High-Pressure Dual-Fuel Combustion Systems for Sustainable Maritime Engines

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17th June 2025

MariNH$_3$

Clean, green ammonia engines for maritime

RICARDO

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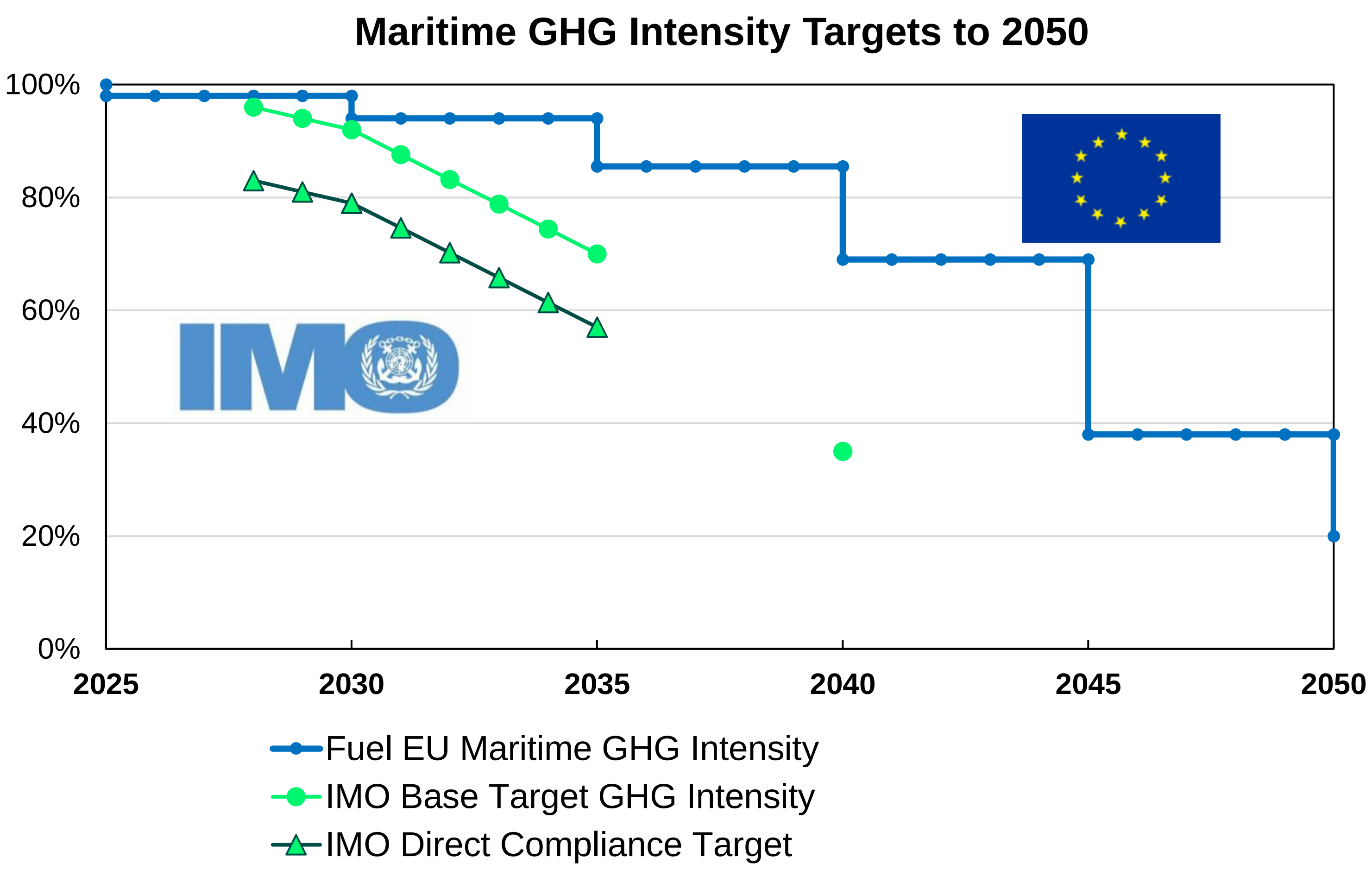
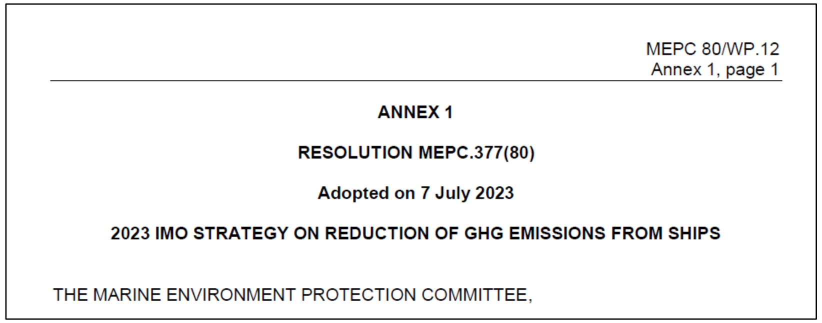
The IMO has committed the industry to net-zero greenhouse gas emissions




