Mitsubishi Heavy Industries, Ltd.
Energy Systems
3-3-1, Minatomirai, Nishi-ku, Yokohama,
Kanagawa, 220-8401, Japan
power.mhi.com

METP-01FC01E1-A-0, (1.0)21-09, ZEG

MITSUBISHI POWER

SOFC HANDBOOK

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

MOVE THE WORLD FORW>RD MITSUBISHI HEAVY INDUSTRIES GROUP

INTRODUCTION

Fossil fuels have provided humanity with great power, enabling many civilizations on our planet to thrive, and continues to play a crucial role in the advancement of modern society.

However, large amounts of CO_2 emissions from inefficient combustion methods have led to global warming, causing uncertainty in the future of humanity. Therefore, the most important issue for our planet right now is the reduction of our reliance on fossil fuels to realize a low-carbon or decarbonized society.

Under such circumstances, a beacon of hope that has been attracting much attention from the international community is a clean and highly efficient power generation system using fuel cells (FC) that generate electricity. The fuel cell is an epoch-making device that generates electricity directly through the chemical reactions of hydrogen with oxygen in the air.

As high-efficiency power generation is expected to have a major positive impact on environmental issues by improving energy efficiency and reducing CO_2 emissions, the development of its practical implementation methods is getting increasingly competitive worldwide.

For many years, Mitsubishi Power has been working on the development of an expandable Solid Oxide Fuel Cell (SOFC) that uses a ceramic electrolyte and has the highest power generation efficiency among the various types of fuel cells. The result is a high-efficiency combined power generation system called "MEGAMIE*" that will lead the next generation of high-efficiency power generation.

In order to protect the global environment, promote the continued prosperity of humanity, and support clean energy development in developing countries, the world's leading engineers are striving to achieve even higher levels of advancement in fuel cell development.

∗ The name "MEGAMIE" is a combination of "mega," evoking an image of the high-output fuel cells with stable operating performance, and "megami," a Japanese word meaning a goddess of the land or beauty. The blended term conveys strength, elegance, and warmth. The final "E" represents the three "Es" of Environment (environmental conservation), Energy security (stable supply), and Economy (economic efficiency), thereby expressing the value that Mitsubishi Power provides to customers, and the role the company plays in society.

INDEX

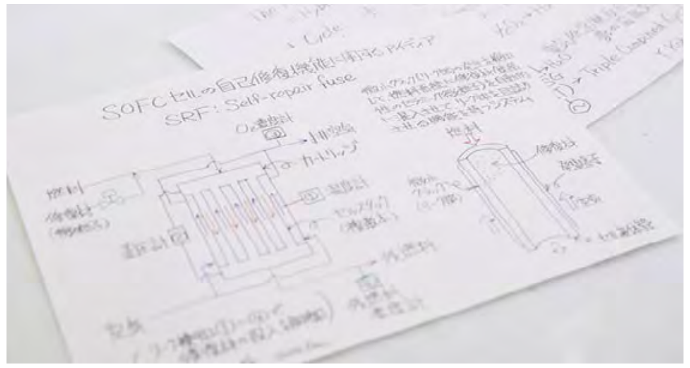
Power the Globe with Mitsubishi Power's MEGAMIE System,

a High-Efficiency Combined Power Generation System for Solid Oxide Fuel Cells (SOFC)

Yoshinori Kobayashi,
Ph.D. in Engineering,
Authority of Technology
Fuel Cell Business Department,
GTCC Business Division,
Energy Transition & Power Headquarters,
Energy Systems,
Mitsubishi Heavy Industries, Ltd.

On March 11, 2011, Yoshinori Kobayashi was at the Tohoku Electric Power Company (Tohoku EPCO) headquarters to attend a session on fuel cell systems research. About 15 minutes after the meeting began, he felt a tremor that was unlike any that he – or anyone else in Japan – had experienced before.

Only later would Kobayashi, the head of fuel cell development at Mitsubishi Power, discover the extent of destruction that the Great East Japan Earthquake had caused. But as he watched Tohoku EPCO employees cut the meeting short and rush to affected sites, he thought how critical it was to ensure that people have access to electricity at a time like this. His mind immediately went to a project that he had been working on – one that he believed would have significant impact on power infrastructure not just in Japan but all around the world.



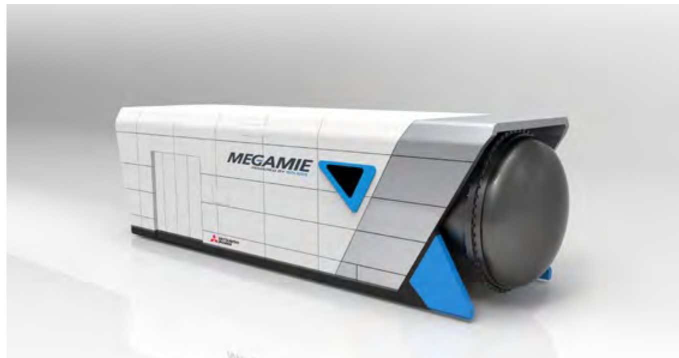
Kobayashi scribbled his thoughts for better SOFC performance even as aftershocks from the 9.0-magnitude earthquake continued.

Creating systems for sustainable power generation

The challenge of providing stable and sustainable power supply

Climate change is a defining issue of our time. Its effects can be felt widely, with extreme weather conditions impacting communities all around the world. Meanwhile, world population continues to grow and with it, the demand for power.

Given both these factors, countries face a dilemma: they must work towards making a low- or no-carbon society a reality while making sure that citizens have enough power to survive and thrive. The severe effects of climate change are vital signs that the planet needs to look towards building a more sustainable future. And that begins with the way we generate and utilize power.



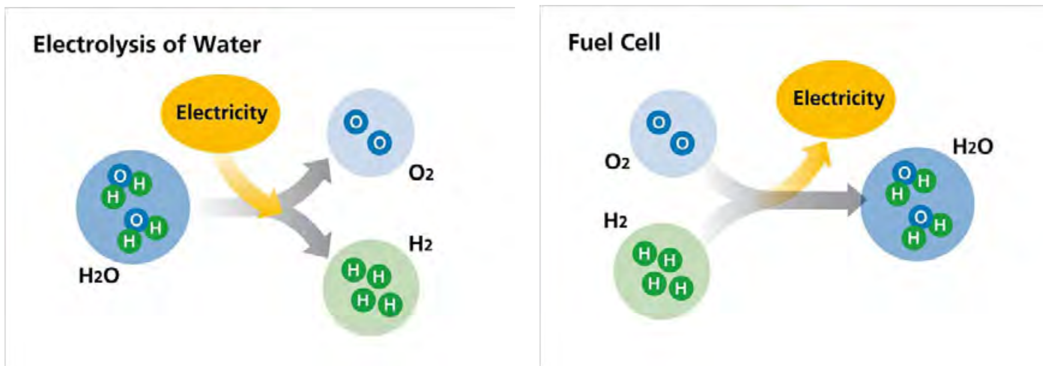
250kW class MEGAMIE

Fuel cells: a potential solution to clean power generation

Fuel cells (FCs) differ from conventional power generation systems in that they can use hydrogen as a carbon-free power source. With built-in electrochemical converters, FCs can combine hydrogen and oxygen in the air to produce energy directly without the carbon dioxide byproduct. As such, they maintain high efficiency while emitting less carbon.

On the cutting edge of fuel cell technology

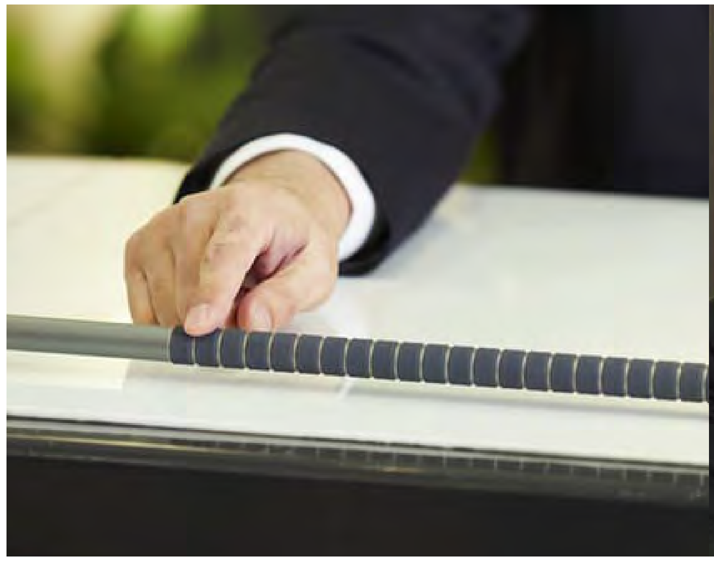
For over four decades, Yoshinori Kobayashi has been at the forefront of revolutionary developments with FCs. Mitsubishi Power's latest innovation in this space came in the form of a solid oxide fuel cell (SOFC) called MEGAMIE. This SOFC was the result of joint research with Japan's New Energy and Industrial Technology Development Organization (NEDO).



Fuel cells produce electricity through reverse electrolysis. The process of combining hydrogen and oxygen releases energy, with water as a byproduct.

