March 16, 2025
Carbon-Free Fuel Combustion Workshop
14th US National Combustion Meeting (USNCM) @Boston

Ammonia Power Generation Technology Development and Challenges in Combustion Technology

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Company Profile (As of March 31, 2024)

IHI

Year of establishment
1853

Capital
107.1 Billion yen

Revenue(Consolidated)
1,322.5 Billion yen
(fiscal 2023)

Number of employees (consolidated)
28,237

Works
6

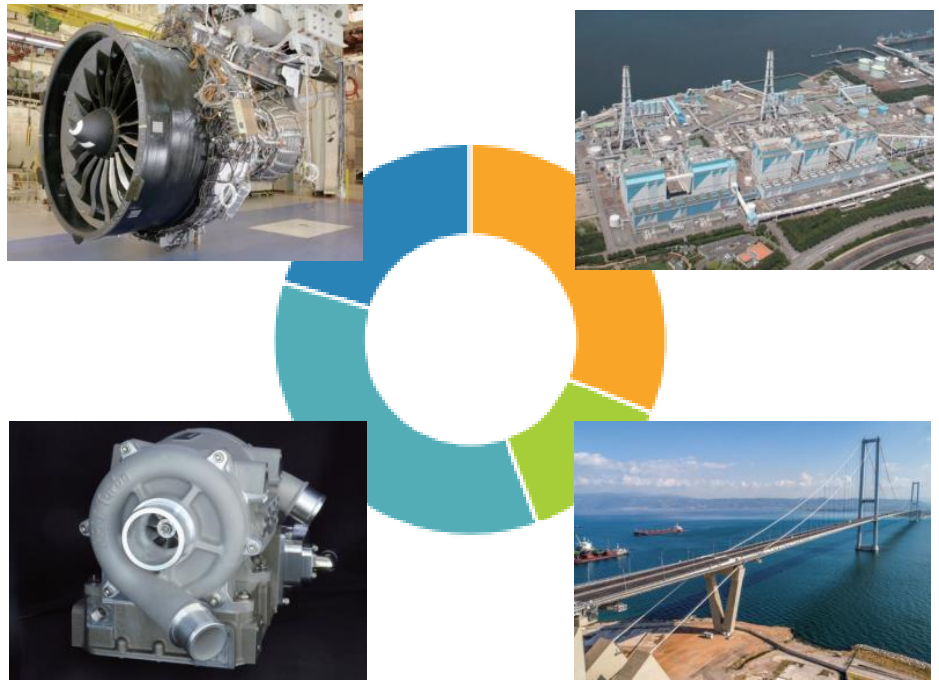
Branches in Japan
8

Business Development Bases
21
(as of April 1, 2024)

Group companies in Japan
60
[Subsidiaries: 41 Affiliates: 19]

Overseas Group companies
135
[Subsidiaries: 113 Affiliates: 22]

Revenue Composition by business areas (Consolidated/fiscal 2023)



Resources, Energy & Environment	31%
Social Infrastructure	13%
Industrial Systems & General-Purpose Machinery	35%
Aero Engine, Space & Defense	20%

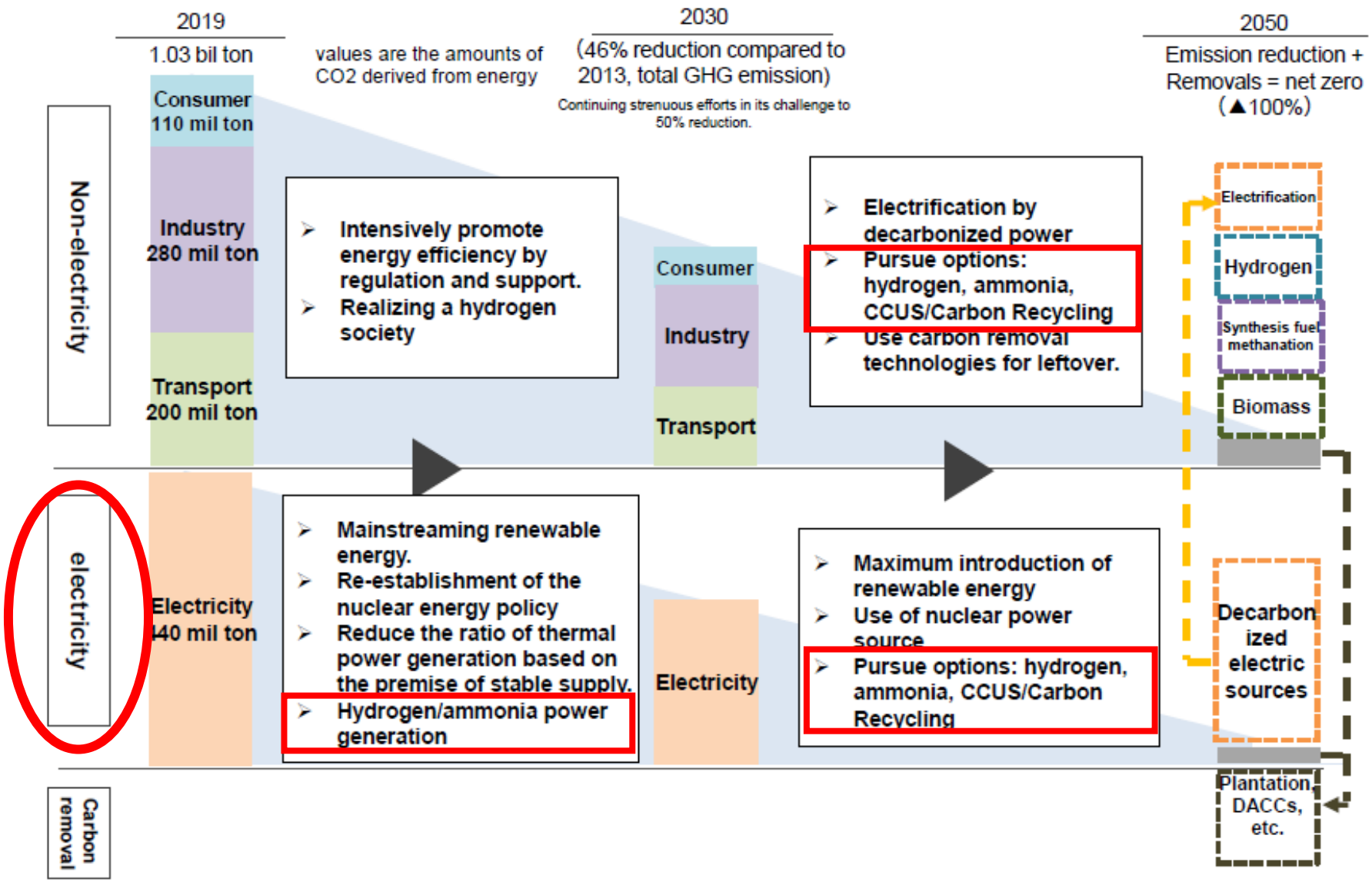
Note : The total may not be 100% owing to the exclusion of "Other" and "Adjustments".

