Periodic Table of the Elements

Atomic number — Element symbol — Element name — Atomic weight (key: 1 H Hydrogen 1.008)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 H Hydrogen 1.008																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.81	6 C Carbon 12.01	7 N Nitrogen 14.01	8 O Oxygen 16.00	9 F Fluorine 19.00	10 Ne Neon 20.18
11 Na Sodium 22.99	12 Mg Magnesium 24.31											13 Al Aluminum 26.98	14 Si Silicon 28.09	15 P Phosphorus 30.97	16 S Sulfur 32.07	17 Cl Chlorine 35.45	18 Ar Argon 39.95
19 K Potassium 39.10	20 Ca Calcium 40.08	21 Sc Scandium 44.96	22 Ti Titanium 47.87	23 V Vanadium 50.94	24 Cr Chromium 52.00	25 Mn Manganese 54.94	26 Fe Iron 55.85	27 Co Cobalt 58.93	28 Ni Nickel 58.69	29 Cu Copper 63.55	30 Zn Zinc 65.38	31 Ga Gallium 69.72	32 Ge Germanium 72.63	33 As Arsenic 74.92	34 Se Selenium 78.97	35 Br Bromine 79.90	36 Kr Krypton 83.80
37 Rb Rubidium 85.47	38 Sr Strontium 87.62	39 Y Yttrium 88.91	40 Zr Zirconium 91.22	41 Nb Niobium 92.91	42 Mo Molybdenum 95.95	43 Tc Technetium (99)	44 Ru Ruthenium 101.1	45 Rh Rhodium 102.9	46 Pd Palladium 106.4	47 Ag Silver 107.9	48 Cd Cadmium 112.4	49 In Indium 114.8	50 Sn Tin 118.7	51 Sb Antimony 121.8	52 Te Tellurium 127.6	53 I Iodine 126.9	54 Xe Xenon 131.3
55 Cs Cesium 132.9	56 Ba Barium 137.3	57-71 Lanthanoid	72 Hf Hafnium 178.5	73 Ta Tantalum 180.9	74 W Tungsten 183.8	75 Re Rhenium 186.2	76 Os Osmium 190.2	77 Ir Iridium 192.2	78 Pt Platinum 195.1	79 Au Gold 197.0	80 Hg Mercury 200.6	81 Tl Thallium 204.4	82 Pb Lead 207.2	83 Bi Bismuth 209.0	84 Po Polonium (210)	85 At Astatine (210)	86 Rn Radon (222)
87 Fr Francium (223)	88 Ra Radium (226)	89-103 Actinoid	104 Rf Rutherfordium (267)	105 Db Dubnium (268)	106 Sg Seaborgium (271)	107 Bh Bohrium (272)	108 Hs Hassium (277)	109 Mt Meitnerium (276)	110 Ds Darmstadtium (281)	111 Rg Roentgenium (280)	112 Cn Copernicium (285)	113 Nh Nihonium (278)	114 Fl Flerovium (289)	115 Mc Moscovium (289)	116 Lv Livermorium (293)	117 Ts Tennessine (293)	118 Og Oganesson (294)

57 La Lanthanum 138.9	58 Ce Cerium 140.1	59 Pr Praseodymium 140.9	60 Nd Neodymium 144.2	61 Pm Promethium (145)	62 Sm Samarium 150.4	63 Eu Europium 152.0	64 Gd Gadolinium 157.3	65 Tb Terbium 158.9	66 Dy Dysprosium 162.5	67 Ho Holmium 164.9	68 Er Erbium 167.3	69 Tm Thulium 168.9	70 Yb Ytterbium 173.0	71 Lu Lutetium 175.0
89 Ac Actinium (227)	90 Th Thorium 232.0	91 Pa Protactinium 231.0	92 U Uranium 238.0	93 Np Neptunium (237)	94 Pu Plutonium (239)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (252)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (262)

Source : “SCIENCE & TECHNOLOGY WEEK ” (MEXT) https://stw.mext.go.jp

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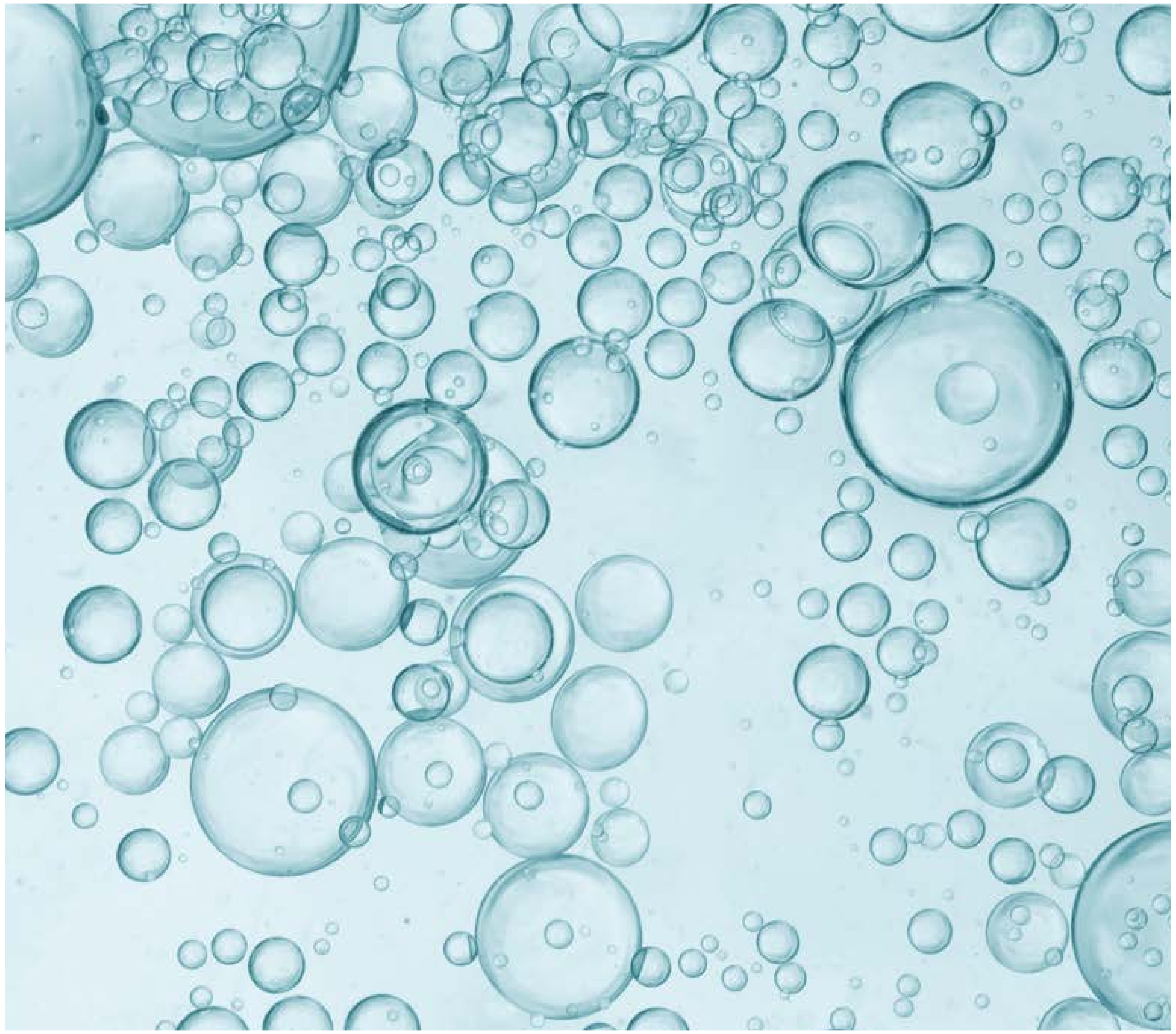
MITSUBISHI POWER

HYDROGEN POWER GENERATION HANDBOOK (Third Edition)



Mitsubishi Power is a power solutions brand
of Mitsubishi Heavy Industries.

MOVE THE WORLD FORW>RD MITSUBISHI HEAVY INDUSTRIES GROUP

INTRODUCTION

Hydrogen—atomic number 1.
It's the first element we learn about as students.
It forms water, which is essential for life on Earth, the planet of water.
It is abundant throughout the universe.
It is light, diffuses rapidly, and burns.

"Burning" forms the foundation of civilization, because it is a source of energy.
Energy is essential to our daily lives, and meeting the world's increasing needs, while reducing CO_2 emissions, is a critical issue of our times.

We have arrived at a watershed in the history of energy with the diversification of energy sources such as renewables and the impact of their evolution on the best energy mix.

Hydrogen is a clean energy source that does not emit CO_2 upon combustion.
The accelerated introduction of IT, continued economic development in emerging nations, and a forecast for increased demand, plus reliable technology for control of the highly flammable element, make hydrogen power generation—clean and abundant—a viable alternative.

Competition among developers of the technology is taking place around the world, where engineers are solving a host of issues.

INDEX

Notes on the Publication of the Revised Edition (3rd edition) of the Hydrogen Power Generation Handbook

In publishing this revision, we introduce new trends in hydrogen energy and add a trivia column to the handbook and elsewhere that summarizes insider engineering knowledge. In addition, at the end of the book, we provide an introduction of our activities by URL and 2D barcode. We hope that this book will be useful for everyone.

Realizing a carbon-neutral society

Decarbonization with a power-generation technology
that emits no CO_2.

The world faces a tipping point that could be called the "decarbonization revolution." Energy industries around the world have taken a major turn toward decarbonization, and the leaders of many countries have expressed their determination to achieve carbon neutrality.
At the same time, there is an urgent need for a stable supply of electricity to meet the increasing power demand due to population growth and economic development. Increasing supply of renewable energy such as wind and solar power also demand a stable power supply as they depend on natural conditions for their output.

Under such circumstances, the Mitsubishi Heavy Industries (MHI) Group announced the 2040 Carbon Neutrality Declaration "MISSION NET ZERO" in October last year (2021). Achieving a carbon-neutral society is a global issue, and we at Mitsubishi Power, as a leader with a proven track record in the decarbonization field, believe it is our responsibility to lead climate change measures. We will contribute to the realization of a carbon-neutral society by cooperating with partners around the world through products, technologies, and services that can promote CO_2 reduction. For some time, Mitsubishi Power, in collaboration with MHI Group companies, has lit a path to solutions for achieving both economic efficiency and the expansion of renewable energy through the "Energy Transition" (switching to energy with a low environmental impact). Moreover, we have set the direction of technological development toward carbon-neutrality. Mitsubishi Power has been developing and cultivating highly efficient power generation and environmental technologies over the years and is working on the use of fuels that do not emit CO_2, such as hydrogen and ammonia, with the aim of reducing CO_2 emissions of and decarbonizing thermal power generation.

The hydrogen power generation technology we introduce in this handbook replaces natural gas, the fuel for gas turbine combined cycle (GTCC) power generation, which currently emits the least amount of CO_2 among thermal power generation systems, with hydrogen, which does not emit any CO_2 during combustion. Mitsubishi Power's hydrogen power generation technology achieves a low cost of installation by maximizing the use of existing facilities and converting them for hydrogen power generation.

A 400MW class GTCC power plant uses about the same amount of hydrogen as 2 million fuel-cell vehicles. By developing hydrogen power generation technology, we are aiming to contribute to the realization of a hydrogen society by creating a virtuous cycle of stimulating large-scale hydrogen utilization and cost reduction.

To respond to diversifying demands in the power market, we are moving forward with the development of solid oxide fuel cells (SOFC), as we are advancing initiatives for both the concentrated power supply of large-frame GTCC and the distributed power supply of SOFC.

MHI Group has a track record of producing and supplying various hydrogen-related products including rocket engines that use hydrogen as a liquid fuel and hydrogen production facilities. In the half century between 1970 and the present, we have abundant accomplishments in the use of by-product gas that contains hydrogen for utilization of the power we generate. In addition to supplying equipment, Mitsubishi Power is also involved in the entire fuel value chain, from the production, transportation, storage, and utilization of carbon-free hydrogen and ammonia. With our proven technological capabilities and our promotion of decarbonized energy, Mitsubishi Power will continue to contribute to the protection of the global environment and move the world closer to a carbon-neutral society.

The world's fastest aircraft, the X-15, which flew at Mach 6.7, flew on ammonia!

Ammonia combustion, which is anticipated to be useful in carbon-free initiatives, is actually an old technology. The North American X-15, an experimental high-altitude hypersonic aircraft equipped with an ammonia engine, began flight in 1961 and in 1967, set the world speed record of Mach 6.7. This record remains unbroken in manned winged aircraft even today. Ammonia is fuel for the dreams of mankind.

Why are liquid oxygen and liquid hydrogen used as rocket fuel?

It can be said that the greater the speed a combusted gas is ejected from a rocket engine, the greater the propulsive force and the better the engine. Furthermore, the lighter the gas used in combustion, the easier it accelerates, which leads to higher ejection speed.
In other words, the combustion gas, mainly H_2O, generated by burning oxygen and hydrogen is a lighter substance than the combustion gas of other fuels.

Accelerating the shift to decarbonization. Driving the potential of hydrogen generation.

Accelerated effort towards a Hydrogen Society

On October 14, 2020, the online Special Event of Hydrogen Energy Ministerial Meeting was held for concerned countries to work together to further promote the use of hydrogen on a global scale. Representatives from 23 different countries, regions, and international organizations, as well as representatives of companies participated in the event. Mitsubishi Power, a pioneer that is working on the practical application of hydrogen, sent its executive senior vice president assistant to the president, executive officer and CTO (at that time), Muyama to the event. His talk, titled "Hydrogen Power Generation towards Beyond Zero Society," stressed the importance of hydrogen power generation and introduced Mitsubishi Power's activities around the world.

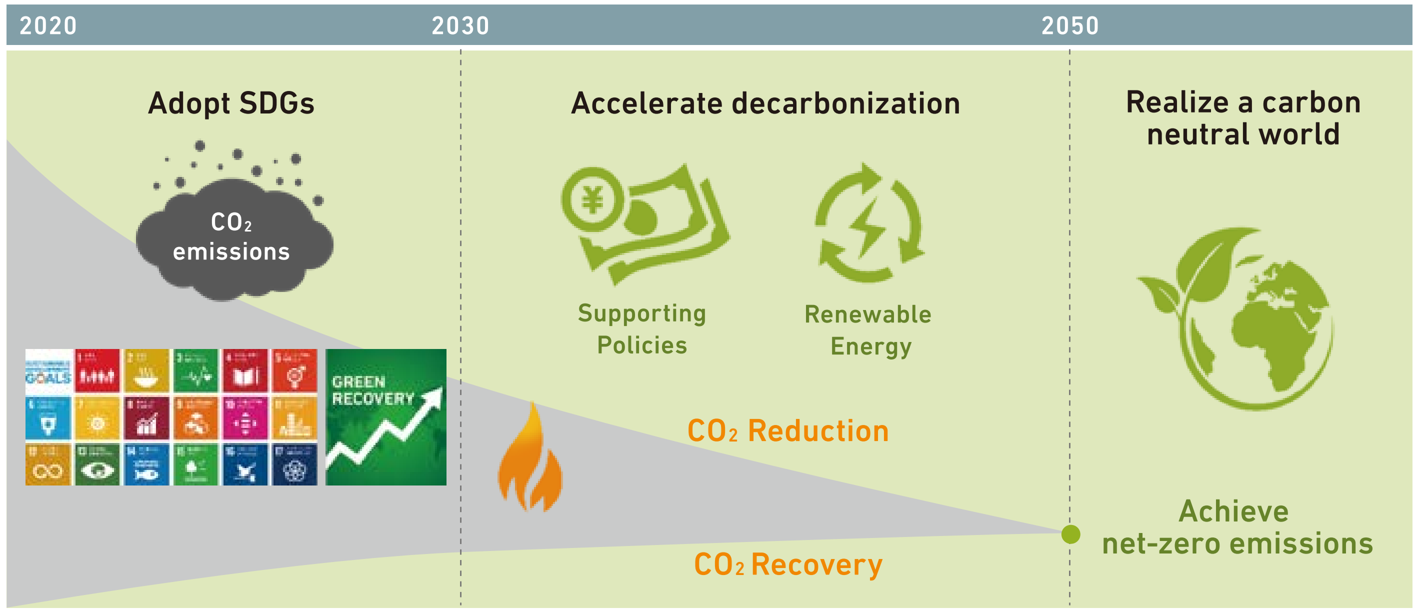
There are increasing number of examples of hydrogen application coming out of Europe. In January 2017, the Hydrogen Council, a global initiative to position hydrogen as the new energy was set up, which started with 13 world-leading companies in energy, transport, and manufacturing. As of 2022, over 141 companies have joined the initiative. Mitsubishi Power is participating in the initiative as a supporting member.

The world is now aligned to become a Hydrogen Society

In 2019, the EU announced their action plan to achieve the carbon-neutral target by 2050. On October 26, 2020, Prime Minister Suga (at that time) declared that by 2050, Japan aims to become a decarbonized nation with zero greenhouse gas emissions. A month earlier, President Xi Jinping of China announced that they aim to go carbon-neutral by 2060. And in January 2021, the new U.S. president, Joe Biden signed an executive order to rejoin the Paris Treaty. The world is now picking up the pace to achieving carbon-neutrality with increasing usage of hydrogen to produce CO_2 free energy.

The Roadmap towards a Carbon-Neutral Society

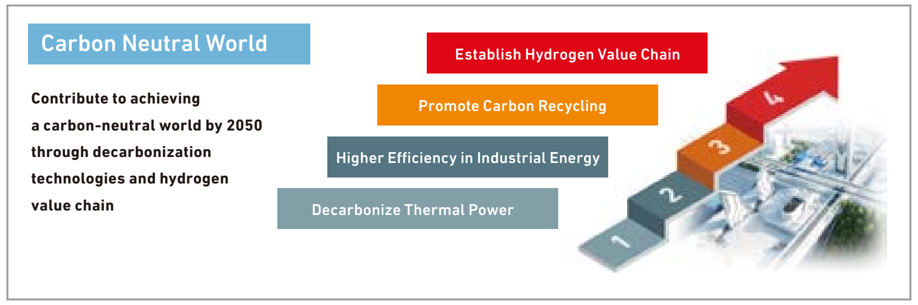
At present, the majority of energy production in the world relies on thermal power using an affordable, safe, and stable fossil fuel. To realize the carbon-neutral society in the future, Mitsubishi Power will continue to support the current power generating methods with a major focus of reducing CO_2 emissions and driving carbon capture. At the same time, it will continue to promote the use of renewable energy as well as mixed combustion of hydrogen or ammonia which produces no CO_2. In addition, Mitsubishi Power will continually increase the ratio of hydrogen to 100%, eventually removing all carbon emissions, enabling us to reach our goal.



The world will change to a carbon-neutral society by 2050 through the advancement of carbon reduction and capture technologies.

Energy Transition and Solution

Mitsubishi Heavy Industries (MHI) Group identifies the four steps to a carbon-neutral society as: "Decarbonization of Thermal Power Generation," "Efficient Energy Use in Industries," "Promoting Carbon Recycle," and "Developing the Hydrogen Value Chain." MHI aims to offer solutions for each step along the way. We are already a part of several large-scale global projects and continue to support their success.



Mitsubishi Power's Hydrogen Project

Working toward conversion to the hydrogen-fired M701F gas turbine

Mitsubishi Power is participating in a decarbonization business plan for the largest industrial cluster in the country (Humber Cluster), which is in progress in the delta area of the Humber River Basin on the east coast of the United Kingdom. Twelve companies and institutions in the global decarbonization industry including Equinor ASA, a major energy company based in Norway, have joined forces to form the "Zero Carbon Humber Partnership (ZCH)". By utilizing hydrogen (H_2) produced from natural gas and making full use of carbon dioxide (CO_2) recovery and removal technologies, the industrial cluster aims to achieve virtually zero CO_2 emissions by 2040.

As such, Mitsubishi Power will undertake technical studies and a feasibility study (FS) to convert fuel from a natural gas to a hydrogen for its three M701F gas turbines operating at a natural gas-fired 1200MW class gas turbine combined cycle (GTCC) power plant in Saltend Chemicals Park, an industrial cluster in the northern part of the country. Using this project participation as an impetus for MHI Group's strategic business, Energy Transition, we will stimulate demand for the utilization of hydrogen by thermal power generation companies. In addition, we will contribute to the realization of a decarbonized society by being involved in the construction of an international hydrogen value chain for hydrogen supply, transportation, and storage while working closely with these technologies and partners.

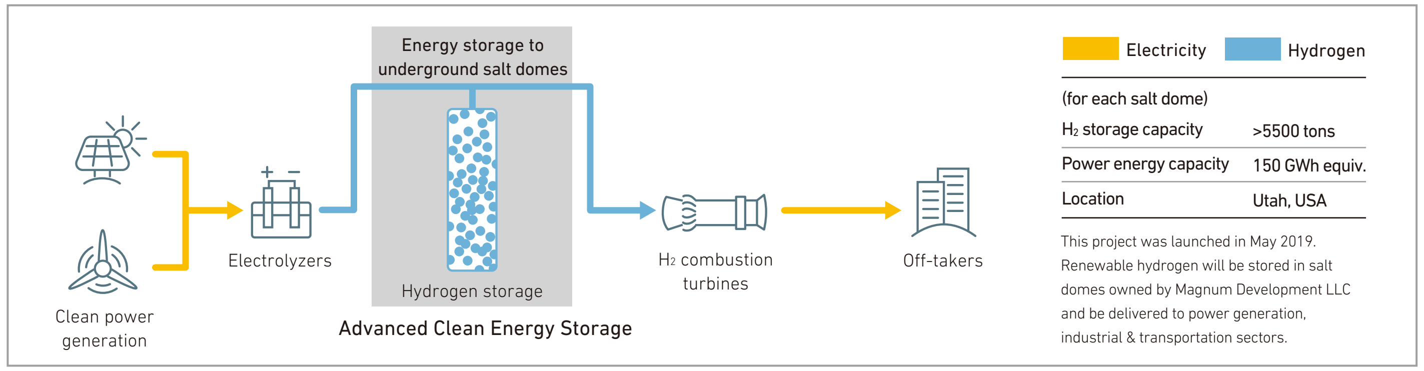
Zero Carbon Humber Partnership：ZCH
Source: https://www.zerocarbonhumber.co.uk/

Saltend GTCC Power Plant

Storing green hydrogen in salt domes

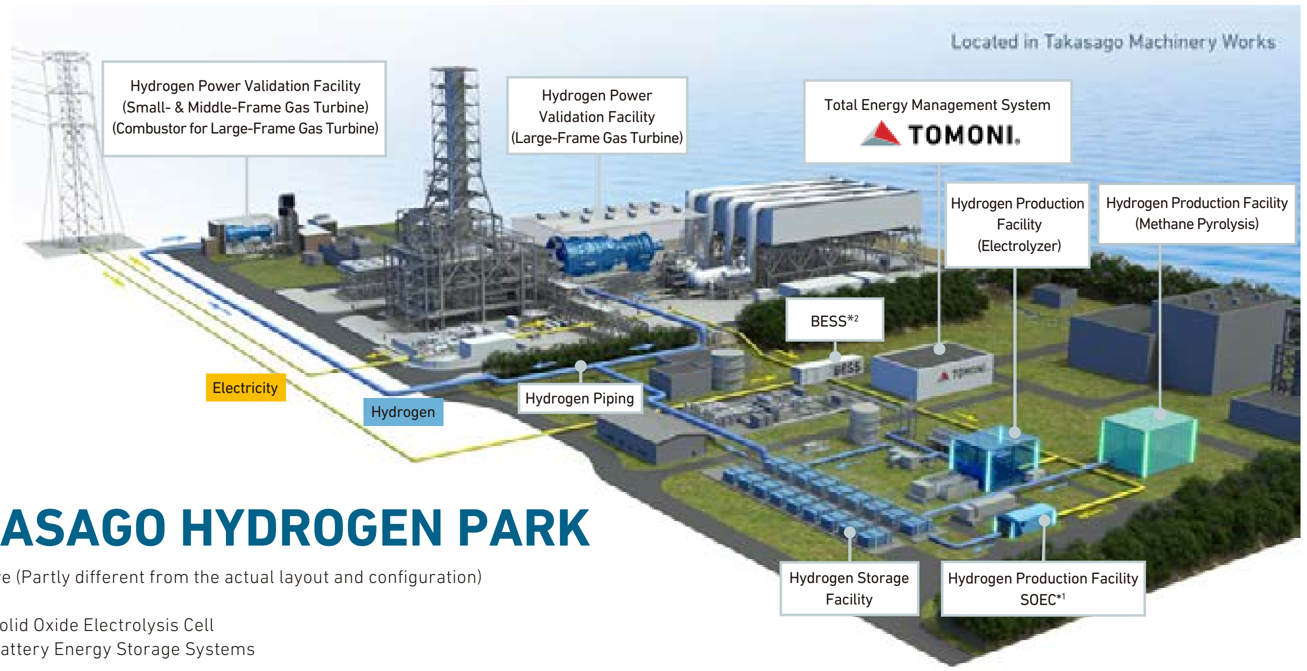
Together with Magnum Development, Mitsubishi Power is driving the Advanced Clean Energy Storage Project. Using power generated from wind and solar power, the electrolyzer produces green hydrogen which is then stored in two massive underground salt domes controlled by Magnum Development. Hydrogen is then provided to the power plants as needed. The salt dome has the capacity to store the equivalent of 150GWh of energy. In June 2022, the world's largest green hydrogen hub entered the execution phase with a loan guarantee from the U.S. Department of Energy.

Mitsubishi Power has cutting-edge hydrogen combustion technologies, and its hydrogen gas turbine requires minimum modification to the existing infrastructures at the power plants. In 2018, Mitsubishi Power had already achieved 30% hydrogen co-combustion and aims to make this 100% hydrogen by 2025. Large-frame hydrogen generation is a crucial piece in creating a truly sustainable society across the globe. Cost is a challenge today, however as technology evolves, we will continue to reduce the cost of green hydrogen. Mitsubishi Power is fully committed to playing a significant leadership role in addressing this global obligation and deliver technological advancements to attain a carbon-free hydrogen society.



