

Extremely High-efficiency Thermal Power System-Solid Oxide Fuel Cell (SOFC) Triple Combined-cycle System



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A solid oxide fuel cell (SOFC) is a fuel cell that can operate at high temperature. By applying its high-temperature exhaust heat to gas turbine (GT) combined-cycle power generation, an extremely high-efficiency thermal power system can be constructed, with a power generation efficiency of up to 70%. Mitsubishi Heavy Industries, Ltd. (MHI) is one of the first companies to focus on the potential of the SOFC as a component of large-scale power generation systems and has promoted both element and system development since the 1980s. In a project commissioned by the New Energy and Industrial Technology Development Organization (NEDO), MHI has been working on the production and operation of a 200-kW class SOFC-MGT combined-cycle system, integrating tubular SOFCs and a micro gas turbine (MGT), since fiscal year 2004. From that point onward, the company has promoted practical application of this technology. Aiming at full-scale development of a triple combined-cycle system that integrates a gas turbine combined cycle (GTCC) and SOFCs, MHI initiated a joint research venture with Tohoku Electric Power Co., Inc. in fiscal year 2010 to promote the development of a maximum-efficiency power generation system.

1. Introduction

To secure a stable power supply (which is now indispensable for society) while reducing CO₂ emissions (to prevent global warming), it is necessary to rationally combine renewable and other energy sources with advanced power grids based on centralized power sources, such as thermal power generation. Under such circumstances, the efficiency enhancement of thermal power generation is essential. Additionally, to conserve energy resources, it is vital to thoroughly and effectively utilize fossil fuels via the widespread use of ultra-high-efficiency thermal power systems.

2. Significance of Triple Combined Cycle Development

From the era of the Rankine cycle with steam turbines (ST) (single engine) and through the peak years of the Brayton–Rankine combined cycle with gas turbines (GT) and ST (combination of two engines), Mitsubishi Heavy Industries, Ltd. (MHI) has been striving to maximize power generation efficiency by continuously increasing operating temperature and pressure (**Figure 1**). The company is currently involved in developing a triple combined cycle integrated with solid oxide fuel cells (SOFCs; high-temperature fuel cells) for practical use.

As **Figure 2** indicates, the triple combined cycle is integrated with SOFCs located upstream of the gas turbine combined cycle (GTCC). Because the SOFCs are placed in a high-pressure area upstream of the GT combustor, they must have a robust structure, and hence tubular ceramic SOFCs are suitable for this purpose.

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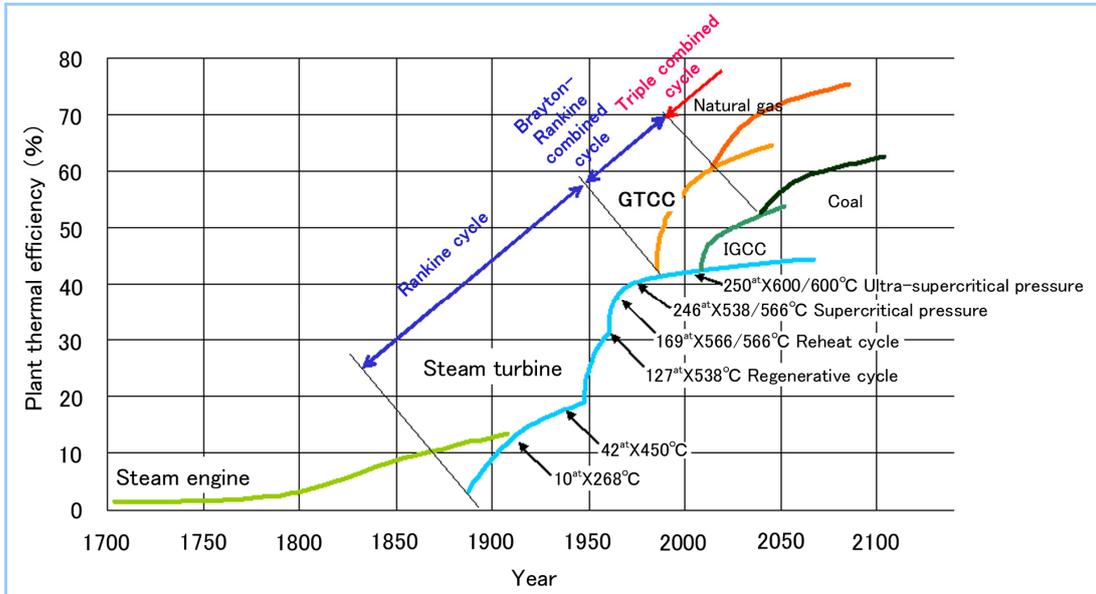