MEPC 80/WP.12
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ANNEX 1

RESOLUTION MEPC.377(80)

Adopted on 7 July 2023

2023 IMO STRATEGY ON REDUCTION OF GHG EMISSIONS FROM SHIPS

THE MARINE ENVIRONMENT PROTECTION COMMITTEE,

Sustainable fuel pathways to de-fossilize transport

- Mainstream
- Viable but niche
- Unlikely

		Fossil	Biofuels ICE			Synthetic Fuels ICE				Electrification				
		Gasoline/ Diesel	Methane (Natural Gas)		Ethanol Methanol	Drop in E-Fuels	Green Hydrogen		Green Ammonia	H_2 Fuel Cell Hybrid Electric		Battery Electric		Power [kW]
		Liquid	Gas	Liquid	Liquid	Liquid	Gas	Liquid	Liquid	Gas	Liquid	Battery		
Road	Motorcycle	Mainstream	Viable but niche	Unlikely	Viable but niche	Viable but niche	Viable but niche	Unlikely	Unlikely	Viable but niche	Unlikely	Mainstream	LD	20 - 100
Road	PC & LCV	Mainstream	Viable but niche	Unlikely	Mainstream	Viable but niche	Viable but niche	Unlikely	Unlikely	Viable but niche	Unlikely	Mainstream	LD	50 - 500
Road	Bus	Mainstream	Mainstream	Unlikely	Viable but niche	Viable but niche	Viable but niche	Unlikely	Unlikely	Mainstream	Unlikely	Mainstream	MD	200 - 400
Road	HD Truck	Mainstream	Viable but niche	Mainstream	Viable but niche	Viable but niche	Mainstream	Unlikely	Unlikely	Viable but niche	Viable but niche	Mainstream	Heavy Duty	350 - 600
Non Road	Off-Highway	Mainstream	Viable but niche	Unlikely	Viable but niche	Viable but niche	Mainstream	Unlikely	Unlikely	Viable but niche	Unlikely	Viable but niche	Heavy Duty	56 - 400
Non Road	HD Marine	Mainstream	Unlikely	Viable but niche	Viable but niche	Mainstream	Viable but niche	Viable but niche	Viable but niche	Unlikely	Mainstream	Unlikely	Heavy Duty	56 - 400
Non Road	Mining	Mainstream	Unlikely	Viable but niche	Viable but niche	Mainstream	Unlikely	Viable but niche	Viable but niche	Unlikely	Viable but niche	Viable but niche	Extreme Duty	500 - 2,000
Non Road	Rail	Mainstream	Unlikely	Viable but niche	Viable but niche	Mainstream	Unlikely	Viable but niche	Viable but niche	Unlikely	Viable but niche	Viable but niche	Extreme Duty	500 - 10,000
Non Road	Marine Prop	Mainstream	Viable but niche	Viable but niche	Mainstream	Mainstream	Unlikely	Viable but niche	Mainstream	Unlikely	Viable but niche	Unlikely	Extreme Duty	500 - 20,000

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Key alternatives to fossil fuels for marine engines