Establish Hydrogen Power Validation Facility "Takasago Hydrogen Park"
-- Systematic Validation of Hydrogen Value Chain from Production to Power Generation --

Mitsubishi Power is working toward early commercialization of hydrogen-fueled gas turbines. For this reason, we established the Takasago Hydrogen Park, which is the world's first center for validation of hydrogen-related technologies ranging from hydrogen production to power generation in one location closely, and co-located it at the combined cycle power plant validation facility (T-Point 2) on the premises of the Takasago Machinery Works, where our development and manufacturing bases are located. The Takasago Hydrogen Park will be successively expanded and developed going forward. Mitsubishi Power has already announced its 30% hydrogen co-firing for large-frame gas turbines and will be verified at Takasago Hydrogen Park to commercialize small and large-frame gas turbines on a path to 100% hydrogen firing starting in 2025. Currently, preparations are underway to begin testing and validation of hydrogen production and storage as well as hydrogen combustion technology in gas turbines, with the aim of starting operations in fiscal year 2023. The hydrogen production facility utilizes electrolyzers, and Mitsubishi Power plans to conduct successive testing and verification of other next-generation hydrogen production technologies such as turquoise-hydrogen production by pyrolysis of methane into hydrogen and solid carbon, etc. The T-Point 2 facility conducts long-term reliability validation of newly developed technologies, including verification of the next-generation JAC (J-series Air-Cooled) large-frame gas turbines conducting operations equivalent to an actual power plant while connected to the local power grid. This unique facility, unlike any other anywhere in the world, began long-term verification testing on July 1, 2020, as a leading-edge, 566MW class gas turbine combined cycle (GTCC) power generation facility. For large-frame gas turbines, the JAC class gas turbine will be used to validate 30% hydrogen co-firing power generation. In addition, firing of 100% hydrogen in small and medium-frame gas turbines will be validated with the H-25 gas turbine.

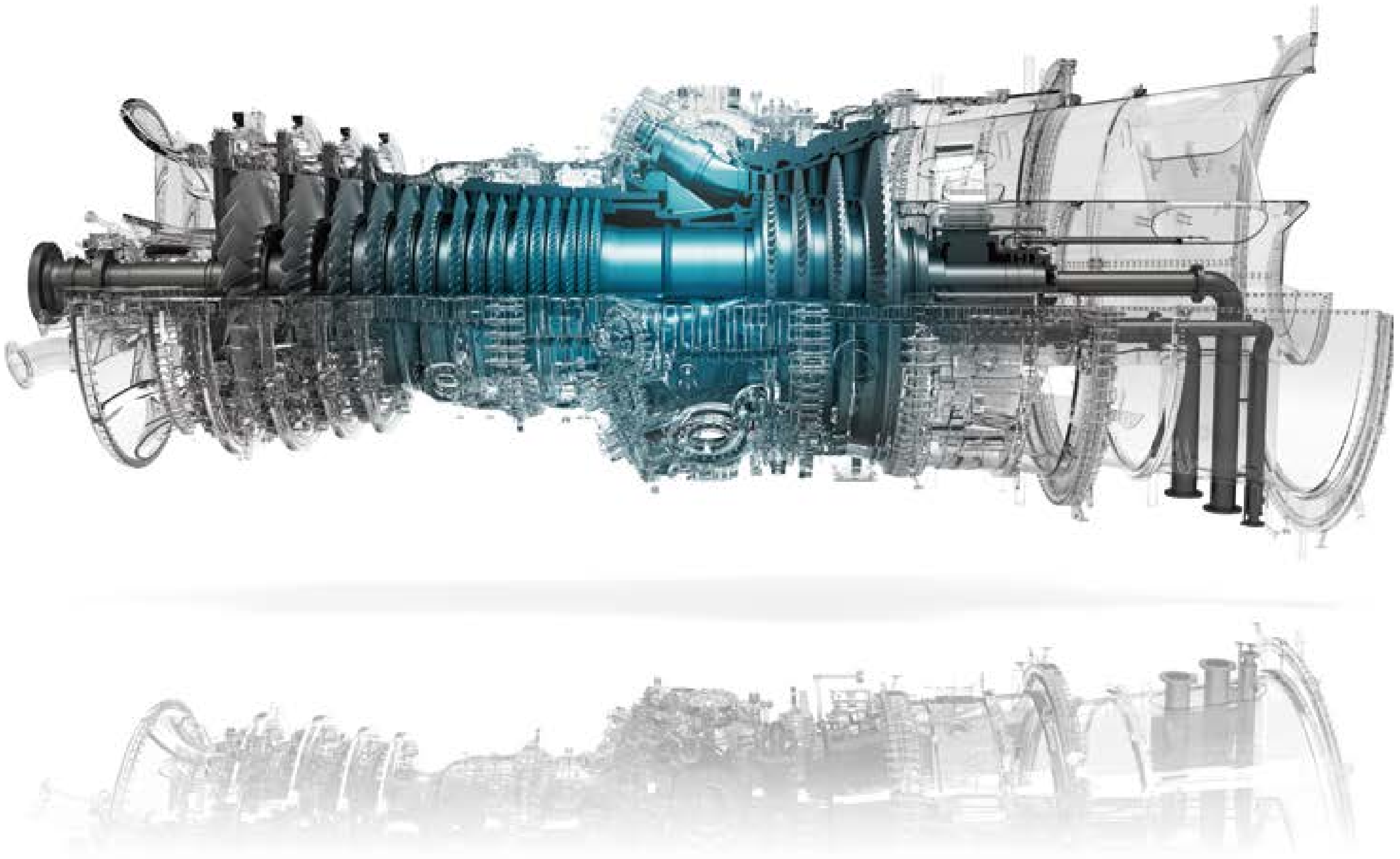


TAKASAGO HYDROGEN PARK

Image figure (Partly different from the actual layout and configuration)

*1 SOEC: Solid Oxide Electrolysis Cell
*2 BESS: Battery Energy Storage Systems

Moving toward commencing demonstration of the hydrogen gas turbine 30% co-firing technology



Expectations for hydrogen energy and technologies

Coping with the conflict between robust energy demand and global decarbonization

"Energy is the cornerstone of industry," said Satoshi Tanimura—Chief Engineer, GTCC Business Division, Energy Transition & Power Headquarters, Energy Systems, Mitsubishi Heavy Industries, Ltd.—a leader in the development of hydrogen-fueled gas turbines that feature CO_2-free combustion technology. "If demand exists, supply will be provided by electric power companies, and power-generating facilities are necessary to provide this supply. At the same time, there is increasing public scrutiny toward power-generation that produces CO_2 emissions. They want electricity, but they don't want the attendant CO_2 emission. It's the mission of engineers to pursue thermal power generation that emits zero CO_2."

In Japan, the country's primary energy is mainly converted into electricity, accounting for 46% of all energy. Thermal power accounts for 75.7% of the electricity supply volume with the fuel type break-down being as follows: LNG at 37.1%; oil and petroleum at 6.8%; and coal at 31.8% (as of 2019).
Source: https://sustainablejapan.jp/2021/06/23/electricity-proportion/13961

As energy choices steadily increase, thermal power still remains a key energy source. "With regard to thermal power using fossil fuels, efforts have continuously been made toward reducing emissions by enhancing efficiency through technological innovation," said Tanimura. "CO_2 emissions per unit with gas turbine combined cycle (GTCC) plants, which combine gas and steam turbines, are less than half of those generated by coal-fired thermal power. But it doesn't change the fact that CO_2 is still emitted in the generation of gas-fired thermal power; we cannot close our eyes to this fact. As an engineer, I'm particularly sensitive to global issues and expectations toward resolving them. And we must develop technology to cope with the conflicting issues of strong demands for energy and for CO_2 reduction."

A clear roadmap to the achievement of a hydrogen society

Satoshi Tanimura's focus is on thermal power generation that does not emit CO_2. "Our area of involvement is the development of hydrogen gas turbines," he said.

Japan's Basic Hydrogen Strategy includes the target of commercialization of hydrogen power generation by 2030. However, is it possible to commercialize hydrogen power generation in about ten years? Even if technology is successfully developed, how many power plant operators can afford to renew their facilities?

"Even if hydrogen power-generating facilities are installed at power plants already scheduled for renewal, it's not realistic to expect substantial power generation volume to be secured in only ten years," said Tanimura. "That's where Mitsubishi Power comes in—we conceived a hydrogen power generation system that utilizes existing gas turbine facilities."

Tanimura and his colleagues at MHI have developed a gas turbine combustor that can steadily use a 30% hydrogen mix with LNG, which is the fuel for gas-fired power plants. It burns hydrogen while allowing suppression of NOx emissions to the level of gas-fired thermal power. The technology is compatible with an output equivalent to 700MW (with temperature at turbine inlet at 1600°C), and it offers a reduction of about 10% in CO_2 emissions compared with GTCC.

As this technology enables the use of existing facilities, large-scale modification of power generation facilities becomes unnecessary. This makes it possible to lower costs and other hurdles, promoting a smooth transition to a hydrogen society.

But can hydrogen be infused into the fuel mix of existing facilities so easily? Aspects such as fusion, combustion, and the quality and behavior of hydrogen must be different from those of LNG. What is this hydrogen-mixed combustion technology developed by Mitsubishi Power? Where was the technological breakthrough? And what is the next move? We will now introduce the many challenges that Tanimura had to overcome.

Commercialization of 30% hydrogen co-firing opens pivotal door to a hydrogen-powered society

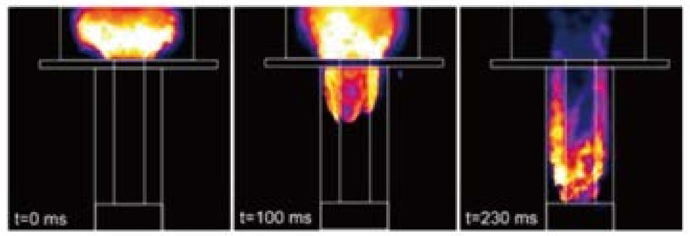
Easy-to-burn hydrogen and the struggle for safety

Hydrogen—atomic number 1—is the first element students learn about, and the lightest of all elements. Hydrogen is clean—when it burns, it produces only water. Conversely, it is a substance that is difficult to handle. It burns violently, so the idea of hydrogen is often accompanied by the fear of explosions. It is highly combustible, only needs energy equivalent to static electricity to ignite, and has a broad combustion range. These are difficulties that come with such a combustible element. Thus there are many challenges that engineers must overcome in order to realize a 30% hydrogen co-firing.

"We had already confirmed through in-house combustion tests at Mitsubishi Power that 20% hydrogen co-firing could be handled with existing gas turbines. Combustion at the McDonough-Atkinson power plant, a large-scale plant in the United States, had been undertaken together with Georgia Power and the Electric Power Research Institute (EPRI). The success of the demonstration cemented our ability to achieve 20% hydrogen co-firing. At the same time, gas turbine designers gained considerable confidence in the prospect of 30% hydrogen co-firing, which has been a big challenge up until now. In the future, we need to further improve our understanding of combustion characteristics and further control the mixing with air and its behavior at that time." Even with excellent materials, it cannot be called technology unless it is controllable, durable, and capable of producing high-quality results on a continuous basis. Engineers are the ones who solve these problems.

Obstacles standing in the way of a 30% hydrogen co-firing are flashback, combustion pressure fluctuation, and NOx.

The unique characteristics of hydrogen and the mixing of hydrogen with air are the cause of flashbacks. Flashback is a phenomenon where the flames inside the combustor travel up the incoming fuel and leave the chamber. As hydrogen burns rapidly, flashback commonly occurs.



Source: University of Michigan at the 2014 University Turbine Systems Research Workshop

Burning of fuel anywhere but inside the combustor absolutely must be avoided. If flashback cannot be prevented, a hydrogen gas turbine cannot be successfully developed. Mitsubishi Power has completed the development of a 30% hydrogen co-firing combustion test, and is also having success with 50% hydrogen co-firing combustion.

Innovative technology to control combustion pressure fluctuation that can destroy a combustor

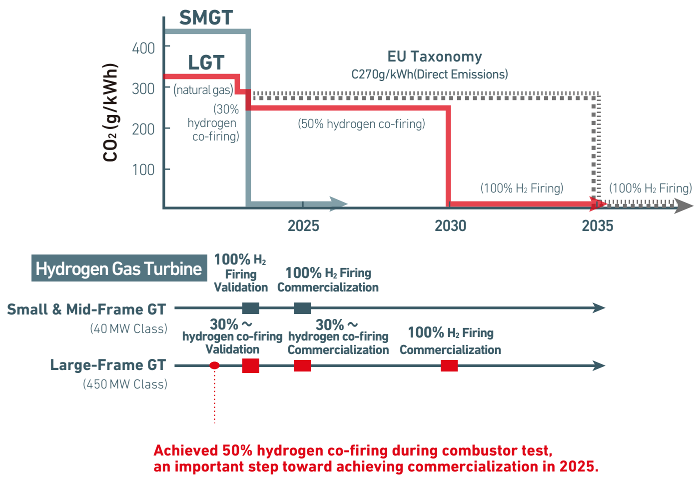
Combustion oscillation presents yet another obstacle. Temperatures inside the combustor reach 1,600°C, and it is known that imposing an extremely high thermal load on the combustor cylinder results in the generation of a very loud noise due to the cylinder's specified eigenvalue. This is the phenomenon known as combustion pressure fluctuation.

Put the oscillation from the loud sound together with the oscillation of the flames from combustion and they amplify, producing immense power. Also, given the particularly short interval when combusting hydrogen, the flame and the oscillation are more likely to match, increasing the likelihood of combustion pressure fluctuation.

So how loud is the sound?

"It's actually beyond loud. And once oscillation occurs, it will destroy the combustor in an instant," said Tanimura. "In order to avoid this, not only do we adjust the location and method of fuel burning, we continue to incorporate a number of innovations such as a sound absorption device."

While suppressing these phenomena and satisfying the necessary conditions, Tanimura and his team must also extend the service life of the facility by enhancing maintenance capabilities and the performance of the facility overall. Moreover, they must constantly search for the best materials, the optimum form, and the ideal combination—from the optimization of the shape and material of the fuel delivery nozzle and the combustor shape and material to the quality of the thermal insulation ceramic coating and adjustment of particle size. The repetition of this trial-and-error process brings them ever closer to the development of a CO_2-free power generation system and ultimately to the realization of a carbon-free society.

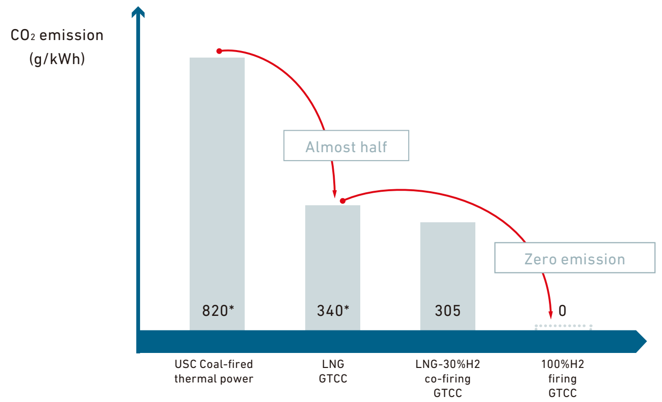


100% hydrogen power generation — achieving a complete hydrogen-fired gas turbine

The dream of a CO_2-free society—100% hydrogen thermal power generation

The values below are emissions per unit indicating CO_2 emission volume when generating 1kWh of electricity.

Standard coal-fired power generation: 863g-CO_2 /kWh
Ultra-supercritical (USC) coal-fired power generation: 820g-CO_2 /kWh
GTCC power generation: 340g-CO_2 /kWh
Hydrogen 30% mixed-combustion gas turbine: 305g-CO_2 /kWh



*Source: METI Web Site (https://www.meti.go.jp/committee/kenkyukai/energy_environment/jisedai_karyoku/001_haifu.html)

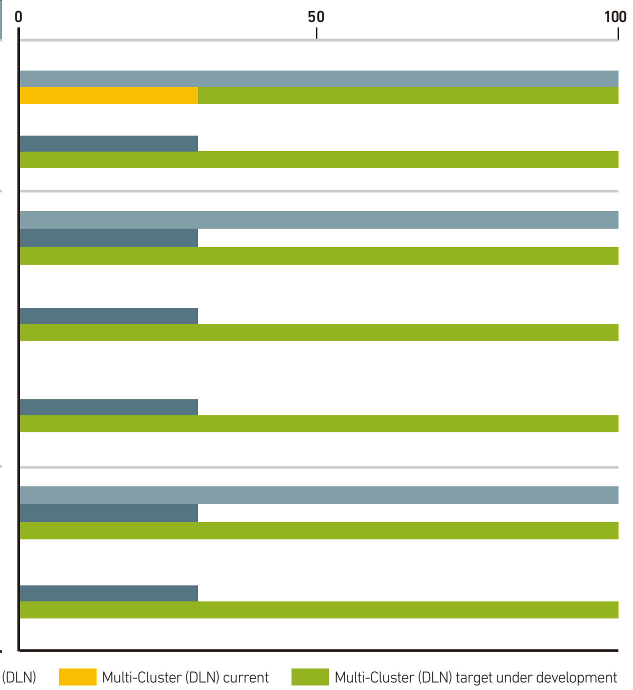
Development Status of Hydrogen Combustion Technology

As Mitsubishi Power has successfully achieved mixed-combustion power generation at 30% hydrogen, Satoshi Tanimura's next objective is CO_2-free power generation, or 100% hydrogen power generation technology. However, with a high concentration of hydrogen, the risk of flashback rises, as does the concentration of NOx. A combustor for hydrogen-fired power generation demands technology that enables efficient mixing of hydrogen and air, and stable combustion.

"There are important conditions concerning the mixing of hydrogen and air as well," said Tanimura. "It is difficult to mix hydrogen and air in a large space, and using a rotational current and mixing them well requires a rather large space. This is what pushes the risk of flashback upward. In order to mix hydrogen and air in a short period of time, it has to be done in as confined a space as possible. The problem is that in this case the fuel nozzle jets and flame are in closer proximity, making flashback increasingly likely. We thought about how to deal with this, and it occurred to us that we needed to disperse the flame and reduce the fuel spray particle size. The key technology to this method is the fuel delivery nozzle. We upgraded the design, which normally features eight nozzles, and created the distributed lean burning, or multi-cluster combustor, which incorporates many nozzles. We reduced the size of the nozzle opening and injected air, and then sprayed hydrogen and mixed them. As this method does not employ a rotational current, mixing is possible on a smaller scale, and low-NOx combustion can be accomplished."

Hydrogen is an excellent fuel, but difficult to handle. Changing thinking in mixing methods by upgrading the nozzle. That's the kind of challenges engineers are wrestling with in the battlefield of development.

GT Model		Combustor Type	H_2 (vol%)
H-25	60/50Hz	Diffusion Multi-Cluster (DLN*)	100 30→100 (target)
H-100	60/50Hz	Pre-Mix (DLN) Multi-Cluster (DLN)	30 100 (target)
M501F	60Hz	Diffusion Pre-Mix (DLN) Multi-Cluster (DLN)	100 30 100 (target)
M501GAC	60Hz	Pre-Mix (DLN) Multi-Cluster (DLN)	30 100 (target)
M501J M501JAC	60Hz	Pre-Mix (DLN) Multi-Cluster (DLN)	30 100 (target)
M701F	50Hz	Diffusion Pre-Mix (DLN) Multi-Cluster (DLN)	100 30 100 (target)
M701J M701JAC	50Hz	Pre-Mix (DLN) Multi-Cluster (DLN)	30 100 (target)



* DLN: Dry Low NOx

Creating a hydrogen fuel supply chain as a bridge to the future

A gas turbine alone is not enough to achieve 100% hydrogen-fired combustion technology: Stable sources of hydrogen must be secured; a supply source and way to transport the hydrogen to a pipe-less Japan must be considered; technology to extract hydrogen from the source material, and technology to collect and retain the CO_2 emitted during the process must be developed. Such hydrogen infrastructure must mature along with the development of hydrogen combustion technology.

"Simply increasing gas turbine efficiency does not necessarily lead to enhanced efficiency overall," said Tanimura, when taking a comprehensive perspective of the practical use of hydrogen. "In Japan, we simply assume we'll have hydrogen transported from abroad and use it in fuel-cell vehicles and industry. Meanwhile, there is a blueprint overseas from the hydrogen supply phase through to use, including the CCS scheme for processing CO_2 emitted during manufacturing. In Europe, with the advantage of their existing natural gas pipeline being well-developed, they are proceeding with hydrogen use while taking a holistic view through to supply, considering it part of the overall infrastructure," he said.

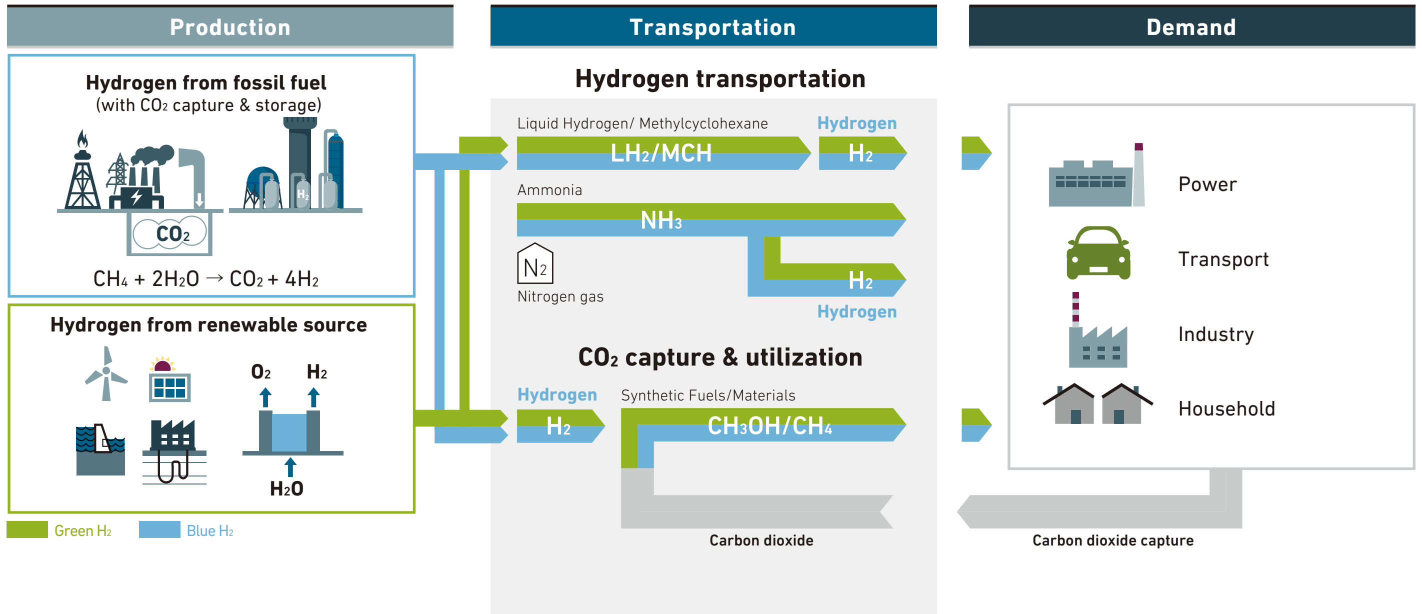
As engineers developing gas turbines, Tanimura and his colleagues have a clear understanding of the need for a comprehensive hydrogen usage plan. "In Japan, as we don't have a developed pipeline, naturally the transport of hydrogen constitutes a major issue," Tanimura said. "As of now, there are schemes for extracting hydrogen from renewable energy, petroleum, and natural gas. If renewable energy, regarded as unstable, is converted into hydrogen, the storage and transport of energy becomes possible, which is a huge benefit. Today, liquid hydrogen, methyl cyclohexane (MCH), and ammonia (NH_3) are regarded as the most promising hydrogen transport vehicles, and if demand increases further, we should see economies of scale emerge in transport as well," said Tanimura.

Gas turbine engineers factor in everything from production to costs. "We need a vision for hydrogen use, encompassing everything from creation of infrastructure to the various methods of use," Tanimura said. "For instance, a fuel mix of 20% hydrogen can be used without any technological improvements, and if we use a gas turbine with an output capacity of 500MW, and a turbine efficiency rating of 60%, it requires 1.4 tons of hydrogen per hour. This equals the volume of hydrogen used by around 100,000 to 130,000 fuel-cell vehicles. If we are going to proceed in earnest with hydrogen use, it's imperative that we quickly move to upgrade the hydrogen infrastructure, through measures such as proactively increasing the number of turbines using hydrogen. This is another reason hydrogen gas turbines will drive the forthcoming hydrogen society," he said.

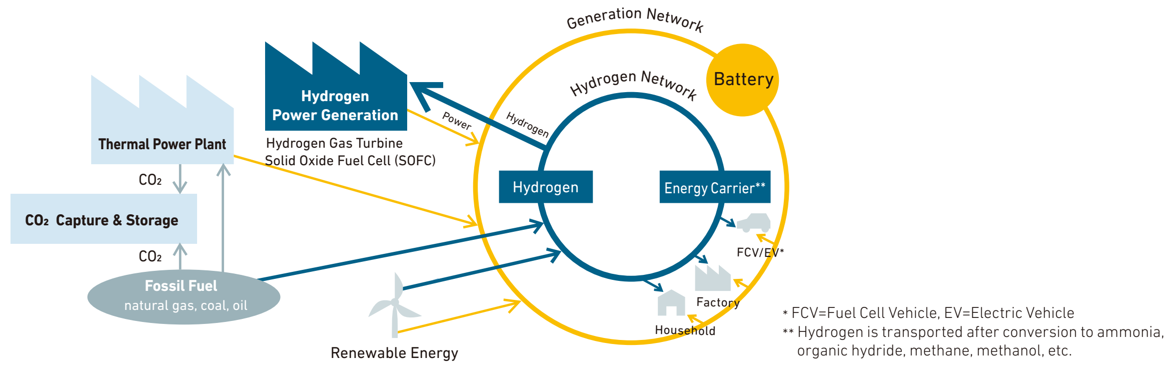
Human beings discovered fire and began using it purposefully about 500,000 years ago. And now with CO_2-free combustion in hand, we can set our sights on the energy that will support a carbon-neutral society.

Tanimura and his colleagues remain dedicated to achieving 100% hydrogen combustion technology by 2025.

Overview of Global Hydrogen Supply Chain



The relation between Mitsubishi Power's hydrogen power generation technology and the hydrogen network



• FCV=Fuel Cell Vehicle, EV=Electric Vehicle
•• Hydrogen is transported after conversion to ammonia, organic hydride, methane, methanol, etc.

Satoshi Tanimura

Chief Engineer, GTCC Business Division,
Energy Transition & Power Headquarters, Energy Systems,
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An expert in gas turbine combustor development, from basic design to combustion adjustment, his focus. Tanimura joined Mitsubishi Heavy Industries in 1986 and was assigned to the Gas Turbine Engineering Department, where he pursued the development of large-scale gas turbine combustors and also served as an engineer. He worked on the development of a 1300°C-class gas turbine combustor, and spearheaded efforts to develop low-NOx technology for the 1500°C- and 1600°C-class models.