The Great East Japan Earthquake in 2011 strengthened Kobayashi's drive to commercialize SOFCs. With their high efficiency and low carbon emissions, SOFCs are a potential solution to address the tension between energy security and environmental sustainability that many countries face.

Kobayashi put this fortified conviction into action. In 2015, a 250 kW class system prototype was set up at Kyushu University, and by 2017, MEGAMIE had its commercial launch in Japan. As of February 2020, the Kyushu University prototype has achieved a continuous run of 25,000 hours.



Developing next-generation solid oxide fuel cells

Managing a balancing act

The process of developing MEGAMIE was filled with many intellectual and engineering puzzles. The toughest challenge, Kobayashi recalled, was to figure out how to build a robust power unit with ceramics which are essential for SOFC function. Each MEGAMIE unit uses a cell stack – a cylindrical substrate tube designed to trigger reactions for power generation. Cell stacks are made entirely of ceramics and take about a year of development at Mitsubishi Power.

The pressurizing system Mitsubishi Power uses in MEGAMIE combines the delicate ceramics with a gas turbine that must withstand extreme temperature and pressure conditions. These different components had conflicting properties but they had to be integrated into a single complex system – a significant engineering challenge. "Many industry-leading players and research institutes have tried to commercialize similar fuel cells," Kobayashi noted, "but combining these technologies proved to be too difficult."

Overcoming challenges through collaboration

To build such a complex system, Kobayashi brought together experts from different domains. To be sure, there were challenges in the collaboration, and there were even conflicting opinions among the team on what aspects of the system to prioritize fixing. "But the key to success is that everyone works as one to overcome such conflicts," Kobayashi acknowledged.

"Today, we live in a world where productivity and speed are prized above all, at the expense of teamwork and collaboration. Sometimes though, not taking time to consider different expert opinions causes unexpected problems. Working as a team and leveraging our own individual strengths – whether chemicals or system mechanics – we were able to fill in the gaps in each other's knowledge. Ultimately, this collaboration made MEGAMIE better."

Other big challenges were increasing production yield and ensuring quality control throughout the supply chain. Part of Kobayashi's concern was the "balance of plant" (BOP), which refers to all the supporting components and auxiliary systems that a power plant needs to deliver energy apart from the generating unit itself. For MEGAMIE, this term applies to micro gas turbines, heat exchangers, piping, valves, and electrical components. Kobayashi needed to ascertain that the suppliers of BOP components would be willing to provide the parts in good condition even as MEGAMIE had yet to go to market.

"To ensure the quality of all raw materials, you have to deploy your people to the manufacturers' factories," Kobayashi said. "Many suppliers would have been reluctant to do this, but our partners willingly allowed us to do so, and I am thankful for that. Project members also kept talking to the partners. They negotiated costing of the BOP components and made improvements to boost the performance of the SOFC, helping alleviate partners' concerns."

1MW class half-module demonstration unit

Going global with MEGAMIE

Standing out against competition

Among the many factors that distinguish MEGAMIE from other SOFCs is its versality. It is a high efficiency power system that can use multiple types of fuel gases – from city gas and LPG in local infrastructure to methane gas from sludge, food waste and agricultural waste. Furthermore, MEGAMIE can accommodate multiple forms of hydrogen.

Another key differentiating factor is MEGAMIE's ability to leverage pressurized gas, as in conventional power systems which use gas turbines. "Pressurized gas produces more power," Kobayashi explained. "When you look at the shape of the cell, you notice it needs to be sealed only at two locations at both ends of the cylinder. That is sufficient to shield the fuel flowing inside the cell from the air outside. With fewer sealing locations, the cell could be more readily combined with gas turbines."

Working towards global commercialization

In 2019, the first commercial 250 kW class MEGAMIE started operation at the Marunouchi Building, housing numerous shops and offices at the heart of Tokyo. So while still far from the goal of delivering sustainable power to the rest of the world, MEGAMIE is already generating impact in Japan.

Now, the question on Kobayashi's mind is how Mitsubishi Power can make the MEGAMIE technology more available to a wider market. For instance, since 2014, preparations for mass production of the cell stack have been underway with NGK Spark Plug Co., Ltd., a top ceramic manufacturer.

Cost is one of the barriers to greater market penetration. MEGAMIE must be offered at a much more reasonable price to increase adoption across the globe. Kobayashi and his team are working to address this cost challenge, which includes increasing cell output density, enhancing material quality, simplifying production processed and collaborating with partners to optimize the supply chain.

Another issue is how to ensure safe and efficient operations. Polymer electrolyte fuel cells used for automobiles work within a relatively low-temperature range of 60-100°C; thus, start/stop functions would not pose major difficulties. However, SOFCs work in temperatures as high as 900°C, and take much longer to start or stop.

Yet, if there is anything the Great East Japan Earthquake taught Kobayashi, it is that the world urgently needs MEGAMIE. And just as he solved the many challenges in MEGAMIE's development, he is now finding a way to bring this game-changing technology to the world.

For more information, please visit the website.

System Overview

High-Efficiency combined Power Generation System for SOFC (Solid Oxide Fuel Cell), which are operated under High Temperatures

MEGAMIE POWERED BY SOLIDIA

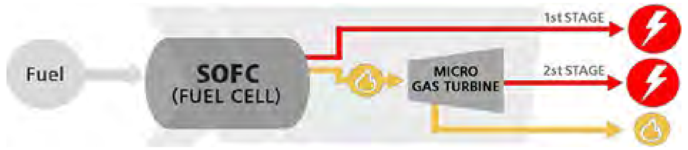
A multifuel power generation system that utilizes natural gas, biogas, hydrogen, and other fuel sources. Available for a wide variety of uses, from business to industrial.

Features

- Uses distributed power sources to achieve power generation efficiencies equivalent to large scale power (55% LHV power generation efficiency, total efficiency 73% LHV/hot water recovery)
- Electricity mainly generated with fuel cells that convert directly into electricity without burning any fuel
- Efficient energy utilization achieved by also generating power from micro gas turbines
- Cogeneration achieved by recovering steam or hot water from the exhaust gas of micro gas turbines

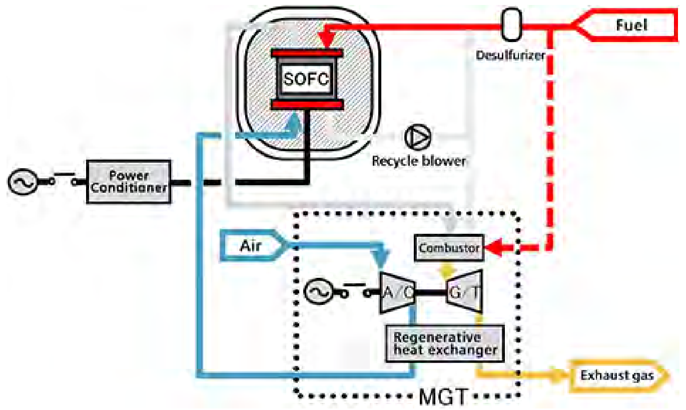
Mechanisms of Power and Heat Generation

- Fuel gas is inserted into the SOFC to generate power (first stage)
- High-temperature SOFC exhaust gases are inserted into the micro gas turbine (MGT) to generate additional power (second stage)
- Heat is removed from the high-temperature MGT exhaust gases to produce heated water or steam
- Optimum co-generation system for sites with high electricity demand, characterized by high power generating efficiency
- A wide range of fuels can be used for the fuel gas, including natural gas, biogas, hydrogen, propane, and butane.



System

The hybrid system is made up of a fuel system (red line in figure), air system (blue line) and exhaust gas system (yellow line). Fuel gas passes through the desulfurizer to remove its sulfur content, and is then inserted into the SOFC after being pressurized in a compressor. Meanwhile, air is inserted into the SOFC after being pressurized through the MGT. Exhaust fuel from the SOFC is pressurized by a recirculating blower. Then, part of it is returned to the SOFC, with the remainder inserted into the combustion chamber of the MGT together with exhaust air. The exhaust gases combusted in the combustion chamber undergo heat exchange with air sent to the SOFC by means of a regenerative heat exchanger, and after heated water and steam have been produced with the exhaust heat recovery unit, the exhaust is released into the air.