Carbon-neutral fuels

Biofuel

- HVO (renewable diesel), FAME and others
- Liquid fuels with high energy density
- Drop-in fuels require no engine change
- Feedstock not fully scaleable

Methanol

- Liquid fuel with reasonable energy density
- SI and dual-fuel CI combustion options
- Mainstream engines available
- Bunkering relatively straightforward

Ammonia

- Liquid fuel but lower energy density
- SI combustion for ammonia-hydrogen blends
- CI combustion for ammonia-diesel dual-fuel
- Severe toxicity challenge

Hydrogen

- Compressed gas or cryogenic liquid
- Major energy density challenge
- Significant engine changes required
- Safety (explosion) challenges

Zero-carbon fuels

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Many **combustion concepts** are possible for ammonia engines

Main fuel	Ammonia				
Supporting fuel	Diesel		Hydrogen		None
Ignition	Compression ignition (pilot)		Spark ignition (pre-chamber option)		Novel ignition system
Cycle	Diesel (diffusion combustion)	Otto (pre-mixed combustion)			
Fuel ratio	Ammonia up to 85–95% by mass		Ammonia up to 95% by mass		Mono-fuel ammonia
Main fuel injection	Direct injection (HP)	Gas port or single-point injection in manifold			
Supporting fuel injection	Direct injection		H_2 injected as gas blend with ammonia	Injected separately in port or manifold	N/A
Air-fuel ratio	Lean				
Aftertreatment	SCR + ASC (ammonia slip catalyst) + N_2O catalyst option				
Redundancy	Dual fuel: Diesel		None	Potentially hydrogen only at low power	None

Not exhaustive – other combinations possible

Source: Ricardo Analysis

Ricardo study – Decision matrix used to select diesel-ammonia combustion concepts

- Assessment criteria used
  - **Technology maturity**
  - **Engine performance**
  - **Durability**
  - Cost impact
  - Thermal efficiency
  - Greenhouse gas emissions
  - Pollutant emissions
  - Ammonia slip
  - Fallback capability

ID	Fuel 1	Fuel 2	Ignition	Cycle	Fuel 1 injection	Fuel 1 timing	Fuel 2 injection	Fuel 2 timing	Score
BL	*Diesel*	*LNG*	*Pilot*	*Otto*	*In-cylinder*	*Late compression*	*Intake system*	*Intake*	*136*
1	**Diesel**	**Ammonia**	**Pilot**	**Otto**	**In-cylinder**	**Late compression**	**Intake system**	**Intake**	**110**
2	Diesel	Ammonia	Pilot	Otto	In-cylinder	Late compression	In-cylinder	Early intake	87
3	Diesel	Ammonia	CI	RCCI	In-cylinder	Mid compression	Intake system	Intake	82
4	**Diesel**	**Ammonia**	**CI**	**Diesel**	**In-cylinder**	**Late compression**	**In-cylinder**	**Late compression**	**104**
5	None	Ammonia	CI	PPC	None	N/A	Intake system	Intake	44

Marine engine application

- Industrial vessels with four-stroke ammonia engines will precede passenger vessels
- Leading applications could include
  - Offshore support vessels (OSVs)
  - Dredging ships

Engine type	Four-stroke Medium-speed
Cylinder bore	~500 mm
Boost system	Two-stage turbocharging
Engine speed	600 rev/min
Rated power per cylinder	>1,200 kW