TECHNICAL REVIEW

As a leading provider in the fields of thermal power generation and environmental technology, Mitsubishi Power is developing high efficiency power generation technologies. This includes the field of gas turbine power generation technologies where Mitsubishi Power has made possible hydrogen-mixed combustion and is in the process of taking the technology to it's next phase. Energy market needs are diversifying and Mitsubishi Power is working to meet such decentralized needs. We will now introduce our large-scale hydrogen gas turbines, which have potential for mass consumption, and fuel cells that are able to efficiently employ a diverse array of fuel types including hydrogen as dispersion type power sources through the Mitsubishi Heavy Industries technical review.

Hydrogen Gas Turbine

- Hydrogen-fired Gas Turbine Targeting Realization of CO_2-free Society
  Hydrogen single fuel firing technology in high efficiency gas turbines.
  We lead the field in creating an international hydrogen supply chain to achieve a CO_2-free Hydrogen Society.
- Operation Status of 1650°C Class M501JAC Gas Turbine at T-point 2 Power Plant Demonstration Facility
  Verification test results and operation status of the next-generation 1650°C class M501JAC gas turbine, which uses an enhanced air-cooled combustor system, ultra-thick film TBC, and high-pressure ratio compressor as core technologies.
- Development of Hydrogen/Ammonia Firing Gas Turbine for Decarbonized Society
  By stimulating large-scale demand for hydrogen through large-capacity, high-efficiency GTCC, MHI will lead the construction of an international hydrogen supply chain and contribute to the realization of a decarbonized society.

Fuel Cells

- Market Introduction Status of Fuel Cell System "MEGAMIE" and Future Efforts
  In 2017, the 250kW class machine was launched on the market. In the future, we plan to consider system specifications focusing on marketability in the case of a verified 1 MW class machine and make plans to introduce it to the market.

Source: Mitsubishi Heavy Industries Technical Review
Authors and affiliation names shown here are true and accurate at the time of writing

Mitsubishi Heavy Industries Technical Review Vol. 55 No. 4 (December 2018)

Hydrogen-fired Gas Turbine Targeting Realization of CO_2-free Society

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SATOSHI TANIMURA[*4]

Gas turbine combined cycle power generation (GTCC) is clean and highly efficient and accounts for a large proportion of power generation today. Therefore, for the realization of a CO_2-free society, it is important to use hydrogen for large power generation gas turbines on a largescale. Mitsubishi Heavy Industries group is proceeding with the development of natural gas and hydrogen co-fired and hydrogen-fired large gas turbines, and has succeeded in a 30 vol% hydrogen co-firing test. In addition, we also started research on the use of ammonia, which shows promise as one of the energy carriers of hydrogen, in GTCC carriers, and are participating in a GTCC plant hydrogen firing conversion project in Europe. Through these activities, Mitsubishi Hitachi Power Systems, Ltd. (MHPS) will contribute to the realization of a hydrogen society by leading the establishment of an international hydrogen supply chain for the supply, transportation, and storage of hydrogen.

1. Introduction

To handle the rapid increase in electricity demand since the 1980s, GTCC power generation using natural gas/LNG (liquefied natural gas) as fuel has attracted attention, and its capacity and efficiency improvement have been promoted. GTCC power generation is the cleanest and most efficient facility among the thermal power generation systems using fossil fuels. In Japan, primary energy is converted mainly to electricity, which accounts for as much as 43% of the total. Among this total, the proportion of electricity supply from thermal power generation is as high as 85% (as of 2015). For this reason, GTCC power generation is required to continue to handle lively energy demand and to further reduce CO_2 for the effective use of resources and the realization of a low-carbon society.

In Japan, as a basic hydrogen strategy for a low carbon society, the commercialization of hydrogen power generation around 2030 has been targeted. To more realistically promote commercialization (from the development of technologies to the introduction of equipment to electric power companies) in a short term of 10 or more years, we devised a system that can carry out hydrogen power generation using existing gas turbine equipment. This system does not require a large-scale renewal of power generation equipment other than gas turbine combustors. Therefore, it is expected to lower the cost hurdle for hydrogen conversion and to promote a smooth shift to a hydrogen society. Currently, with the support of the New Energy and Industrial Technology Development Organization (NEDO), we have succeeded in developing a combustor that can use 30% hydrogen mixed with LNG fuel for large power generation gas turbines. The emission of NOx, which is a concern along with the combustion of hydrogen, can be suppressed to the conventional level. This technology can handle output equivalent to 700,000 kW (GTCC power

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generation with a turbine inlet temperature of 1,600°C), and the CO_2 emissions during power generation can be reduced by approximately 10% in comparison with conventional GTCC power generation. This is a big step toward building a hydrogen society. This report presents our efforts toward realizing a hydrogen society, centered on hydrogen-fired gas turbines.

2. Large power generation gas turbines and hydrogen society

Efforts toward achieving the greenhouse gas reduction targets in the "Paris Agreement" adopted at the 2015 United Nations Climate Change Conference (COP 21) have begun in countries around the world, and the introduction of renewable energy has been accelerating. **Figure 1** [(1)] shows the forecast of the total global CO_2 reduction amount from the present to 2060 in the IEA (International Energy Agency) report. The reduction of CO_2 emissions using renewable energy is estimated to account for about 30% of the total.

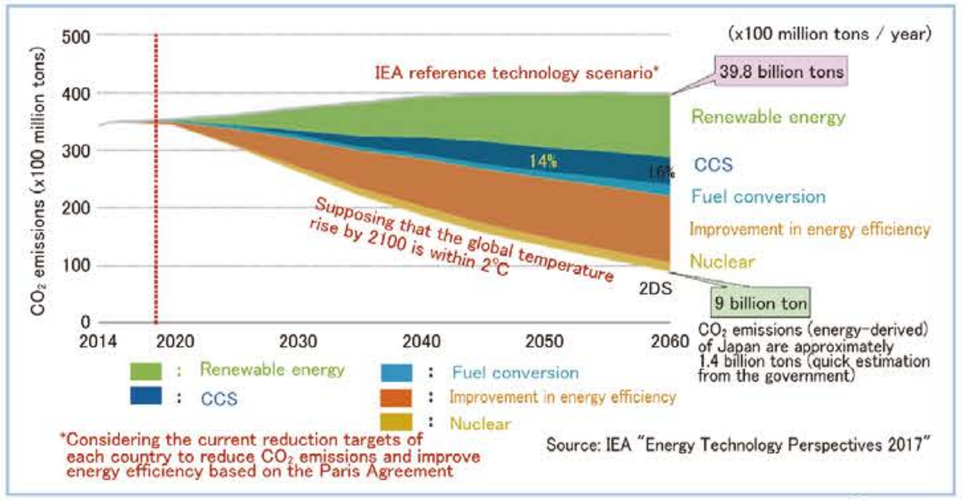


Figure 1 Forecast of total global CO_2 reduction amount from the present to 2060[(1)]

Power generation using renewable energy such as wind power generation, photovoltaic power generation, and hydroelectric power generation requires flexible and stable power production and supply systems for the efficient utilization of such electric power because the power generation amount fluctuates depending on the climate and weather conditions and the time zone (day and night), and the power generation amount is unevenly distributed around the world. On the other hand, it is considered that converting renewable energy into hydrogen for storage, transportation, and usage is effective against energy fluctuations. Even in Japan, which is far away from large-scale power generation areas using renewable energy, it is important and urgent to build a hydrogen supply chain and develop relevant technologies.

In addition, in the previous report[(1)], it is expected that the use of hydrogen produced by reforming fossil fuels including natural gas will start to increase from around 2030 and will account for 14% of the cumulative CO_2 reduction amount to 2050. Together with carbon dioxide capture and storage (CCS), which collects CO_2 generated in large quantities at the time of manufacturing and stores it in the ground, technology for the utilization of hydrogen produced from a combination of fossil fuel reforming and CCS is also required in the transition period of shifting to a renewable energy-based society.

As illustrated in **Figure 2**, we are working on maximizing the utilization of hydrogen derived from renewable energy and fossil fuel and applying power generation products, one of our major strengths, to the hydrogen value chain. Among these efforts, large gas turbines for power generation can not only generate power with high efficiency, but can also use low-purity hydrogen (with relatively low hurdles of manufacturing cost and technology), which leads to large and stable hydrogen demand. As the hydrogen usage vision, including the expansion of infrastructure and various methods of utilization toward realizing a hydrogen society, has been presented, the role of our large gas turbines for power generation will increase further in the future.

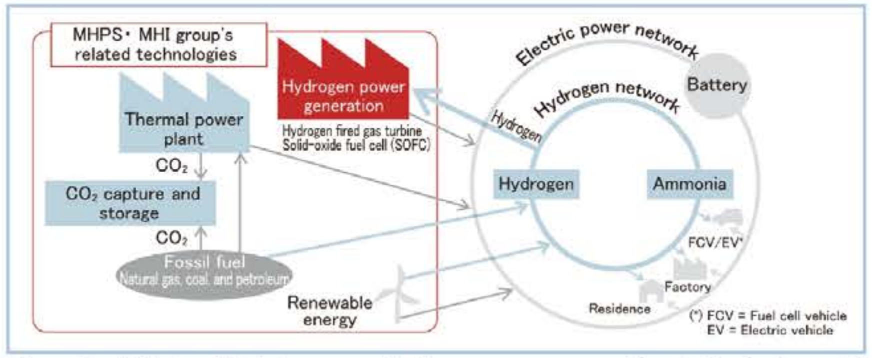


Figure 2 Relationship between our hydrogen power generation technologies and hydrogen network

3. Combustor for hydrogen gas turbine

The development of large gas turbines for power generation has advanced up to now, while the turbine inlet temperature (combustion temperature) has been raised to achieve high efficiency. To handle the NOx emissions increasing exponentially along with the rise in the combustion temperature, a premixing combustion method is adopted for the Dry Low NOx (DLN) combustor installed in our large gas turbines for power generation.

The premixing combustion method mixes fuel and air in advance to put them into the combustor. Since the flame temperature can be made uniform compared with the diffusion combustion method, steam or water injection for NOx reduction is unnecessary and a decrease in the cycle efficiency does not occur. On the other hand, the stable combustion range is narrow, there is a risk of the occurrence of combustion oscillation and backfire (flashback), and unburned hydro carbons tend to be easily discharged.

Depending on the hydrogen mixing ratio, the fuel component changes, resulting in a change in the flame property Hydrogen has a higher combustion speed in comparison with natural gas, so the risk of flashback phenomenon in the case of natural gas and hydrogen co-firing is higher than that in the case of natural gas firing. Therefore, for the development and practical realization of combustors for hydrogen gas turbines, the reduction of NOx and the stabilization of combustion centering on improvements for the prevention of flashback together with improvements in marketability (low cost, long service life, etc.) are necessary.

The development status of our combustors for hydrogen-fired gas turbines that can be used for the co-firing and firing of hydrogen is described below. **Figure 3** provides an overview.

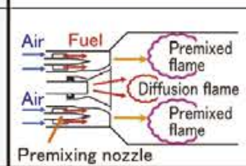
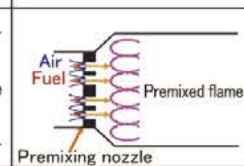
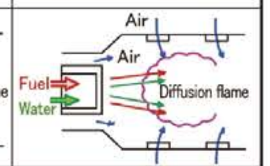
Combustor	Multi-nozzle combustor	Multi-cluster combustor	Diffusion combustor
Combustion method	Premixed flame combustion	Premixed flame combustion	Diffusion flame combustion
Structure			
NOx	Low NOx due to flame temperature uniformed by premixing nozzle	Low NOx due to flame temperature uniformed by small premixing nozzle	Fuel is injected in to air. There is a high-flame temperature region and the NOx is high
Flashback	High flashback risk in the case of hydrogen mono-firing because of the large flame propagating area	Low flashback risk due to the narrow flame propagating area	No flashback risk because of diffusion flame
Cycle efficiency	No efficiency drop due to no steam or water injection	No efficiency drop due to no steam or water injection	Efficiency drop occurs because steam or water are injected to reduce NOx
Hydrogen co-firing ratio	Up to 30 vol%	Up to 100 vol% (under development)	Up to 100 vol%

Figure 3 Our combustors for hydrogen gas turbines

(1) Dry Low NOx (DLN) multi-nozzle combustor for hydrogen co-firing

Figure 4 gives an overview of a newly developed combustor for hydrogen co-firing based on the conventional DLN combustor with the aim of preventing an increase in the occurrence risk of flashback because of hydrogen co-firing. The air supplied from the compressor to the inside of the combustor passes through a swirler and forms a swirling flow. Fuel is supplied from a small hole provided on the wing surface of the swirler and mixed rapidly with the surrounding air due to the swirling flow effect. On the other hand, it is clear that a region with a low flow rate exists in the center part of the swirling flow (hereafter the vortex core). A flashback phenomenon in a swirling flow is considered as flame moving back in a slow-flow velocity portion of the vortex core. The new-type combustor characteristically injects air from the tip of the nozzle to raise the flow velocity of the vortex core. The injected air compensates for the low flow velocity region of the vortex core and prevents the occurrence of flashback.

As a result of a combustion test under the actual engine pressure using one full-scale new combustor, NOx was within the operable range even under the condition where 30 vol% of hydrogen was mixed in, so it was found that operation without the occurrence of flashback or a remarkable increase of combustion oscillation is possible.

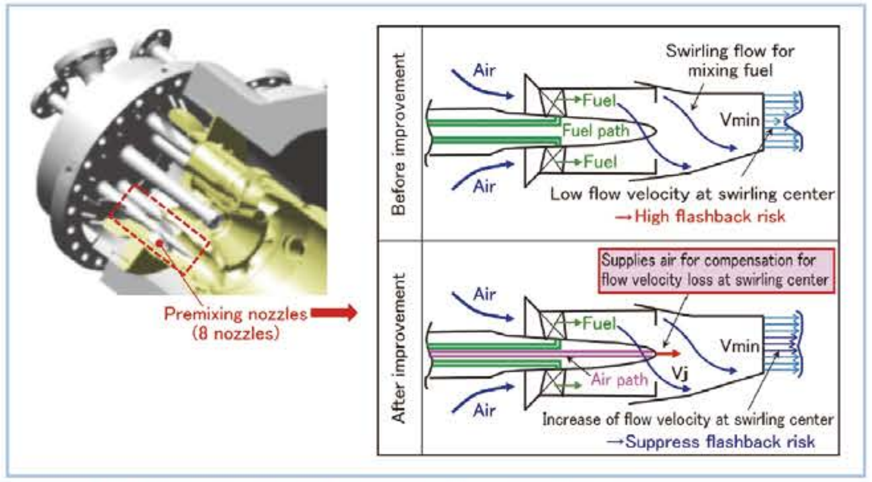


Figure 4 Outline of new combustor for hydrogen co-firing

(2) Multi-cluster combustor for hydrogen firing (**Figure 5**)

The higher the concentration of hydrogen is, the higher the risk of flashback becomes. To mix fuel and air using swirling flow like a hydrogen co-firing DLN combustor, a relatively large space is necessary and the risk of flashback increases, so it is necessary to mix them in a short time in a narrow space. Therefore, we devised a mixing system that disperses the flame and blows out the fuel smaller and more finely. Based on the multi-cluster combustor illustrated in Figure 5 with a greater number of nozzles than the fuel supply nozzles (eight nozzles) of a DLN combustor, for the hole of one nozzle, we adopted a system where the nozzle hole was made smaller, air was fed in, and hydrogen was blown in for mixing. It is possible to mix air and hydrogen at a smaller scale without using swirling flow, which may allow for the compatibility of high flashback resistance and low NOx combustion. We are currently studying the basic structure of the fuel nozzle.

(3) Diffusion combustor

A diffusion combustor injects fuel to air into the combustor. Compared with a premixed combustion method, a region with a high flame temperature is likely to be formed, and the amount of NOx generated increases, so a measure for NOx reduction using steam or water injection is necessary. On the other hand, the stable combustion range is relatively wide, and the allowable range for the fluctuation of the fuel property is also large.

Figure 6 is our diffusing combustor. This combustor has actual results with fuels with a wide range of hydrogen content (up to 90 vol%) through the utilization of offgas (exhaust gas generated in refinery plants, etc.) as fuel in small to medium size gas turbine power generation

facilities, and also succeeded in a hydrogen-fired combustion test when taking part in the International Clean Energy Network Using Hydrogen (World Energy NETWORK (WE-NET) technological research and development project.

Figure 5 Multi-cluster combustor (under development)

Figure 6 Diffusion combustor

4. Ammonia cracking GTCC

To make it possible to stably use the large amount of hydrogen required for a large-sized gas turbine for power generation, it is a prerequisite that a supply chain that produces, transports, stores, etc., hydrogen is established. The transportation and storage of hydrogen presented in the Hydrogen Basic Strategy[2] includes not only a method of liquefying hydrogen before transporting and storing, but also the utilization of energy carriers such as ammonia and organic hydride.

MHPS has been participating in the SIP (Strategic Innovation Promotion Program) of the Cabinet Office and studying gas turbine systems using ammonia as an energy carrier since fiscal 2017. Ammonia has a volumetric hydrogen density 1.5 times higher than that of liquefied hydrogen, and has the feature that existing transportation and storage infrastructure for liquefied petroleum gas can be used. In the program, studies have been made to directly burn ammonia as a fuel in a micro gas turbine[3] and a small gas turbine. However, there are problems as can be seen in **Table 1** with its application to large gas turbines. Therefore, as noted in **Figure 7**, we are studying a system that thermally cracks ammonia to hydrogen and burns it in a gas turbine. To crack ammonia, it is necessary to introduce a heat of reaction of 46 kJ/mol per 1 mole of raw ammonia while heating ammonia to high temperature under catalytic contact. Since this heat of the reaction results in an increase in the heat value of hydrogen (chemical recuperation), there is no efficiency reduction in principle. Since a trace amount of residual ammonia remaining after cracking causes NOx formation in the combustor, the configuration of a cracker capable of reducing the amount of residual ammonia, the selection of the cracking catalyst, etc., are being promoted through the program.

Table 1 Characteristics of ammonia combustion and consideration for large gas turbines

Characteristics of ammonia combustion	Considerations for large gas turbines
Low combustion speed (about 1/5[3] of that of methane)	- The size of the combustor increases to secure the time necessary for completing the combustion. - Since the large gas turbine is composed of a multi-can combustor, there is a restriction on the size expansion of the combustor.
Nitrogen contained in fuel	- Fuel NOx is generated, but the combustion gas temperature of a large gas turbine has been increased to the extent permitted by Thermal NOx, and there is little room to allow Fuel NOx. - Lowering of NOx by two-stage combustion is considered, but in the case of a large gas turbine, there are many technical problems such as upsizing and complication of the combustor.

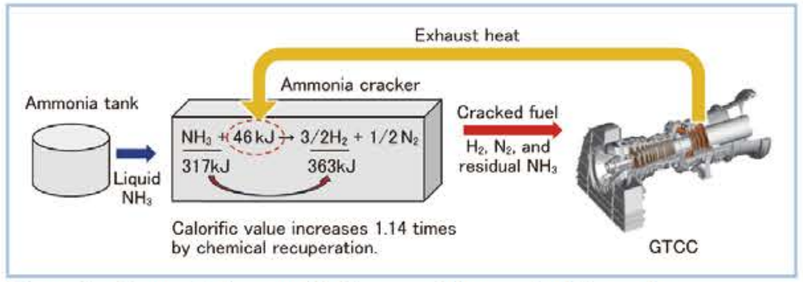


Figure 7 Concept of ammonia decomposition gas turbine cycle

As presented in Table 2, this system can be characteristically applied to high-efficiency and large-capacity GTCC systems with a relatively small number of modifications, thereby contributing to a large amount of CO_2 reduction by using CO_2-free ammonia. By applying this system, it is possible to not only utilize a hydrogen combustor for gas turbines currently under development, but also to use the developed ammonia cracker as a component of a general-purpose hydrogen supply chain.

Table 2 Characteristics of ammonia cracking gas turbine system

Item	Characteristic
High efficiency	- Since the heat necessary for the ammonia decomposition reaction is used for increasing the heat value of hydrogen produced (chemical recuperation), there is no theoretical efficiency drop. - A system with high overall efficiency can be constructed by combining with a high-efficiency GTCC.
Introducibility	The major development equipment is ammonia cracker, so the number of modifications on the gas turbine side that is necessary for the application of the system is relatively small such as modification of hydrogen combustor, etc.
Flexibility	By changing the type of the combustor, such as hydrogen mono-firing or co-firing with natural gas, a system suitable for the fuel infrastructure and site conditions can be built.
CO_2 reduction effect	In cases where the GTCC output is 500 MW, the capacity factor is 70%, and 100% ammonia-cracked gas is used, 800,000 tons of CO_2 emissions can be reduced annually.
Expandability	The heat source required for the ammonia cracker is not limited to exhaust heat of the gas turbine, so the system can be used as a component of a general-purpose hydrogen supply chain.

5. Efforts in overseas projects

Overseas, a comprehensive hydrogen utilization plan that covers the supply, transport, storage, and use of hydrogen is proposed, such as a system that processes CO_2 generated during the production of fossil fuel-derived hydrogen using CCS. Especially in Europe where there is an advantage that existing natural gas pipelines have been developed, hydrogen utilization projects are underway as cross-border comprehensive infrastructure.

Among them, we are participating in a project to convert a natural gas-fired gas turbine combined cycle (GTCC) power generation plant with 1.32 million kW-class output operated by N.V. Nuon, a Dutch energy company, to hydrogen-fired power generation. This project calls for the conversion of one of the three units of the M701F gas turbine power generation plant, which we delivered to the Nuon Magnum power plant (Figure 8) located in the state of Groningen in the northernmost part of the Netherlands, to a 100% hydrogen-fired power generation plant by 2023. We have carried out an initial feasibility study where we examined the application of a diffusion combustor, which is existing technology, and verified that the conversion to hydrogen-fired power generation is possible. Natural gas-fired power generation emits approximately 1.3 million tons of CO_2 annually per system of 440,000 kW GTCC power generation, most of which can be reduced by conversion to a hydrogen-fired power generation plant. We will continue to handle the feasibility study in the field of gas turbine technology and will continue to cooperate toward the realization of the project including planning specific modification ranges, etc.

Vattenfall's gas power plant Magnum. (Photo: Koos Boertjens / Vattenfall)

Figure 8 Nuon Magnum power plant in the Netherlands

6. Conclusion

The contents described in chapter 3 of this paper are part of the outcome of the project "Technology Development for the Realization of a Hydrogen Society" of the New Energy and Industrial Technology Development Organization (NEDO). In this grant project, we worked on the development of combustors for hydrogen and natural gas co-fired gas turbines and found that gas turbine operation under a 30 vol% co-firing condition is possible. We are continuing with the development of hydrogen-fired systems.

The contents described in chapter 4 of this paper are part of the outcome of the Council for Science, Technology and Innovation (CTSI), Cross-ministerial Strategic Innovation Promotion Program (SIP), "Energy Carriers" (Funding agency: JST). With this research, we began the development of ammonia cracking GTCC systems using ammonia, which is promising as one of the energy carriers for hydrogen.

Our hydrogen-fired gas turbines play a major role in the realization of a global CO_2-free hydrogen society using renewable energy by 2050 and in the utilization of fossil fuel-derived hydrogen combined with CCS in the transition period. We will continue to lead the construction of an international hydrogen supply chain with hydrogen power generation that produces a large and stable supply of hydrogen to contribute to the realization of a CO_2-free hydrogen society.

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Mitsubishi Heavy Industries Technical Review Vol. 58 No. 3 (September 2021)

Operation Status of 1650°C Class M501JAC Gas Turbine at T-point 2 Power Plant Demonstration Facility

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KENTARO SUZUKI[*1] SUSUMU WAKAZONO[*3]
MASAHITO KATAOKA[*4] MASANORI YURI[*5]

Renewable energy has become more widespread in recent years. At the same time, the importance of gas turbine combined cycle (GTCC) power generation has also been on the rise because of the power supply instability of renewable energy. For higher GTCC efficiency, a higher temperature of the gas turbine is important. Mitsubishi Power, Ltd. (Mitsubishi Power) developed the high-efficiency M501J gas turbine, which attained the world's first turbine inlet temperature of 1600°C, utilizing the development results from the "1700°C class Ultrahigh-Temperature Gas Turbine Component Technology Development" national project in which it has participated since 2004. We have since steadily accumulated operating results. At T-point 2 in January 2020, we started test operation of the next-generation 1650°C class JAC series gas turbine, which is based on the proven J series and uses an enhanced air-cooled system for cooling the combustor, a thicker TBC (thermal barrier coating) and a compressor with a high pressure ratio as its core technologies, all of which have been validated as individual elements at the T-point demonstration facility. The final confirmation of the integrity of equipment reliability, performance, etc., was completed and commercial operation started in July 2020. This report presents the verification results of the test operation and the operation status thereafter.

1. Introduction

Since it has recently become very important to reduce CO2 emissions, power supply by renewable energy sources such as wind power generation and solar photovoltaic power generation has been planned and carried out. However, such renewable energy sources are unstable and natural fluctuations are unavoidable and present concerns such as sudden frequency and load fluctuations in the power system. Against this background, GTCC power generation, which is more efficient and more operable than conventional thermal power generation, is becoming more important in terms of global environmental conservation and a stable energy supply. For higher GTCC efficiency, a higher temperature of the gas turbine plays an important role. We developed the M701D, a 1150°C class large-capacity gas turbine, in the 1980s. This was followed by the M501F, which had a turbine inlet temperature of 1350°C and the M501G, which employed a steam-cooled combustor and had a turbine inlet temperature of 1500°C (**Figure 1**). Through these developments, we have verified the high plant thermal efficiency and reliability, as well as low emissions. From 2004, we participated in the "1700°C class Ultrahigh-Temperature Gas Turbine Component Technology Development" national project to conduct research and development of the latest technology necessary for higher temperature and efficiency and utilized the results of these

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efforts to develop the M501J, which attained the world's first turbine inlet temperature of 1600°C. Verification operation of the M501J GTCC started in 2011 at the gas turbine combined cycle power plant demonstration facility (T-point) located in Mitsubishi Power Takasago Works and operating results have been steadily accumulated.