Ammonia value chain (AVC)

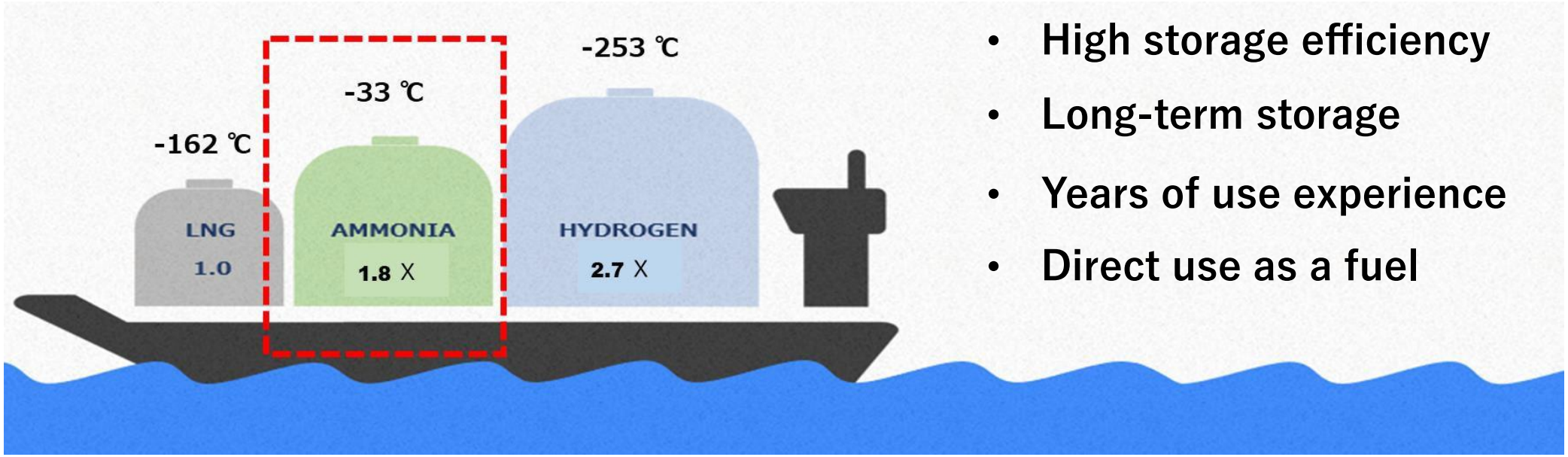
Japan Green Growth Strategy for Carbon Neutrality in 2050

Target of carbon neutral energy mix in 2050

- Renewable (50-60%)
- Nuclear
  Thermal with CCS (30-40%)
- H2 and Ammonia (10%)



Ammonia as an Energy Carrier

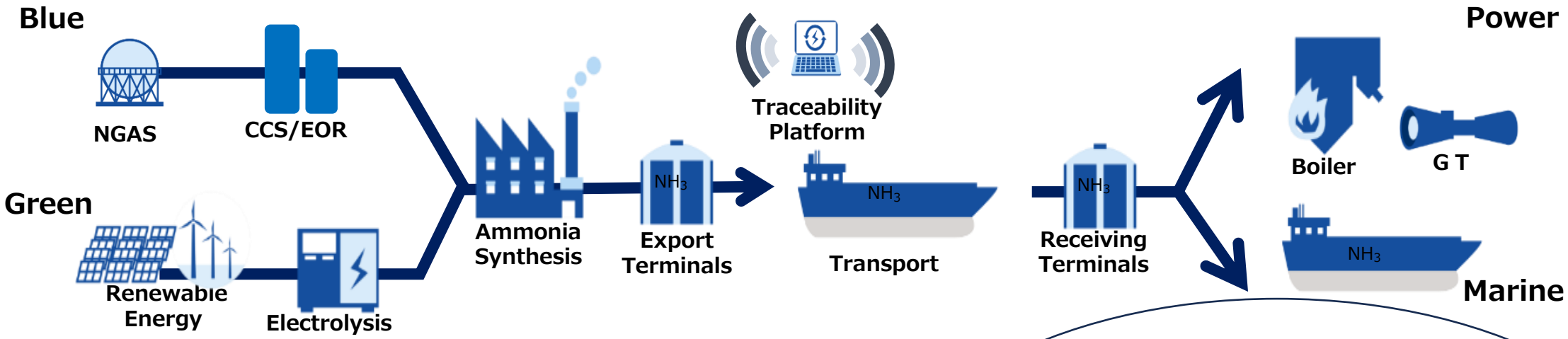


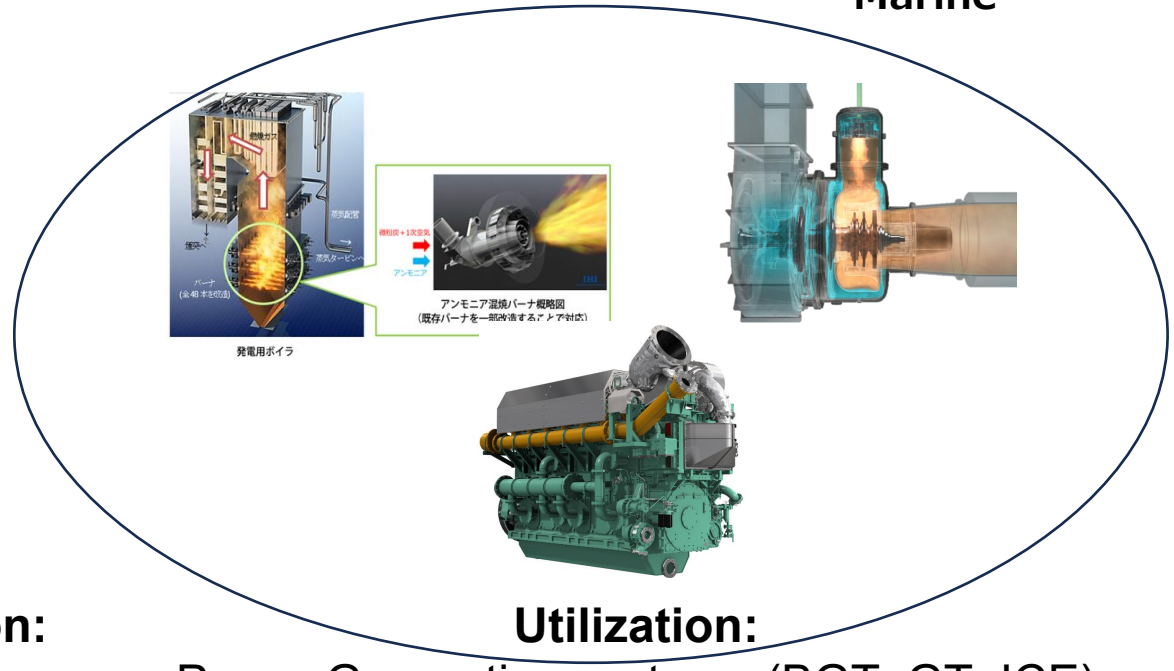
- High storage efficiency
- Long-term storage
- Years of use experience
- Direct use as a fuel