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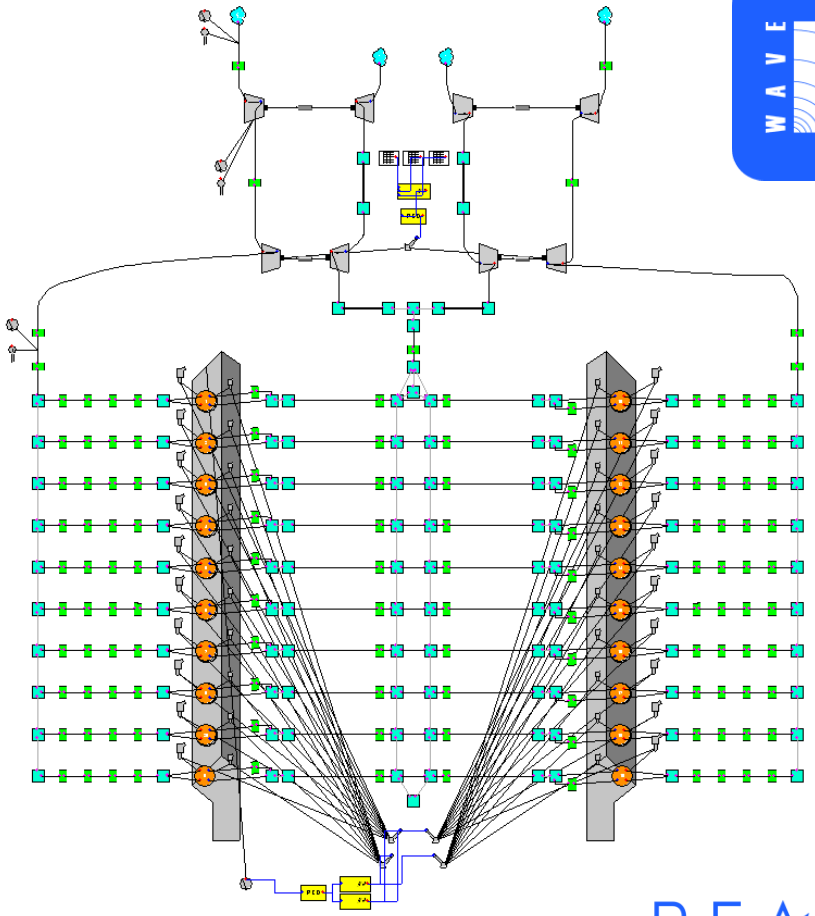
1-D performance simulation

- Simulation study undertaken in Realis WAVE

Engine speed [rev/min]	600
BMEP [bar]	23
Excess air factor	1.4
Diesel fuel fraction	0.03, 0.1, 0.2, 0.4