The J series gas turbine adopts a steam-cooled system for cooling the combustor, but if an air-cooled system can be used while maintaining the high turbine inlet temperature, further improvement in the efficiency and operability of GTCC is expected. Therefore, we worked on the development of next-generation GTCC that realizes air cooling of high-temperature gas turbines and devised the enhanced air-cooled system that is one of its core technologies. In the spring of 2015, we completed the validation test of the entire system at T-point and since then the system has been in operation for more than 10,000 hours. This core technology is applied to the next-generation high-efficiency JAC (J-Air-Cooled) series gas turbine, which has achieved a high turbine inlet temperature of 1650°C. We have been proceeding with the construction of the second gas turbine combined cycle power plant demonstration facility (hereinafter referred to as T-point 2) located in Mitsubishi Power Takasago Works for long-term actual-equipment validation of the JAC series gas turbine. T-point 2, which is state-of-the-art GTCC equipment with an output of 566 MW that combines the 1650°C next-generation JAC high-efficiency gas turbine and the newly-developed high-efficiency steam turbine, has been in test operation since January 2020 and achieved a combined rated output of 566 MW on April 2. We then carried out various tests and adjustments necessary to operate T-point 2 as a power plant, completed all the functional confirmations and started commercial operation on July 1. Due to the adoption of the JAC series gas turbine, the power generation efficiency of the GTCC reached 64%. During test operation, in order to verify the underlying technology, we carried out thousands of temporary large-scale measurements in addition to those provided by regular measurement instruments and monitored and evaluated them online. This report presents the development concept of the state-of-the-art high-efficiency JAC series gas turbine, the verification results obtained at the T-point 2 demonstration facility and the operation status including commercial operation for about one year thereafter.

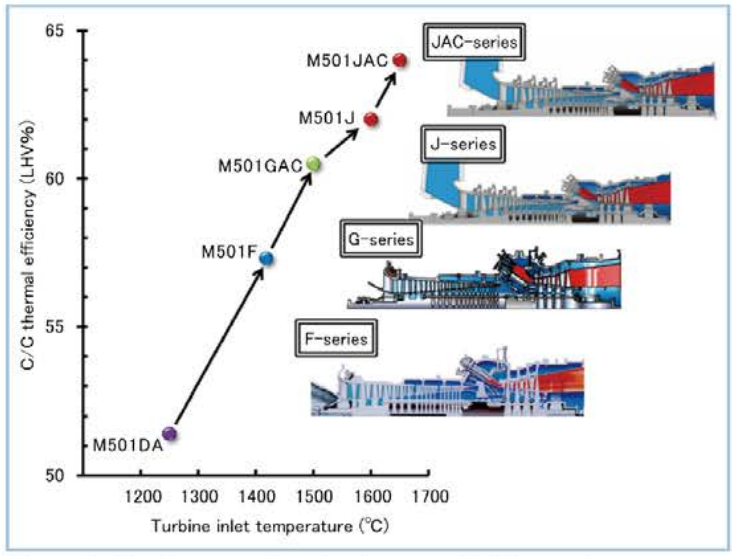

Figure 1 Developmental trend of large gas turbine models

2. Development concept of 1650°C class M501JAC gas turbine

We proceeded with the development of the next-generation 1650°C class JAC series gas turbine in order to further improve the efficiency and operability by applying to the proven M501J gas turbine the following validated component technologies: (1) an enhanced air-cooled system for cooling the combustor, (2) a thicker TBC and (3) a compressor with a high pressure ratio.

The basic concept of this gas turbine is as follows (**Figure 2** and **Figure 3**). Validation of these individual component technologies was completed at the T-point demonstration facility and they were then applied to the 1650°C class JAC series gas turbine (**Table 1**).

(1) Adopting an enhanced air-cooled system to improve operability and increase the turbine inlet temperature in comparison to that of the J series.

(2) Adopting a thicker TBC developed based on the technology resulting from the national project to achieve both high performance and reliability despite the increased turbine inlet temperature.

(3) Adopting a compressor with a high pressure ratio design equivalent to the M501H (validated from 1999 to 2000, hereinafter referred to as the H series) to suppress the increase in the exhaust gas temperature at the gas turbine outlet.

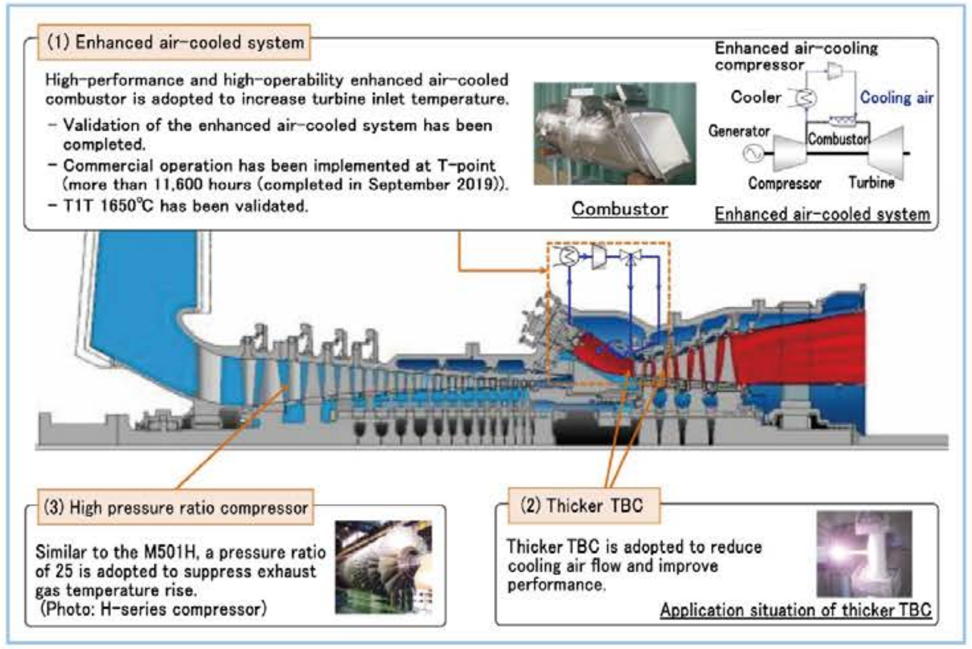

Figure 2 Development concept of 1650°C class JAC gas turbine

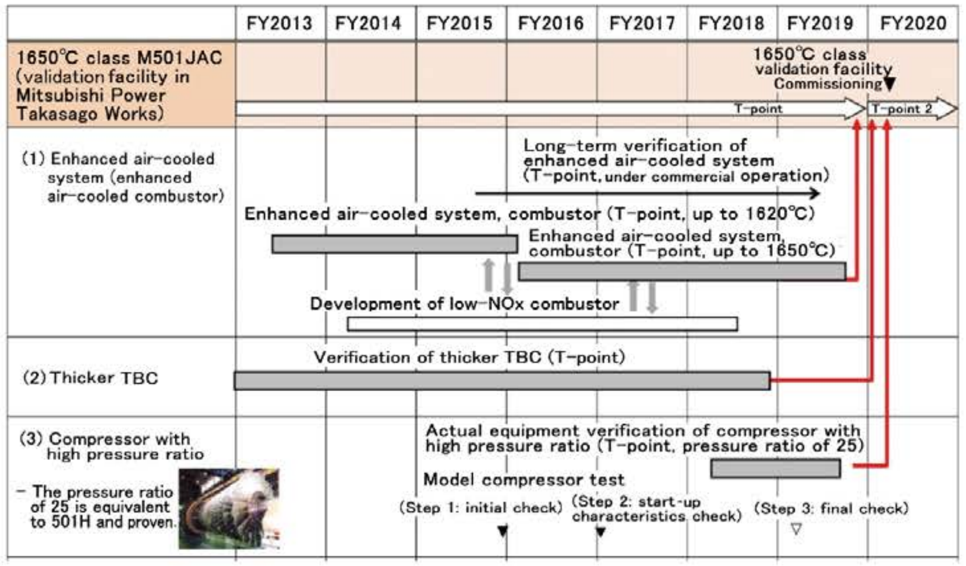

Figure 3 Application flow of component technology to 1650°C class JAC gas turbine

Table 1 Comparison of gas turbine performance (ISO, standard conditions)

	M501J	M501JAC
Frequency (Hz)	60	60
Pressure ratio (-)	23	25
Gas turbine output (MW)	330	435
Gas turbine efficiency (%-LHV)	42	44
Combined cycle output (MW)	484	630
Combined cycle efficiency (%-LHV)	62	>64

3. Verification results and operation status of the 1650°C class M501JAC gas turbine at T-point 2

T-point 2 is a state-of-the-art GTCC facility with an output of 566 MW that combines a 1650°C next-generation high-efficiency JAC series gas turbine and a newly-developed high-efficiency steam turbine. The M501JAC gas turbine was shipped and installed in the spring of 2019 and test operation at T-point 2 commenced in January 2020. In this test operation, first the gas turbine alone was operated and reached its rated load after 10 starts from the first ignition. After steam ventilation, the operability confirmation test was carried out by Combined Cycle (CC) operation and commercial operation began on July 1 (**Figure 4** and **Figure 5**). In test operation, we constantly monitored the start-up acceleration, no-load rated speed and state quantity during partial-load and rated-load operation of the gas turbine in order to make a final confirmation of the reliability, actual performance, exhaust gas emissions, etc., of the equipment. Next, functional tests and special tests required for actual commercial plants were completed.

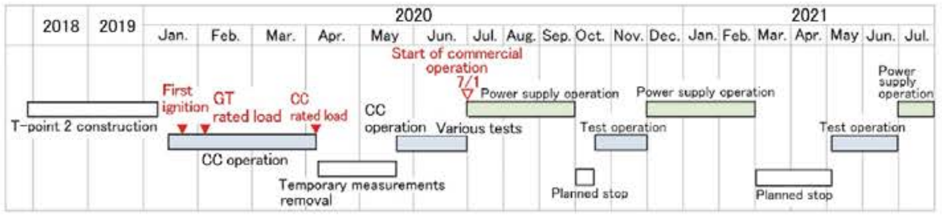

Figure 4 Test operation schedule at T-point 2

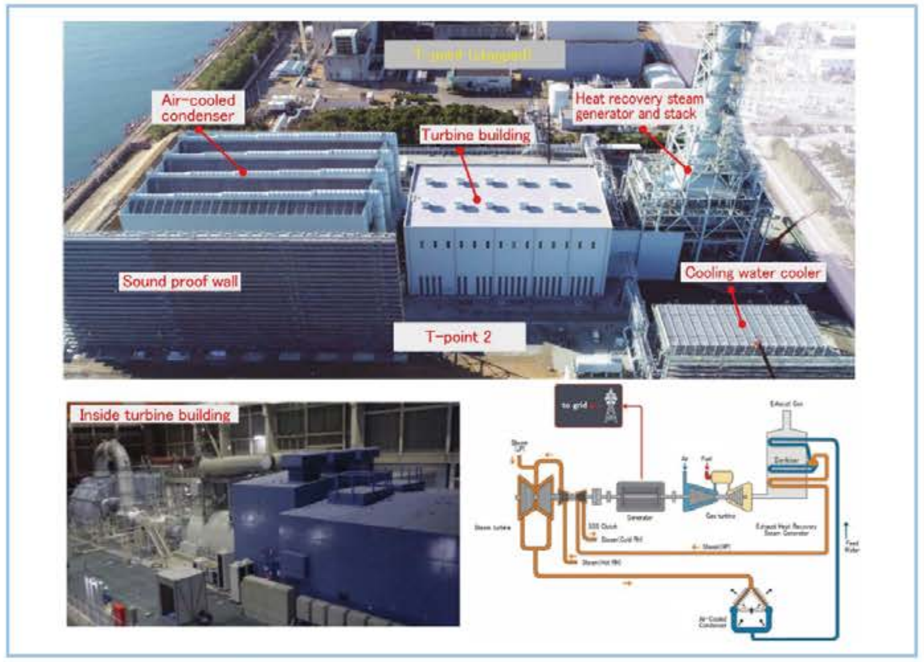

Figure 5 Overview of T-point 2 combined cycle plan

During test operation, more than 2,800 temporary large-scale measurements were conducted to evaluate the integrity in order to verify the technologies that are the basis of the JAC series gas turbine. For the rotating parts, roughly 100 large-scale telemetric measurements were carried out to confirm the metal temperature and vibration stress integrity of the compressor rotors and turbine blades. This chapter presents the final confirmation results of the integrity of each component (**Figure 6**), as well as the status following the commercial operation verification test run over approximately one year after the final integrity confirmation observed in the inspection during a planned stop in March 2021.

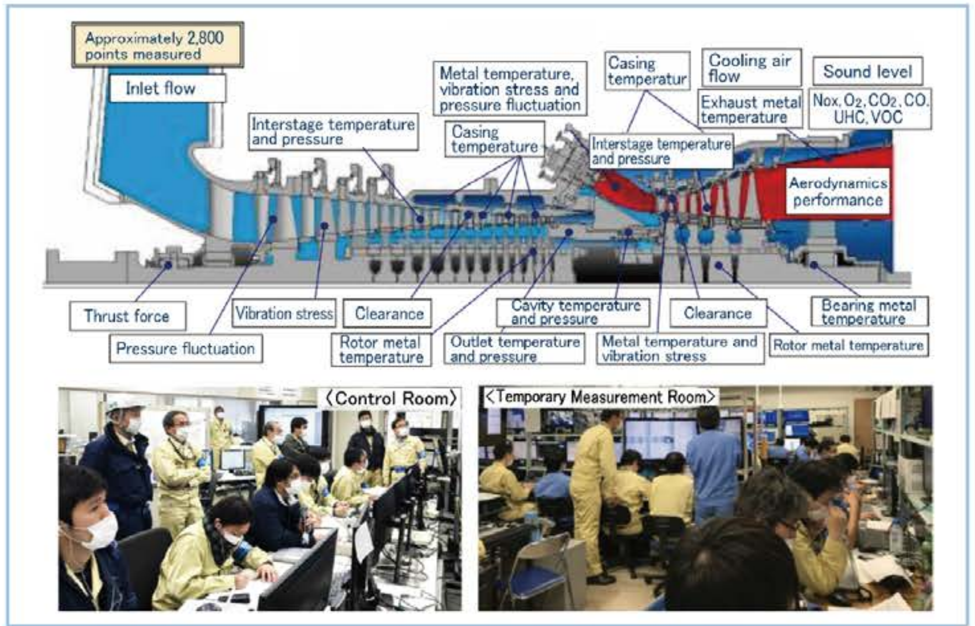

Figure 6 Implementation status of test operation and temporary measurements

3.1 Enhanced air-cooled combustor and enhanced air-cooled system

The enhanced air-cooled system had already been validated at the T-point demonstration facility, including its ability to follow transient changes. In addition, the metal temperature of the enhanced air-cooled combustor was measured in this test operation and its cooling performance in the actual equipment was ultimately validated. As a result, it was confirmed that the combustion casing metal temperature distribution was lower than the design allowance value, so there were no problems in terms of cooling performance (**Figure 7**). It was also confirmed that there were no particular problems with the combustion vibration characteristics and exhaust gas emissions and stable operation was possible under partial-load to rated-load conditions.

The JAC series gas turbine uses a system that enables clearance control during under-load operation based on the enhanced air-cooled system. This system uses two cooling air supply methods: one causes cooling air to bypass the turbine blade ring and introduces it directly into the combustor and the other causes cooling air to pass through the turbine blade ring in advance to supply it to maximize the performance by reducing the turbine clearance during load operation. These two systems can be switched by the switching valve (three-way valve) even during load operation. The former can handle operation with large load fluctuations by opening the clearance (Flexible Mode). On the other hand, the latter can close the clearance during load-hold operation and maximize the performance of steady operation (Performance Mode). **Figure 8** shows the behavior of the clearance when the three-way valve is switched during load operation. It was ultimately confirmed that this system can improve operability more than before while maximizing performance.

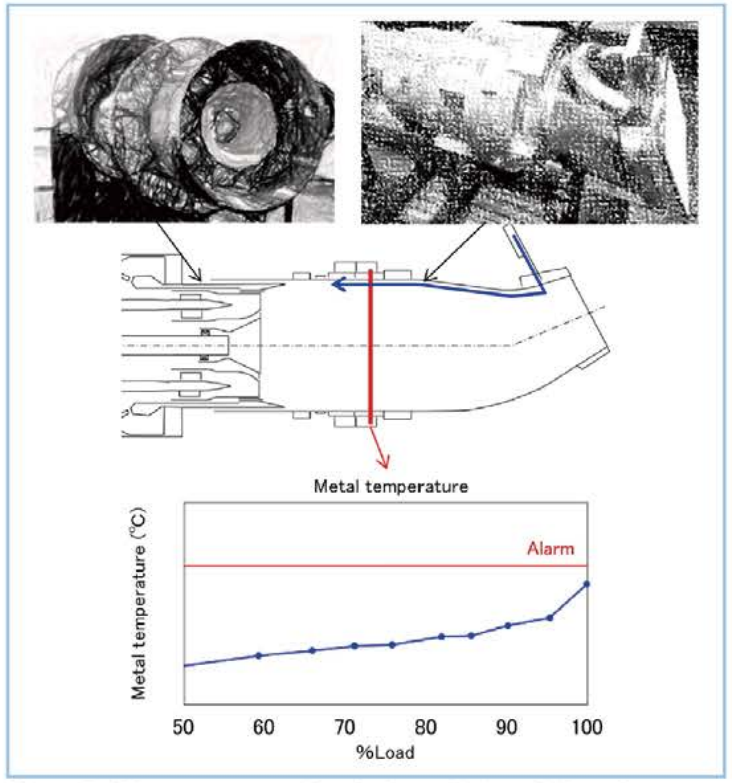

Figure 7 Measurement results of enhanced air-cooled combustor metal temperature

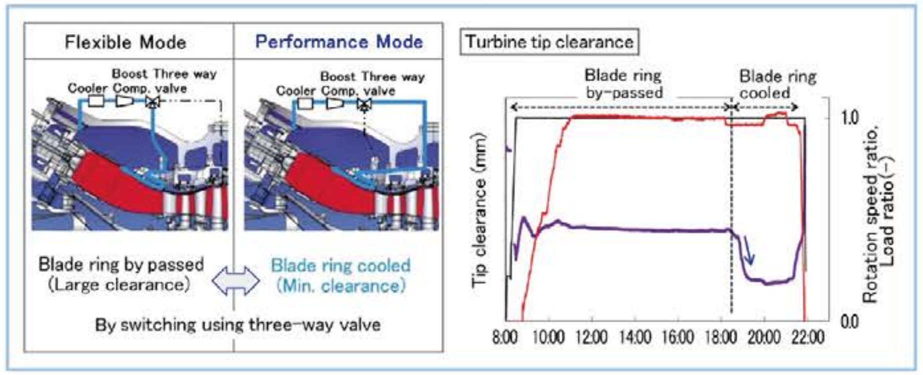

Figure 8 Turbine clearance control using enhanced air-cooled system

3.2 Turbine blade metal temperature

The turbine inlet temperature of the 1650°C class JAC series gas turbine can become 50°C higher than that of the J series and adopts a thicker TBC to achieve both high performance and reliability. As mentioned above, the integrity of the thicker TBC has been verified and confirmed at T-point over the long term. **Figure 9** shows the specially-measured metal temperature distribution of the JAC series turbine row 1 vane to which the TBC is applied in order to optimize the cooling design. It was confirmed that although the turbine row 1 vane was subjected to the strictest heat load and its cooling structure was complicated, there were no local high temperature parts, all parts were below the design allowance temperature and the integrity was maintained under the condition of an inlet gas temperature of 1650°C. The integrity was also confirmed in the inspection after operation.

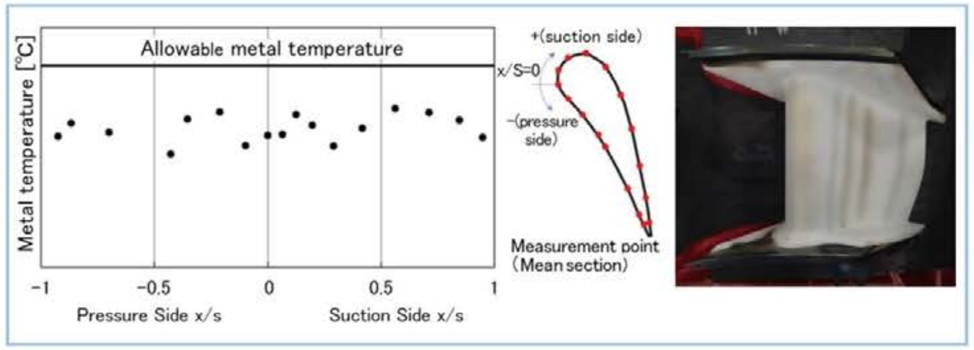

Figure 9 Metal temperature distribution measurement results of turbine row 1 vane and inspection results after operation

For the turbine row 1 blade, in addition to confirmation of the blade surface metal temperature and vibration stress using telemetric measurements, pyrometric measurement, which has been introduced at T-point, was carried out. The pyrometer was inserted into the gas path from the standby position through the insertion hole provided in the combustor casing and the turbine row 1 vane to confirm the integrity of the blade surface temperature distribution around the leading edge of the blade surface, which was subjected to a particularly high heat load. The integrity was also confirmed in the inspection after operation (**Figure 10**).

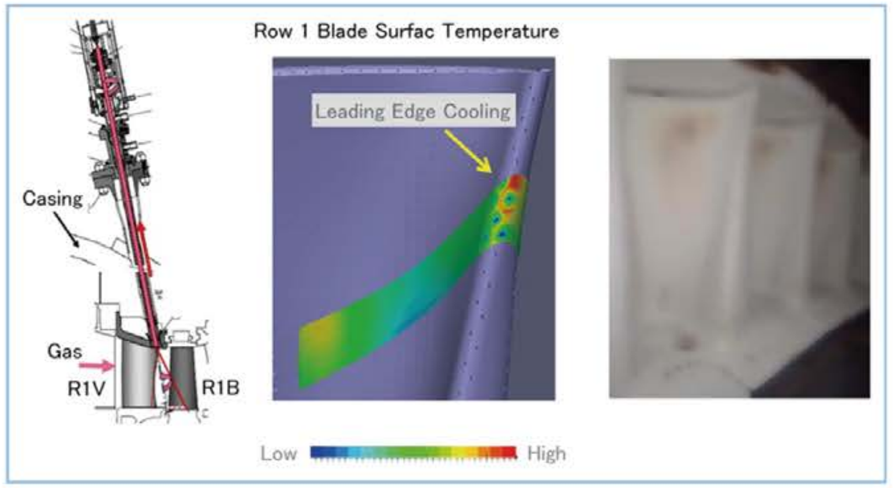

Figure 10 Surface temperature distribution measurement results of turbine row 1 blade and inspection results after operation

3.3 High pressure ratio compressor

The compressor of the 1650°C class JAC series gas turbine has a pressure ratio that was increased from 23 to 25. However, since a high pressure ratio compressor has a design in which the outlet flow path area is relatively narrow, there is a concern that the flow rate will decrease and the rotating stall will relatively deteriorate during startup with a low pressure ratio. As mentioned above, an H series compressor with a similar pressure ratio of 25 was validated, as was a compressor with a pressure rate of 25 based on the J series in May 2018 at T-point. Detailed temporary measurements were also carried out for the JAC series and it was ultimately confirmed that the starting characteristics, blade vibration stress and aerodynamic performance were favorable (**Figure 11**).

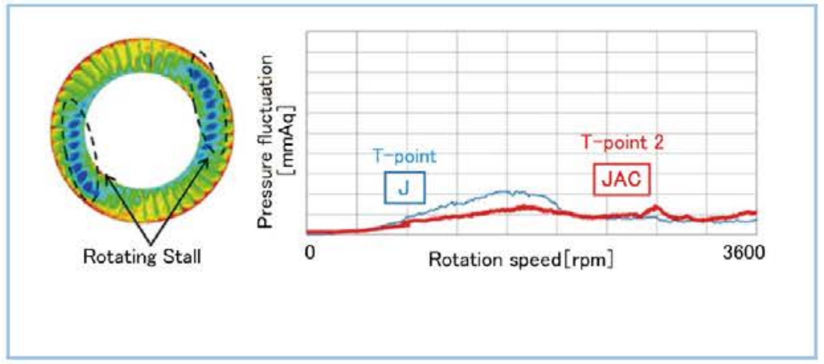

Figure 11 Verification results of JAC gas turbine high pressure ratio compressor

3.4 Status of gas turbine after one year of operation

Commercial operation commenced on July 1, following the test operation that started in January 2020. It has been confirmed that the components are sound after about one year of power supply operation and verification test operation, as a result of inspection of various parts including the compressor, combustor, turbine and inlet/exhaust systems and thus there is no problem in terms of the long-term reliability (**Figure 12**). After the completion of the verification test operation in the spring of 2021, power supply operation will be continued again and operational hours and the number of starts will be further accumulated to continuously confirm the long-term reliability.

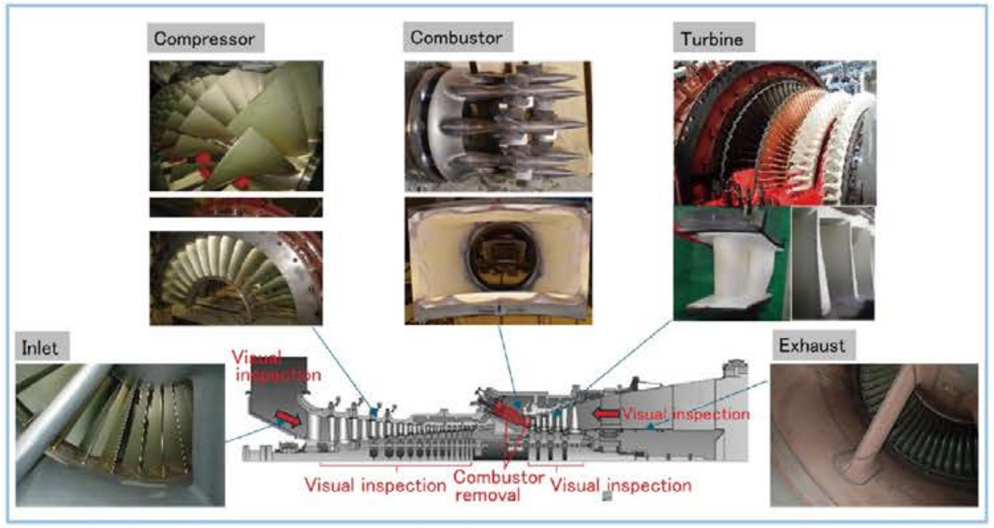

Figure 12 Overview of JAC series gas turbine inspection results in March 2021

3.5 Future development of JAC series gas turbine

As shown below, the construction and operation of customers' commercial plants using JAC series gas turbines that have been verified at our power plant demonstration facility T-point 2 and confirmed to offer long-term reliability as described above have commenced, striving steadily for realizing a more stable global energy supply. 60 Hz M501JAC gas turbines have been shipped to commercial plants in North America and other countries one after another since September 2020 and the local installation work is being carried out (**Figure 13**). The first of the eight 50 Hz M701JAC gas turbines for Thailand started operation on March 31, 2021, as scheduled despite the COVID-19 disaster. The construction work of the remaining units is progressing toward the start of operation of all turbines in 2024 (**Figure 14**).