Characteristics of Liquefied Gas Fuels

	LNG	LNH_3	LH_2
Energy Density (MJ-LHV/l)	22.6	12.7	8.5
Tank Material	SUS (9%Ni)	C/S (SLA325A)	SUS
Boiling Point (℃)	-162	-33	-253
Storage Period	14 Days	Long Term	7 Days

Ammonia Value Chain and Key Eeuipments





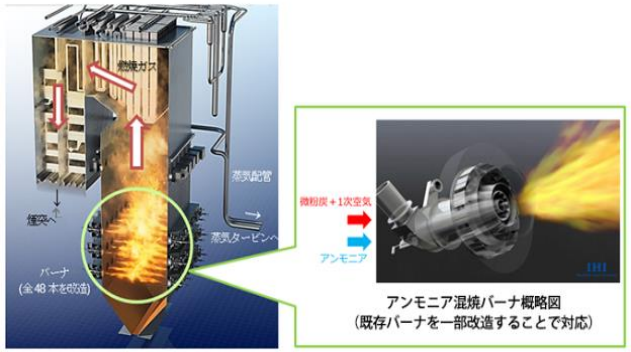
Production:
Water Electrolyzer

Storage & Transportation:
Tank and Burge

Utilization:
Power Generation systems (BGT, GT, ICE)

Ammonia Power Generation Technology

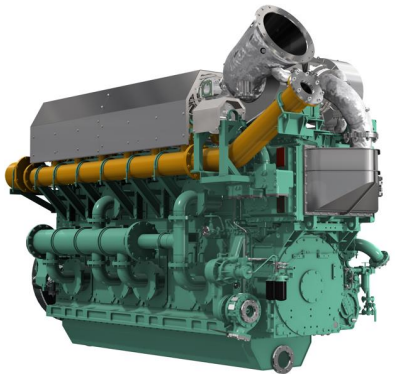
Boiler turbine generator



発電用ボイラ

Gas turbine

Diesel engine

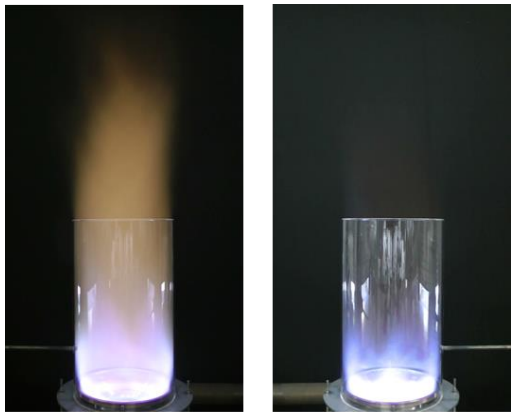


FY2014-2020	SIP 戦略的イノベーション創造プログラム Cross-ministerial Strategic Innovation Promotion Program / NEDO	R&Ds and Feasibility Study
FY2021-present	NEDO Green Japan, Green Innovation	Technology Demonstrations

Ammonia as a fuel

Challenges in combustion

- Stable combustion
- Emission (NOx,N2O,NH3) control
- Lower flame temperature and emissivity
- Nitriding

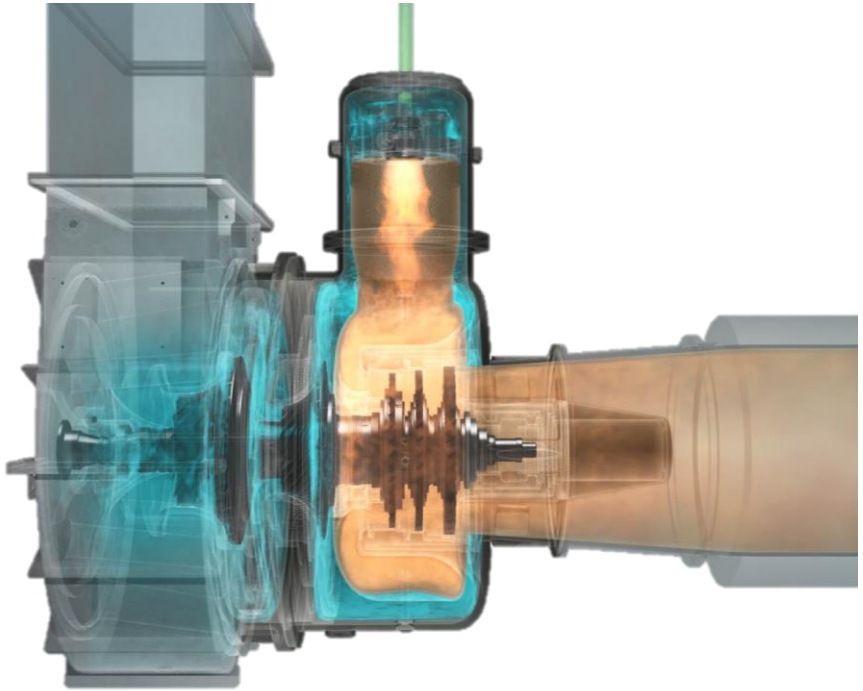


90% ammonia　Methane

Fuel	NH3	H2	CH4	C3H8
Heating value LHV (MJ/kg)	18.6	120	50.0	46.4
Flammability limit （Equivalence ratio)	0.63~1.40	0.10~7.1	0.50~1.7	0.51~2.5
Adiabatic temp. （°C)	1800	2110	1950	2000
Max. burning velocity (m/s)	0.07	2.91	0.37	0.43
Auto ignition temp. (°C)	650	520	630	450

IHI Ammonia Firing IM270 Gas Turbine

- Developing a fully ammonia-powered 2MW-class gas turbine.
- Built an ammonia gas turbine test facility in Yokohama Works, Japan.
- Achieved 50% - 100% load operation with pure liquid ammonia combustion in 2022.



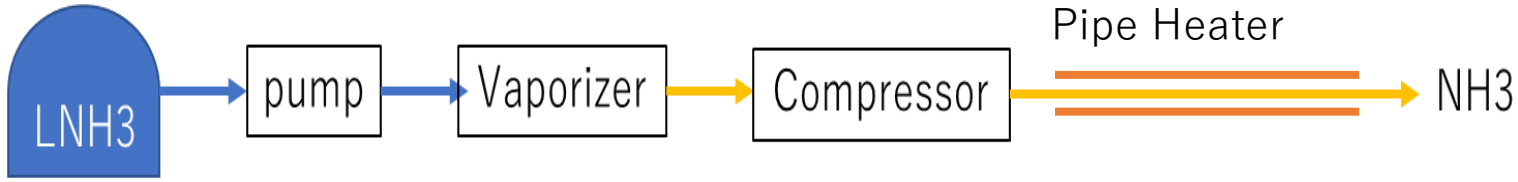
IHI IM270 gas turbine

Ammonia GT test facility & Fuel Supply System at IHI Yokohama

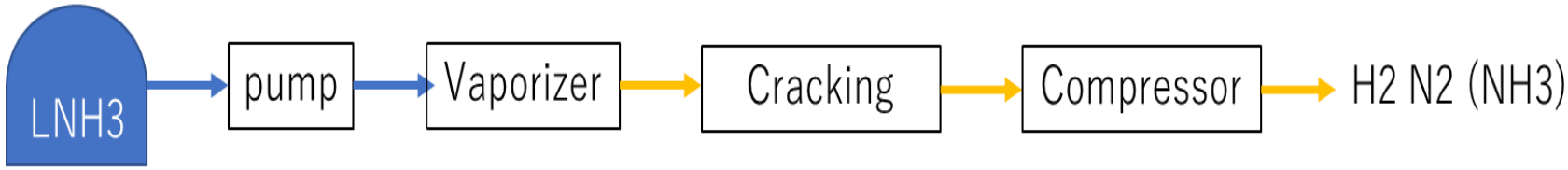
Fuel supply method of ammonia

1. Liquid ammonia (LA)
   - Simple
   - Fast response
   - Loss of Latent heat
   - Suitable for high pressure combustion system