Diesel fuel LHV [MJ/kg]	43.06
Ammonia fuel LHV [MJ/kg]	18.60
Diesel fuel stoichiometric AFR	14.22
Ammonia fuel stoichiometric AFR	6.05



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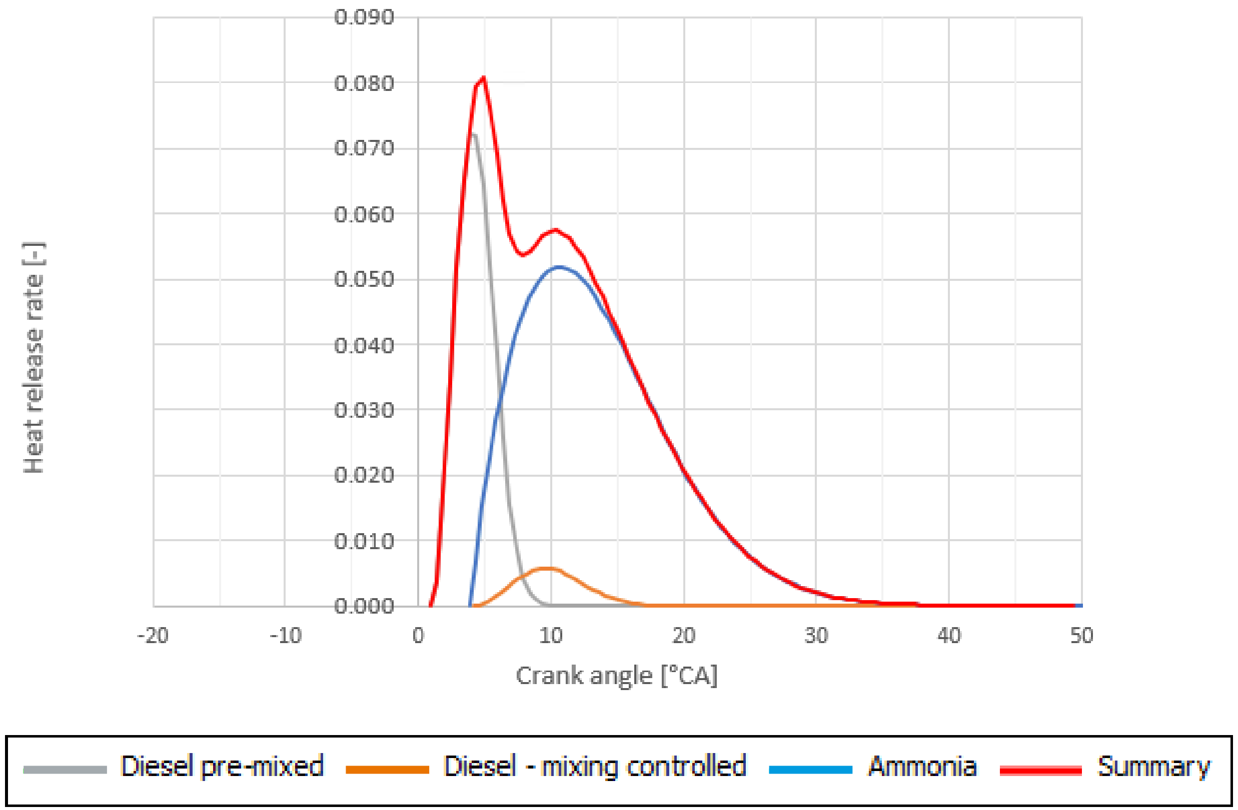
Dual-fuel combustion model