Figure 13 Shipping of commercial 60 Hz M501JAC gas turbine

Figure 14 Operation start of commercial 50 Hz M701JAC gas turbine

4. Conclusion

For higher GTCC efficiency, a higher temperature of the gas turbine plays an important role. Mitsubishi Power has participated in the "1700°C class Ultrahigh-Temperature Gas Turbine Component Technology Development" national project since 2004. We utilized the results of these efforts to develop the high-efficiency M501J gas turbine, which attained the world's first turbine inlet temperature of 1600°C and we have since steadily accumulated operating results. In order to further improve the efficiency and operability of GTCC, we developed the next-generation 1650°C class JAC series gas turbine, which is based on the proven J series and uses an enhanced air-cooled system for cooling the combustor, a thicker TBC and a compressor with a high pressure ratio as its core technologies and completed the validation of the individual elements at the T-point demonstration facility.

We had been proceeding with construction of the second gas turbine combined cycle power plant demonstration facility (T-point 2) at our Takasago Works for long-term verification of the JAC series gas turbine. We started its test operation in January 2020, carried out as many as about 2,800 temporary large-scale measurements and made final confirmation of the integrity of the JAC series components, such as the reliability and performance during 1650°C operation. At T-point 2, the combined rated output reached 566 MW on April 2 and all the functional confirmations as a power generation facility were completed. Commercial operation commenced on July 1. Since then, both operational hours and number of starts continue to be accumulated in the operation according to the supply and demand requirements. It has been confirmed that the components after about one year of operation are sound and that they offer long-term high reliability.

Verified M501JAC gas turbines have been shipped to commercial power plants in North America, etc., one after another and the 50 Hz M701JAC gas turbine also started operation in Thailand in March 2021 as scheduled despite the COVID-19 disaster. Hydrogen co-firing is planned for a future GTCC power generation project in Utah in the United States. By incorporating our proprietary combustor technology, we aim to start the operation of the JAC series gas turbine with a hydrogen co-firing rate of 30% and to realize 100% hydrogen-fired operation in the future.

The long-term verification operation at T-point 2 is carried out from our RMC (remote monitoring center). We aim to improve the reliability of not only major equipment such as gas turbines, but also the entire plant including auxiliary equipment, validate various applications included in the "TOMONI" digital solution, such as shortening the startup time and automatically optimizing operating parameters and realize autonomous operation in the future.

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Mitsubishi Heavy Industries Technical Review Vol. 58 No. 3 (September 2021)

Development of Hydrogen/Ammonia Firing Gas Turbine for Decarbonized Society

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In the midst of globally accelerating moves toward a decarbonized society, Mitsubishi Power, Ltd. (Mitsubishi Power) has made continuous efforts to develop hydrogen/ammonia-firing Gas Turbine Combined Cycle (GTCC) power generation systems. The development of a gas turbine combustor that can operate with a mix of natural gas and 30 vol% of hydrogen has been completed for large frame gas turbines. Mitsubishi Power is also developing a 100% hydrogen-firing combustor. A promising Gas Turbine Combined Cycle using ammonia is also under development, facilitating energy transportation of hydrogen to further expand the lineup of carbon-free power generation systems. With these technologies, Mitsubishi Power is participating in hydrogen-firing GTCC projects in Europe, North America and other continents targeting commercialization in the mid-2020s.

By increasing hydrogen demand, especially through large-capacity and high-efficiency GTCC systems, Mitsubishi Power is set to lead the establishment of an international hydrogen supply chain and contribute to the realization of a decarbonized society.

1. Introduction

In 2015, the "Paris Agreement", which constitutes the international framework on prevention of global warming, was adopted at COP 21. Since then, many governments, financial institutions, investors and companies throughout the world have committed to make efforts toward decarbonization. The actual implementation of the agreement started in 2020 and movements toward the achievement of CO_2 emissions reduction targets are being proactively initiated around the world. The EU, including the environmentally-advanced regions in northern Europe, has already announced guidelines for becoming carbon neutral by 2050. China and the United States, which are the world's largest and second largest CO_2 emitters, issued a joint statement recently committing to cooperate on tackling global warming. Japan being a large energy-consuming country and mostly dependent on imports for its energy has also committed to become carbon neutral by 2050.

The Great East Japan Earthquake in 2011 triggered substantial efforts to dispatch renewable energy, however, roughly 80%[(1)] of the total electricity supply in the country is produced from thermal power generation which emits considerable CO_2. The degree of dependence on thermal power generation still remains high representing approximately 44% of the total primary energy consumption.

GTCC systems provide highly-efficient power generation, therefore emitting the lowest amount of CO_2 among conventional thermal power generation systems. The GTCC deployment will continue to meet growing energy demand while contributing to effort to reach a decarbonized society. On the other hand, the acceleration of the introduction and dissemination of renewable energy and the effective utilization of fossil fuels with consideration given to environmental impact are required.

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Mitsubishi Power has continuously worked on the development of decarbonization technologies for thermal power generation. Development of advanced technologies for GTCC power generation facilities are focused on:

(1) reduction of CO_2 emissions by a further increase in efficiency and capacity through higher combustion gas temperature, and other key technologies[(2)]
(2) promotion of technical development[(3)] for enhanced gas turbine flexibility targeting a rapid and flexible response to compensate for power generation fluctuations resulting from the increase of renewable energy use and
(3) promotion of technical development of gas turbines using hydrogen (H_2) or ammonia (NH_3) as fuel with lower or zero CO_2 emissions, thereby aiming at realizing a decarbonized society by 2050.

In Japan, as a basic hydrogen strategy[(4)] for a decarbonized society targets the commercialization of hydrogen power generation by around 2030. The development and commercialization of technologies for the introduction of equipment to electric power companies must be promoted in a short period of around 10 years. With the support of the New Energy and Industrial Technology Development Organization (NEDO), the development of combustors capable of operating on a mix of natural gas and 30 vol% of hydrogen have been successful for large frame gas turbines for power generation[(5)]. The developed combustor is expected to lower the hurdle for the implementation of hydrogen power generation and promote a smooth shift to a hydrogen society. With the continuous support of NEDO, 100% hydrogen-firing power generation is also under development. Research and development of a GTCC system using ammonia is also under development, with the associated promising future as an effective hydrogen energy carrier.

This report presents Mitsubishi Power efforts toward the realization of a decarbonized society, mainly covering prior studies about gas turbines for power generation under the application of hydrogen and ammonia for power generation projects around the world.

2. Decarbonized society and gas turbines for power generation

Power generation using renewable energy, including wind and photovoltaic power generation, will continue to spread and expand globally toward the realization of a decarbonized society. There is an estimation[(6)] that the reduction of CO_2 emissions through the utilization of renewable energy will account for about 30% of the total emission in 2060. The output of renewable energy is greatly affected by the ambient or meteorological conditions of the sites. The effective utilization or storage of electric energy surplus needs to be addressed using batteries, conversion into hydrogen and other technologies to avoid energy waste. Long and significant cycle fluctuations can involve considerable amounts of energy, converting renewable energy into hydrogen for utilization is effective to avoid energy waste. GTCC power generation has the capability and operability to follow abrupt output fluctuations of renewable energy and can flexibly fill the gap between the electric power demand and the renewable energy output. In addition, GTCC power generation can effectively use hydrogen as fuel, thereby producing large and stable hydrogen demand. Therefore, expectations for GTCC power generation have been growing.

A potential future scenario toward decarbonization is shown in **Figure 1**. In the mid-term, the spread of fossil fuel-derived hydrogen (blue hydrogen) using Carbon Capture Utilization and Storage (CCUS) is expected. GTCC will offer increased power generation efficiency and reduced CO_2 emissions while providing conventional inexpensive, safe and stable power generation using fossil fuels. The utilization of blue hydrogen will be promoted to generate power through the co-firing of hydrogen or ammonia fuels, which do not emit CO_2. In the long term, cost reduction and technical innovation will prioritize the use of renewable energy-derived hydrogen (green hydrogen), eventually becoming mainstream with hydrogen-firing power generation using green hydrogen helping reach the goal of eliminating CO_2 emissions.

The use of hydrogen for large-capacity and highly-efficient power generation gas turbines offers the environmental and economic advantages described below (**Figure 2**).

First, existing gas turbine facilities can be used with minimum modifications toward decarbonization, mainly requiring adjustments of the gas turbine combustion components and fuel supply systems. This reduce investment costs and lowers the cost hurdle for hydrogen conversion, promoting a smooth transition to a hydrogen society.

Next, in addition to liquid hydrogen, hydrogen carriers such as methylcyclohexane and ammonia can be transported and hydrogenerated to be used as fuel. There are flexible options for carriers and hydrogen with lower purity can be used compared to hydrogen for fuel cell electric vehicles. Therefore, the hydrogen cost can be reduced.

Lastly, power generation hydrogen-firing gas turbines require large amounts of hydrogen compared to fuel cell electric vehicles (the hydrogen consumption of one large frame GT equates 2 million fuel cell vehicles). The hydrogen use for power generation is expected to facilitate large hydrogen demand and to promote the expansion of the supply chain and the reduction of hydrogen cost.

As described above, it is considered that the utilization of hydrogen for large-capacity and highly-efficient gas turbines for power generation has an essential and important role in realizing a decarbonized society.

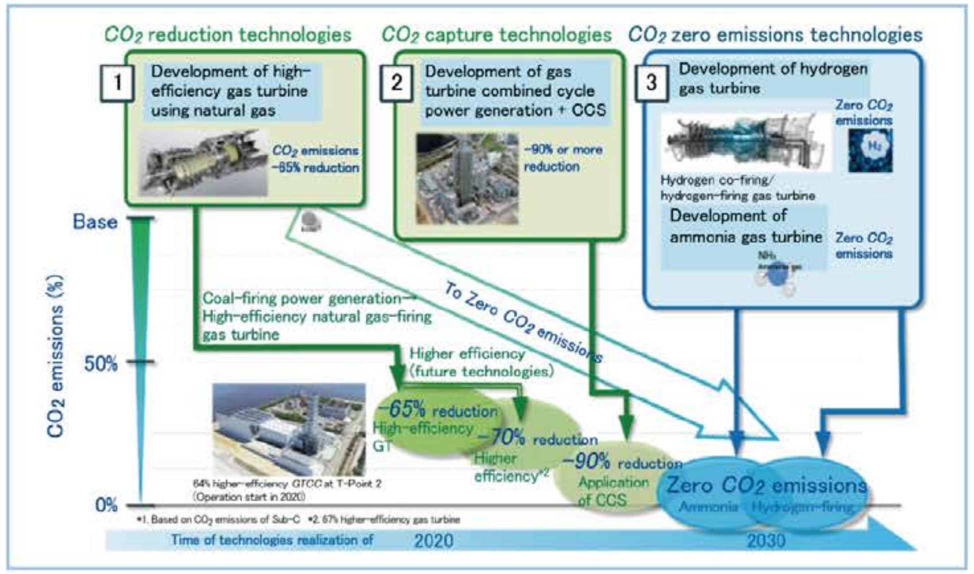

Figure 1 Scenario toward decarbonization

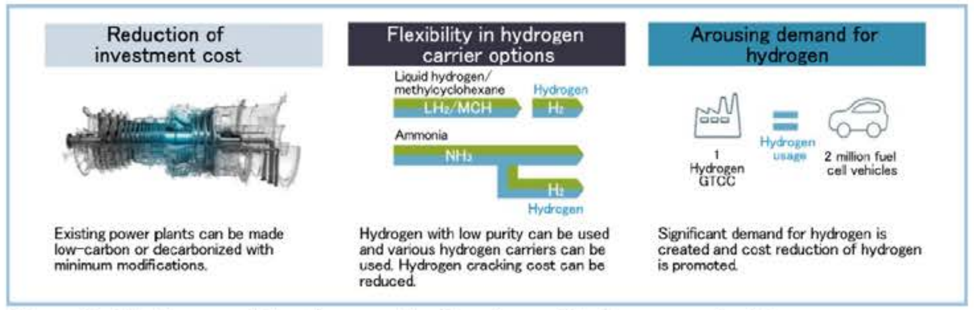

Figure 2 Environmental and economic advantages of hydrogen gas turbines

3. Hydrogen-firing gas turbines

The key point in the development of hydrogen-firing gas turbines is the development of combustors, which are the heart of gas turbines and combustion technologies.

Targeting higher efficiency for power generation large frame gas turbines typically involves increase of the Turbine Inlet Temperature (TiT), as well as the combustion temperature, leading to an exponential increase in NOx emissions. Mitsubishi Power large frame gas turbines apply premixing combustion method to the Dry Low NOx (DLN) combustor. Fuel and air is mixed prior to combustion to reduce NOx emissions. This approach results in a lower flame temperature in the combustor compared with the conventional diffusion combustion method, therefore, steam or water injection for NOx reduction is unnecessary and prevents a decrease in the cycle efficiency. On the other hand, the stable combustion range is narrow, there is a risk of the occurrence of combustion dynamics and backfire (flashback) and unburned hydrocarbons tend to be discharged.

Hydrogen has a higher combustion speed in comparison with natural gas. Therefore, in the case of natural gas and hydrogen co-firing or hydrogen firing in a premixed combustor, the risk of the occurrence of flashback is higher than firing natural gas. There is a possibility that flame from the flashback moves back upstream of the combustor, causing overheating of upstream components. Therefore, combustors for hydrogen-firing gas turbines should be designed to prevent flashback while also reducing NOx emissions with stable combustion. **Figure 3** provides an overview of Mitsubishi Power combustors for gas turbines hydrogen co-firing and hydrogen firing.

		Type	Low NOx technology	H_2 density (Vol%)
Large frame gas turbines	Ready	Type 1 : Diffusion combustor	N_2 dilution Water/steam injection	100%
		Type 2 : Premixed combustor (DLN)	Dry	30%
	Under development	Type 3 : Multi-cluster (DLN)	Dry	100% (target)
Middle and small gas turbines	Ready	H-25 Diffusion combustor	Water/steam injection	100%
	Under development	H-25 Multi-cluster (DLN)	Dry	30%
			Dry	100% (target)
	Ready	H-100 Premixed combustor (DLN)	Dry	30%
	Under development	H-100 Multi-cluster (DLN)	Dry	100% (target)

Figure 3 Combustors for hydrogen-firing gas turbines

(1) Dry Low NOx (DLN) multi-nozzle combustor for hydrogen co-firing

Figure 4 gives an overview of the newly developed combustor for hydrogen co-firing based on the conventional DLN combustor. It aims reduced risk of flashback under operation with hydrogen co-firing. The air supplied from the compressor to the combustor passes through a swirler and forms a rotating flow. Fuel is supplied from a small hole provided on the surface of the swirler and mixed rapidly with the surrounding air by the swirling flow. On the other hand, a low flow rate region exists in the center part of the swirling flow (hereinafter referred to as "vortex core") and it is considered that flashback occurs as flame moves back toward the low flow rate region. The new-type combustor injects air from the tip of the nozzle to raise the flow velocity of the vortex core, so that the injected air compensates for the low flow velocity region of the vortex core and prevents the occurrence of flashback.

The main combustion issues of gas turbine combustors are emissions, including NOx and combustion oscillation. Since they are affected by the combustion pressure condition, verification is needed under actual equipment pressure condition. Combustion tests need to be conducted under the actual equipment pressure (hereinafter referred to as "actual pressure combustion test") using one full-scale hydrogen co-firing combustor out of 16 to 20 combustors (60 and 50 Hz respectively) installed in the actual equipment, to evaluate the hydrogen co-firing effects on the combustion characteristics.

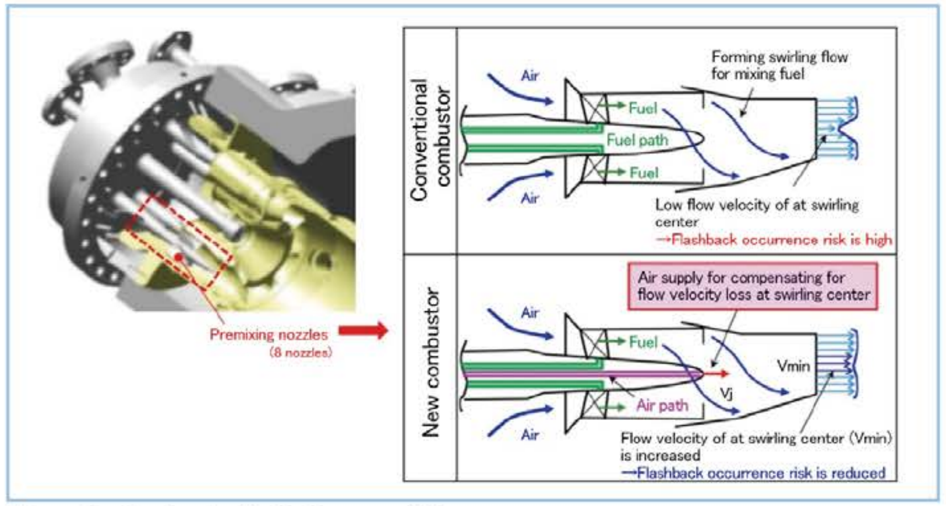

Figure 4 Combustor for hydrogen co-firing

Figure 5 shows the change in NOx with respect to the hydrogen mixing ratio under air and fuel ratio conditions in the test that correspond to the rated load of a gas turbine with a turbine inlet temperature of 1600°C. It was observed that as the hydrogen mixing ratio increased, NOx gradually increased by a small amount. It is considered that when hydrogen is mixed in the fuel, the combustion speed increases, the flame position in the combustor moves to the upstream and combustion occurs under an insufficient mix of fuel and air ratio. However, even under the condition where 30 vol% of hydrogen was mixed in the fuel, NOx was almost the same as that in the operation with natural gas and no hydrogen, within the operable range.

Figure 6 shows the change in combustion dynamics under the same condition. The combustion vibration pressure level is also equal to or lower than that in the operation with natural gas and it was verified that the combustion dynamics was not greatly affected by a change in the hydrogen mixing ratio. In addition, no flashback was observed in 30 vol% hydrogen co-firing. With these test results, it became clear that the DLN multi-nozzle combustor for hydrogen co-firing can be operated without the occurrence of flashback or a significant increase in combustion dynamics.

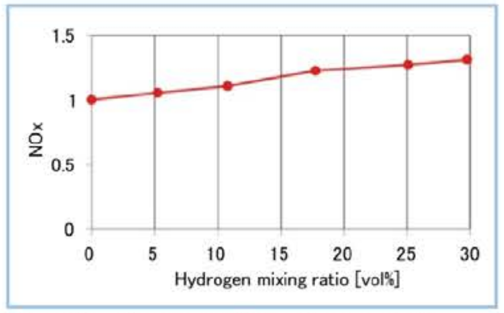

Figure 5 Change in NOx with respect to hydrogen mixing ratio (when NOx is 1 with 0% hydrogen)

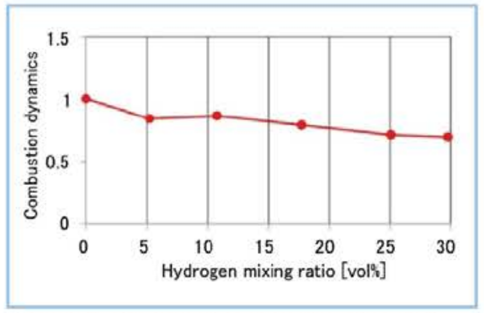

Figure 6 Change in combustion dynamics with respect to hydrogen mixing ratio (when the combustion vibration 1 with 0% hydrogen)

(2) Multi-cluster combustor for hydrogen firing

When the concentration of hydrogen becomes higher than 30% vol, the fuel and air mixing method using swirling flow adopted for the hydrogen co-firing combustor described in the previous section (shown in Figure 4) involves higher risk of flashback occurring in the low flow velocity region of the vortex core. A smaller scale of air and hydrogen mixing method without applying swirling flow is considered to provide resistance to flashback. Mitsubishi Power is developing a hydrogen-firing combustor based on the so-called multi-cluster design that was developed for IGCC[7] applications and currently in operation at the Osaki CoolGen facility in Japan. This design shown in **Figure 7**, has a greater number of fuel supply holes compared to the eight nozzle design of the hydrogen co-firing combustor described in the prior section. The size of the holes is smaller. It is possible to mix supplied air and hydrogen on a smaller scale resulting in a more effective flame dispersion allowing high flashback resistance and lower NOx combustion.

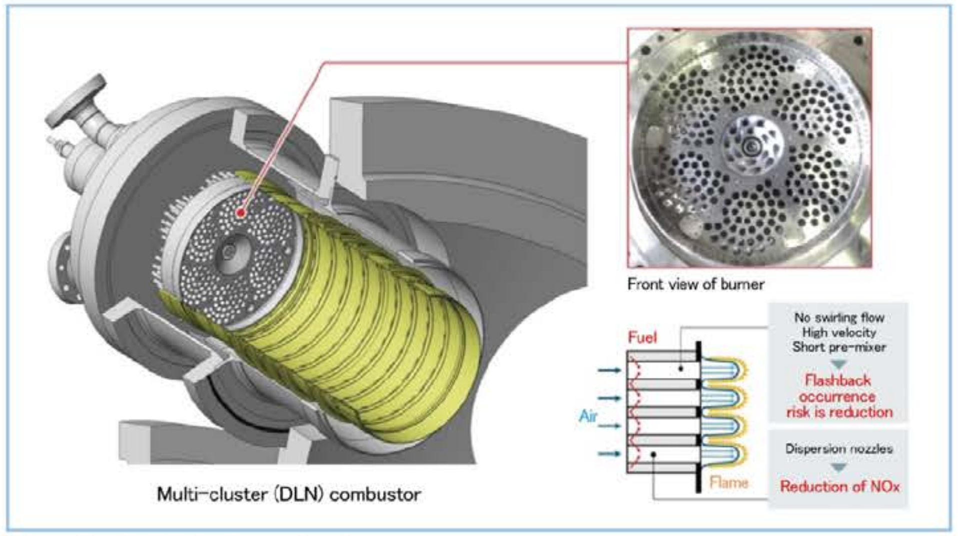

Figure 7 Multi-cluster combustor

(3) Diffusion combustor

A diffusion combustor injects fuel and combustion air separately into the combustor. Compared with the premixed combustion method, the flame temperature is higher and the amount of NOx emissions increases and imposes steam or water injection as a countermeasure for NOx reduction. On the other hand, it features a relatively wide stable combustion range and is more tolerant to fuel property fluctuations.

Figure 8 shows Mitsubishi Power diffusion combustor. This mature design has a long track of successful operation with fuels featuring a wide range of hydrogen content (up to 90 vol%). A long list of plants that have successfully operated with these combustors under high hydrogen content includes, among others, refineries and other industrial plants' off-gas . These include small to medium size gas turbine for power generation facilities and also succeeded in a hydrogen-firing combustion test as part of the International Clean Energy Network Using Hydrogen (World Energy NETWORK (WE-NET) technological research and development project[8]. The application of this diffusion combustor to the hydrogen-firing conversion project at Vattenfall's Magnum power plant in the Netherlands will be described in point 5 below.

Figure 8 Diffusion combustor

4. Ammonia-firing gas turbine

The stable application of large amount of hydrogen for a large frame gas turbine for power generation imposes stringent requirements to its supply chain including production, transportation and storage of hydrogen. One alternative to liquefied hydrogen is the use of other chemical compounds such as ammonia (NH_3), methylcyclohexane and others, as carriers for transportation and storage of hydrogen. Compared to liquid hydrogen or methylcyclohexane, ammonia has a higher volumetric hydrogen density and is a carrier that can transport and store hydrogen with high efficiency. In addition, existing transportation and storage infrastructure for liquefied petroleum gas and other industrial applications can be used for ammonia simplifying the development of hydrogen processing infrastructure. This facilitates hydrogen usage in remote locations including islands where large-scale hydrogen infrastructure development is difficult. Ammonia can also be directly combusted as a carbon-free fuel. Early introduction of ammonia-based power generation equipment is expected to be considered by power companies and independent power providers (IPPs) as a future use in a carbon-free fuel society.

Mitsubishi Power has commenced the development of a 40 MW-class gas turbine system for small to medium-scale power plants that uses 100% ammonia as a fuel for gas turbine power generation. One challenge that is being addressed with the direct combustion of ammonia is the production of nitrogen oxide (NOx) caused by oxidation resulting from the combustion of the nitrogen component of the fuel. Mitsubishi Power is aiming to resolve this issue through the establishment and commercialization of a gas turbine system that combines NOx removal equipment with a newly developed combustor that reduces NOx emissions. This is being applied to the H-25 series gas turbines (output: 40MW class) shown in **Figure 9**[(9)]. The direct combustion of ammonia has never been applied to this scale of power output gas turbine and it is expected that it will increase demand of hydrogen and ammonia and contribute to decarbonization.

Figure 9 H-25 series gas turbine

Table 1 lists issues to be considered for the combustion of ammonia in large frame gas turbines. Mitsubishi Power is evaluating the use of waste heat from a gas turbines in GTCC systems used to reconvert ammonia into hydrogen and nitrogen as shown in **Figure 10**. Simultaneous efforts include the developed hydrogen co-firing combustor or the developing hydrogen-firing combustor[(10)].

Decomposing ammonia requires heat in the order of 46 kJ per one mol of ammonia. This heat is chemically recuperated through a 1.14 times increase in the heat value of the fuel as a result of the conversion of ammonia to hydrogen. Therefore in principle, there is no reduction in thermal efficiency with the exception of energy losses that take place at the gas processing unit installed downstream of the ammonia decomposer.