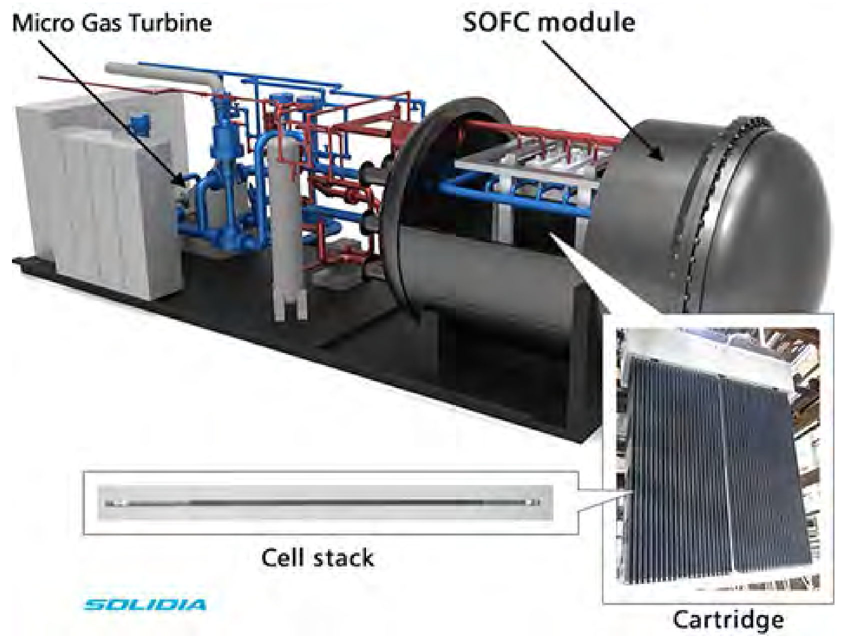


Pressurization-type SOFC Module

System Configuration

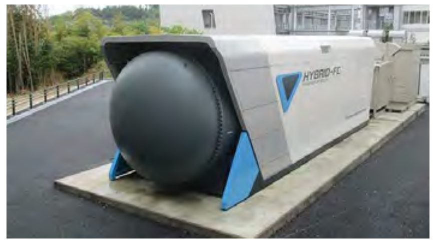
Multiple fuel cells (single cells) are connected in series on the outside of substrate tube (ceramic) to form cell stacks, which are bundled to create cartridges (with outputs of several dozen kW). These cartridges are gathered together and stored in a pressure vessel. This configuration is collectively referred to as a "module." Adopting this sort of layered structure offers easy installation and maintenance. In addition, since electrical output can be adjusted depending on the number of cartridges or modules, it is possible to supply the right amount of electricity as needed.

- **Module**
  A structure with cartridges gathered together and stored within a pressure vessel.
- **Cartridge**
  A bundle of cell stacks that functions as a bearing member, supplies and discharges fuel and air, and collects current.
- **Cell Stack**
  Elements that react to power generation (fuel cell stack of fuel electrodes, electrolyte and air electrodes) are formed on the outer surface of a substrate tube that serves as a structural member made from highly-strengthened ceramic. As elements are connected in a series with inter-connectors made from electrically conductiv e ceramic, high voltage electrical output can be efficiently collected at low currents.



TYPICAL DELIVERY RESULTS

Kyushu University

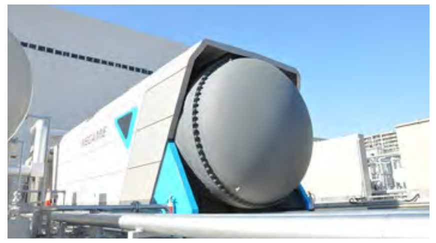


Specifications
Outdoor Installation
- Operational from March 2015
- Cumulative Power Generation Time >22,000 Hours

Mitsubishi Estate Company, Limited
Marunouchi Building

Specifications
Steam Recovery, Indoor Installation (basement 4th floor)

Hazama Ando Corporation
Technical Research Institute



Source:Hazama Ando Corporation

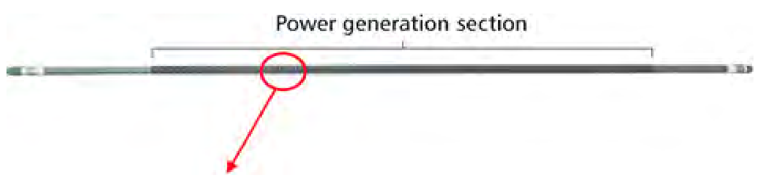
Specifications
Hot Water Recovery, Outdoor Installation
Hydrogen Mix Power Generation (under construction)

Principles of Power Generation

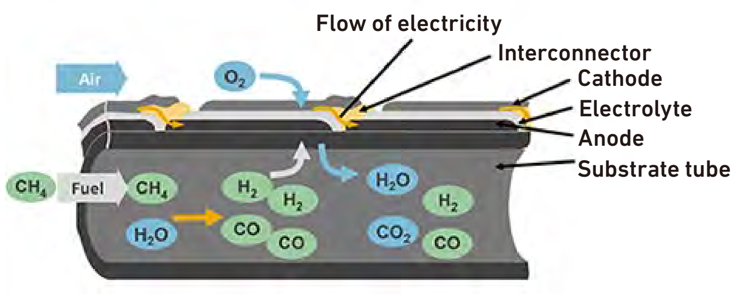
The SOFC generates power at between 700°C and 1000°C by being supplied fuel gas (hydrogen, carbon monoxide, etc.) to the fuel electrodes and air (oxygen) to the air electrodes.

Methane (CH_4), the main ingredient of the fuel gases inserted into the cell stack, and water vapor (H_2O), which is contained in the exhaust fuel that is recirculated, become hydrogen (H_2) and carbon monoxide (CO) inside the cell stack due to the internal reforming reaction that is a characteristic of SOFC.
Oxygen ions (O_{2-}) that move from the air electrode side to within the electrolyte react with the hydrogen (H_2) and carbon monoxide (CO) of the fuel at the interface between the fuel electrodes and electrolyte, emitting electrons (e_-) while simultaneously generating water vapor (H_2O) or carbon dioxide (CO_2).

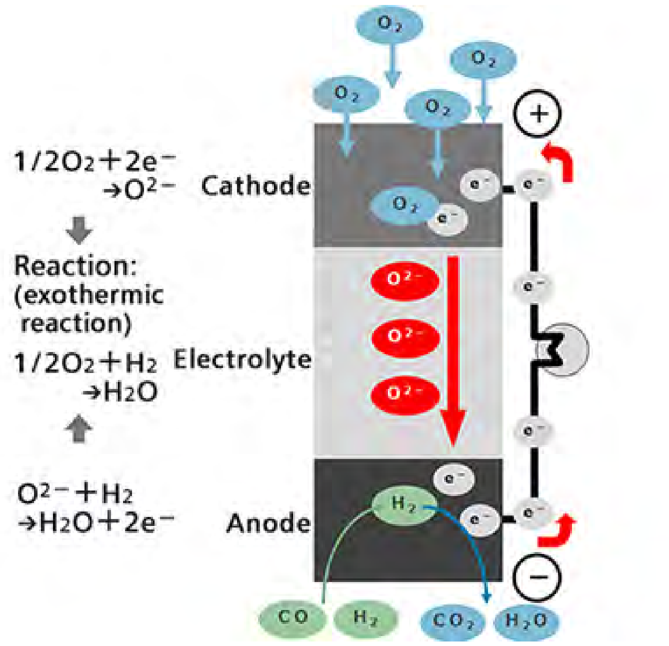
Meanwhile, after the electrons emitted by the oxygen ions have performed electric work through the outer electric circuit, they move to the air electrodes.
At the interface between the air electrodes and electrolyte, oxygen in the air (O_2) reacts with the electrons that have moved over to produce oxygen ions, and these oxygen ions are captured in the electrolyte and move to the fuel electrode side.
In terms of overall power generating reaction, hydrogen or carbon monoxide reacts with oxygen to generate water or carbon dioxide, and electricity flows with the resulting electrons move through the outer circuit.
The air electrode is the cathode, and the fuel electrode is the anode.



Cell Stack*



Cell Stack Structure



Chemical Reactions inside the SOFC

*NGK Spark Plug Co.,Ltd. and Mitsubishi Power have established "CECYLLS", a joint venture company that manufactures and sells cylindrical cell stacks. The company was established in order to mass produce and sell high quality cylindrical cell stacks that feature long life and heat utilization capabilities.

Next-Generation Fuel Cell Power Generating System Initiatives

An integrated power generating system comprising SOFC + gas turbines + steam turbines shows promise for high-efficiency power generation as future replacement for thermal power plants in future large-scale projects.

However, considering the limitations of the SOFC mass production in the initial stages of market adoption, we will first focus on developing the market with small-to-medium-sized systems. As a measure to improve the efficiency of existing gas turbine combined cycle generating equipment in addition to co-generation for medium-sized power supply, we are examining ways to accelerate adoption, including topping improvements that involve partially expanding small-capacity SOFC facilities in relation to their gas turbine capacity.