- A Multi-Wiebe combustion model was used to model dual-fuel combustion
- Multi-Wiebe combustion profile sums up the burn-rate of different fuels
  - Final combustion profile combines three curves
    - Diesel premixed (Wiebe curve 1)
    - Diesel mixing controlled (Wiebe curve 2)
    - Ammonia (Wiebe curve 3)
    - Overall heat release is sum of above (Multi-Wiebe)
- The input for each Wiebe curve is phasing, duration, Wiebe exponent and mass ratio and these parameters are used to modify combustion profile

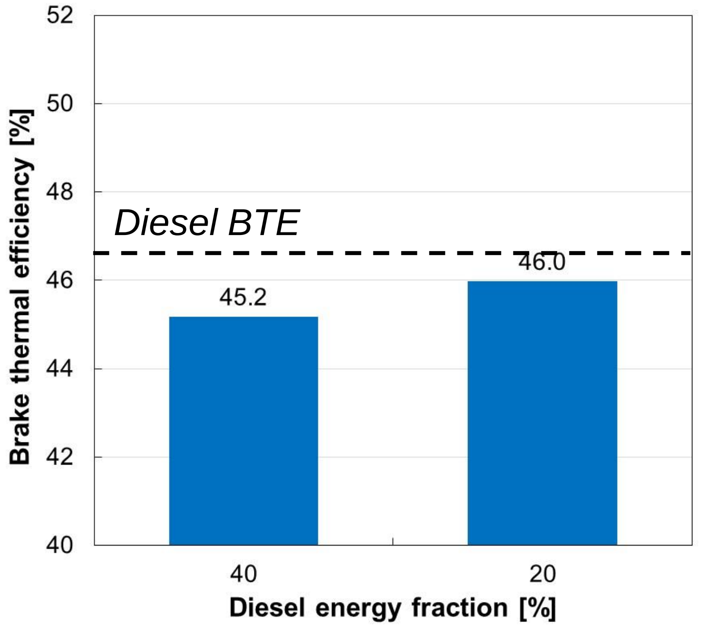


Engine performance and efficiency

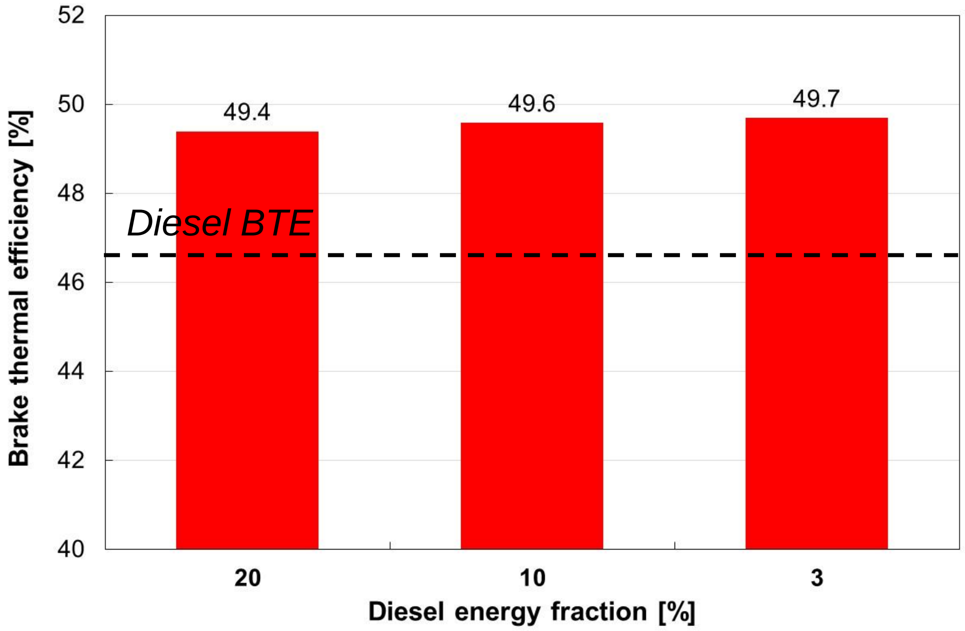
- Each of the ammonia engines were able to match the **performance** of the baseline engine (23 bar BMEP)
- The **brake thermal efficiency** of the LPDF engine is slightly reduced compared with diesel-only operation, but for HPDF combustion is can be increased by several percentage points

	Diesel	LPDF	HPDF
Engine speed [rev/min]	600	600	600
BMEP [bar]	23	23	23
Diesel fraction	100	**20**	**10**
Excess air ratio	2.6	1.4	1.4
Intake man. pressure [bar]	6.7	4.0	4.0
Turbine inlet temp [°C]	538	598	557
Peak cylinder pressure [bar]	190	166	182