Figure 1 Transition of power generation efficiency

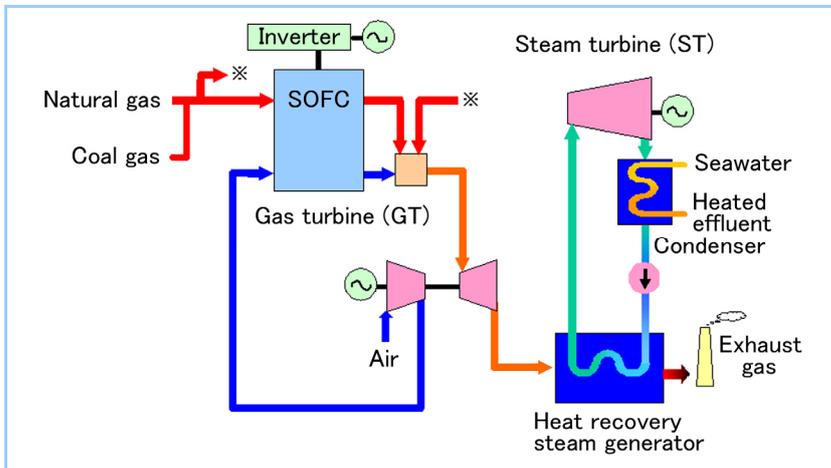


Figure 2 Triple combined-cycle system

Figure 3 shows an example of the energy balance in a triple combined-cycle system. By cascading the energy from fossil fuels (including coal) in three stages (SOFCs, GT, and ST), the system is capable of generating power with extremely high efficiency. Compared with other existing heat engines, it is expected to achieve a tremendous improvement in efficiency.

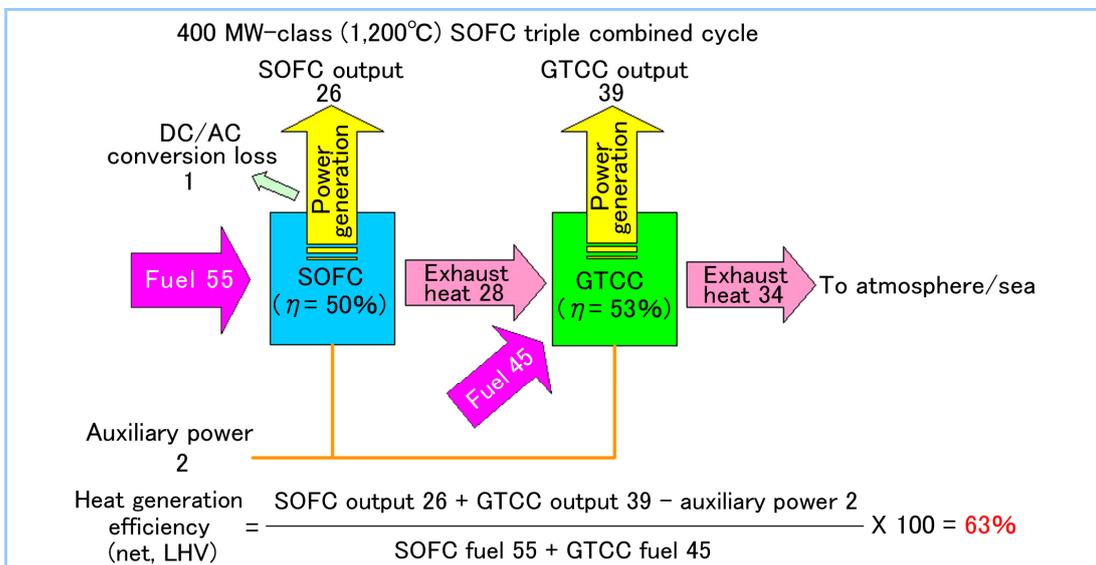


Figure 3 Example of the energy balance in a triple combined-cycle system

3. Development Status

3.1 Structure of a Tubular SOFC

Figure 4 illustrates the structure of a cell stack, which is the power-generating element of a tubular SOFC. The cells are composed of a fuel electrode, electrolyte, and air electrode and induce a power generation reaction. They are formed on the outer surface of a ceramic substrate tube, which is a structural member. The cells are connected in series via interconnects made of electron-conductive ceramics. A cartridge consists of several cell stacks (bundled together to produce an electrical output of several to several dozen kilowatts), together with support members and the functions to feed/exhaust fuel and air, as well as to extract electrical current. A module is composed of a specified number of cartridges contained in a pressure vessel (**Figure 5**).