2. Gas ammonia (GA)
   - Heat of vaporization
   - Re-liquification in hi-P
   - Suitable in low pressure combustion system



3. Cracked ammonia (CA)
   - Chemical regeneration
   - Complexity
   - Suitable for Industrial applications

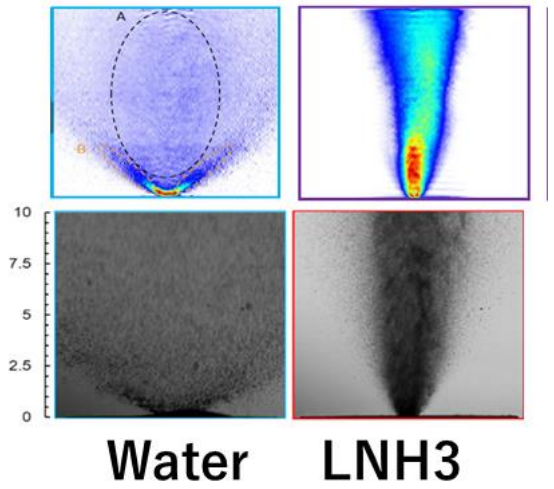


Ammonia Gas Turbine Combustor

IHI

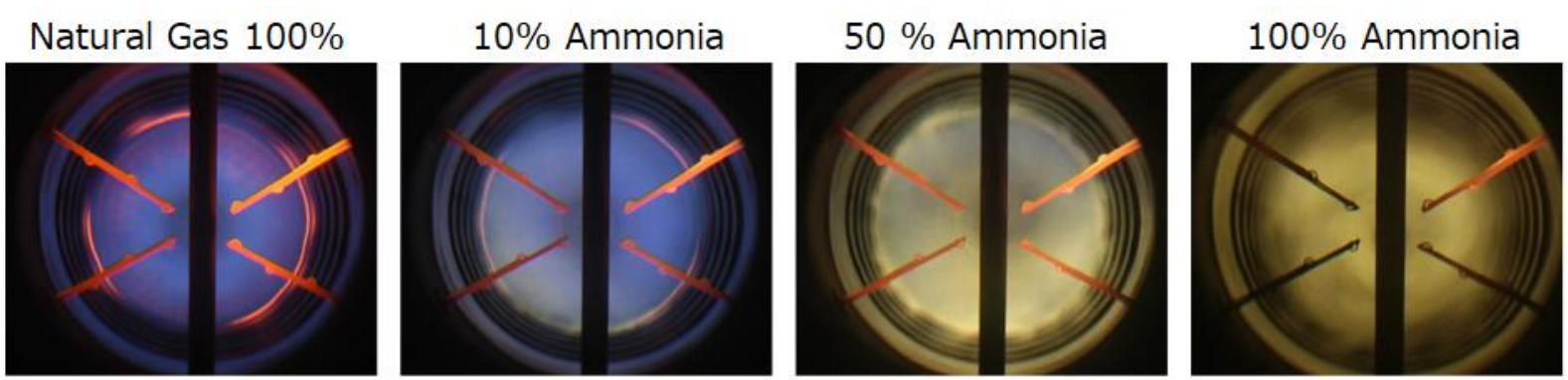
Direct Liquid Ammonia Spray

- **Flash spray**
- **Good atomization and temperature drop**
- **Simple supply system**
- **Fast load changing**