LPDF



HPDF

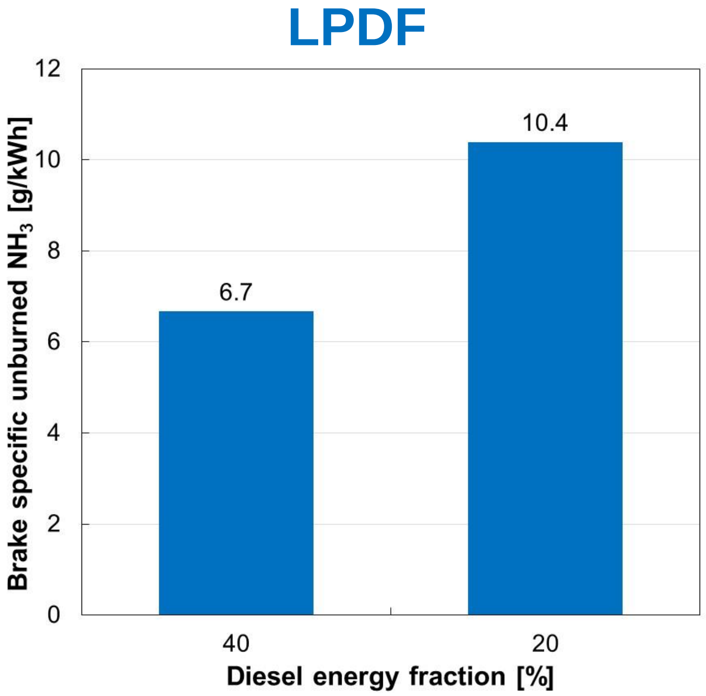


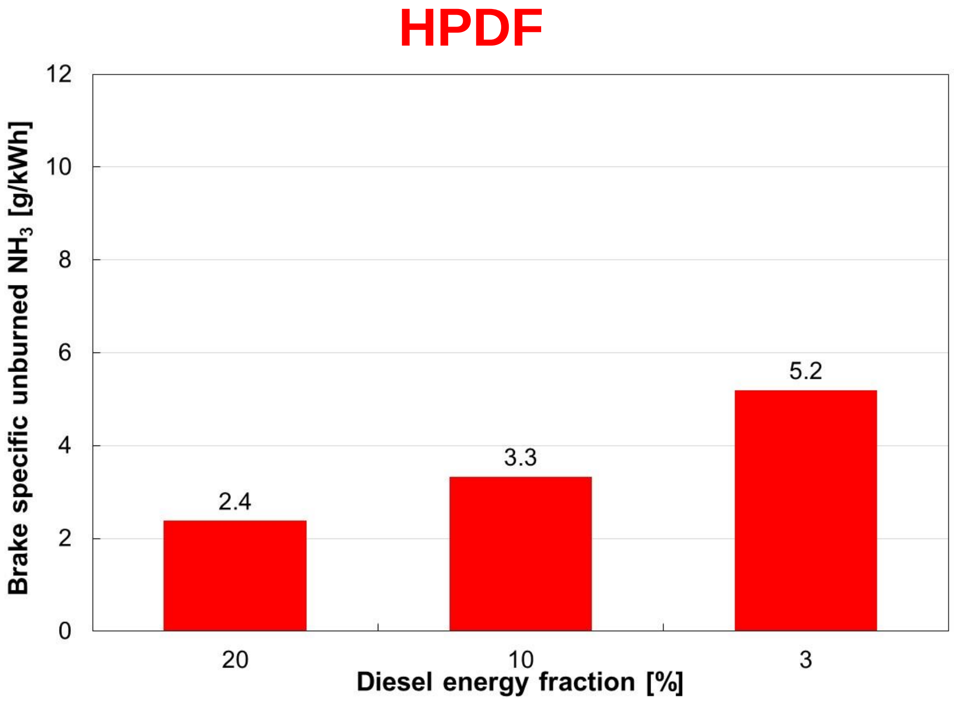
Source: Ricardo analysis

Engine-out emissions

- HPDF has reduced unburned ammonia emissions compared with LPDF
- NOx and N_2O emissions are also significantly reduced for the HPDF concept
- For both LPDF and HPDF operation molar NOx and NH_3 are balanced at approx. 1:1

	Diesel	LPDF	HPDF
Engine speed [rev/min]	600	600	600
BMEP [bar]	23	23	23
Diesel fraction [%]	100	**20**	**10**
Excess air ratio	2.6	1.4	1.4
CO_2 [g/kWh]	539	83	39
NOx [g/kWh]		27.0	8.5
N_2O [g/kWh]		0.87	0.03





Source: Ricardo analysis, Li et al. (2022) ‘A comparison between low- and high-pressure injection dual-fuel modes of diesel-pilot-ignition ammonia combustion engines’

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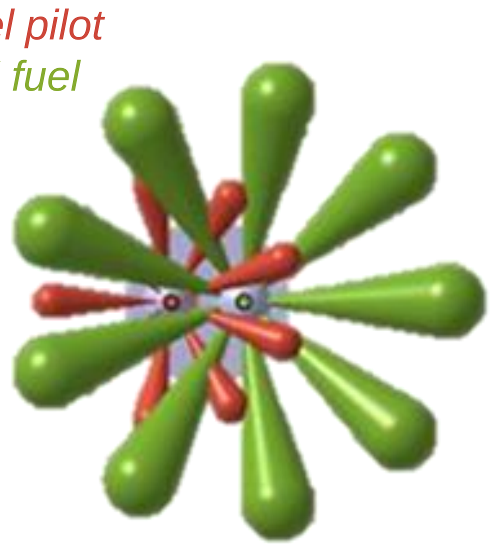
High-pressure dual-fuel engines need advanced fuel injectors