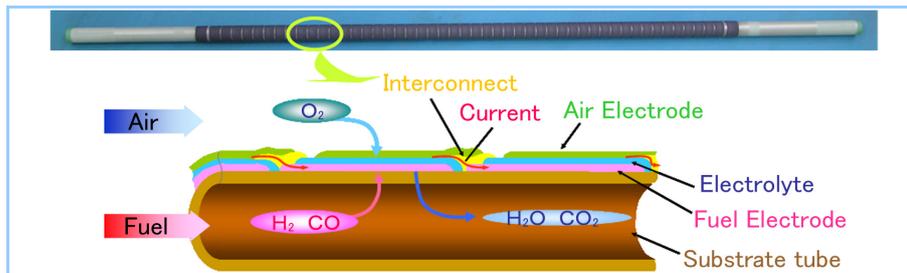


Figure 4 Structure of the tubular cell stack

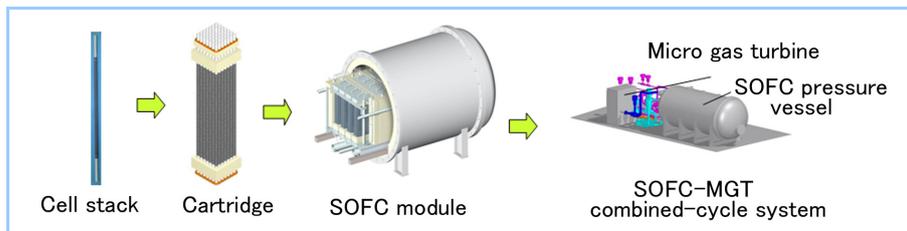


Figure 5 Structure of SOFC power generation system

Using the layered structure outlined above, MHI aims to provide a systemized module for installation and maintainability. An SOFC combined-cycle system (**Figure 6**) is constructed by coupling a pressurized SOFC module with a GT. In this system, the pressurized SOFC module is installed upstream of the MGT combustor. The fuel (city gas) is first supplied to the SOFC module, and the chemical energy of the fuel is directly converted into electrical power by the module. Residual fuel is then fed to the MGT combustor. Meanwhile, air is compressed to approximately 0.3 MPa-a by the MGT compressor and supplied to the SOFC module. A portion of this air is consumed as an oxidant, and the remainder is returned to the MGT, together with high-temperature exhaust heat. Because the sensible heat and pressure of air are also treated as energy and converted into electricity by the MGT located downstream, the system as a whole can achieve high power generation efficiency.

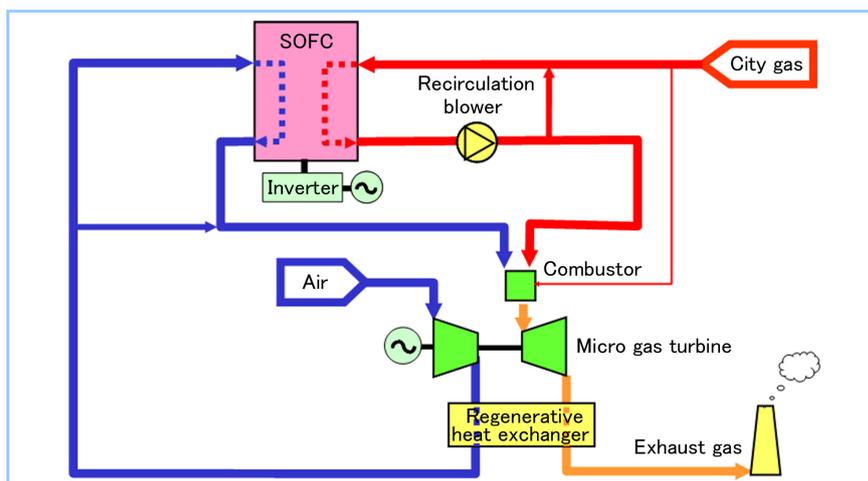


Figure 6 SOFC-MGT combined-cycle system

3.2 Development of the SOFC-MGT Combined-cycle System

As part of the research commissioned by the New Energy and Industrial Technology Development Organization (NEDO), MHI designed and manufactured a 200-kW class SOFC-MGT combined-cycle system and conducted a performance test in 2007 (Figure 7). The test demonstrated that this system has the world's highest-class gross power output of 229 kW-AC (SOFC: 204 kW-DC/188 kW-AC; MGT: 41 kW-AC). The test results also confirmed that the system attained a power efficiency of 52.1%-LHV at the operating point with a net power output of 204 kW-AC, which is at the highest level in its class. Thus, the target efficiency of 50%-LHV was also exceeded (Table 1).