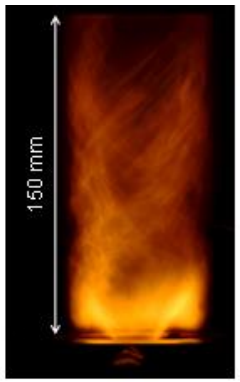


Kobayashi,
Tohoku University

Stable combustion of 100% ammonia firing by high swirl flow and mixing control



Flame of combustor test rig at 1 bar

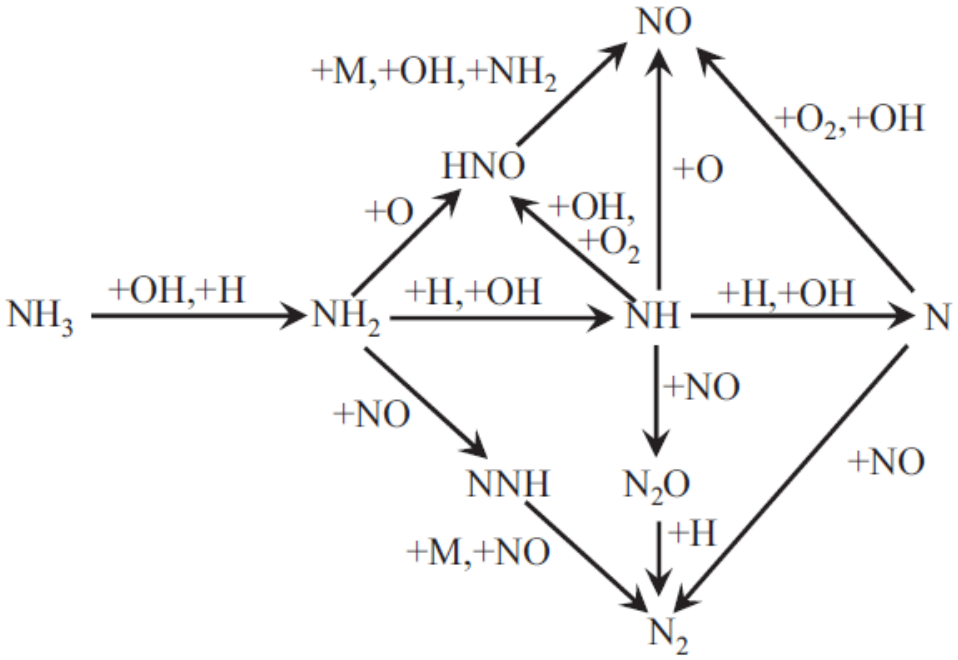


Liquid spray flame

Emission control by two-stage combustion

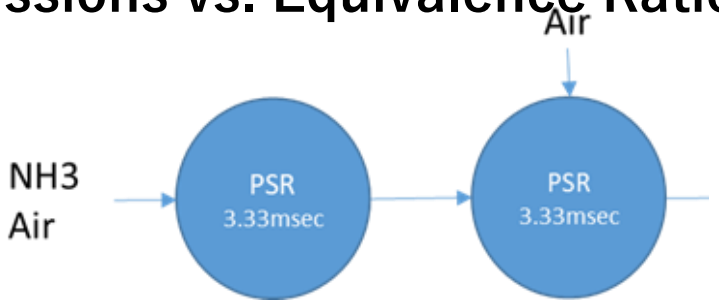
NH3 Reaction Mechanism

Oxidizing to NOx in lean mixture

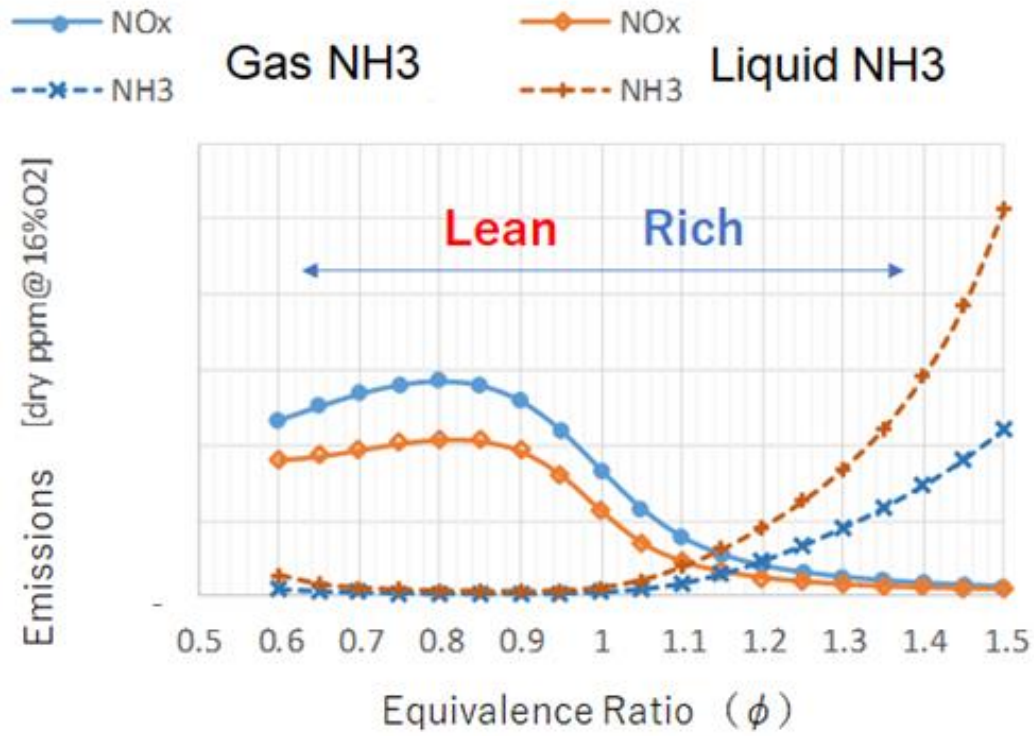


Reducing to N2 in rich mixture

Emissions vs. Equivalence Ratio(ϕ)



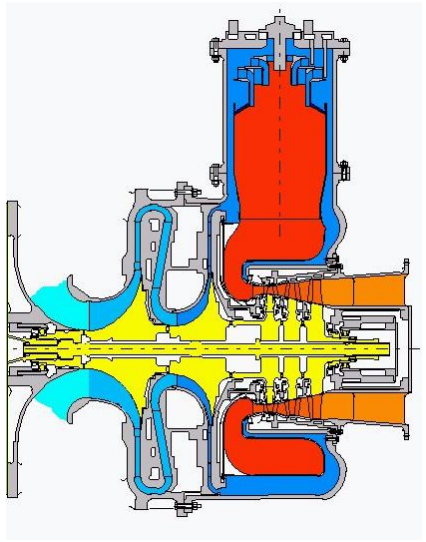
Simulation

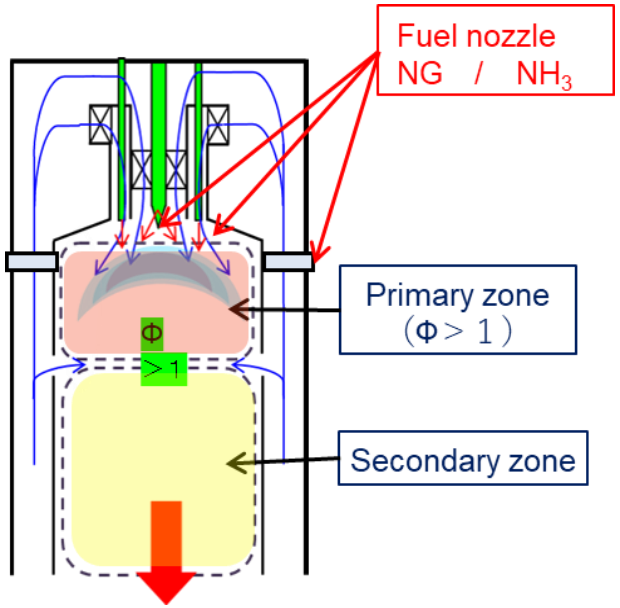


The first 100% Liquid Ammonia-fired Gas Turbine

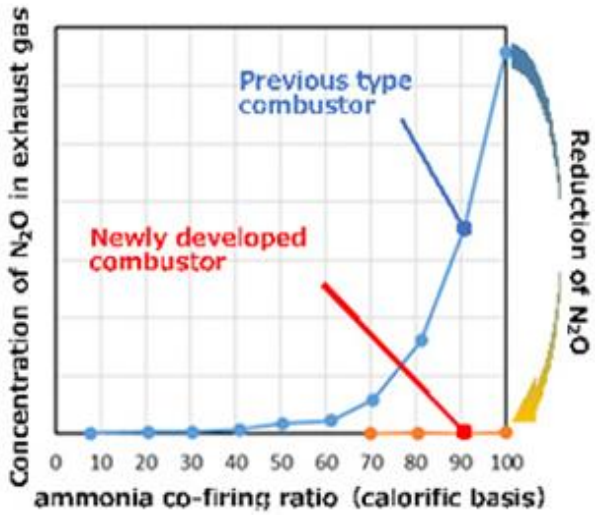
- **Rich and lean two stage combustion system**
- **Successful operation from NG to 100% liquid Ammonia**
- **99.8% GHG reduction**
- **NOx emissions meet Japan's urban regulations with SCR**

$$GHG_{Reduction} = 1 - \frac{(W_{CO2} + 286\,W_{N2O})A}{(W_{CO2})NG}$$

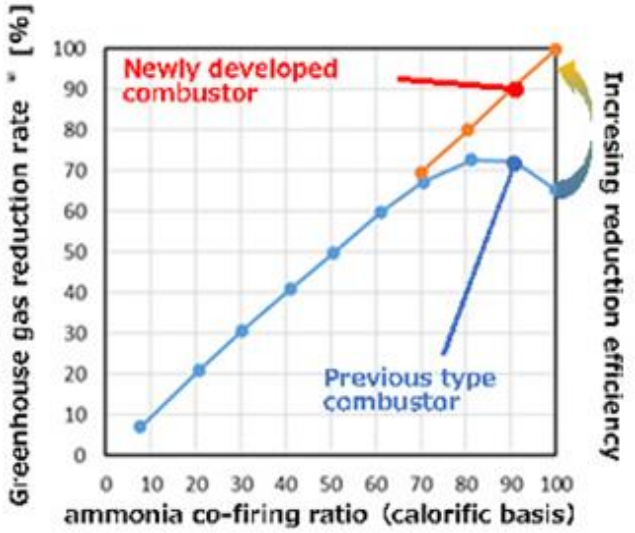




2MW single can NH3 spray combustor gas turbine (IHI, IM270)