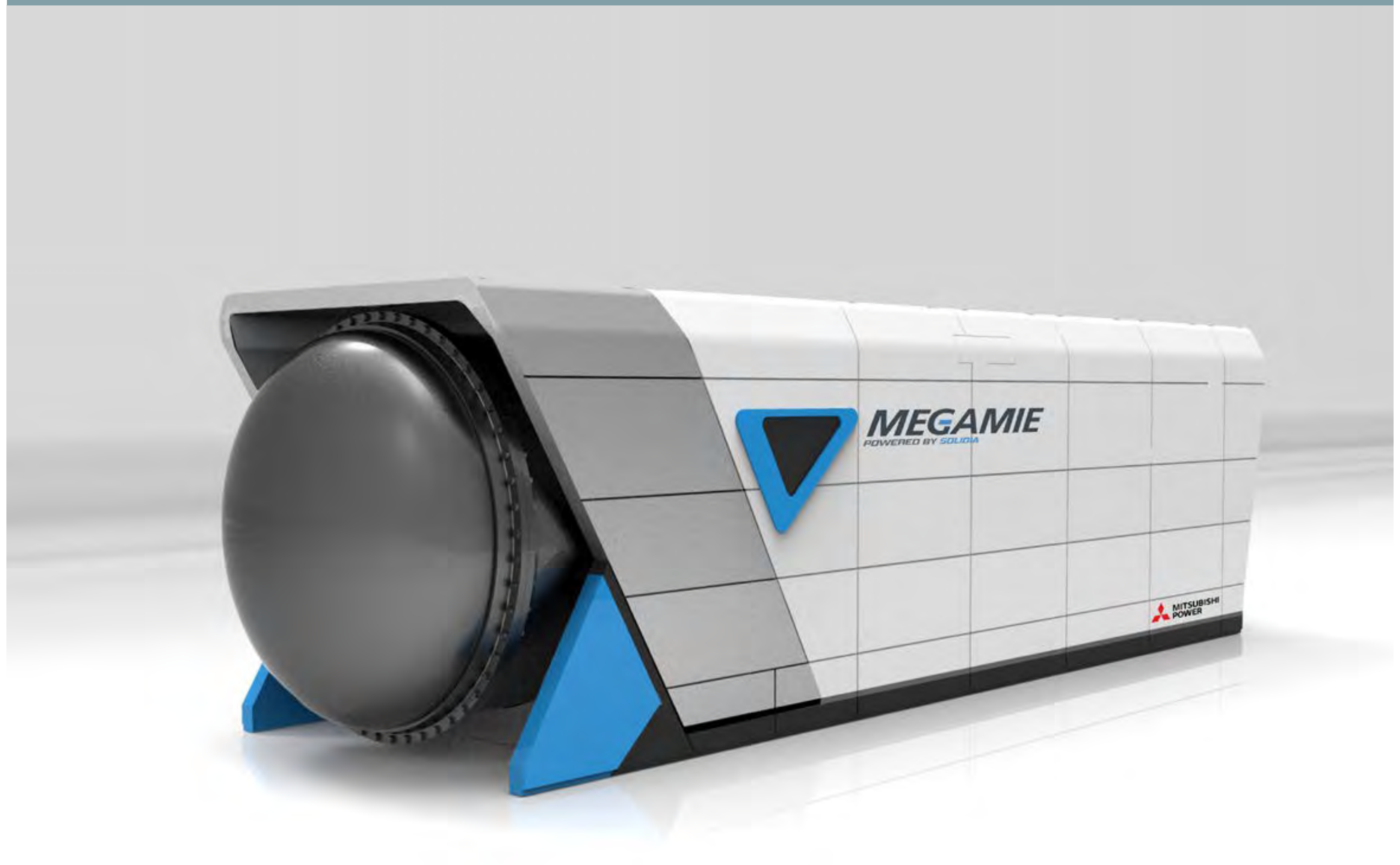
A transmission end-power generation efficiency of more than 70 percent (lower heating value, LHV) can be expected from a future natural gas-fired 100-megawatt-class SOFC + gas turbine + steam turbine combined-cycle system (Gas Turbine Fuel Cell combined cycle, or GTFC, Figure 1), which is positioned as a future replacement for large-scale thermal power plants. This will enable carbon dioxide (CO_2) emissions from thermal power stations to be reduced by around 20%. Even when coal is used as fuel, a transmission end-power generation efficiency of more than 60 percent (LHV) can be expected in 100-megawatt-class integrated coal gasification + SOFC + gas turbine + steam turbine combined-cycle systems (Integrated coal Gasification Fuel Cell combined cycle, or IGFC, Figure 2), and similarly, this would allow CO_2 emissions to be reduced by around 30%.

Mitsubishi Power will lead the technological development of fuel cells and aim to achieve even higher capacity and efficiency gains, culminating in the development of actual systems for utility use.


Figure 1: Gas Turbine Fuel Cell combined-cycle Power Plant


Figure 2: Integrated coal Gasification Fuel Cell combined-cycle Power Plant

TECHNICAL REVIEW



As a leading provider of power generation and environmental technology, Mitsubishi Power is developing high efficiency power generation technologies.
Energy market needs are diversifying and Mitsubishi Power is working to meet such decentralized needs.
We will now introduce our 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.

- Development of Next-Generation Large-Scale SOFC toward Realization of a Hydrogen Society.
  Our fuel cell power generation technology meets today's decentralized energy source needs.
  We contribute to the realization of a "safe and sustainable energy environment based society".

- Efforts toward introduction of SOFC-MGT Hybrid System to the Market.
  Development with the goal to achieve a Low Carbon Society.
  The 250kW class have been empiracally demonstrated. We have begun testing the 1MW class.

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

Development of Next-Generation Large-Scale SOFC toward Realization of a Hydrogen Society

YOSHINORI KOBAYASHI[*1] KAZUO TOMIDA[*2]
MASANORI NISHIURA[*3] KENICHI HIWATASHI[*3]
HIROSHI KISHIZAWA[*3] KOICHI TAKENOBU[*4]

Mitsubishi Hitachi Power Systems, Ltd. (MHPS) is developing a combined power generation system by combining a solid oxide fuel cell (SOFC), which is a fuel cell that can operate at high temperature, with other power generation systems including gas turbines. For commercial application of the hybrid system, MHI has been conducting demonstration tests at Tokyo Gas Co., Ltd.'s Senju Techno Station and the operation was started in March 2013. The pressurized-type SOFC-MGT hybrid system brought about by combining the 200-kW-class SOFC with a micro gas turbine (MGT) achieved 4,100 hours of continuous operation for the first time in the world, and exhibited a stable operation state even during the heavy-load season in summer. Based on this accomplishment, a new compact-type demonstration system was designed and set up at national university corporation Kyushu University in March 2015. It is planned to be used in demonstration studies and basic research in the future.

1. Introduction

In order to solve global warming problems, energy problems and economic problems at the same time, it is indispensable to reduce carbon emissions from energy sources and to increase efficiency in energy use. Therefore, to reduce emissions of CO_2, one of the major greenhouse effect gases, it is necessary to combine decentralized power sources rationally according to location and capacity on the basis of the present state of an electric power base infrastructure established with a centralized power source of high efficiency thermal power generation, etc., and then, to introduce new energies including renewable energies in the most economical and rational way possible. And, partly for global preservation of energy resources, it is indispensably and urgently required to use fossil fuel as effectively as possible by developing and quickly diffusing a high efficiency power generation system.

This article introduces the current development status of MHPS's SOFC, the status of the demonstrations of the SOFC-MGT hybrid system, which is a combined power generation system of the SOFC and a MGT, being conducted through the project of the National Research and Development Agency New Energy and Industrial Technology Development Organization (NEDO), and future developments.

2. Composition of SOFC combined power generation system

2.1 Cell stack

Figure 1 illustrates the structure of a cell stack of MHPS's tubular type SOFC. On the outer surface of the substrate tube, which is a structural member, a cell (anode, electrolyte, and cathode) reacting to generate power is formed and an electron-conductive ceramic used as an interconnector connects these cells in series. By selecting components with similar thermal expansion coefficients and the adoption of integral sintering through the improvement of manufacturing technology, the production cost has been reduced, the bonding strength of components has been increased, and the performance and durability have been improved.

*1 Senior Manager, Fuel Cell Business Department, Mitsubishi Hitachi Power Systems, Ltd.
*2 Deputy General Manager, Fuel Cell Business Department, Mitsubishi Hitachi Power Systems, Ltd.
*3 Group Manager, Fuel Cell Business Department, Mitsubishi Hitachi Power Systems, Ltd.
*4 Engineering Manager, Boiler Products Headquarters, Mitsubishi Hitachi Power Systems, Ltd.

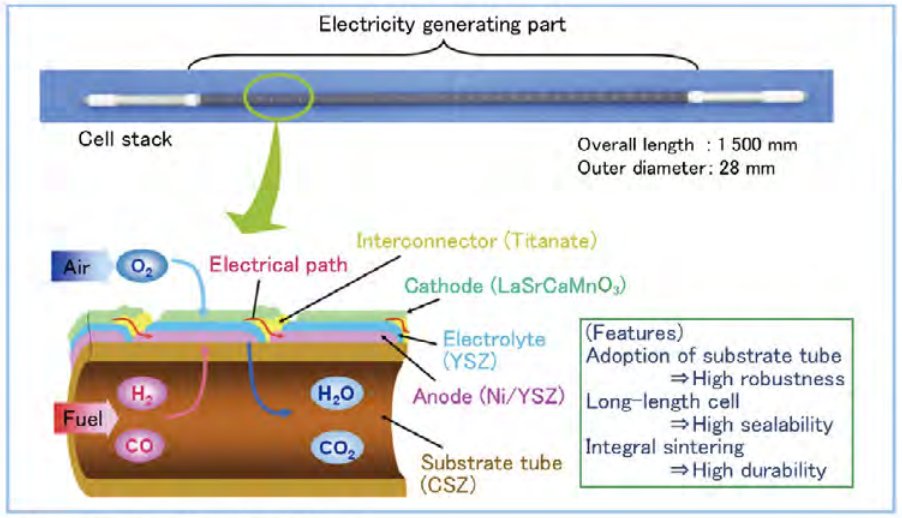


Figure 1 Structure of cell stack

MHPS has been developing our own high performance cell stacks. The Model 10 cell stack raised the number of cells to 85, and at the same time, the power output per cell stack has been enhanced by 30% by optimizing the interconnector composition, adjusting the cathode, etc. In the Model 15 cell stack, with which we have been attempting to further improve efficiency, the interface between the electrodes and the electrolyte has been improved to further increase the output density by 50% compared with Model 10 (**Figure 2**).