Table 1 Characteristics of ammonia combustion and consideration for large frame gas turbine

Characteristics of ammonia combustion	Considerations for large frame gas turbines
Low combustion speed (about 1/5 of that of methane)	- The size of the combustor increases to secure the time necessary for completing the combustion. - Large frame gas turbines are limited in the size expansion of combustors because they are multi-combustors.
Nitrogen contained in fuel	- The combustion gas temperature of a large frame gas turbine is high and a large amount of Fuel NOx is generated by the combustion of ammonia. - Lowering of NOx by two-stage combustion is being considered, but in the case of a large frame gas turbines, there are many technical problems such as upsizing and complexity of the combustor.

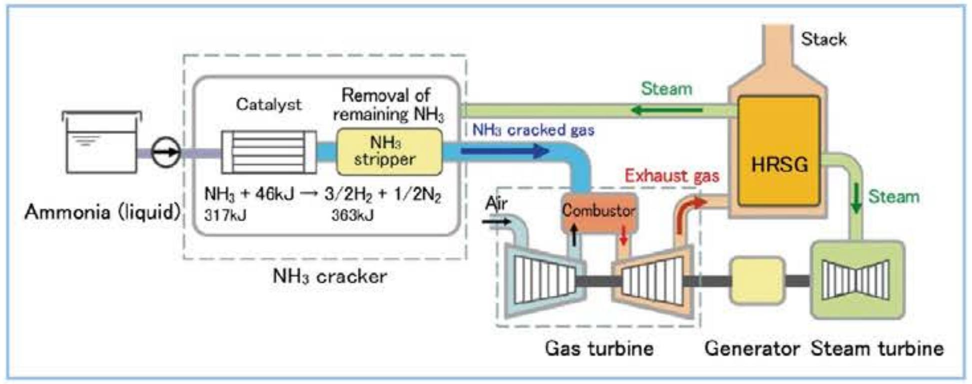

Figure 10 Concept of ammonia decomposition gas turbine cycle

It should be noted that in the combustion of ammonia decomposed gas, any trace amount of residual ammonia remaining after decomposition would be converted to fuel NOx in the combustor. It is considered that the fuel NOx is emitted together with the NOx originally produced in the combustor. In order to meet the NOx emission standard value, it is necessary to determine the amount of NOx increased by the remaining amount of ammonia. A combustion test under the actual pressure using a 1650℃-class hydrogen co-firing gas turbine combustor was conducted to evaluate how the trace amount of remaining ammonia contained after decomposition affects NOx while verifying the stability of combustion. **Figure 11** shows the relationship between the concentration of ammonia in the fuel and the concentration of NOx in exhaust gas at a JAC rated condition turbine inlet temperature of 1650℃ and in co-firing of natural gas and ammonia decomposition gas (fuel composition: 20 vol% of hydrogen, 6.7 vol% of nitrogen, 73.3 vol% of natural gas, trace amount of ammonia). As the concentration of ammonia in fuel increased, the concentration of NOx increased linearly (indicated by ● marks in the figure) and the conversion ratio of ammonia to NOx (CR in the figure: Conversion Ratio) was about 90%. Even if the concentration of ammonia in fuel was changed, the pressure level of combustion dynamics did not largely change, keeping a sufficient margin to the control value. It was verified that the combustion was stable without the occurrence of flashback.

Through the development of the gas turbine systems using ammonia as described above, it is expected to expand the lineup of carbon-free power generation systems.

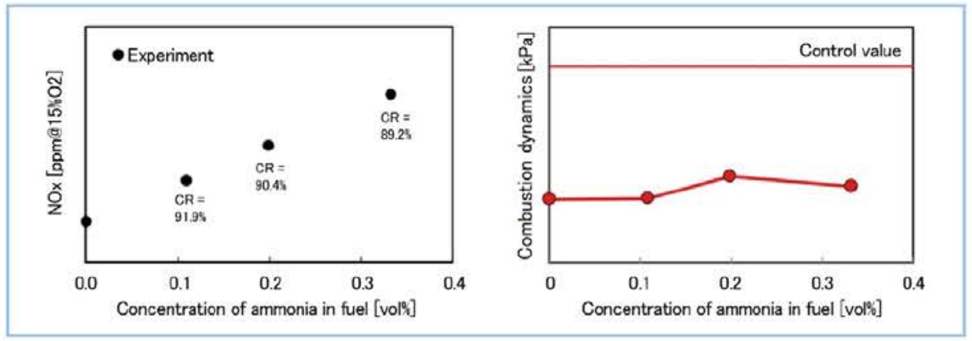

Figure 11 Relationships between the concentration of ammonia in fuel and the concentration of NOx in exhaust gas and between the concentration of ammonia in fuel and combustion dynamics (at the turbine inlet temperature of 1650℃)

5. Overseas gas turbine projects toward decarbonization

Many comprehensive hydrogen utilization plans are being considered oversees. These include the production, transportation, storage and utilization of hydrogen for the development of large-scale system ranging from the production to the utilization of renewable energy-derived green hydrogen and plans for the development of systems including CCUS processing of CO_2 generated from hydrogen production under utilization of fossil fuel-derived blue hydrogen. Various effects from the utilization of hydrogen are expected, such as an increase in the reliability and independence of energy in a region, job creation, avoidance of construction of uneconomical grids, reuse of existing infrastructure and diversification of fuels in multiple industrial sectors. Transnational projects have been implemented by nations, local governments and consortiums of companies in cooperation.

Among them, three hydrogen gas turbine projects in Europe and the United States involve Mitsubishi Power's participation are described below.

5.1 Vattenfall's Magnum power plant

The first project is intended to convert a 1,320 MW-class natural gas-firing GTCC power generation plant operated by Vattenfall, a Swedish energy company, to hydrogen-firing power generation. This project aims to convert one of three M701F gas turbines power generation blocks featured by the Vattenfall's Magnum power plant to a 100% hydrogen-firing power generation plant by 2027. This plant shown in **Figure 12**, is located in the Groningen province in the northernmost part of the Netherlands. The initial feasibility study (FS) was conducted considering the application of conventional diffusion combustor technology —and verified that the conversion to hydrogen-firing power generation is possible. One line of 440 MW-scale natural-gas-firing GTCC power generation units emits about 1.3 million tons of CO_2 annually, most of which can be reduced by conversion to a hydrogen-firing power generation plant. Evaluation, planning and design of specific modification ranges in the gas turbine technological field continue to be conducted by Mitsubishi Power.

Figure 12 Vattenfall's Magnum power plant in the Netherlands

5.2 Humber Cluster/ Saltend Power Plant

The second project involves a decarbonization efforts for the UK's largest scale industrial cluster in the delta area of the Humber River basin (east coast of Britain). Several companies and organizations actively working on decarbonization related industries are globally expanding their businesses toward the utilization of hydrogen (blue hydrogen) produced from natural gas with application of carbon dioxide capture and removal technologies, aiming net zero CO_2 emissions by 2040. In this project, Mitsubishi Power is conducting a technological and feasibility study of the conversion of one of the M701F gas turbines originally supplied to the Saltend Power Plant for the natural gas-firing GTCC (**Figure 13**). This effort includes conversion of one unit to 30 vol% hydrogen co-firing toward full hydrogen firing in the future.

Figure 13 Saltend power plant in UK

5.3 Intermountain Power Agency in Utah in the United States

The third project involves a brand new GTCC power generation using hydrogen planned by the Intermountain Power Agency in Utah in the United States. Mitsubishi Power received an order for this 840 MW-class GTCC power generation facility with two M501JAC gas turbines as the core. It aims achieving 30 vol% hydrogen co-firing power generation by 2025, followed by full hydrogen firing by 2045. This project involves replacement of an existing coal-firing power generation facility to reach initial CO_2 emissions reduction in the order of up to 4.6 million tons per year. The hydrogen fuel is expected to be supplied from an adjacent energy storage project using renewable energy-derived electricity in Utah. Mitsubishi Power is involved in this effort and the generated electricity will be supplied from the Intermountain Power Plant to a wide area in Utah and California across the Rocky Mountains.

Mitsubishi Power has promoted utilization of hydrogen for thermal power generation through participation in various projects in Japan and overseas for power generation using hydrogen including those mentioned above. Mitsubishi Power will continue generating momentum for the Energy Transition to low environmental load contributing to the realization of a decarbonized society.

6. Schedule toward commercialization

The introduction of hydrogen power generation is expected to start in the mid-2020s. Mitsubishi Power will promote demonstrations using actual gas turbines for the next several years, based on the results of past element developments, that have included verification tests for each element at the basic design stage, reflecting the test results in the detailed design and finally conducting demonstration using actual equipment. By implementing this development cycle in the same works, Mitsubishi Power has promoted rapid and secure development and commercialization. Regarding hydrogen gas turbines, detailed demonstrations will be conducted on hydrogen co-firing (30 vol%) large frame gas turbines for near future commercialization as shown in **Figure 14**. These efforts will be followed by commercialization of hydrogen-firing large frame gas turbines in the project in Utah in the United States. Demonstrations using the H-25 gas turbines will be also conducted for hydrogen-firing middle and small gas turbines as well as ammonia-firing toward commercialization.

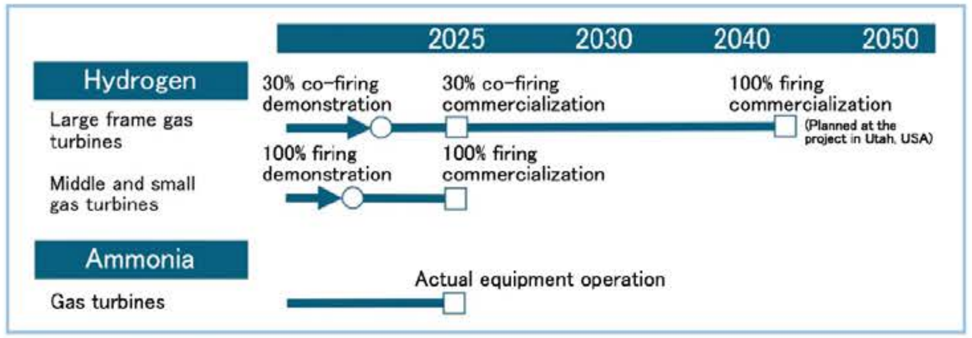

Figure 14 Schedule toward commercialization

7. Conclusion

This paper describes Mitsubishi Power efforts to use hydrogen and ammonia on power generation gas turbines. It also discusses the company's involvement in overseas hydrogen power generation projects efforts toward the realization of a decarbonized society. The contents described in point 3 of this paper are part of the outcome of the grant project ("Technology Development Project for Building a Hydrogen-based Society": JPNP14026) of the New Energy and Industrial Technology Development Organization (NEDO). In this grant project, Mitsubishi Power worked on the development of combustors for hydrogen and natural gas co-firing gas turbines and found that the operation of gas turbines under the 30 vol% co-firing condition is possible by modifying current combustion hardware.

The development of GTCC using ammonia decomposition gas contents described in point 4 of this paper was implemented by the Cross-ministerial Strategic Innovation Promotion Program (SIP), "Energy Carriers" (Funding agency: JST) and the grant project ("Technology Development for Building a Hydrogen-based Society": JPNP14026) of the New Energy and Industrial Technology Development Organization (NEDO).

The utilization of fossil fuel-derived hydrogen combined with Carbon Capture Utilization and Storage (CCUS) will start in the mid-2020s. This will contribute to the realization of a society using mainly renewable energy-derived hydrogen by 2050. Mitsubishi Power will contribute to the realization of a decarbonized society by leading the establishment of an international hydrogen supply chain through hydrogen- and ammonia-firing gas turbines being developed.

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Mitsubishi Heavy Industries Technical Review Vol. 58 No. 3 (September 2021)

Market Introduction Status of Fuel Cell System "MEGAMIE®" and Future Efforts

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Toward the realization of a carbon-free society by 2050, we are developing a system that uses a solid oxide fuel cell (SOFC), which can generate electricity with high efficiency. SOFC-MGT (Micro Gas Turbine) hybrid systems have been introduced to the market after the demonstration of a 250 kW class system and are scheduled to be delivered to Gas- und Wärme-Institut Essen e.V. (GWI) in Germany in fiscal 2021 for the first time for overseas installation, following deliveries to the Marunouchi building of Mitsubishi Estate Co., Ltd., the Technical Research Institute of Hazama Ando Corporation (hydrogen utilization) and the Ibaraki Plant of Asahi Breweries, LTD (biogas utilization). We are also proceeding with the development of MW class systems that apply MGT by reflecting the elemental technology in the integrated coal gasification fuel cell combined cycle (IGFC) for the Osaki CoolGen Project. We are also promoting the development of an improved system that uses a turbocharger (TC) as an air supply source instead of the MGT. The TC system uses a cascade system, which combines SOFCs in two stages and is expected to improve partial load efficiency. The demonstration tests are scheduled to be conducted in 2021.

1. Introduction

To curb global warming and realize a sustainable global environment, countries have set ambitious goals to rapidly shift to an energy system for decarbonization and are accelerating the movement to promote decarbonization as a strategic industrial policy. Japan has also declared its aim to realize a carbon-neutral, carbon-free society by 2050. In order to realize a carbon-free society, it is necessary to establish an appropriate energy mix by introducing highly-efficient distributed power sources and renewable energy into the advanced power grid constructed by large-scale centralized power sources, while ensuring safety, supply stability, economy and environmental friendliness. In order to establish the energy mix, it is effective to combine CCS (Carbon dioxide Capture and Storage) as a CO2 capture and storage technology and CCUS (Carbon dioxide Capture, Utilization and Storage) that uses the captured and stored CO2, in addition to converting the surplus electricity of renewable energy to hydrogen by P2G (Power to Gas) or operate it in combination with electricity storage, instead of suppressing it. Since the demand for power supply security has been increasing due to the frequent occurrence of disasters such as typhoons and torrential rains in recent years—in addition to earthquakes—it is also important to secure BCP (Business continuity plan) and power resilience.

Mitsubishi Power, Ltd. (Mitsubishi Power) is developing the "MEGAMIE" commercial industrial fuel cell system that uses SOFC (Solid Oxide Fuel Cell). SOFC can also electrolyze steam to generate hydrogen by reverse operation and is positioned as an effective application for the realization of a carbon-free society. We are currently promoting the introduction of 250 kW class SOFC-MGT hybrid systems to the market and the development of a TC system that is expected to improve operability through features such as higher partial load efficiency. We were

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also commissioned by the New Energy and Industrial Technology Development Organization (NEDO) to develop gas turbine fuel cell combined cycle power generation (GTFC) and are proceeding with the development to apply the elemental technology in the integrated coal gasification fuel cell combined cycle (IGFC) for the Osaki CoolGen Project. This paper introduces the development status of MEGAMIE.

2. Composition of MEGAMIE

Figure 1 illustrates the structure of a cell stack, which is the power generation element of tubular type SOFC. On the outer surface of the substrate tube, which is a structural member made of ceramics, cells (laminated anode, electrolyte and cathod) reacting to generate power are formed and an electron-conductive ceramic interconnector connects these cells in series. Several hundred cell stacks are bound to form a cartridge and several cartridges are contained in a pressure vessel. This is called an SOFC module (**Figure 2**). This system consists of the SOFC, MGT, recycle blower, etc. Power is generated in the two stages of the SOFC and MGT. Furthermore, when a waste heat recovery device is installed on the exhaust gas line, it can be utilized as a co-generation system that supplies steam or hot water at the same time (**Figure 3(A)**).

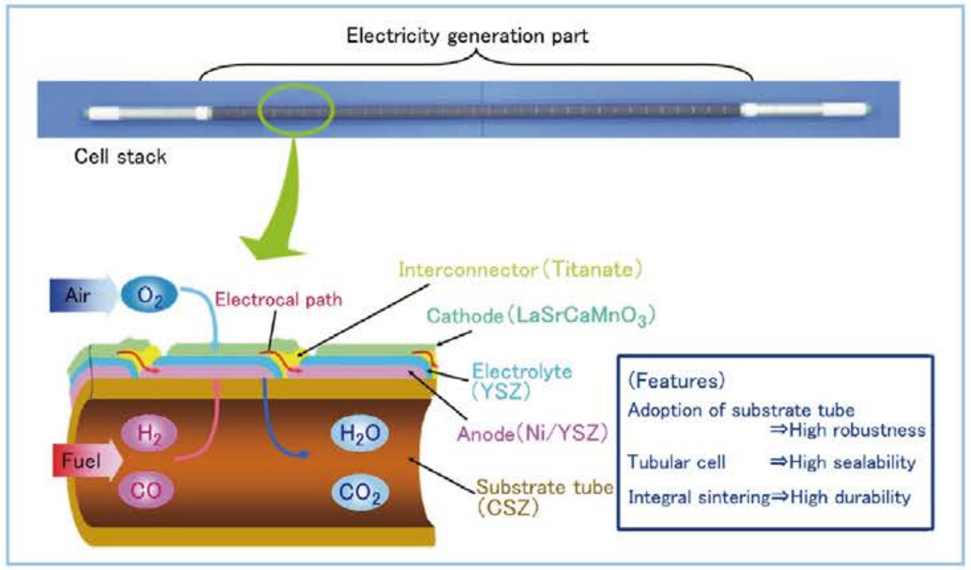

Figure 1 Structure of cell stack

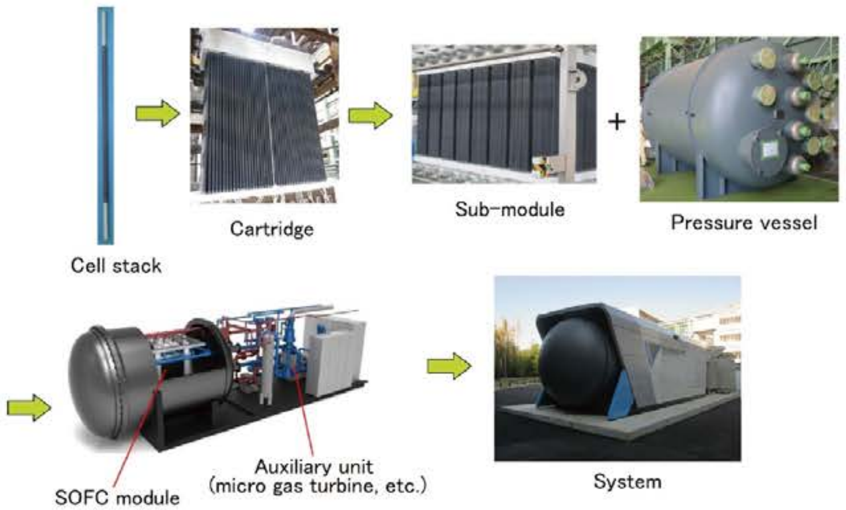

Figure 2 Composition of hybrid system

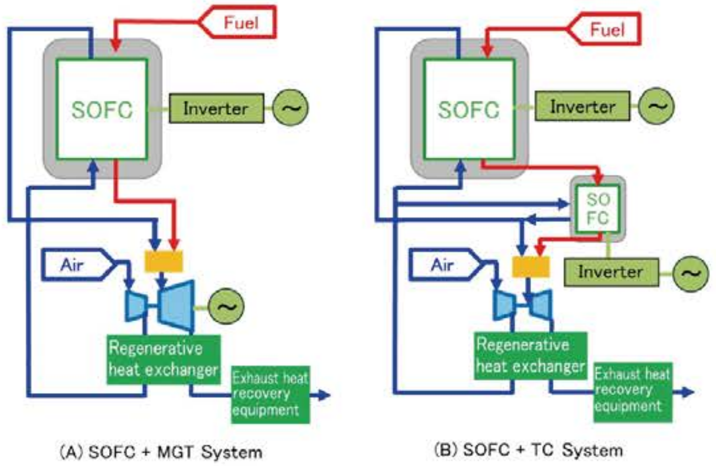

Figure 3 Comparison of MGT system and TC system

3. Status of MEGAMIE market introduction and initiatives

We introduced a 250 kW system to the "Next-Generation Fuel Cell Research Center (NEXT-FC)" established in Kyushu University aiming to fully disseminate SOFC by promoting industry-academia cooperation to use it for the "Verification of a Smart Fuel Cell Society" in the Green Asia International Strategic Comprehensive Special Zone. After that, in fiscal 2015, under the NEDO-subsidized project "Technical demonstration of commercial system using solid oxide fuel cells," demonstration tests under an actual load environment were conducted at four sites: Motomachi Plant of Toyota Motor Corporation, Komaki Plant of NGK Spark Plug Co., Ltd., Senju Techno Station of Tokyo Gas Co., Ltd. and Technology Center of Taisei Corporation (**Figure 4**). This subsidized project is a task setting type, the respective main subjects/verification items have been set at each site as follows and the demonstration tests were carried out: the start/stop operation test (once a month) for Toyota Motor Corporation, the continuous endurance test for NGK Spark Plug Co., Ltd., the start/stop operation test (once a week for 31 weeks) for Tokyo Gas Co., Ltd. and the self-sustaining function verification test for Taisei Corporation.

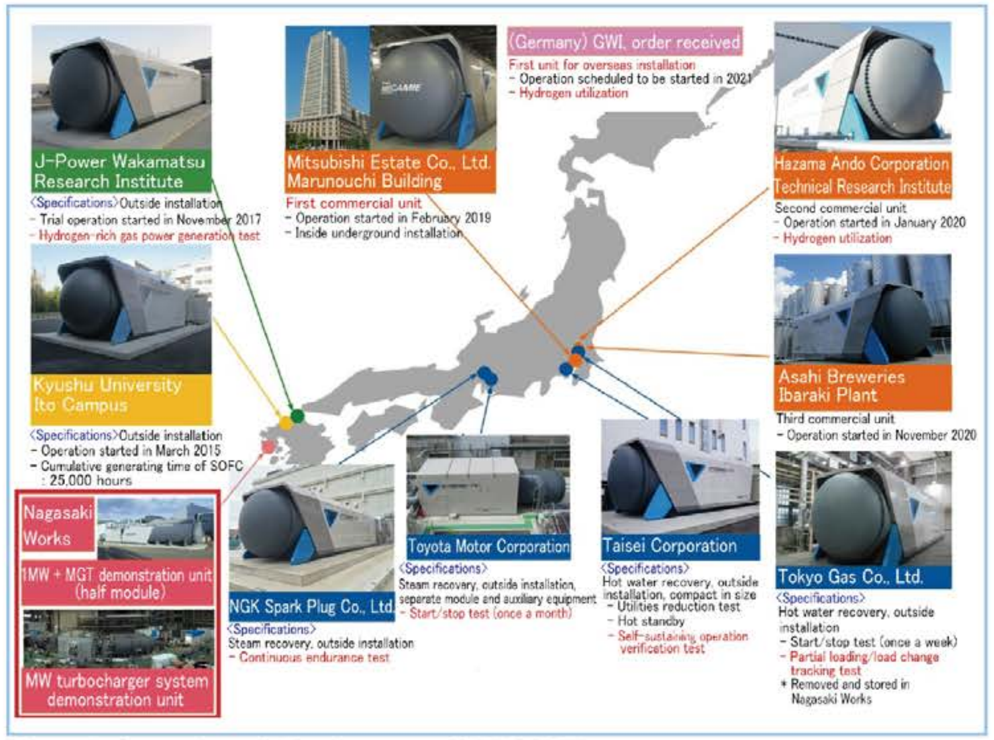

Figure 4 Operation and planning status of MEGAMIE

Based on the results of the demonstration tests, the introduction of the 250 kW class system to the market commenced in 2017. The first commercial machine was delivered to Marunouchi building of Mitsubishi Estate Co., Ltd., the second one to Technical Research Institute of Hazama Ando Corporation and the third one to Ibaraki Plant of Asahi Breweries, LTD. We will also examine the hydrogen utilization at Hazama Ando and the biogas utilization at Asahi Breweries, LTD. In addition, the system is scheduled to be delivered to Gas- und Wärme-Institut Essen e.V. (GWI) in Germany in fiscal 2021 for the first time for overseas installation.

Figure 5 shows an overview of the OCG project. This project calls for the installation of an integrated coal gasification combined cycle power generation facility (IGCC) in the first step, a CO_2 separation and capture facility in the second stage and SOFC in the third step to verify the IGFC. Toward this third step, for the NEDO Research and Development Project "Research on coal gas application for fuel cell module," which was implemented by Electric Power Development Co., Ltd. (J-POWER), we delivered a 250 kW class system to J-POWER's Wakamatsu Research Institute in fiscal 2017 and conducted a verification test using hydrogen-rich gas, which was coal gasified fuel. Since fiscal 2016, we have been verifying a larger module (output 1 MW class and operating pressure 0.6 MPa class) at Mitsubishi Power Nagasaki Works under the NEDO commissioned project "Gas turbine fuel cell combined cycle (GTFC) technology development." We are designing and manufacturing SOFCs for the OCG third stage using these elemental technology developments as basic design data and planning to start the installation work in fiscal 2021 and verify the coal gasified fuel and high pressure (targeted at 2 MPa) after the trial operation and adjustment.

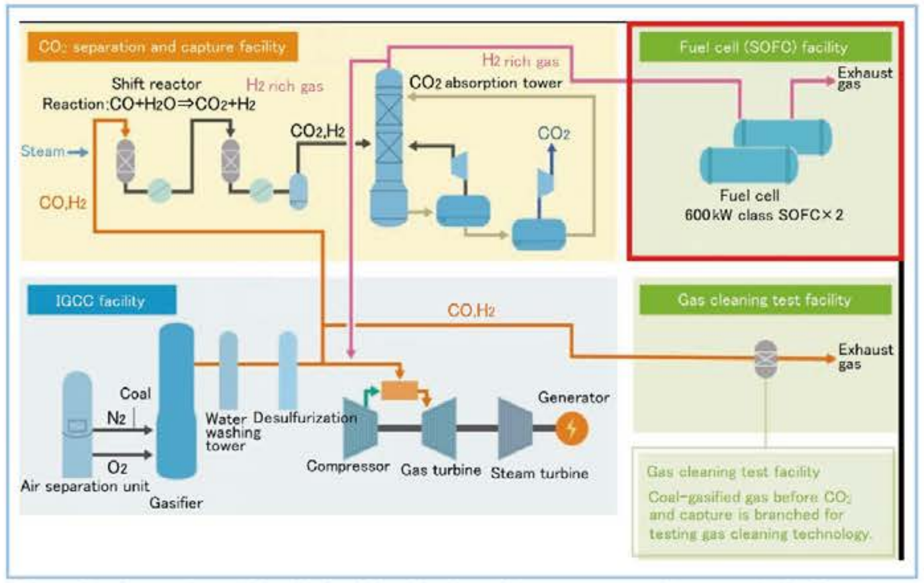

Figure 5 **Overview of Osaki CoolGen Project (first step, second step and third step)**

4. Development status of improved MEGAMIE system

Figure 3 compares the SOFC-TC combined system currently under development and the conventional SOFC-MGT combined system. The SOFC-MGT (Figure 3(A)) system is a hybrid system where the MGT is driven by burning the fuel used and diluted during SOFC power generation and air in the MGT combustor. On the other hand, the SOFC-TC system (Figure 3(B)) is a cascade system where the fuel diluted at the SOFC module is used to generate electricity at the subsequent SOFC module stage. The upper-stage SOFC is called the topping module and the subsequent SOFC stage is known as the bottoming module. The SOFC-TC system uses fuel for power generation using a highly-efficient fuel cell, so efficiency can be expected to improve. In addition, since the amount of air under partial load can be changed, the efficiency under partial load can also be expected to improve. Furthermore, since the temperature of the turbine inlet combustor can be lowered, it is expected that its applicability to diversified fuels including hydrogen can be easily expanded.