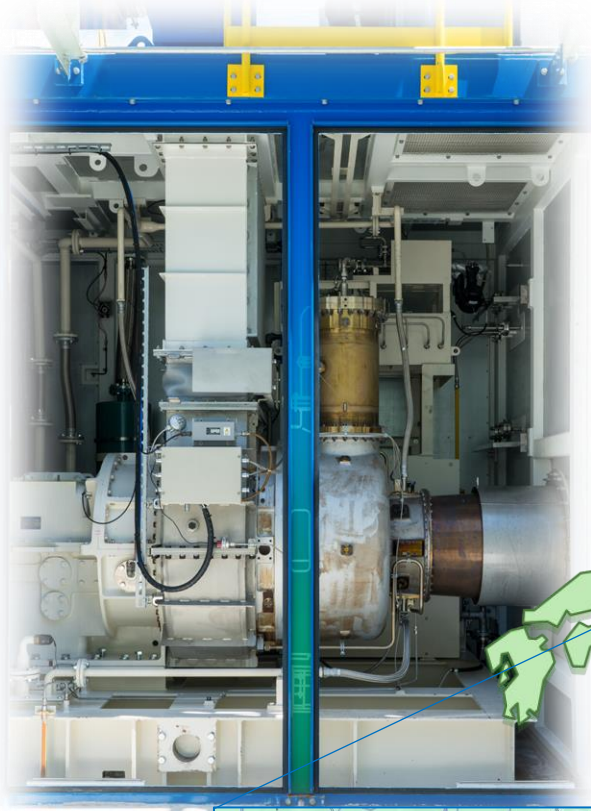
N2O emission vs. NH3 co-firing ratio

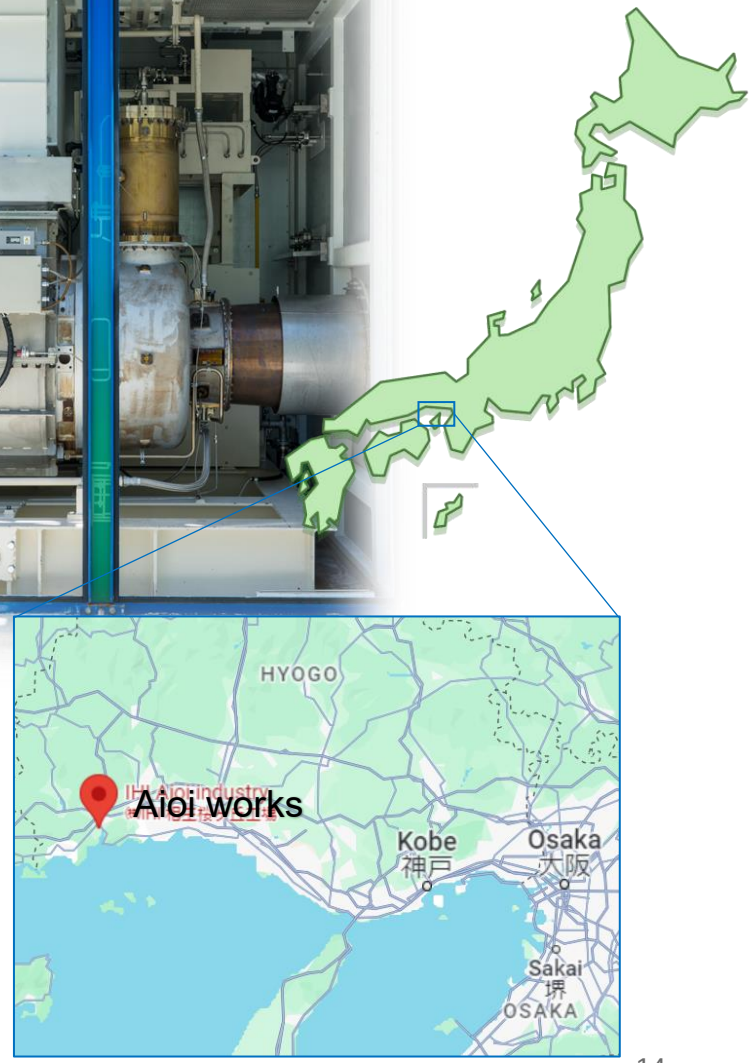


Reduction of greenhouse gas emission vs. NH3 co-firing ratio

「NEDO委託業務（JPNP16002/JPNP21020）」

In 2024, Long-term durability test at IHI Aioi factory





NEDO:JPNP16002/JPNP21020

Joint goals: F-class technology readiness by 2030

Up to 100%

2-Stages (Rich & Lean) combustion system

- ✓ Configured to burn up to 100% of ammonia @ normal operation with 99+% GHG reduction
- ✓ Start-up with Natural Gas or carbon neutral fuel

Retrofittable

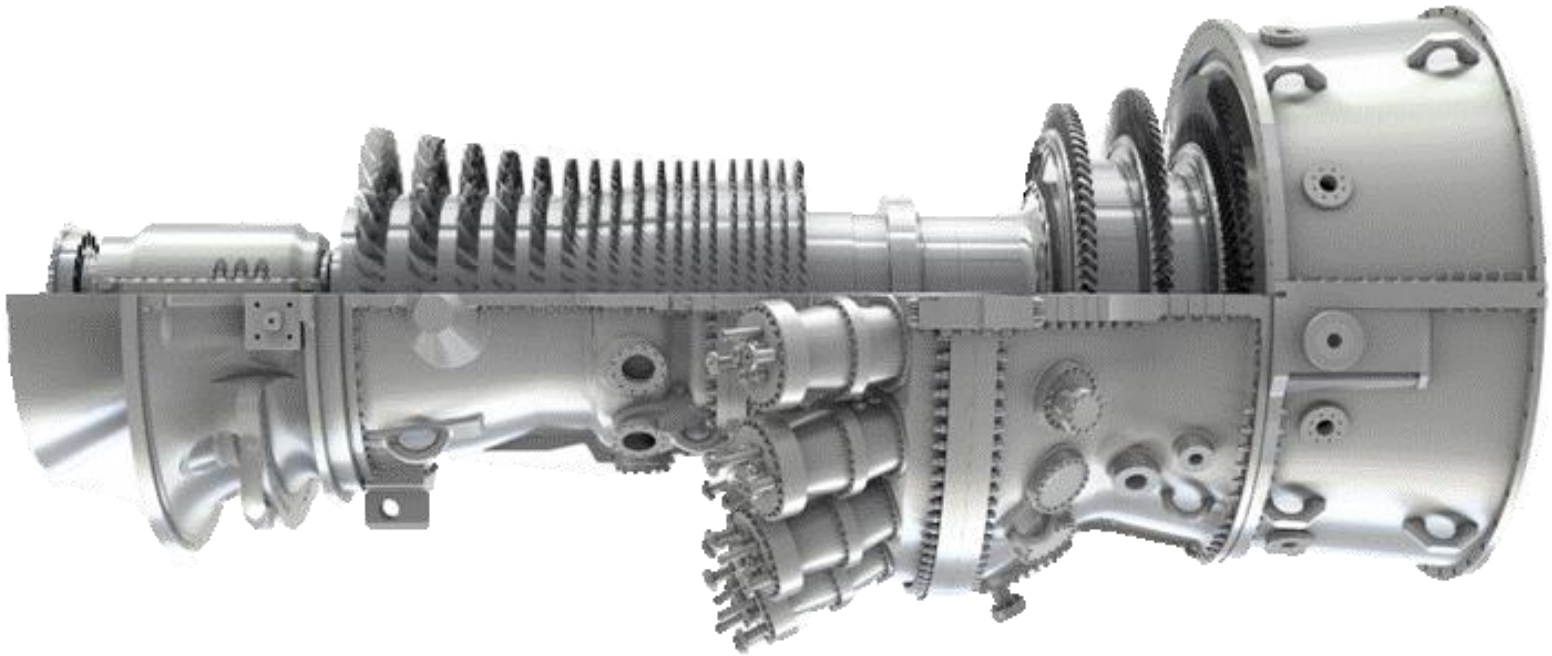
Reduced investment & same life as existing

