Lloyd’s Register in September 2023.

This was followed by successful AiP agreements with other Classification Societies as China Classification Society, and Bureau Veritas.

6 RESULTS

In this section the results of the testing facilities are discussed to show how the major aspects of the ammonia engine technology have been validated.

6.1 Injection Performance

The results indicate that the injector system demonstrates overall good functionality, reliable behavior over time, and strong alignment with simulation data. Figure 14 illustrates an exemplary injection curve of an X-DF-A injector over 50 cycles, highlighting actuation oil pressure, fuel high pressure, and injection rate. Minimal shot-to-shot dispersion confirms the injector's reliable behavior.

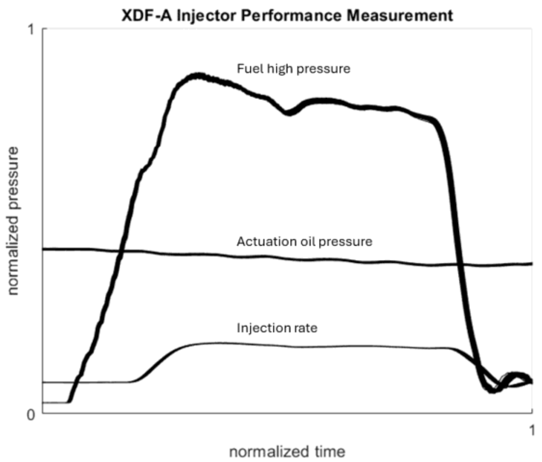


Figure 14. Exemplary injection curve over 50 cycles.

The fuel HP curve shows nearly an ideal behavior: a rapid initial rise as the injector opens, reaching peak pressure, followed by a sustained pressure phase, and finally a rapid drop as the injector closes. The steady-state pressure during the sustained phase is reflected in the injection rate curve, ensuring a constant injection velocity. This behaviour was consistently observed across multiple injectors tested. Reliable performance was validated over tens of thousands of injection cycles, confirming a robust operation.

The actuation oil unit has separately been successfully tested under varying conditions, including temperatures up to 55 °C and oil pressures up to 350 bar, enduring up to one million cycles. Inspections of both the injector and the actuation oil unit reveal robust performance and durability, validating the system's capability to operate under demanding conditions.

6.2 Spray Combustion Chamber Results

As aforementioned (see Par. 4), WinGD's SCC plays a key role in the successful development of ammonia technology. This facility allowed rapid and detailed investigations of key components and parameters already several years ago at an early stage in the technology development process and is following WinGD's future fuel technology development approach described here [15][17].

Figure 15 shows the ammonia injection and ignition process via flame luminosity measurements — near main injector field of view — at a typical engine operating condition of 50% load with pre-injection pressure and temperature of 116 bar and 860 K, respectively. At 0.24 ms after the start of ammonia injection (aSOInj.), the diesel pilot flame is approaching the main injector location and thus the ammonia spray that has just started to admit fuel. In Figure 15, right at 3.92 ms aSOInj. interaction of the diesel pilot flame and the ammonia spray plumes can be seen.

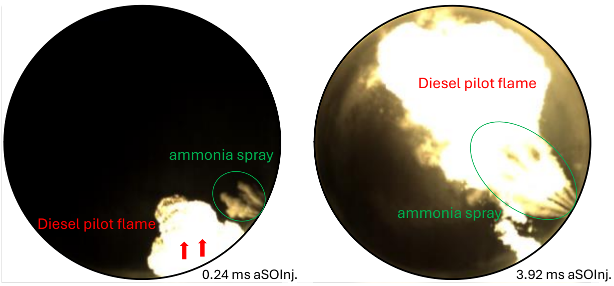


Figure 15: Flame luminosity images showing the beginning of ammonia injection (left) and interaction of pilot and ammonia fuel spray (right).

The ammonia combustion characteristics of the newly developed injection system at the SCC are shown in Figure 16, by means of an exemplary experiment carried out at the same engine operating condition of 50% load with a pressure and temperature before injection of 116 bar and 860 K, respectively.

The Rate of Heat Release (RoHR) and its cumulative (cum. RoHR) of a one pilot/one main injector setup is shown for two injection timings with an engine-like pilot diesel energy share of approximately 5%. Initially, the small pilot fuel combustion can be clearly seen.

After the interaction of the diesel flame with the ammonia spray and the onset of ammonia combustion, the corresponding RoHR can be seen. Increasing the injection duration (see orange dashed curve in Figure 16) results in a very similar combustion behaviour, but with a correspondingly longer RoHR and a higher proportion of energy released.