In terms of operation, it is necessary to verify the controllability of the start-up air blower for starting the TC and the operability at partial load to optimize the controllability in start/stop and rated/partial load operation. For this reason, we installed the SOFC-TC system demonstrator shown in **Figure 6** at the Nagasaki Works. Considering transportability, this demonstrator consists of two topping modules, one bottoming module and an auxiliary equipment unit. The auxiliary equipment unit consists of a fuel recirculation blower, TC, starter blower, etc. In fiscal 2020, we installed SOFCs on one topping module and the bottoming module and conducted a verification test on the half module system. The improved MEGAMIE uses a cell stack that is being jointly developed with NGK Spark Plug Co., Ltd. (NTK). We are planning to install a cell stack with even higher performance on the remaining topping module and conduct verification as a full module system in the future. We will consider system specifications with an eye on the commercial value of the 1 MW class machine and launch it in the market.

Figure 6 **External view of 1 MW class half module demonstrator using MGT**

5. Conclusion

SOFC is an attractive technology that can be applied to SOEC (Solid Oxide Electrolysis Cell), which produces hydrogen, CO, etc., by electrolysis when operated in reverse. Therefore, Mitsubishi Power positions SOFC applications as a trump card that is an effective technology to achieve both the reduction of CO2 emissions and the stable supply of electric power toward the realization of carbon neutrality and decarbonization by 2050, including the transitional period.

Regarding the SOFC-MGT hybrid system, a 250 kW class unit has been on the market since 2017 after demonstration projects at Kyushu University and NEDO. Since fiscal 2016, we have also been developing and verifying MW-class SOFC-MGT units with capacities larger than the 250 kW-class unit and reflecting the elemental technologies cultivated therein in SOFC for OCG, which verifies the application of coal gasified fuel.

We are also developing a TC system to improve operability. We plan to conduct a full-module system test to verify the operability features such as the start/stop characteristics, rated operation, partial load operation characteristics, protection system, etc., in fiscal 2021. We will steadily establish the technology and enhance its commercial value through this verification and put the system on the market to make a great contribution to the construction of a "safe and sustainable energy environment society."

(Acknowledgment)

This report includes the outcomes from joint research, etc., conducted with the National Research and Development Corporation New Energy and Industrial Technology Development Organization (NEDO) and we would like to express our gratitude to all concerned parties. We are deeply grateful to the Ministry of Economy, Trade and Industry, the Ministry of the Environment, the Ministry of Land, Infrastructure, Transport and Tourism, the Tokyo Metropolitan Government and the relevant ministries and agencies for giving us guidance and advice, as well as to all concerned parties including the universities, research institutions, electric power companies, gas utility companies and manufacturers for giving us guidance and advice on development and verification.

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Compendium

In this section, we list the characteristics of hydrogen and information pertaining to engineering for your use. We also provide information about ammonia, which is seen as a potential hydrogen energy carrier from the *Mitsubishi Heavy Industries Technical Review*.

Contents

1. Basic Data

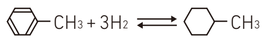
	Hydrogen H_2	Methane CH_4	Ammonia NH_3	Air	Nitrogen N_2	Carbon Dioxide CO_2
Molecular Weight*1	2.016	16.04	17.03	28.97	28.02	44.01
Density (gas)*2 **kg/Nm³**	0.08987	0.717	0.771	1.2932	1.2506	1.977
Density (liquid)*3 **kg/L**	0.071 (-252.9℃, 0.1MPa)	0.427 (-165.0℃, 0.1MPa)	0.682 (-33.7℃, 0.1MPa)	0.898 (N_2:O_2=0.79:0.21) (-200.0℃, 0.1MPa)	0.807 (-196.0℃, 0.1MPa)	1.032 (-20.1℃, 2MPa)
Specific Heat*4 **Cp kJ/(kg・K) [25℃,1atm]**	14.306	2.2317	2.1645	1.0063	1.0413	0.85085
Heat Capacity Ratio*4 **K (-) [25℃,1atm]**	1.4054	1.3062	1.316	1.4018	1.4013	1.2941
Gas Constant R J/(kg・K)	4124.3	518.4	488.2	287.0	296.7	188.9
Freezing Point*5 **℃ [1atm]**	-259.14	-182.76	-77.7	-	-209.86	-56.6
Boiling Point*5 **℃ [1atm]**	-252.87	-161.49	-33.4	-	-195.8	-78.5 (rise)

Source *1: 14102 chemical products (The Chemical Daily), p.1, p265, p275, p277, p288 (excluding Air) *2: Revised 4th edition Chemistry Handbook Basics (Maruzen) I-28, II-3, Gas Density and Specific Gravity (Heishin Mono Pump) *3: NIST Chemistry WebBook, SRD 69 (https://webbook.nist.gov/chemistry/fluid/), Refprop_ver9.0 (NIST Reference Fluid Thermodynamic and Transport Properties Database) *4: Calculated with Refprop_ver9.0 *5: Revised 4th Edition Chemistry Handbook Basics (Maruzen) I-28, I-409, I-176, I-131 (excluding Air)

2. Transport Property

	Liquid Hydrogen H_2	Compressed Hydrogen H_2 (350 atm)	Compressed Hydrogen H_2 (700 atm)	Methane CH_4 (liquid)	Ammonia NH_3 (liquid)	Natural Gas (LNG 13A)	Propane C_3H_8 (liquid)	Methylcyclohexane C_7H_{14} (MCH*)
Molecular Weight	2.016	2.016	2.016	16.04	17.03	18.36	44.1	98.18
Hydrogen Content (weight %)	100	100	100	25.13	17.76	23.77	18.29	6.16
Hydrogen Density (kg-H₂/m³)	70.8	23	39	108.1	120.0	103.0	107.0	47
Boiling Point (℃)	-252.87	-	-	-161.49	-33.4	-161.49 (Methane) Varies by composition	-42.07	101.05
Other properties	High hydrogen density No recycling required High purity	High inflammable Highly combustible Explosive		-	High hydrogen density No recycling required Can be used directly	Composition (%) Methane CH_4: 89.60 Ethane C_2H_6: 5.62 Propane C_3H_8: 3.43 Butane C_4H_{10}: 1.35	-	Normal temperature and pressure Petroleum infrastructure Available for use

* Carrying hydrogen using the difference of hydrogen between MCH toluene (C_7H_8) (molecular weight 92) and MCH (C_7H_{14}) (molecular weight 98)



3. Combustion Property

Fuel Name		Hydrogen H_2	Methane CH_4	Ammonia NH_3	Propane C_3H_8
Density [kg/Nm³]*1		0.08987	0.717	0.771	2.02
Boiling Point (@hPa) [℃]*2		-252.87	-161.49	-33.4	-42.1
Lower-heating Value	**[MJ/kg]***2	120.4	50.2	18.6	46.6
	[MJ/Nm³]	10.82	35.99	14.34	93.67
	[MJ/mol]	0.243	0.805	0.317	2.055
Higher-heating value	**[MJ/kg]**	141.77	55.5	22.5*3	50.32
	[MJ/Nm³]	12.75	39.72	17.1	99
	[MJ/mol]	0.286*4	0.89*4	0.383	2.219*4
Heat Equivalent Ratio [-]*2		0.10〜7.17	0.50〜1.69	0.63〜1.40	0.51〜2.51
Maximum Combustion Potential [m/s]*2		2.91	0.37	0.07	0.43
Minimum Self-ignition Temperature [℃]*2		500	537	651	432
Generated CO_2 [g/MJ]		0	54.8	0	64.4
Generated H_2O [g/MJ]		74.8	44.8	85.4	35.1

Source *1: Chronicle of Scientific Tables 2021, 31 (397) *2: Journal of the Combustion Society of Japan Vol.58, No.183, (2016), 41-48 *3: https://www.jstage.jst.go.jp/article/jsssj/36/11/36_583/_pdf, https://www.jccme.or.jp/11/pdf/2021-06/josei01.pdf *4: Calculated from figures published on page 285 of Combustion Engineering Handbook, edited by the Japan Society of Mechanical Engineers, 1995

The secret of the hydrogen visualization burner

At MHI's Research & Development Center (Takasago), demonstrations of hydrogen combustion are being conducted for visitors. In fact, the burner used there is one of many prototypes that were produced to confirm the manufacturing limits of metal 3D printers when developing a 100% hydrogen firing multi-cluster combustor. It managed to avoid being scrapped and is living a second life.

What is the flame color of hydrogen (H_2), methane (CH_4) and ammonia (NH_3)?

Pale/Translucent (invisible), blue, and orange, respectively. In the process of burning a substance, intermediate products called radicals that cannot exist in normal conditions are formed. Radicals emit light of specific wavelengths when they are formed and dissolved, but the type and ratio of radicals change depending on the combustible material and combustion method, resulting in flames of different colors.

4. Comparison of Heat Required to Produce 1mol of Hydrogen

	Method	Thermochemical Equation	Heat Required to Produce 1mol of Hydrogen
(1)	**Methane Pyrolysis**	CH_4 (g) + 74.4kJ = $2H_2$ (g) + C	37.2kJ/mol
(2)	**Methane Reforming**	① CH_4 (g) + H_2O (g) + 205.7kJ = CO (g) + $3H_2$ (g) ② CO (g) + H_2O (g) = H_2 (g) + CO_2 (g) + 41.2kJ ⇒ CH_4 (g) + $2H_2O$ (g) = CO_2 (g) + $4H_2$ (g) - 164.5kJ (=①+②)	41.1kJ/mol
(3)	**Ammonia Decomposition**	NH_3 (g) + 46.1kJ = $3/2H_2$ (g) + $1/2N_2$ (g)	30.7kJ/mol
(4)	**MCH Dehydrogenation**	$C_6H_{11}CH_3$ + 202.5kJ = $C_6H_5CH_3$ + $3H_2$ (g)	67.5kJ/mol
	(liquid) water electrolysis	H_2O (l) + 286 kJ = H_2 (g) + $1/2O_2$ (g)	0.079* kWh/mol

* In water electrolysis, electrical energy is added to water to generate hydrogen. So, the energy required to generate 1 mol of hydrogen is expressed here as 0.079 kWh/mol in terms of kWh (1 kWh = 3600 kJ).

5. Conversion Tables

5-1. Unit Conversion Table

Energy

	Per Million British Thermal Units (MmBtu)	Per British Thermal Unit (Btu)	Kilowatt Hour (kWh)	Megajoule (MJ)	Kilocalorie (kcal)	Tonne of Oil Equivalent (toe)
Per Million British Thermal Units (MmBtu)	1	1.000×10^{6}	2.931×10^{2}	1.055×10^{3}	2.519×10^{5}	2.519×10^{-2}
Per British Thermal Unit(Btu)	1.000×10^{-6}	1	2.930×10^{-4}	1.055×10^{-3}	2.519×10^{-1}	2.519×10^{-8}
Kilowatt Hour (kWh)	3.412×10^{-3}	3.412×10^{3}	1	3.6	8.598×10^{2}	8.598×10^{-5}
Megajoule (MJ)	9.478×10^{-4}	9.478×10^{2}	2.777×10^{-1}	1	2.388×10^{2}	2.388×10^{-5}
Kilocalorie (kcal)	3.968×10^{-6}	3.968	1.163×10^{-3}	4.186×10^{-3}	1	1.000×10^{-7}
Tonne of Oil Equivalent (toe)	3.968×10^{1}	3.968×10^{7}	1.163×10^{4}	4.186×10^{4}	1.000×10^{7}	1

Volume

	Cubic Meter (m^3)	Cubic Feet (cf)	US Gallon (US gal)	US Barrel (bbl)	Liter (litre)
Cubic Meter (m^3)	1	3.531×10^{1}	2.641×10^{2}	6.29	1×10^{3}
Cubic Feet (cf)	2.831×10^{-2}	1	7.480	1.781×10^{-1}	2.831×10^{1}
US Gallon (US gal)	3.785×10^{-3}	1.336×10^{-1}	1	2.38×10^{-2}	3.785
US Barrel (bbl)	1.589×10^{-1}	5.614	42	1	1.589×10^{2}
Liter (litre)	1×10^{-3}	3.531×10^{-2}	2.641×10^{-1}	6.289×10^{-3}	1

Mass

	Kilogram (kg)	Ton (t)	UK Ton (UK ton)	US Ton (US ton)	Pound (lb)
Kilogram (kg)	1	1.000×10^{-3}	9.842×10^{-4}	1.102×10^{-3}	2.204
Ton (t)	1×10^{3}	1	9.842×10^{-1}	1.102	2.20462×10^{3}
UK Ton (UK ton)	1.016×10^{3}	1.016	1	1.120	2.240×10^{3}
US Ton (US ton)	9.071×10^{2}	9.071×10^{-1}	8.928×10^{-1}	1	2×10^{3}
Pound (lb)	4.535×10^{-1}	4.535×10^{-4}	4.464×10^{-4}	5×10^{-4}	1

5-2. Hydrogen Cost Simple Conversion Table

H_2 Cost		$/Nm³	€/Nm³	Yen/kg	$/kg	€/kg	Yen/MmBtu	$/MmBtu	€/MmBtu	Yen/MJ	$/MJ	€/MJ	Yen/kWh-th	$/kWh-th	€/kWh-th
30.00	**Yen/Nm³**	0.216	0.216	334	2.41	2.40	2480	17.9	17.8	2.35	0.0169	0.0169	8.46	0.0610	0.0608

- Based on the Japanese government's target of 30 yen/Nm₃ by around 2030, the following assumptions have been applied to create the conversion table.
  Gas density: 0.08987 kg/Nm³ Higher heating value: 12.77 MJ /Nm³ – HHV Unit conversion: 1,055 MJ/MmBtu
  Exchange rate: 138.63 yen/US $, 139.03 yen/€ (TTM rate at the end of August 2022)

5-3. Ammonia Cost Simple Conversion Table

NH_3 Cost		Yen/ton	€/ton	Yen/MmBtu	$/MmBtu	€/MmBtu	Yen/MJ	$/MJ	€/MJ	Yen/kWh-th	$/kWh-th	€/kWh-th	Yen/Nm³H₂	$/Nm³H₂	€/Nm³H₂
350.00	**$/ton**	48500	351	2280	16.4	16.4	2.16	0.0156	0.0155	7.77	0.0561	0.0559	27.6	0.199	0.198

- Based on the $350/ton* that CFAA (Cree Fuel Ammonia Association) considers feasible by around 2030, the following assumptions have been applied to create the conversion table.
  Gas density: 0.771 kg/Nm³ Higher heating value: 22.47 MJ/kg – HHV Unit conversion: 1,055 MJ/MmBtu
  Exchange rate: 138.63 yen/US $, 139.03 yen/€ (TTM rate at the end of August 2022)
- The conversion between hydrogen and ammonia was performed using their respective higher heating values, and the mutual conversion loss, etc., were not taken into account.

* Source example of $350/ton: https://www.mlit.go.jp/kowan/content/001418024.pdf

6. Gas Turbines Lineup

Mitsubishi Power gas turbines made with cutting-edge technologies

Small and medium capacity gas turbines (41 MW to 116 MW)

H-25-series
H-100-series

Large capacity gas turbines (114 MW to 574 MW)

For 60 Hz

- M501J-series
- M501G-series
- M501F-series
- M501D-series

For 50 Hz

- M701J-series
- M701F-series
- M701G-series
- M701D-series

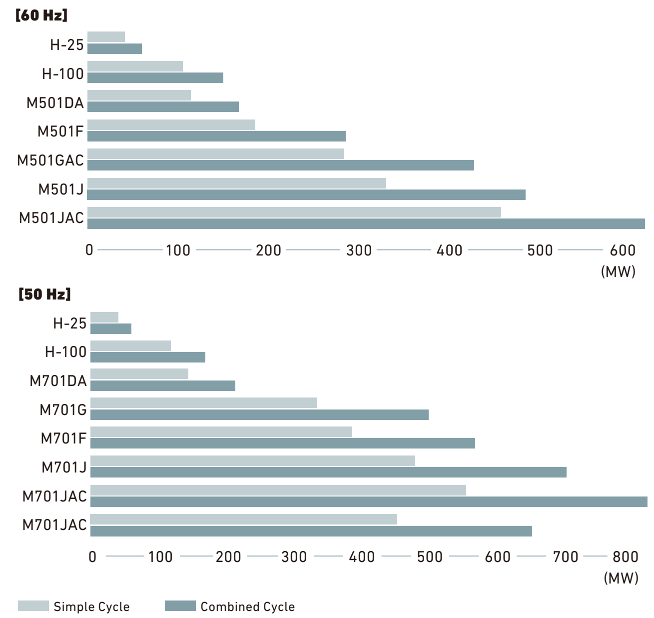
Aero-Derivative Gas Turbines (30 MW to 140 MW)

- FT8® MOBILEPAC®
- FT8® SWIFTPAC®
- FT4000® SWIFTPAC®

Powering the world with a full range of gas turbines

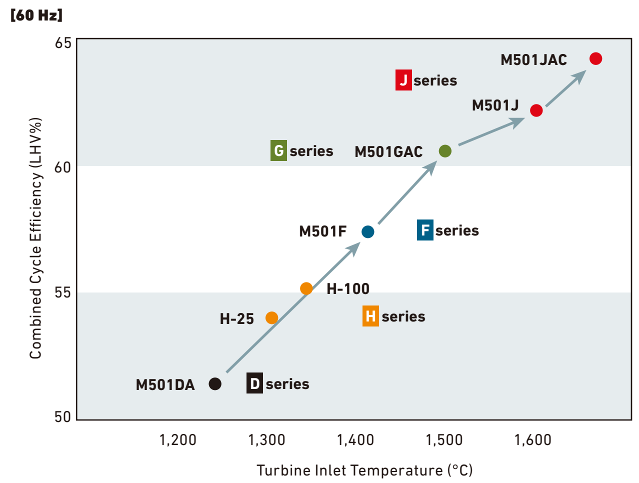
To meet the power demands of industries and societies around the world, Mitsubishi Power produces a wide range of gas turbines from the 30 MW to the 574 MW class for power generation and industrial use. These turbines drive the development and supply of highly-efficient, clean energy around the world. In fact, Mitsubishi Power has delivered more than 1,600 gas turbines to customers in more than 50 countries worldwide.

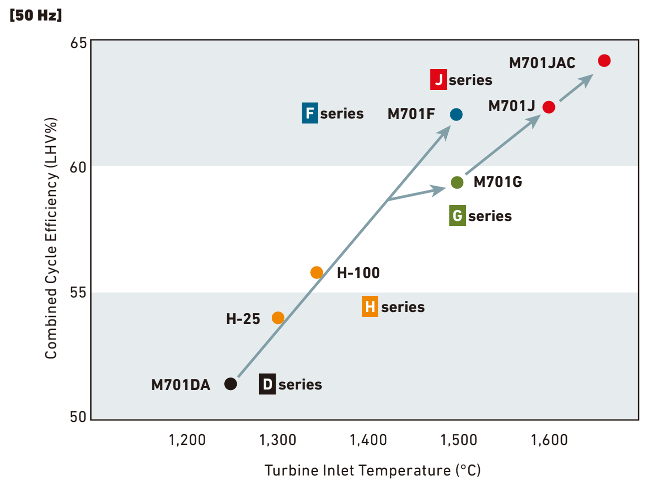
Gas Turbine and Combined Cycle Output



• (ISO, 1 GT + 1 ST, GAS FUEL)

Thermal Efficiency of Combined Cycle Systems





Performance

Simple Cycle Specs

	ISO Base Rating (kW)	LHV Heat Rate (kJ/kWh)	LHV Heat Rate (Btu/kWh)	Efficiency (%-LHV)	Pressure Ratio	Turbine Speed (rpm)	Exhaust Flow (kg/s)	Exhaust Temp (°C)
50Hz / 60Hz								
H-25*	41,030	9,949	9,432	36.2	17.9	7,280	114	569
50Hz								
H-100*	116,450	9,400	8,909	38.3	18	3,000	296	586
M701DA	144,090	10,350	9,810	34.8	14	3,000	453	542
M701G	334,000	9,110	8,630	39.5	21	3,000	755	587
M701F	385,000	8,592	8,144	41.9	21	3,000	748	630
M701J	478,000	8,511	8,067	42.3	23	3,000	896	630
M701JAC	448,000	8,182	7,755	44.0	25	3,000	765	663
M701JAC	574,000	8,295	7,826	43.4	25	3,000	1,024	646
60Hz								
H-100*	105,780	9,421	8,930	38.2	18.4	3,600	293	534
M501DA	113,950	10,320	9,780	34.9	14	3,600	354	543
M501F	185,400	9,740	9,230	37.0	16	3,600	468	613
M501G	267,500	9,211	8,730	39.1	20	3,600	612	601
M501GAC	283,000	9,000	8,531	40.0	20	3,600	618	617
M501J	330,000	8,552	8,105	42.1	23	3,600	620	635
M501JAC	453,000	8,182	7,755	44.0	25	3,600	815	649

Mechanical Drive Specs

	ISO Base Rating (hp)	ISO Base Rating (kW)	LHV Heat Rate (kJ/kWh)	LHV Heat Rate (Btu/hp-hr)	Efficiency (%-LHV)	Pressure Ratio	Turbine Speed (rpm)	Exhaust Flow (kg/s)	Exhaust Temp (°C)
H-100*	144,350	107,650	9,256	6,542	38.9	18.4	3,600	293	534
H-100*	160,780	119,900	9,266	6,549	38.9	20.1	3,000	315	552

Aero-Derivative Gas Turbine Specs

	ISO Base Rating (kW)	LHV Heat Rate (kJ/kWh)	LHV Heat Rate (Btu/kWh)	Efficiency (%-LHV)	Turbine Speed (rpm)	Exhaust Flow (kg/s)	Exhaust Temp (°C)
50Hz							
FT8*	28,528	10,376	9,834	34.7	3,000	92	496
FT4000*	70,154	8,908	8,443	40.4	3,000	183	431
FT4000*	140,500	8,896	8,431	40.5	3,000	367	431
60Hz							
FT8*	30,941	9,825	9,312	36.7	3,600	92	491
FT4000*	71,928	8,686	8,232	41.5	3,600	183	422
FT4000*	144,243	8,661	8,209	41.6	3,600	367	422

Notes: (1) All ratings are defined at ISO standard reference conditions: 101.3kPa, 15°C and 60% RH.
(2) All ratings are at generator terminals and are based on the use of natural gas fuel.
** without inlet and exhaust losses*

Combined Cycle Specs

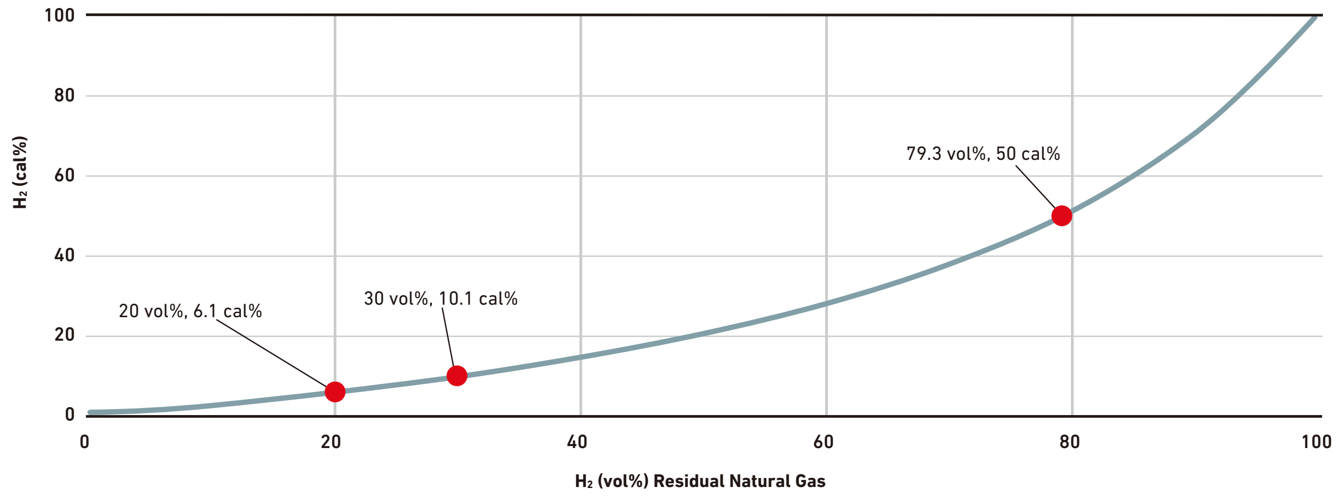
	Plant Output (kW)	LHV Heat Rate (kJ/kWh)	LHV Heat Rate (Btu/kWh)	Plant Efficiency (%)	Gas Turbine Power (kW)	Steam Turbine Power (kW)	Number & Type Gas Turbine
50Hz / 60Hz							
MPCP1(H-25)	60,100	6,667	6,319	54.0	39,600	20,500	1×H-25
MPCP2(H-25)	121,400	6,606	6,261	54.5	79,200	42,200	2×H-25
50Hz							
MPCP1(H-100)	171,000	6,272	5,945	57.4	112,700	58,300	1×H-100
MPCP2(H-100)	346,000	6,207	5,884	58.0	225,400	120,600	2×H-100
MPCP1(M701DA)	212,500	7,000	6,635	51.4	142,100	70,400	1×M701DA
MPCP2(M701DA)	426,600	6,974	6,610	51.6	284,200	142,400	2×M701DA
MPCP3(M701DA)	645,000	6,947	6,585	51.8	426,300	218,700	3×M701DA
MPCP1(M701F)	566,000	5,807	5,504	62.0	379,300	186,700	1×M701F
MPCP2(M701F)	1,135,000	5,788	5,486	62.2	758,600	376,400	2×M701F
MPCP1(M701G)	498,000	6,071	5,755	59.3	325,700	172,300	1×M701G
MPCP2(M701G)	999,400	6,051	5,735	59.5	651,400	348,000	2×M701G
MPCP1(M701J)	701,000	5,779	5,477	62.3	472,300	228,700	1×M701J
MPCP1(M701JAC)	650,000	<5,625	<5,332	>64.0	441,700	208,300	1×M701JAC
MPCP1(M701JAC)	840,000	<5,625	<5,332	>64.0	570,900	269,100	1×M701JAC
60Hz							
MPCP1(H-100)	150,000	6,534	6,193	55.1	102,500	47,500	1×H-100
MPCP2(H-100)	305,700	6,418	6,083	56.1	205,000	100,700	2×H-100
MPCP1(M501DA)	167,400	7,000	6,635	51.4	112,100	55,300	1×M501DA
MPCP2(M501DA)	336,200	6,974	6,610	51.6	224,200	112,000	2×M501DA
MPCP3(M501DA)	506,200	6,947	6,585	51.8	336,300	169,900	3×M501DA
MPCP1(M501F)	285,100	6,305	5,976	57.1	182,700	102,400	1×M501F
MPCP2(M501F)	572,200	6,283	5,955	57.3	365,400	206,800	2×M501F
MPCP1(M501G)	398,900	6,165	5,843	58.4	264,400	134,500	1×M501G
MPCP2(M501G)	800,500	6,144	5,823	58.6	528,800	271,700	2×M501G
MPCP1(M501GAC)	427,000	5,951	5,640	60.5	280,800	146,200	1×M501GAC
MPCP2(M501GAC)	856,000	5,931	5,622	60.7	561,600	294,400	2×M501GAC
MPCP3(M501GAC)	1,285,000	5,931	5,622	60.7	842,400	442,600	3×M501GAC
MPCP1(M501J)	484,000	5,807	5,504	62.0	326,200	157,800	1×M501J
MPCP2(M501J)	971,000	5,788	5,486	62.2	652,400	318,600	2×M501J
MPCP1(M501JAC)	664,000	<5,625	<5,332	>64.0	450,300	213,700	1×M501JAC
MPCP2(M501JAC)	1,332,000	<5,608	<5,315	>64.2	900,600	431,400	2×M501JAC

7. Fuel Consumption by Gas Turbine Type

Gas Turbine Type	Catalog Performance		Hydrogen		Natural Gas		CO_2 Emissions
	ISO Base Rating (kW)	Efficiency (%-LHV)	(ton/hour)	(Nm³/hour)	(ton/hour)	(Nm³/hour)	(g/kWh)
50Hz / 60Hz							
H-25	41,030	36.2	4	45,000	9	12,000	550
50Hz							
H-100	116,450	38.3	10	112,000	24	30,000	520
M701F	385,000	41.9	28	312,000	72	90,000	470
M701J	478,000	42.3	34	379,000	88	110,000	470
M701JAC	448,000	44.0	31	345,000	79	99,000	460
M701JAC	574,000	43.4	40	445,000	103	128,000	450
60Hz							
H-100	105,780	38.2	9	101,000	22	28,000	520
M501F	185,400	37.0	16	178,000	39	49,000	540
M501GAC	283,000	40.0	22	245,000	55	69,000	500
M501J	330,000	42.1	24	267,000	61	76,000	470
M501JAC	453,000	44.0	31	345,000	80	100,000	450

- Atmospheric temperature 15°C base (ISO standard)
- Fuel consumption when 100% hydrogen-fired is estimated based on the performance of a natural gas-fired system.