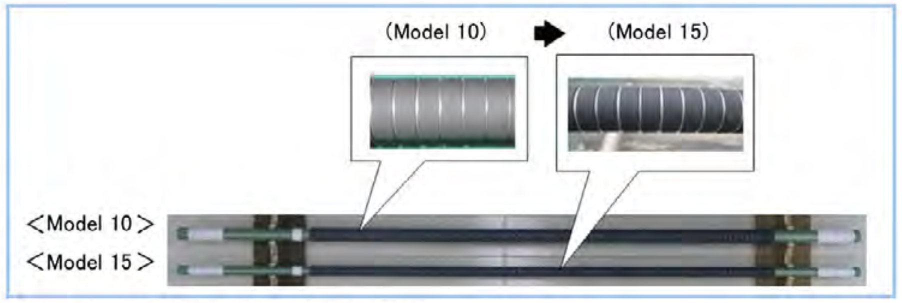


Figure 2 Tubular cell stack for SOFC

2.2 Cartridge

A cartridge that outputs electricity of several tens of kW by binding the cell stacks is formed and a set of cartridges with the necessary capacity, which is collectively contained in a pressure vessel, constitutes a module (**Figure 3**).

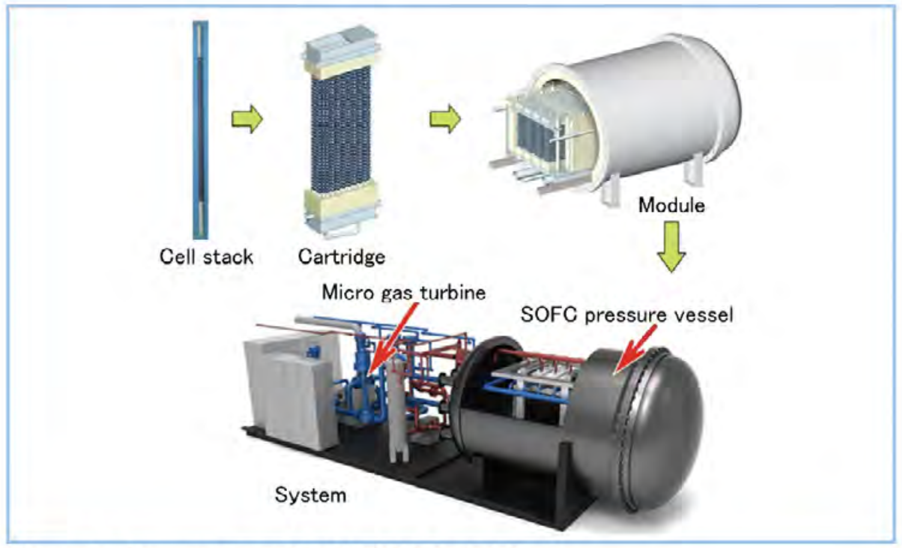


Figure 3 Composition of SOFC-MGT hybrid system

Mitsubishi Heavy Industries Technical Review Vol. 52 No. 2 (June 2015)

The adoption of such a layered structure seeks systematization by taking installation and even maintainability into consideration. In addition, since the electric output can be adjusted by the number of cartridges or the number of modules, a required wide range of electric output can be covered.

For the cartridge, higher per unit volume output density is aimed at. The higher packing density is accompanied by a higher heating density, but the heat transfer/cooling design of cartridges controls the heat transfer characteristics, ensuring the conventional level of heat transfer in the power generating area as well as in the heat exchange area across the power generation area. In Model 15, the reduction of the diameter and increase of the length of a cell stack enable an increase in the output density per unit volume and reduction of the system installation area (**Figure 4**).

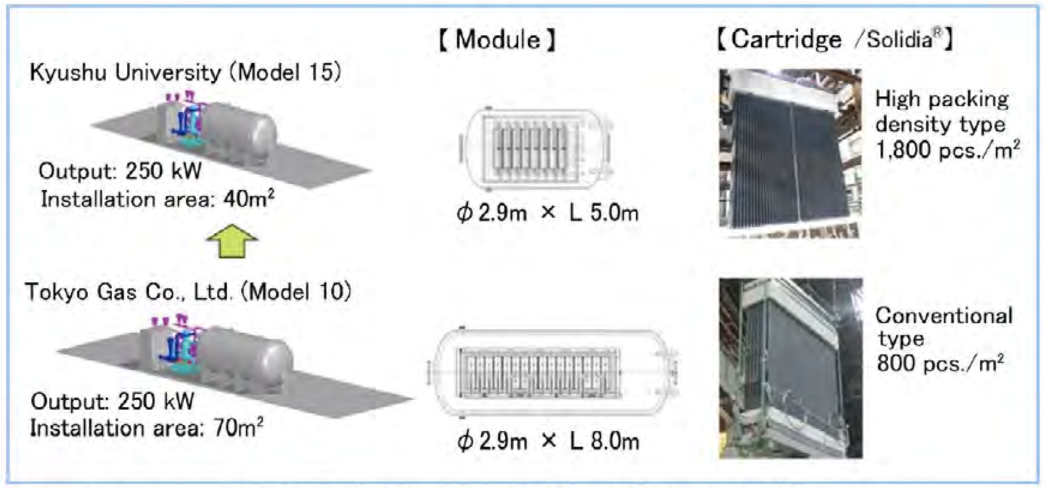


Figure 4 Development of cell stack/cartridge for low-cost mass production

2.3 System

The hybrid system shown in **Figure 5** generates electric power by the SOFC and the MGT in two steps. By installing waste heat recovery equipment on the exhaust gas line, it can function as a co-generation system that supplies steam and hot water at the same time.

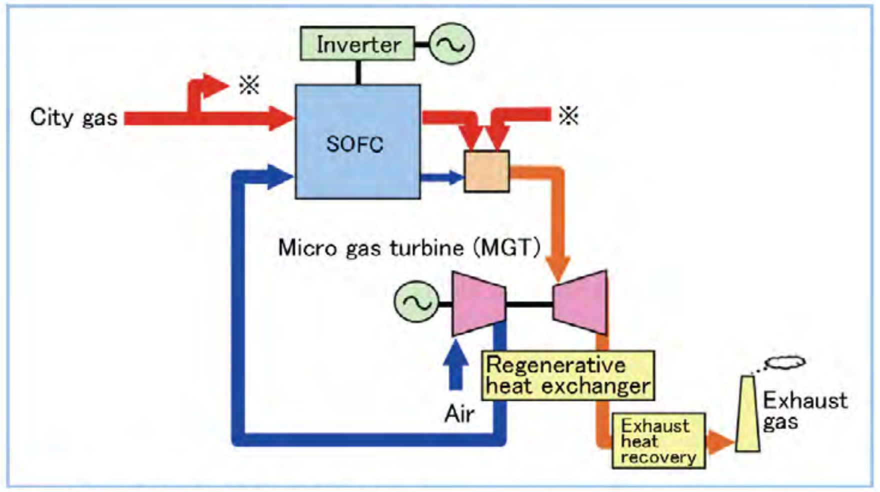


Figure 5 SOFC-MGT hybrid system

3. Market introduction plan for the hybrid system

3.1 Demonstration at Tokyo Gas Co., Ltd. (Model 10 demonstration system)

Based on the achievements thus far, from fiscal 2011 to 2014, we conducted the development and evaluation of the Model 10 250 kW-class SOFC-MGT hybrid demonstration system, under the NEDO project at Tokyo Gas Co., Ltd.'s Senju Techno Station. An MGT made by Toyota Turbine and Systems Inc. was adopted (**Figure 6**).