Figure 7 The 200-kW class SOFC-MGT combined-cycle system

Table 1 Performance test results for the 200-kW class SOFC-MGT combined-cycle system

Item	
SOFC fuel heat input	339.8 kW-th
MGT fuel heat input	51.5 kW-th
SOFC power output	186.8 kW-DC
SOFC power output	176.3 kW-AC
MGT power output	34.8 kW-AC
Gross power output	211.1 kW-AC
Auxiliary power	7.1 kW-AC
Net power efficiency (net, LHV)	52.1 %

In 2009, MHI performed a long-term operation test of the SOFC-MGT combined-cycle system. No deterioration of the SOFC voltage was observed after 3,224 hours of operation. Even though the shutdown–restart process (thermal cycle) was executed four times during the long-term operation, no performance degradation was observed (Figure 8).

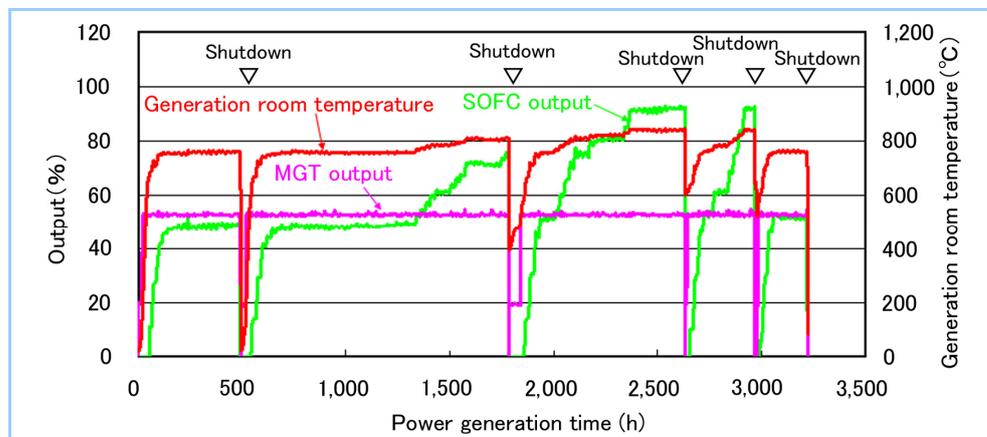


Figure 8 Long-term operation test results for SOFC-MGT combined-cycle system

3.3 Improvement of the Tubular SOFC Power Generation System

As part of the project led by NEDO, MHI has promoted an improvement in reliability and the development of elevated pressure operation and higher efficiency for each cell stack, module, and power generation system from fiscal year 2008 onward.

To improve the durability of the cell stacks, research institutions participating in the project analyzed MHI's tubular cell stack design. Based on the results of these studies, we prototyped a new cell stack designed to reduce cation migration in the cathode interlayer, which was assumed to be the main cause of cell deterioration. We conducted a continuous power generation test at atmospheric pressure for over 6,000 hours and achieved a cell voltage decay rate of 0.13%/1,000 hours (well within the NEDO target of 0.25%/1,000 or lower) (Figure 9).

To reduce the module size, MHI designed and prototyped a condensed-type cartridge (one of the components of the module), increasing the packing density of the cell stacks in the cartridge to 1.7 times that of the conventional module. An operation test was performed on the new prototyped cartridge. To cope with the increased heat density in the generation room (induced by the increased

packing density), we developed an appropriate heat transfer design for cooling. As a result, the new cartridge exhibited voltage–current (V–I) characteristics comparable to those of the conventional cartridge (**Figure 10**).