- ✓ Utilize existing power plant assets with smaller modification for fuel conversion from natural gas to ammonia
- ✓ Target to maintain component durability and existing F-class life

NOx emission

Comply with stringent emission requirement (lower single digit ppm)

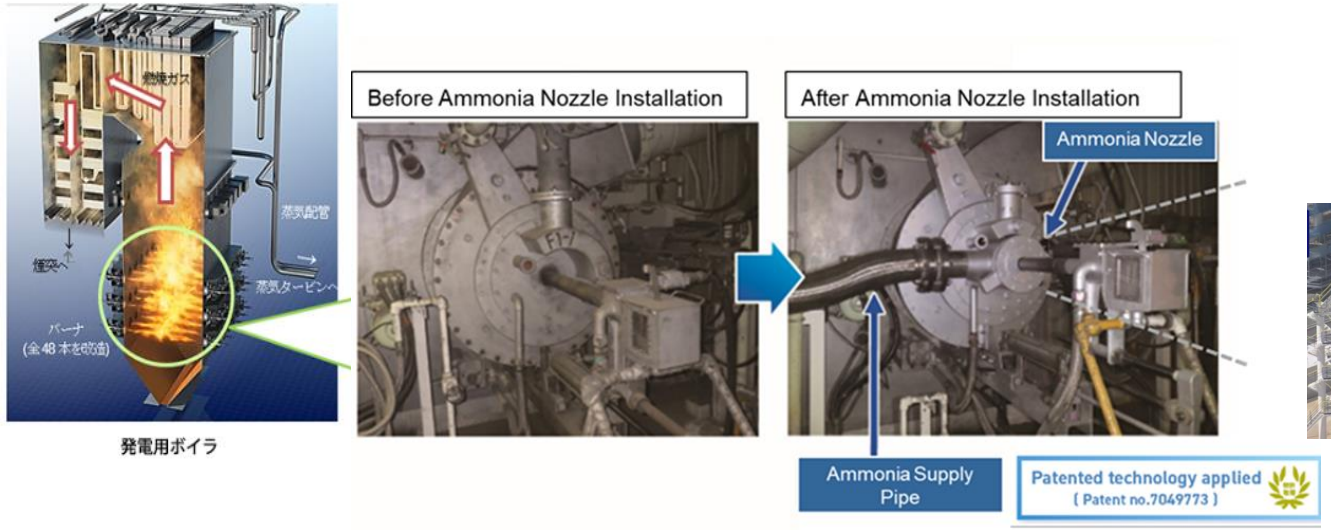
- ✓ New combustion technology with conventional NOx after treatment systems
- ✓ Target to meet Japan's regulation for NOx



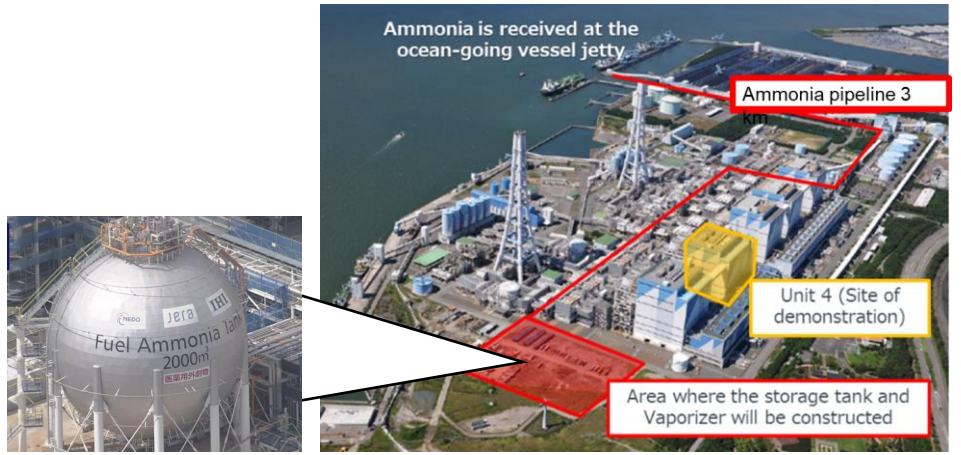
Ammonia Firing Thermal Power Generation

IHI and JERA joint demonstration project from Aril to June in 2024

- The world 1st ammonia power generation in commercial power plant
- 20% NH_3 co-firing in 1GW USC coal-fired power plant
- Annual NH_3 consumption 0.5 MT, CO_2 reduction 1 MT
- Maximize utilization of existing infrastructure
- **Contribution of SPEEDY and SMOOTH energy transition**



JERA Hekinan Power Station

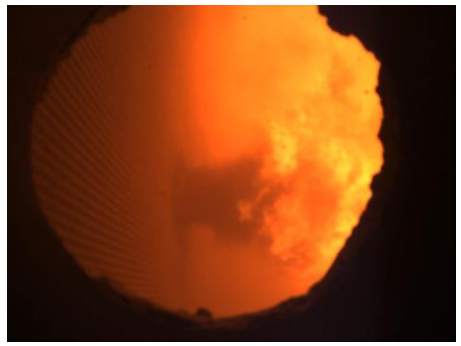


NEDO:JPN16002

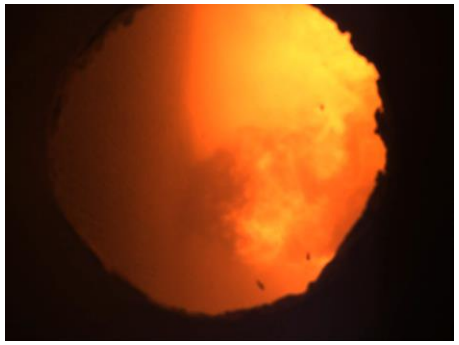
Test results: Flame Image and Emission

- Achieved operation from full load to 25% load while maintaining a 20% co-firing rate
- Succeeded in reducing all emissions