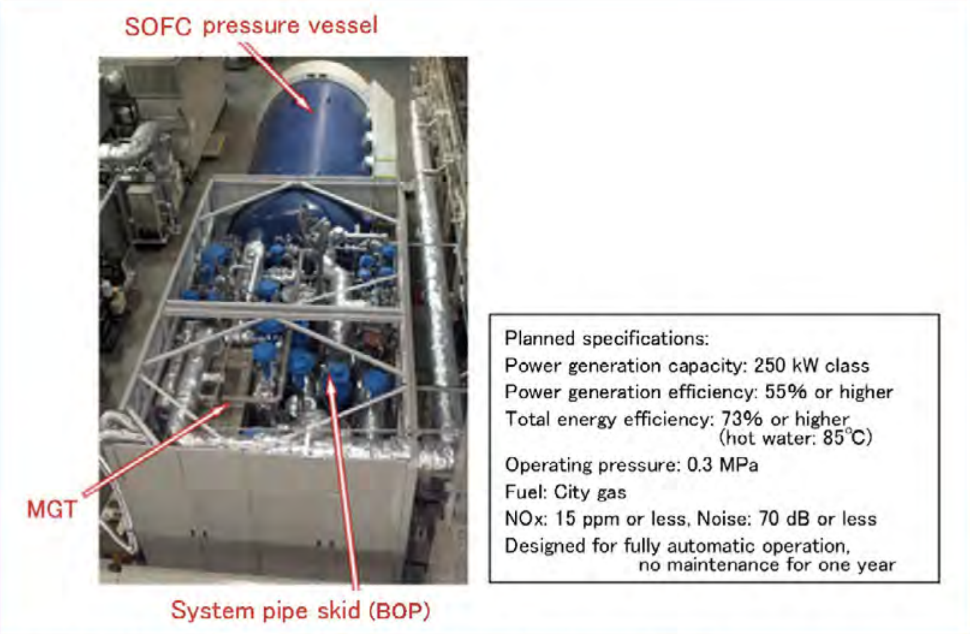


Figure 6 Model 10 SOFC-MGT hybrid system for demonstration

With this demonstration system, we pinpointed problems toward promotion of initial introduction of the SOFC-MGT hybrid system and the examination of deregulation for promotion of its introduction. At present, in particular, because the SOFC-MGT hybrid system is a pressurized system with a fuel gas pressure of 100 kPa or more and is rated as a power generation system that has to be monitored at all times, we are targeting the necessary reconsideration of the regulation requirements for continuous monitoring so that the system would be diffused in earnest. Therefore, we obtained the technical data necessary for deregulation including the grounds for system safety design and the system long-term durability test data, as well as the operation data such as emergency measures on assumed starting and stopping, load change and system problems and verified the system's reliability and safety.

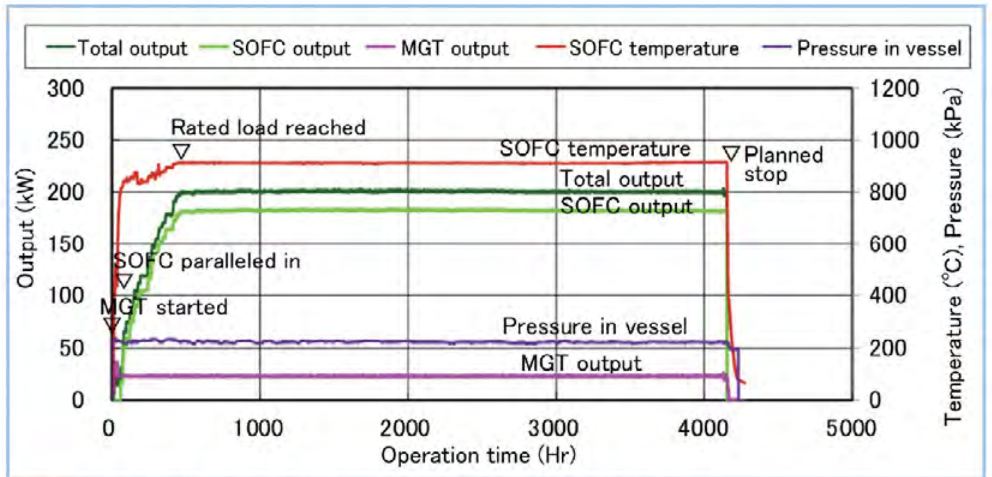


Figure 7 Result of durability test for SOFC-MGT hybrid system

We conducted the evaluations of various kinds of examinations and test data and the deregulation activities, receiving cooperation from the Fuel Cell Commercialization Conference of Japan, Japan Gas Association and Japan Electrical Manufacturers' Association and other entities.

For the system's long-term durability, continuous operation for over 4,100 hours was conducted till the planned shutdown. As a result, no time deterioration was observed under the condition of a constant rated load, and the voltage degradation rate was stable at 0% in 1,000 hours (**Figure 7**).

Mitsubishi Heavy Industries Technical Review Vol. 52 No. 2 (June 2015)

3.2 Model 15 demonstration system at Kyushu University

Based on the achievements of the Model 10 demonstration system, we designed a Model 15 demonstration system, and it was set up at the Ito Campus of Kyushu University (Nishi-ku, Fukuoka City) in March 2015. In the future, it is planned that the Model 15 demonstration system will be used in verification studies and related basic research for improvement of performance, durability and reliability of SOFC at the Green Asia International Strategic Comprehensive Special Zone "Verification of a Smart Fuel Cell Society" in the "Next-Generation Fuel Cell Research Center (NEXT-FC)*" (**Figure 8**).

* Next-Generation Fuel Cell Research Center (NEXT-FC): The institution established with the objective of promoting industry-academia collaboration toward earnest diffusion of SOFC.

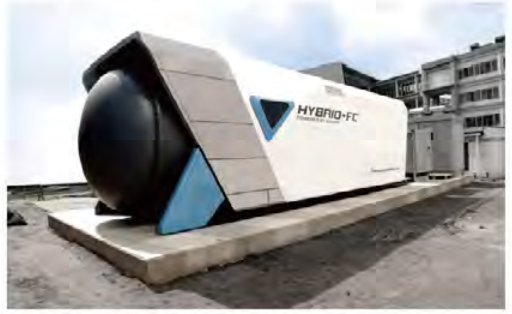


Figure 8 SOFC-MGT hybrid system for demonstration delivered to Kyushu University

Table 1 Specifications of the system

		250 kW SOFC-MGT hybrid system
Appearance		
Rated output	(kW)	250
Net efficiency	(%-LHV)	55
Total heat efficiency	(%-LHV)	73 (hot water), 65 (steam)
Dimensions of the unit	(m)	12.0 x 3.2 x 3.2
Operation		For cogeneration

These specifications indicate planned values.

3.3 SOFC market introduction plan

Taking advantage of the high efficiency, co-generation, quietness, environmental feasibility and other outstanding characteristics of the SOFC-MGT hybrid system, we henceforth intend to introduce it to distributed power sources for business purposes and industrial applications to hospitals, hotels, banks, data centers, etc. The specifications of the system are shown in **Table 1**. In fiscal 2015, we are going to proactively introduce the SOFC-MGT hybrid system as a sample machine on the market for customers' evaluation. Toward the start of its full-fledged introduction on the market in 2017, we are going to make efforts to improve durability, transportability, etc., based on evaluations and findings obtained with the sample machine, improve the system specifications to increase marketability, and bring down costs.

4. Approaches to a hydrogen society

4.1 Multi-energy station (Quatrogen®)

Toward a future low-carbon society/hydrogen society, operations using a hybrid system as noted below are under examination. The SOFC generates electricity and heat using hydrogen and carbon monoxide that are produced by internal reforming of city gas as shown in **Figure 9** (a). In addition, as shown in Figure 9 (b), some of the hydrogen produced by internal reforming may be directly extracted and used without being used for electricity generation. Therefore, electricity, heat and hydrogen can be simultaneously supplied, making it possible to realize Quatrogen, which also supplies city gas as fuel. By applying this mechanism to hydrogen stations, fuel can be simultaneously supplied not only to FCVs (fuel cell electric vehicles), but also to low carbon vehicles such as EVs (electric vehicles) and CNGVs (compressed natural gas vehicles). As a result, an increase in station profitability can be expected (Figure 9 (c)).

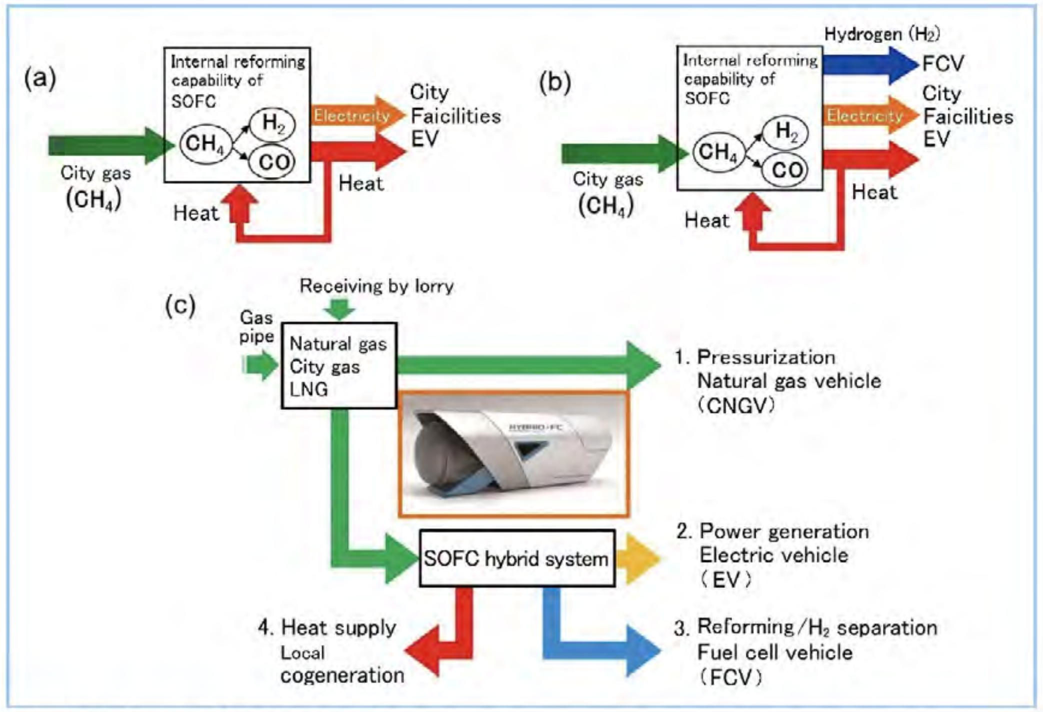


Figure 9 Image of Quatrogen
(a) Supply of electricity and heat by conventional SOFC
(b) Hydrogen production by internal reforming
(c) Application to a hydrogen station.