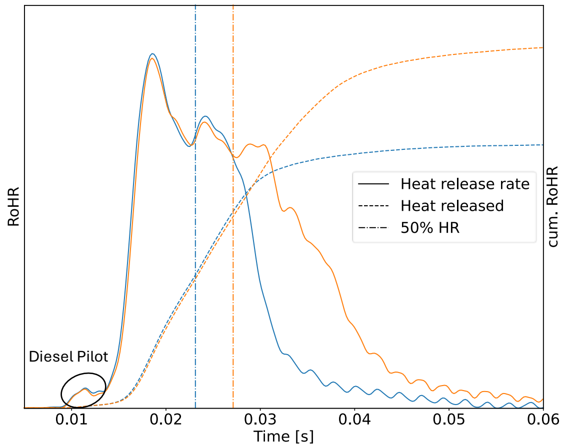


Figure 16: SCC heat release characteristics of two different injection durations with one pilot / one ammonia injector setup.

6.3 Single Cylinder Engine Results

The SCE52 test engine serves as the primary platform for developing advanced engine tuning strategies to optimize both efficiency and emissions performance. This engine enables controlled testing across a wide range of operating conditions and allows precise variations of key tuning parameters, based on key engine indicators like exhaust gas emissions and hot parts' temperatures.

The SCE52 has been operated over the entire load range, up to 100% R1 in ammonia mode. Current testing activities focus on the following variations:

1 Injector nozzle tip modifications, including variations in spray angles and effective flow area.
2 Pilot fuel share ratio, which influences ignition quality and combustion stability.
3 Injection timing parameters, i.e., the offset between pilot and main fuel injections, as well as the injection timing of the main fuel injection.
4 Injection pressure control for both pilot and main fuel injection events.
5 Injector activation strategies, adjusting the number of active pilot and main injectors.
6 Exhaust valve closing timing, impacting trapped air and residual gas.
7 Fuel handling system, engine transfer modes, engine control system validation.

6.3.1 Ammonia Combustion Characterization

The acquired measurement data confirm the expected performance characteristics when operating on ammonia with diesel pilot fuel share ratios as low as 5% (i.e., energy-based) at 100% engine load. A benchmark comparison against conventional diesel operation is presented here.

Figure 17 illustrates the in-cylinder pressure and the RoHR as a function of crank angle. The optimal piloting strategy effectively mitigates ammonia's poor self-ignition tendency. This is attributed not only to the injection rate's dominant influence on the RoHR but also to ammonia's favorable mixing behavior with air. Consequently, a faster burn rate and fast end of combustion are achieved.

Figure 18 provides an overview of selected raw engine emissions as measured on our X-DF-A test engine platform, benchmarked against the corresponding emissions in diesel mode at both 50% (left) and 100% (right) engine load. Despite the earlier combustion phasing and the resulting higher peak firing pressure (see Figure 17), NOx emissions in ammonia mode (Figure 18-a) are substantially lower compared to those observed during diesel operation. This underscores a substantial advantage in terms of indicated efficiency for ammonia operation.

Figures 18- b and c further emphasize the remarkably low engine out emissions of NH_3 and the climate-relevant N_2O. These results demonstrate that X- DF-A engines can achieve high efficiency while maintaining low concentrations of harmful pollutants. Please note that the performance values on commercial X- DF- A engines may vary depending on engine rating.

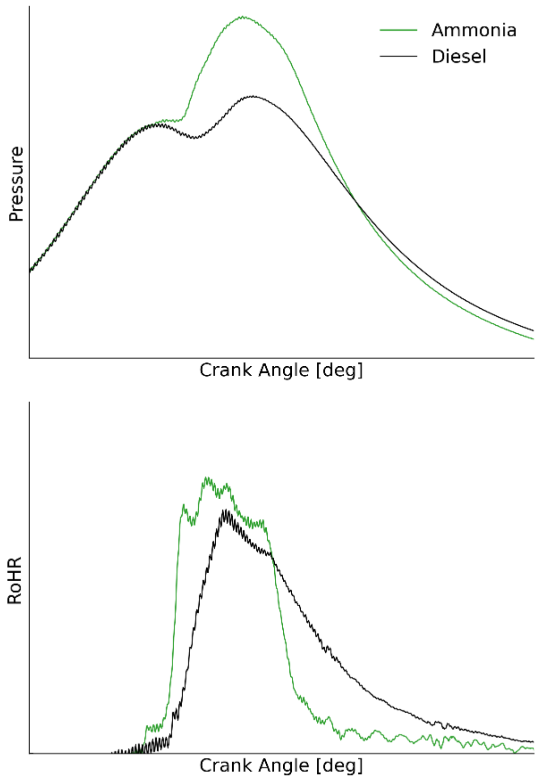


Figure 17: 100% engine load results in Tier II.