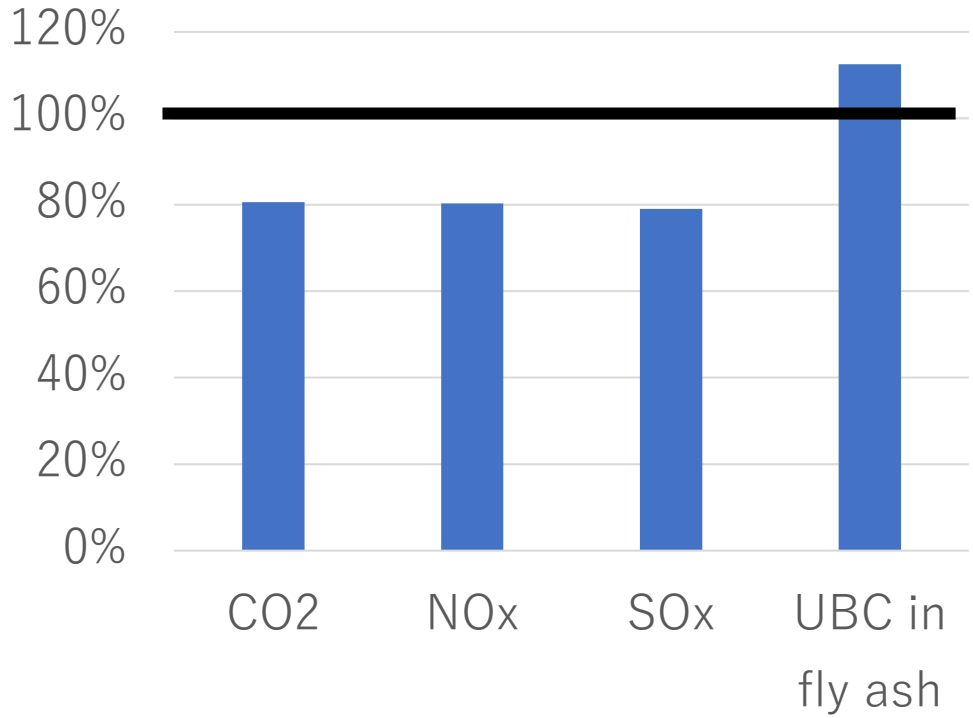
NH3 20% Cofiring



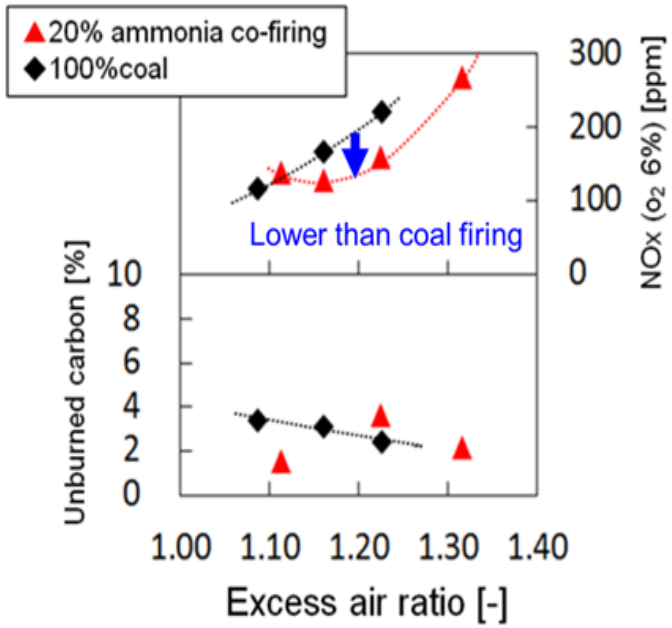
Coal Firing



Flame Image
through furnace side window



Ratio of emissions at NH3 20% cofiring to coal mono-firing
(N_2O and NH_3 < Detection limit)

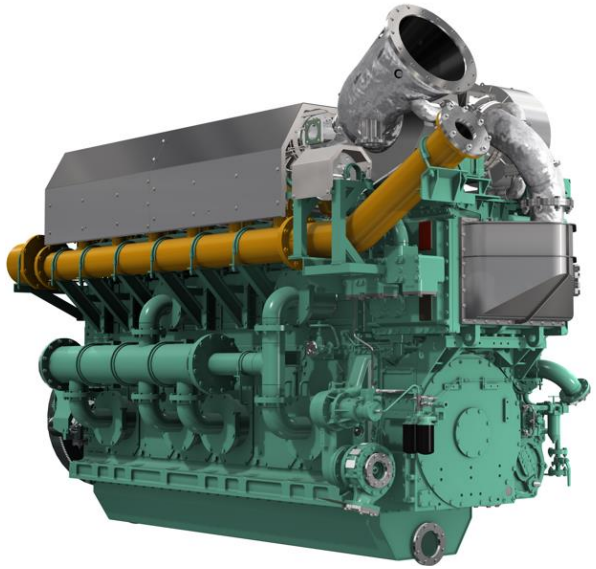


NOx emission

Results in IHI test furnace

Ammonia firing diesel engine

- The world's first ammonia-fueled tugboat was delivered to the Port of Yokohama in August 2024
- 95% NH3 co-firing ratio and GHG reductions over 90%.
- NH3 and N2O are sufficiently removed by the exhaust gas after-treatment system
- Class NK classification approval and IMO NOx certification



Ammonia firing four-stroke diesel engine (28ADF, 2,200PS)

Ammonia-fueled tugboat Sakigake

Toward Social Implementation
- Reliable and Secure Energy -

Roadmap for Ammonia Social Implementation

IHI

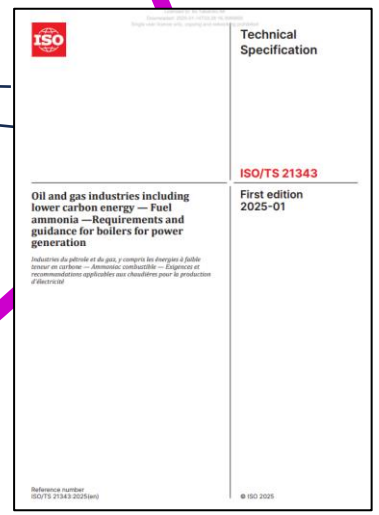
Demand of Ammonia

Phase3. Deployment

Phase2. Standardization

- Standards, Reguration
- Infrastructures
- Traceability
- Safety, Environmentality

Phase1. Technology Development



New ISO for ammonia boiler

2020

2030

2050

Summary

Ammonia Fuel

- Promising energy medium contributing to decarbonization

Technology Status

- First generation power generation technologies advance toward 2030 Market-in

Challenges of Technology

- **Lower emission combustion** in high pressure and short residence time
- Ammonia nitrification-resistant and SCC-resistant materials
- Efficient cracking

Challenges to make it a business

- **Standardization** and **legislation** for reliability and safety
- **Investments with government support** for low-cost and reliable supply chain

IHI

Realize your dreams