8. Co-firing of Hydrogen and Natural Gas: The Relation between Volume Fraction and Calorie Fraction



9. Hydrogen Production Process

	Common name for hydrogen	Origin & Production Method	Related Products & Technologies in MHI Gr.
Carbon-free Hydrogen	Green	Renewable Electricity → Electrolysis $H_2O \rightarrow H_2 + \frac{1}{2}O_2$	Wind Turbines Water Electrolyzer
	Pink	Nuclear Heat → Pyrolysis/Electrolysis $CH_4 \rightarrow 2H_2 + C$	High-temperature Gas-cooled Reactor
	Turquoise	Fossil Fuel → Pyrolysis $CH_4 \rightarrow 2H_2 + C$	Methane Pyrolysis Technology
	Blue	Fossil Fuel → Reforming & CO_2 Capture $CH_4 + 2H_2O \rightarrow 4H_2 + CO_2$	Natural Gas Reforming Apparatus Coal Gasifier CO_2 Capture Technology
Conventional Hydrogen (with CO_2 emission)	Gray	Fossil Fuel → Reforming (CO_2 release into the atmosphere) $CH_4 + 2H_2O \rightarrow 4H_2 + CO_2$	Natural Gas Reforming Apparatus Coal Gasifier

Why is colorless and transparent hydrogen turquoise?

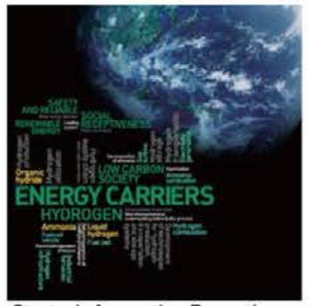
As shown in the table above, carbon-free hydrogen is color-coded according to its origin and production method. Although turquoise hydrogen is derived from fossil fuels thus making it blue, it does not generate CO_2, which causes global warming, during the manufacturing process thus also making it green. So, mixing two colors gives turquoise, today's hot trendy color!

What kind of hydrogen transport and storage methods are there?

The main methods are high pressure compression (most common), use of metal (high transport and storage efficiency), conversion to other substances (for lightweight and compact storage), use of pipelines (for stable mass transport). Nevertheless, each has its own challenges, so we are intensively researching toward the early realization of a hydrogen society.

Mitsubishi Heavy Industries Technical Review Vol. 56 No. 1 (March 2019)

CO_2-Free Energy (Ammonia)



Strategic Innovation Promotion Program (SIP) Energy Carriers[1]

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In order to abide by the Paris Agreement, it is necessary for CO_2 emissions to be reduced to net zero in the second half of this century, and in other words, fuel that emits no CO_2 (CO_2-free fuel) is in demand. Among such fuel, ammonia is a portable fuel which is easy to carry, and it can be easily produced from natural gas. In addition, the capture and storage of CO_2 emitted in the production of ammonia prevent the emission of CO_2. The production of ammonia has a long history, and it is now distributed at relatively low prices throughout the world. The use of ammonia by direct combustion is also becoming feasible through research on Energy Carriers in the Strategic Innovation Promotion Program (SIP). We hope that a system for using CO_2-free fuel will be developed and such fuel will be used to prevent global warming.

1. Introduction

(1) Paris Agreement and zero CO_2 emissions target

In December 2015, the Paris Agreement was adopted. The general objective of the Paris Agreement is to cap the increase in the global average temperature at 2°C above pre-industrial levels. In addition, in consideration for countries especially vulnerable to climate change, it stipulates that efforts to limit the temperature increase to 1.5°C should be pursued.

To that end, the long-term goal that total global greenhouse gas emissions should be limited to the amount that the ecological system could absorb in the second half of this century was set. This goal is intended to reduce greenhouse gas emissions by human activities to substantially zero.

In order to abide by the Paris Agreement, CO_2 emissions reduction in every field, the reduction of CO_2 emissions to zero in the second half of this century and the introduction of methods for reducing CO_2 in the atmosphere known as negative emission technologies, are necessary.

(2) Need for CO_2-free fuel

In recent years, the introduction of renewable energy such as solar power and wind power has been promoted, and the ratio of renewable energy used in the electric power sector will further increase. In the future, the need for CO_2-free fuel will be diversified, for example, for use in time zones that cannot be covered by renewable energy, for the load adjusting function of electric power, for uses as heat sources of general industries where it is difficult to use renewable energy and for use in fields such as transportation where CO_2 capture and storage cannot be applied.

In Japan, the study of the use of hydrogen energy has been promoted since the WE-NET Project was carried out. Recently, the use of hydrogen has been studied for the purpose of preventing global warming rather than enhancing energy security.

For the transportation of hydrogen, the use of liquefied hydrogen, organic hydride and ammonia has been studied. If the production of hydrogen without the emission of CO_2 is made possible, the remaining challenge is how to transport and use hydrogen in economical ways.

In any case, the provision of inexpensive and CO_2-free fuel will be demanded in various fields in the future.

(3) SIP Energy Carriers

We have conducted research and development on liquefied hydrogen, organic hydride and ammonia as "Energy Carriers" in the Strategic Innovation Promotion Program (SIP). The research and development of the production of carriers (i.e., production from petroleum, natural gas and coal and production from renewable energy), transportation and utilization (i.e., use as hydrogen and direct use of ammonia) have been conducted in the 5-year plan since fiscal year 2014. In the production of CO_2-free fuel such as hydrogen and ammonia from fossil fuel such as petroleum, natural gas and coal, CO_2 capture and storage (CCS) is indispensable. We also conducted testing and research for the inexpensive production of hydrogen through the electrolysis of water using electric power and high-temperature heat produced from renewable energy. **Figure 1**[1] shows an overview of testing and research on energy carriers.

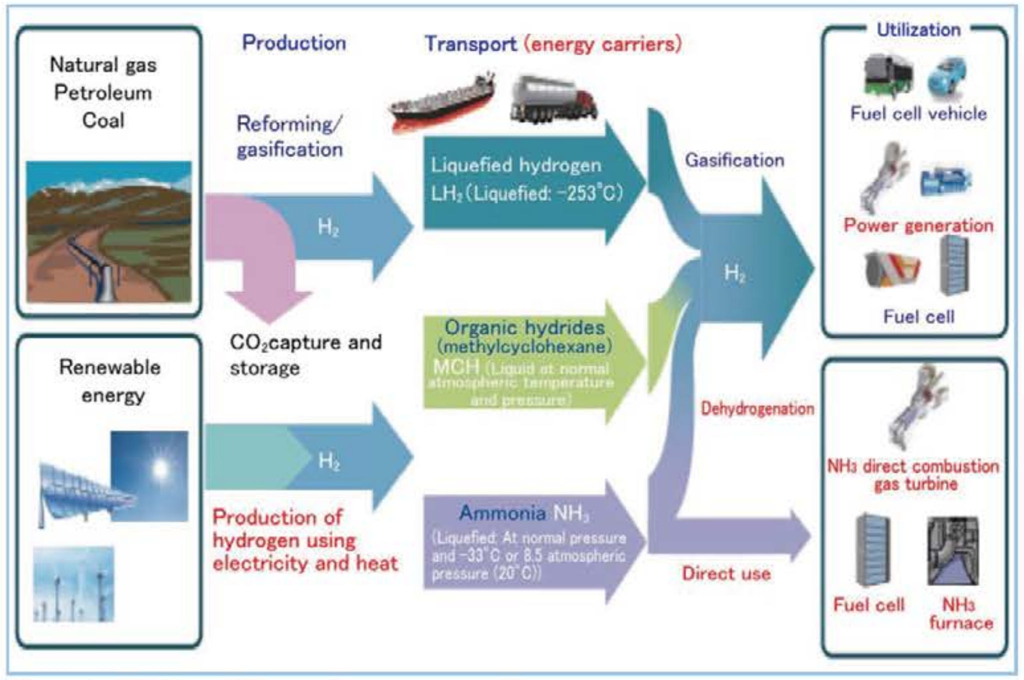

Figure 1 Testing and research on energy carriers

2. Efforts for SIP Energy Carriers

(1) Testing and research on energy carriers as fuel

Testing and research on Energy Carriers[1] have been conducted in the 5-year plan from FY2014 to FY2018 and three methods for carrying hydrogen have been evaluated.

a. High-temperature solar heat supply system
b. Hydrogen production using heat
c. Development of ammonia synthesis process using CO_2-free hydrogen
d. Basic technology for hydrogen station using ammonia
e. Ammonia fuel cell
f. Ammonia direct combustion
g. Development of hydrogen supply technology using organic hydride
h. Development of cargo loading/unloading system for liquid hydrogen and the relevant rules for operation
i. Development of hydrogen engine technology

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j. Safety assessment of energy carrier

This research on hydrogen production and the utilization of hydrogen/ammonia was conducted with the aim of evaluating which methods (including hydrogen transportation methods) are desirable, and to represent Japan's trailblazing development of hydrogen utilization technology ahead of other countries. In the latter half of the 5-year plan, research mainly focused on the direct use of ammonia, and testing and research on ammonia direct combustion in gas turbines, reciprocating engines, boilers and industrial furnaces and direct ammonia use in solid oxide fuel cells (SOFC) were conducted. In July 2017, ammonia mixed combustion testing was conducted at a coal-fired power plant of Chugoku Electric Power Co., Inc. Through this testing and research, the prospect of putting ammonia direct combustion into actual use was obtained, which was a significant outcome of testing and research on energy carriers.

(2) Evaluation of three methods

Japan has few petroleum, natural gas and coal resources, all of which have been conventionally used for fuel. Even if renewable energy is introduced to the fullest extent possible, it is said that it cannot cover all the energy required in Japan. Therefore, it is absolutely necessary to produce CO_2-free fuel from overseas energy sources or import it. In the case of the transport of materials such as fuel in large amounts, the most economical method for liquid or gaseous fuel is to use pipelines, but when transporting over long distances or across the ocean, it must be liquefied and transported by ship.

The liquefying temperature of hydrogen is very low at -253°C and the amount of power required for liquefying it is very large. Furthermore, it is not easy to maintain the temperature at -253°C.

Ammonia becomes a liquid at -33°C and under atmospheric pressure. On the other hand, when ammonia is pressurized, it becomes a liquid at 8.5 atm and at ambient temperature, providing the advantages of ease of handling and its usability as a direct fuel. Concerning organic hydride, methylcyclohexane produced by adding hydrogen to toluene can be transported at ambient temperature and under atmospheric pressure, but a large amount of energy is required for extracting hydrogen from methylcyclohexane.

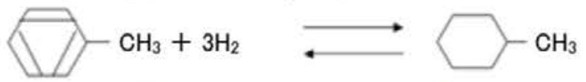
Based on the physical and chemical properties of ammonia and the fact that it is currently distributed throughout the world, the conclusion was reached on "Energy Carriers" in the SIP that ammonia can play an important role as a CO_2-free fuel.

Table 1[2] presents a comparison of the physical properties of compressed hydrogen, liquefied hydrogen, methylcyclohexane and ammonia.

Table 1 Physical properties of NH3 and major energy carriers

	Hydrogen content (weight %)	Hydrogen density ($kg \cdot H_2/m^3$)	Boiling point (°C)	Hydrogen release enthalpy change* ($kJ/molH_2$)	Other properties**
Ammonia	17.8	121	-33.4	30.6	Acutely toxic, corrosive
Methylcyclohexane (MCH)	6.16	47.3	101	67.5	Inflammable, irritant
Liquefied hydrogen	100	70.8	-253	0.899	Highly inflammable, highly combustible, explosive
Compressed hydrogen (350 atm)	100	23.2	—	—	
Compressed hydrogen (700 atm)	100	39.6	—	—	

* Carrying hydrogen using the difference of hydrogen between MCH toluene (C7H8) (molecular weight 92) and MCH (C7H14) (molecular weight 98)



* Hydrogen release enthalpy change: Energy required in extraction of hydrogen
** The descriptions in "Other properties" were excerpted from the summary of "Hazardous information" in the MSDS. For the exact properties of each material, see the MSDS for each material.

(3) Effectiveness of ammonia

The physical properties of ammonia are almost the same as those of LPG, and ammonia can be transported using LPG vessels. At present, the production of ammonia amounts to 180 million tons/year globally. About 80% of the production volume is used in fertilizer such as urea, and about 10%, which is 18 million tons/year, is internationally distributed.

At the present time (October 2018), the price of ammonia on an FOB basis in the Gulf of Mexico region in the U.S. is 250US$/T. This price is converted to 14.3US$ in terms of 1 million BTU (MMBTU), which is equal or slightly higher in terms of calorific value compared with the price of crude oil of 70US$/BBL (13.5 US$/MMBTU) (WTI price).

As with LPG, ammonia becomes a liquid when it is pressurized at ambient temperature and it is a portable fuel that is easy to handle in final use.

In particular, when it is used as a fuel for transportation, its ease of transportation at ambient temperature is a significant advantage. However, ammonia is toxic and emits an odor when it leaks, and if it is used near ordinary households, it may cause problems. Therefore, it is considered that ammonia will mainly be used in controlled areas such as in power plants, factories and cargo vessels.

3. Production method of CO_2-free ammonia

In 1913, Germans Haber and Bosch commercialized the process for synthesizing ammonia from hydrogen and nitrogen using an iron-based catalyst, and today the method is used in the production of ammonia. Mitsubishi Heavy Industries Engineering, Ltd. (MHIENG) has delivered many ammonia plants to various countries around the world since 1958. In current ammonia synthesis, natural gas is generally used as a feed stock.

By passing natural gas through a catalyst while heating it together with steam using a steam reformer, the natural gas is converted into hydrogen and CO. After that, air is injected, and the oxygen in the air is used for further combustion to convert the remaining methane into hydrogen and CO, and at the same time, nitrogen is supplied. Steam is added to the CO, which is converted into CO_2 and hydrogen using a catalyst. After that, the CO_2 is separated to produce hydrogen and nitrogen, and then ammonia is synthesized from the hydrogen and the nitrogen.

Figure 2 depicts the balance of CO_2 at a 2000 T/D-scale plant which is a standard ammonia plant. At the ammonia plant, about 2/3 of the CO_2 is separated from the process system, and about 1/3 of the CO_2 is discharged from the exhaust gas of the steam reformer and the auxiliary boiler. By capturing the CO_2 from this flue gases and storing it underground together with the CO_2 from the process system or using it for Enhanced Oil Recovery (EOR), this ammonia plant emits no CO_2. Thus. an ammonia fuel system that does not emit CO_2 can be established.

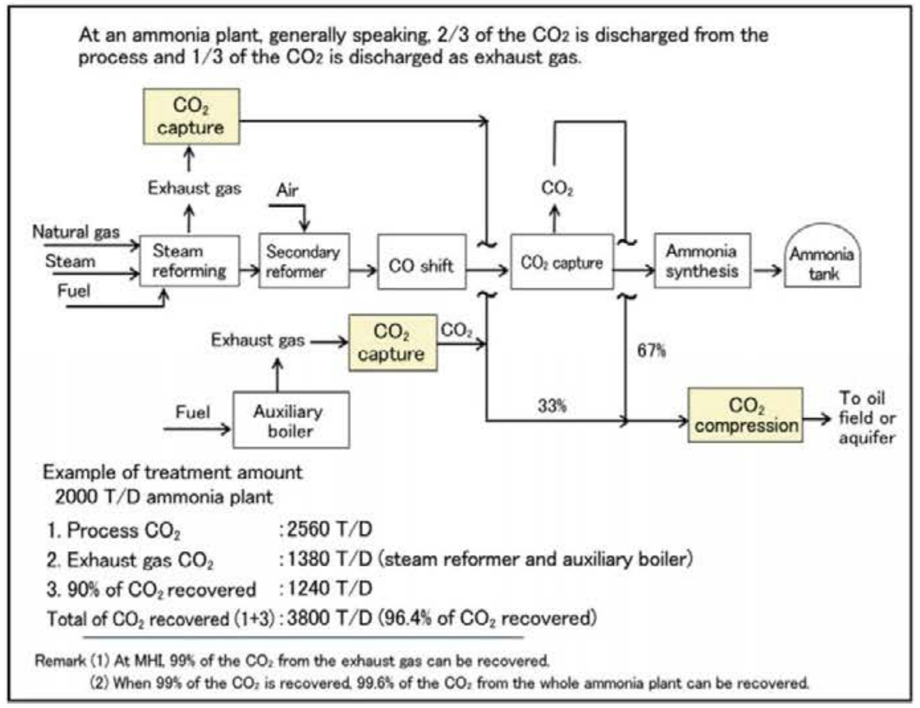
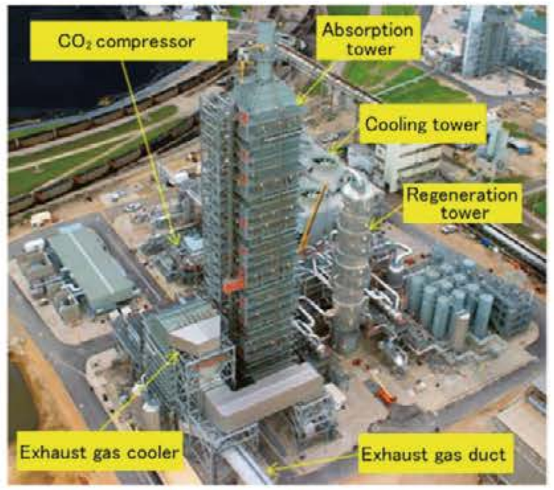


Figure 2 CO_2 balance at an ammonia plant

MHIENG delivered the world's largest CO_2 recovery system to a coal-fired power plant in Texas in the U.S. in January 2017, where the recovered CO_2 is used for EOR at the West Ranch oil field and crude oil is recovered, and CO_2 are stored in an oil reservoir. **Figure 3** gives an overview of the facility for recovering CO_2 from the coal-fired power plant.



NRG Energy, Inc. and JX Nippon Oil & Gas Exploration Corporation
Photo of Petra Nova project

Figure 3 Facility for recovering CO_2 from a coal-fired power plant

Since 2011, in Alabama in the U.S., MHIENG has conducted CO_2 capture from a coal-fired power plant and a demonstration test for storing the captured CO_2 in an aquifer (implemented by SECARB※1) jointly with Southern Company. **Figure 4** illustrates an overview of the CO_2 capture and storage project. As such, CO_2 capture and storage has been conducted on a commercial basis, and the technologies for CO_2 capture from exhaust gas at ammonia plants and the production of CO_2-free ammonia have already been established.

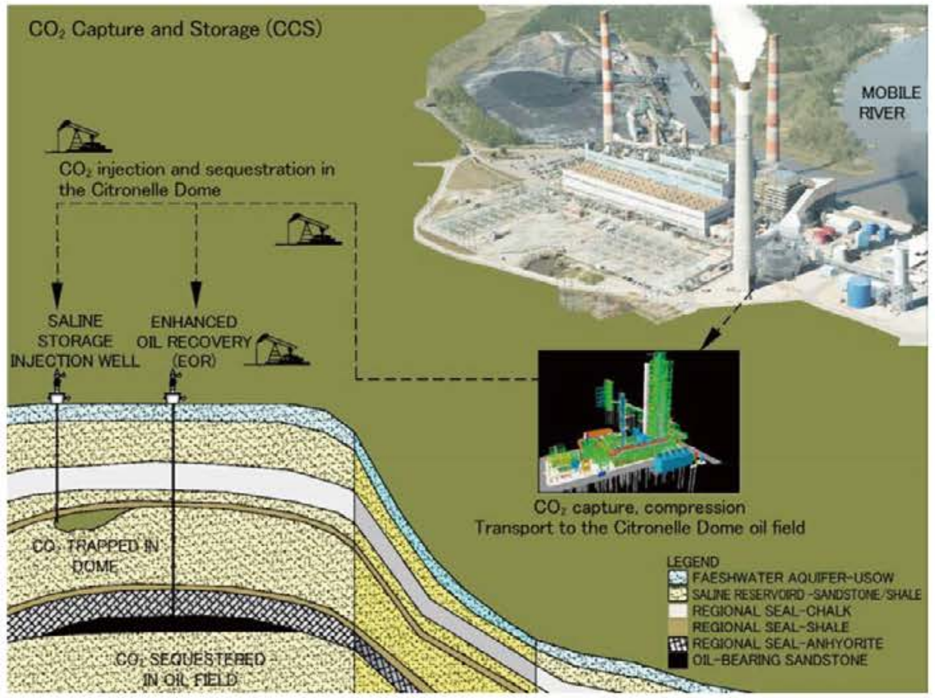


Figure 4 Overview of CO_2 capture and storage project

CO_2 from the process system can be stored as it is a total of 90% of the CO_2 from flue gas can be captured by the CO_2 recovery technology with which MHIENG has a significant amount of experience (KM CDR Process®※2 developed in cooperation with Kansai Electric Power Co., Inc.), and the captured CO_2 is stored together with CO_2 from the process. As a result, 96% of the CO_2 generated in the production of ammonia can be stored. If 99% is captured from exhaust gas, 99.6% of the CO_2 can be stored, allowing the production of ammonia with almost no CO_2 emissions into the atmosphere.

There is another CO_2-free ammonia synthesis method in which electricity produced from renewable energy is used to electrolyze water and separate nitrogen in the air for the synthesis of ammonia. At present, inexpensive natural gas is produced in massive amounts in various places around the world, and therefore ammonia can be produced at a much lower cost by synthesis from natural gas compared with the use of renewable energy.

※1 The Southeast Regional Carbon Sequestration Partnership

※2 KM CDR Process® is a registered trademark of Mitsubishi Heavy Industries Engineering, Ltd. in Japan, the U.S., European Union (EUTM), Norway, Australia and China.

4. History of use of ammonia as fuel

Some people may not be familiar with the use of ammonia as fuel, but looking back to the Second World War, 100 ammonia-powered buses were used in Belgium.

At that time, diesel fuel could not be procured, and out of necessity, ammonia was used as fuel.

In another example from 1959 to 1968, the X-15 manned jet fighter of the U.S. Air Force used ammonia as fuel, and it reached a record speed of Mach 6.7 at an altitude of 107960m. The temperature was very low at an altitude of 100,000 meters, and it is assumed that the fact that ammonia does not solidify at low temperatures was the reason it was chosen as fuel.

5. Conclusion

CO_2-free fuel is strictly intended to prevent global warming. In order to achieve the target of +2°C or lower based on the Paris Agreement, global CO_2 emissions must be reduced to 1/2 by 2050, and advanced countries must reduce CO_2 emissions by 80%. To that end, CO_2-free fuel that can be used everywhere will become more important. MHIENG has already established commercial CO_2-free ammonia production technology and is ready to provide it at any time.

However, ammonia is more expensive than coal or LNG on the basis of its calorific value, and it is more expensive than even crude oil. For ammonia to be widely used as CO_2-free fuel, it seems that some political incentive is necessary in the early stages of introduction.

We are grateful to the people involved with the promotion of the research and development of "Energy Carriers" in the Strategic Innovation Promotion Program (SIP) who were helpful in writing this article.

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Introduction of our activities

Nature

An article about Mitsubishi Power's hydrogen gas turbine was published in the international scientific journal "Nature". An electronic version is also available, so please give it a read.

https://www.nature.com/articles/d42473-020-00545-7