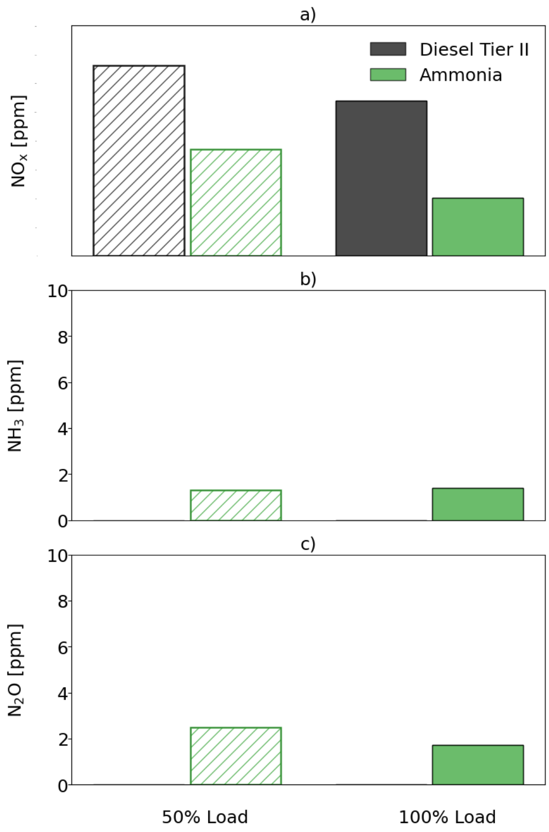


Figure 18: Selection of X-DF-A relevant emissions at 50% and 100% engine load; diesel NO_X emissions are compliant with Tier II limits.

6.3.2 Tuning Potential Analysis

To identify optimal operating points with high efficiency and low emissions, extensive tuning variations were conducted on the SCE52. One of the key characteristics of dual-fuel ammonia combustion is the sequence of diesel pilot and ammonia injection timings, which significantly impacts performance and emissions. As a demonstration example, a focused study was carried out to examine the effect of diesel pilot injection timing, while keeping the ammonia injection timing constant.

The results of this variation, conducted at low engine load with an increased diesel fuel share ratio, are presented in Figures 19-20. The findings highlight a clear optimum in terms of NH_3 and N_2O emissions, demonstrating that proper dwell timing selection can lead to very low emissions. Notably, dwell timing emerged as a highly influential tuning parameter, yet its optimal range is broad and robust, allowing for stable operation across a range of conditions. These results underline significant optimization opportunities for reducing engine-out emissions, further reinforcing the potential of dual-fuel ammonia combustion as a high-efficiency, low-emission solution.

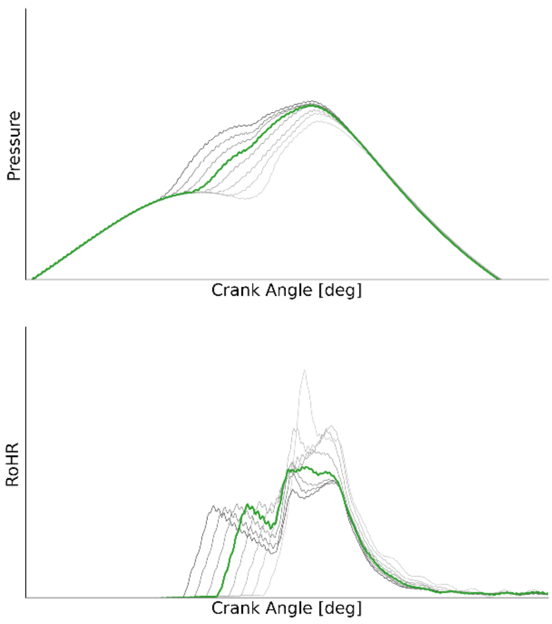


Figure 19: In-cylinder pressure and RoHR for a dwell variation in ammonia operating mode - variation of the pilot diesel injection timing.