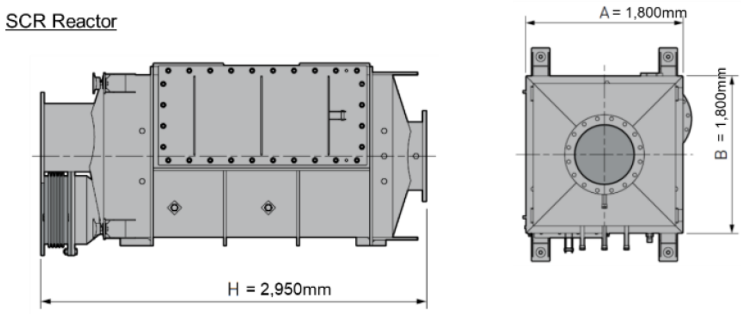
- HPDF combustion systems need high-pressure multi-fuel injectors to achieve late injection of both diesel and liquid ammonia
  - This means at least two injector needles are required
- The cost, complexity and availability of these fuel systems is perhaps the biggest challenge for HPDF engines
- Woodward L' Orange, OMT (now part of Acceleron) and Westport have developed these injectors, among others

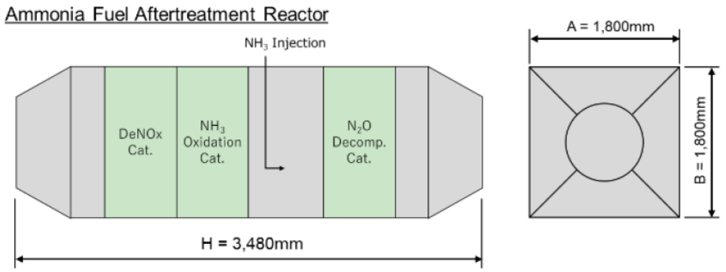


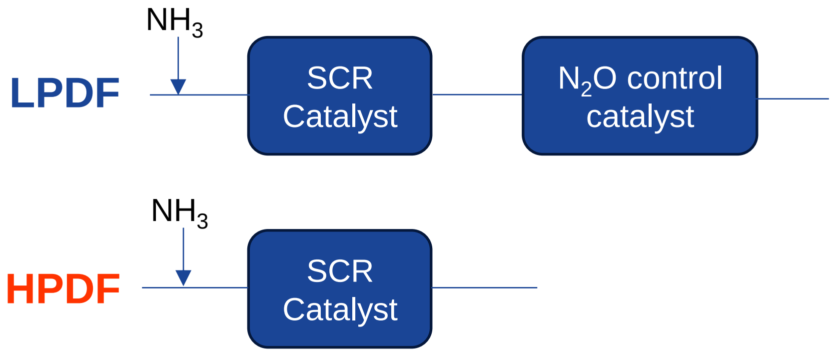
Source: Woodward L 'Orange

Exhaust aftertreatment and N_2O emissions

- All concepts require **SCR control of NOx emissions**
  - For both LPDF and HPDF operation molar NOx and NH_3 are balanced and hence additional NH_3 injection is not required (in this mode and condition)
- Meeting **IMO Tier III limits** (2.50 g/kWh NOx) with SCR and an engineering margin of 20%
  - **LPDF** NOx was 27 g/kWh, requiring **93%** conversion efficiency
  - **HPDF** NOx was 8.5 g/kWh, requiring **76%** conversion efficiency
- **LPDF** operation produces N_2O emissions of 0.87 g/kWh (231 g/kWh CO_{2eq})
  - This equates to **43%** of the GHG of the baseline diesel engine
- **HPDF** operation produces N_2O emissions of 0.03 g/kWh (8 g/kWh CO_{2eq})
  - This equates to **1.5%** of the GHG of the baseline diesel engine







Source: Ricardo analysis, Daihatsu

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Conclusions

- The IMO has committed the industry to **net-zero** greenhouse gas emissions
    - A number of sustainable fuel solutions will be required, including green ammonia
- A range of combustion approaches are possible for ammonia
    - Ricardo are concentrating on diesel-ammonia dual-fuel combustion
- High-pressure dual-fuel (HPDF) combustion delivers higher efficiency and lower N_2O and unburned NH_3 emissions compared with LPDF
- Fuel injection equipment for HPDF engines remains a significant challenge