4.2 Local production of energy for local consumption (use of renewable energy)

It is expected that digestive gas generated at sewage treatment plants in urban areas can be used for the generation of electricity. Furthermore, methane generally constitutes about 60% of digestive gas. Accordingly, it is also considered that the use of the CO_2 separation technique enables high-efficiency digestive gas power generation using high-purity methane as fuel. The application of the aforementioned Quatrogen enables the production of "hydrogen produced in urban areas" derived from digestive gas, and therefore, the "local production of energy for local consumption in urban areas" can be expected (**Figure 10**).

With the creation of these added values through the hybrid system, we would like to accelerate the introduction of SOFC into the market.

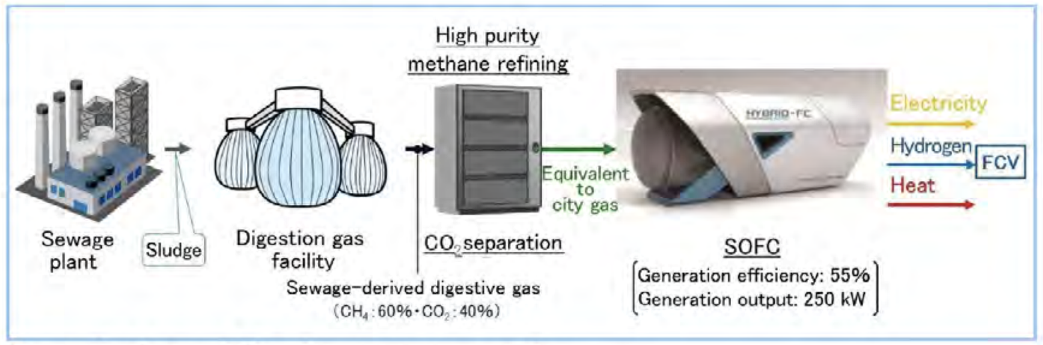


Figure 10 Image of digestive gas power generation

5. Conclusion

The Strategic Road Map for Hydrogen and Fuel Cells of the Ministry of Economy, Trade and Industry was developed in June 2014. In the roadmap, the introduction of stationary fuel cells for commercial and industrial use on the market in fiscal 2017 was also explicitly stated. MHPS would like to steadily establish the SOFC-MGT hybrid system and expedite its commercial application, thus greatly contributing to the development of "a safe and sustainable energy/environmental society."

Efforts toward Introduction of SOFC-MGT Hybrid System to the Market

KAZUO TOMIDA*1 KIMI KODO*2
DAIGO KOBAYASHI*2 YOSHIKI KATO*2
SHIGENORI SUEMORI*3 YASUTAKA URASHITA*4

Toward a future low-carbon society, the development of the SOFC-MGT hybrid system, in which a Solid Oxide Fuel cell (SOFC) that can generate power with high efficiency and a gas turbine are combined, has been promoted. In a program subsidized by the National Research and Development Agency New Energy and Industrial Technology Development Organization (NEDO) starting in fiscal 2015, 250 kW class demonstration systems were set up at four locations in Japan. The verification of durability and demonstrations of start/stop tests and load change tests under an actual load environment were conducted toward introduction to the market, and stable operation was verified. As a result, the introduction of the 250 kW class system to the market started in 2017. Furthermore, since fiscal 2016, in another NEDO commissioned project, the verification of the 1 MW class system, which features increased capacity, has been conducted, and the demonstration test is currently being conducted at the Nagasaki Works of Mitsubishi Hitachi Power Systems, Ltd. (MHPS).

1. Introduction

Recently, the energy situation in Japan has reached a major turning point, and it seems that awareness of high-efficiency power generation and power security has increased. To strike a balance between CO_2 reduction to mitigate global warming and the stable supply of power, which is indispensable in modern society, it is important to combine an advanced power grids constructed with centralized power sources such as thermal power plants and high-efficiency distributed power sources or new energy sources such as renewable energy in the best mix in terms of both quality and quantity. To preserve global energy resources, it is also a necessary and urgent issue to ensure the effective use of fossil fuel through the development and early adoption of high-efficiency power generation systems. In Japan, the industrial sector accounts for more than 40% of all energy consumption, and the consumer and industrial sectors account for slightly more than 60% combined. It is considered that the spread of the use of fuel cells in the commercial field is one effective measure for improving the Japanese energy situation.

MHPS has focused on developing the high-efficiency SOFC hybrid power generation system with a very wide range of power output. The system covers everything from medium-capacity (250 kW class) distributed power sources to large-capacity centralized power sources including Gas Turbine Fuel Cell (GTFC) combined cycle and Integrated Coal Gasification Fuel Cell (IGFC) combined cycle technologies, which are advocated by the "Council for promoting the early achievement of next-generation thermal power generation" of the Ministry of Economy, Trade and Industry.

2. Composition of SOFC-MGT hybrid system

Figure 1 illustrates the structure of a cell stack which is a power generation element of tubular type SOFC. On the outer surface of the substrate tube, which is a structural member made

*1 Manager, Fuel Cell Business Department, Mitsubishi Hitachi Power Systems,Ltd.
*2 Fuel Cell Business Department, Mitsubishi Hitachi Power Systems,Ltd.
*3 Chemical Research Department, Research & Innovation Center
*4 Heat Transfer Research Department, Research & Innovation Center

of ceramics, an element (laminated anode, electrolyte, and cathode) reacting to generate power is formed and an electron-conductive ceramic interconnector connects these elements 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**).

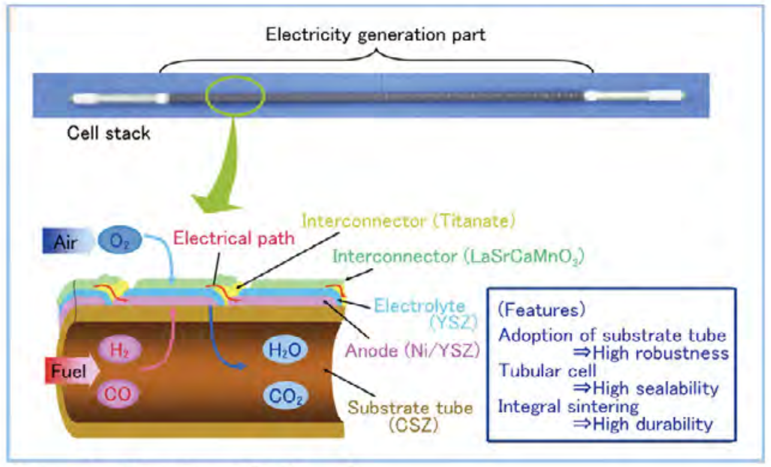


Figure 1 Structure of cell stack

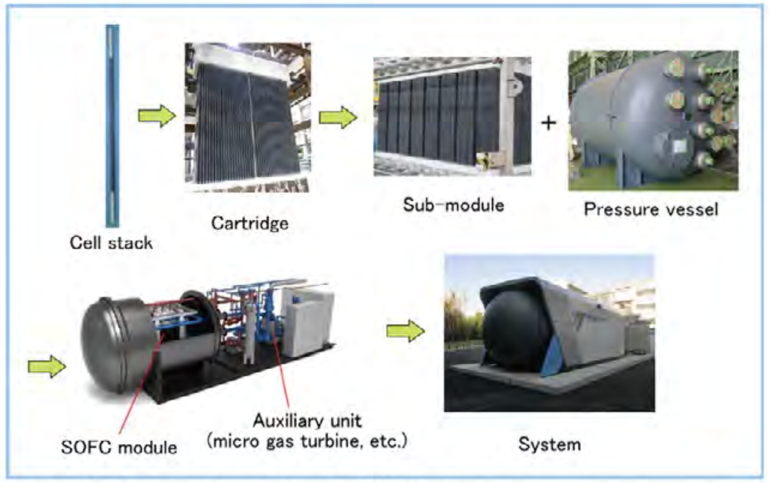


Figure 2 Composition of hybrid system

This system consists of the SOFC, Micro Gas Turbine (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**).