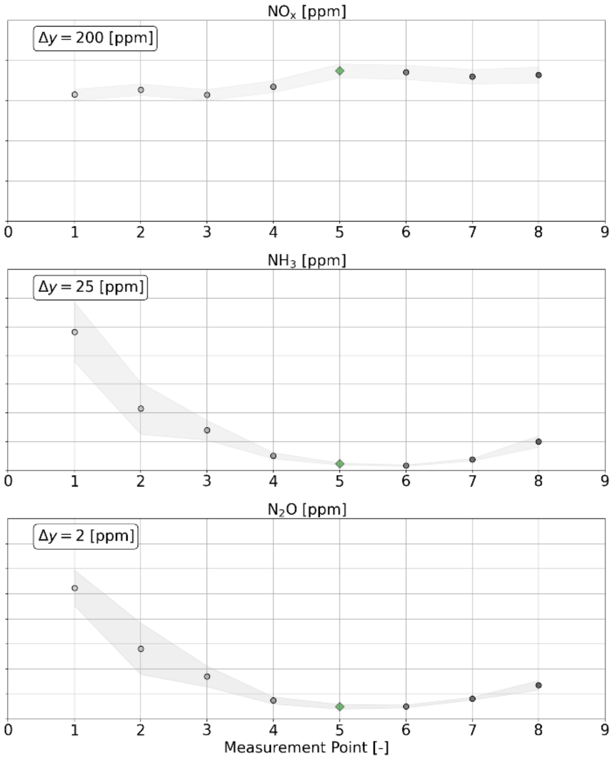


Figure 20: Engine out raw emissions for diesel pilot injection timing variation in ammonia operating mode.

7 CONCLUSIONS

This work presents the design innovations introduced in WinGD's ammonia engine technology for the new X-DF-A family. Global testing facilities have been utilized to validate fundamental combustion aspects and optimize potential tuning strategies.

In summary, the key findings demonstrate:

- A thorough risk assessment and safety features integrated into the design, leading to the world's first engine Approval in Principle.
- Reliable injection behavior of the X-DF-A fuel injection system.
- A detailed characterization of ammonia dual-fuel combustion using an optically accessible combustion chamber.
- Additional flexibility in engine tuning enabling lower NO_x emissions despite higher peak firing pressures compared to diesel.
- Exceptional combustion and emission performance on ammonia mode with diesel pilot fuel share ratio as low as 5%, assuring NH_3 slip below 10 ppm and N_2O below 3 ppm.

A follow-up publication is planned to report on full-scale testing currently underway on the RTX-8 multi-cylinder engine. The X-DF-A design will be implemented in the world's first commercial large-bore ammonia engine, which is currently in final assembly and scheduled for its factory acceptance test in Q2 2025.

8 DEFINITIONS, ACRONYMS, ABBREVIATIONS

Herein definitions, acronyms, abbreviations and symbols are presented in alphabetical order.

ACU Actuation Control Unit

AEGL Acute Exposure Guideline Limits

AICWS Ammonia Injector Cooling Water System

AiP Approval in Principle

aSOInj Start of ammonia injection

AT Ammonia Trip

AVPS Ammonia vapor processing system

BSEC Brake Specific Energy Consumption

CH_3OH Methanol

CI Cetane Index

CMCR Contracted Maximum Continuous Rating

CO_2 Carbon Dioxide

$CO_{2,eq.}$ Equivalent Carbon Dioxide emissions

cum.RoHR Cumulative Rate of Heat Release

DW Double Wall

EAS Exhaust aftertreatment system

EPA Environmental Protection Agency

ER Engine Room

ESS Engine safety system

FIS Fuel injection system

FL Flammability Limit

FSS Fuel supply system

FVU Fuel Valve Unit

GTD General Technical Data

GHG Green-House Gas

H_2 Hydrogen

HAZID Hazard Identification

HP High-Pressure

H*v* Vaporization enthalpy

IMO International Maritime Organization

LHV Lower Heating Value

LNG Liquefied Natural Gas

LP Low-Pressure

MDO Marine diesel oil

MN Methane number

N_2O Dinitrogen Monoxide

NH_3 Ammonia

NO_X Nitrogen Oxide

OCV Oil Control Valve

pc Critical pressure

RON Research Octane Number

RoHR Rate of Heat Release

RPM Revolution per minute

RTX-8 Multi-cylinder test engine

SCC Spray Combustion Chamber

SCE52 Single Cylinder Engine

T*ai* Auto-ignition temperature

T*b* Boiling temperature

T*c* Critical temperature

tEbT Exhaust temperature before Turbine

T*fp* Flash point temperature

X-DF-A WinGD's Ammonia Engine Technology

ρl Liquid density

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