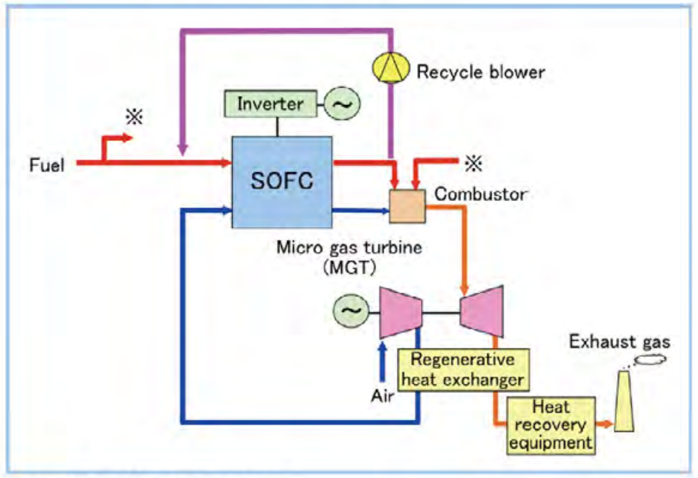


Figure 3 Hybrid system

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

3. Efforts with 250 kW class

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 started toward introduction to the market.

The demonstration sites consist of four bases: 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**).

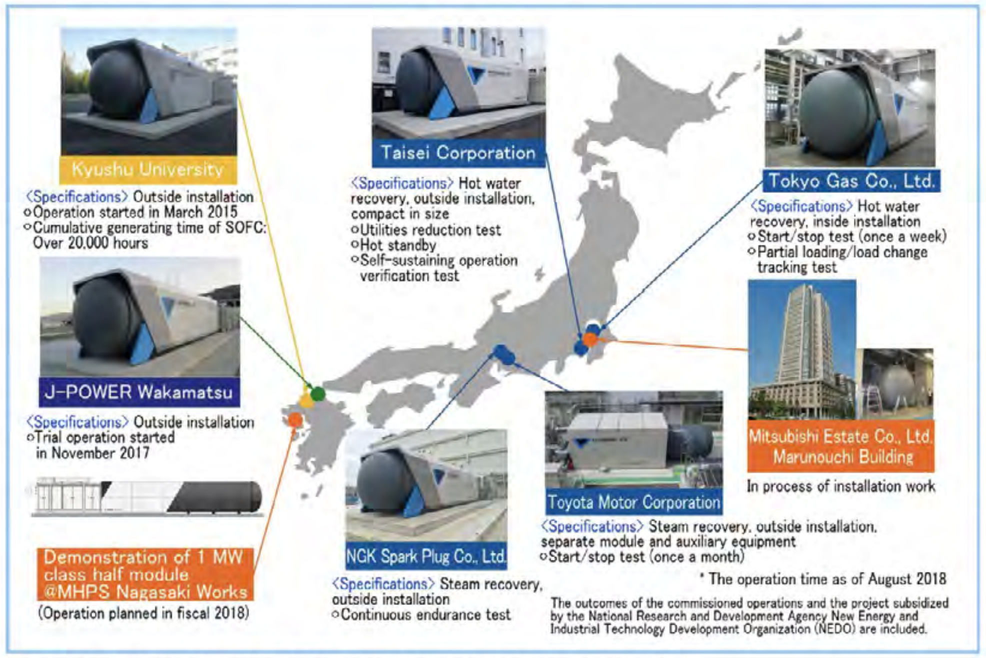


Figure 4 Operation and planning status for the fuel cell SOFC

In this subsidized project, the respective main subjects/verification items have been set at each site and the demonstration tests are being carried out. The details of the demonstration test at each site are as described below. At each site, the effects of changes in power demand and start/stop operation on the performance and durability are assessed.

-The demonstration system for Toyota Motor Corporation: The start/stop operation test (once a month) is continuing.

-The demonstration system for NGK Spark Plug Co., Ltd.: The continuous durability test is continuing.

-The demonstration system for Tokyo Gas Co., Ltd.: The start/stop operation test (once a week) was conducted 31 times.

-The demonstration system for Taisei Corporation: The self-sustaining function verification test was completed.

Based on the results of the demonstration tests, the introduction of the 250 kW class system to the market commenced in 2017. The results of the demonstrations at the four sites have been reflected in the models to be introduced to the market. The first commercial system was delivered to the Marunouchi Building owned by Mitsubishi Estate Co., Ltd. and its operation will commence by the end of the current fiscal year. As of August 2018, the installation of the main body has been completed.

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), the 250 kW class system was delivered to Wakamatsu Laboratory of J-POWER in fiscal 2017.

4. Status of Demonstration of 1 MW class SOFC-MGT hybrid system

Concerning GTFC, in which SOFC and a gas turbine are combined, the "Technology Roadmap for Next-Generation Thermal Power Generation" developed by the government and private sector committee in July 2015 indicates that the commercialization and mass production of the small-size GTFC (1 MW class) will be promoted to reduce the cost of SOFC, and demonstration projects using small- and medium-sized GTFC (100,000 kW class) will be conducted toward the establishment of the technologies around 2025.

In fiscal 2016, under the NEDO commissioned project " Gas turbine fuel cell combined cycle (GTFC) technology development", the verification of the small-sized GTFC (output: 1 MW class, operating pressure: 0.6 MPa class), which has a capacity/pressure condition closer to the small- and medium-sized GTFC (output: 100,000 kW class, operating pressure: 1.0 to 1.5 MPa class) compared with the conventional unit (output: 250 kW class, operating pressure: 0.2 MPa class) started at MHPS Nagasaki Works, toward introduction to the market. In the actual 1 MW class system, two SOFC module units will be installed. In this research and development project, only one SOFC module unit, which is half the number of units required for 1 MW class, is used to conduct the test, and is called a half module (**Figure 5**).

As of September 2018, the installation of the half-module demonstration unit has been completed and the half-module unit is being adjusted in the trial operation before power generation (**Figure 6**). In the future, the demonstration operation of the half-module unit will be conducted to study the system specifications of an actual 1 MW class unit with its marketability being considered.

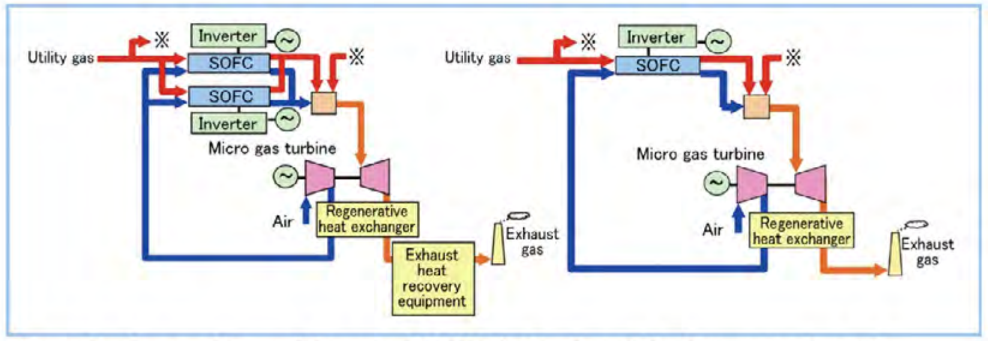


Figure 5 Compositions of the actual 1MW class unit and the demonstration unit

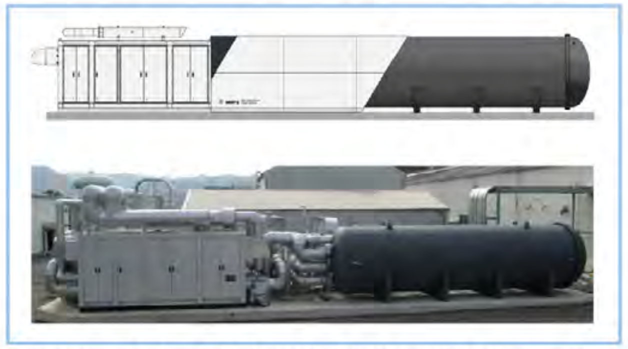


Figure 6 State of the installed half-module demonstration 1MW class unit

5. Conclusion

MHPS positions the SOFC hybrid power generation system as a key effective technology for making the reduction of CO_2 emissions and the stable supply of power compatible.

The 250 kW class demonstration units were installed at four sites in Japan in fiscal 2015, and the demonstration was conducted toward introduction to the market and its stable operation was verified. Based on the results, the system's introduction to the market started in fiscal 2017. The first commercial unit has already been delivered to the Marunouchi Building owned by Mitsubishi Estate Co., Ltd. and its operation will commence by the end of the current fiscal year.

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

Since fiscal 2016, the verification of the 1 MW class unit, which has an increased capacity compared with the 250 kW class unit, has been carried out. Currently, the demonstration test is being conducted at MHPS Nagasaki Works. We are willing to steadily establish the technologies through this demonstration test, promote early commercialization, and greatly contribute to the establishment of a "safe and sustainable energy environment society."

(Acknowledgment)

This paper includes the outcomes from joint research, etc., by the National Research and Development Agency New Energy and Industrial Technology Development Organization (NEDO). We are deeply grateful to all the concerned parties, the universities and research institutions for giving us guidance and advice and the electric power companies, gas utility companies, manufacturers and others for giving us guidance on development and verification.

References

(1) Y. Kobayashi, et.al. Development of Next-Generation Large-Scale SOFC toward Realization of a Hydrogen Society, Mitsubishi Heavy Industries Technical Review Vol. 52 No. 2(2015)

(2) Y. Ando, et.al. Demonstration of SOFC-Micro Gas Turbine (MGT) Hybrid Systems for Commercialization Vol.52 No.4 (2015)