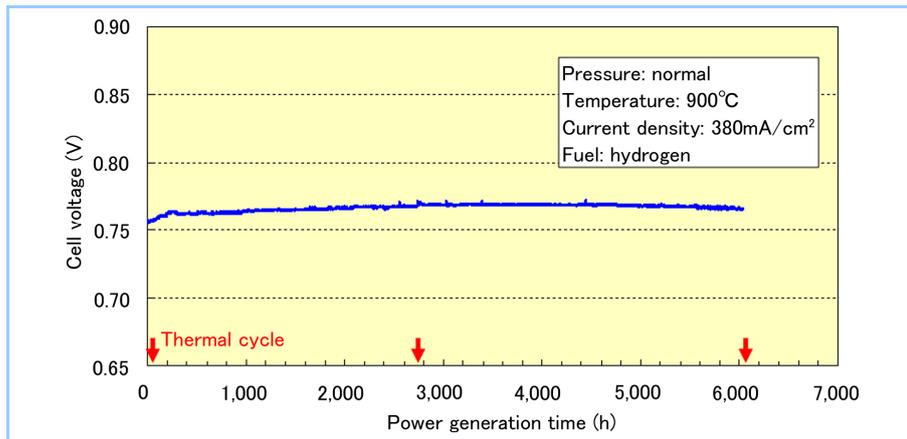


Figure 9 Long-term operation test results for improved cell stack

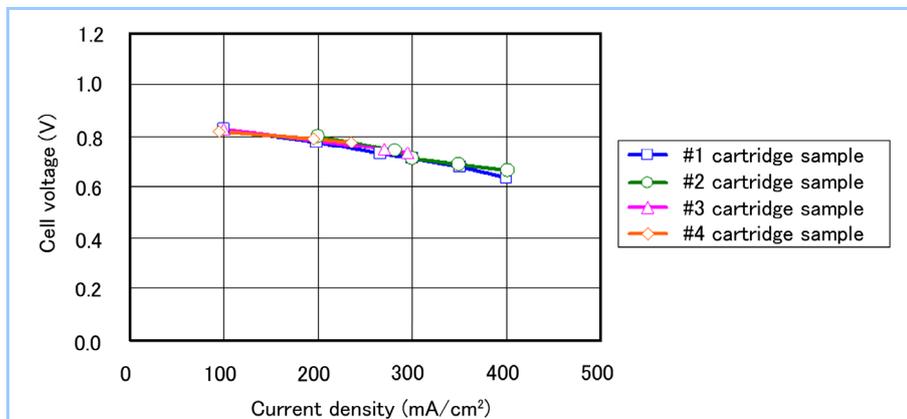


Figure 10 Performance of condensed-type cartridge

To improve the reliability of the system as a whole, we used an MGT manufactured by Toyota Turbine & Systems, Inc., which has an established track record as a utility turbine. MHI carried out a joint research venture with Toyota Motor Corp. to enhance both the performance and reliability of the overall system. In view of requirements for SOFC and MGT protection (i.e., avoiding a lack of fuel and oxidant for the SOFCs and preventing over-speed rotation of the MGT), we developed a protection logic circuit for the 200-kW class SOFC-MGT combined-cycle system and conducted startup, rated operation, and emergency shutdown tests. The protection interlock worked properly, demonstrating that the system can be safely shut down without damaging the SOFC module or MGT (**Figure 11**).

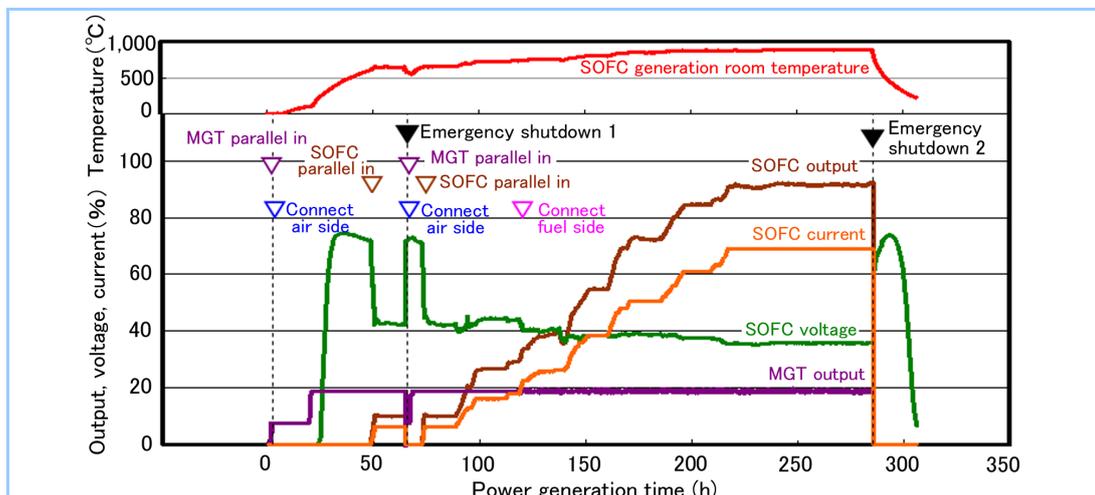


Figure 11 Operation test results for the SOFC-MGT combined-cycle system

A triple combined-cycle system is a system that integrates a utility GT and SOFCs and has an SOFC working pressure of 1–2 MPa-a. The SOFC operating voltage increases as the working pressure rises. Meanwhile, the flow velocities of air and fuel decrease, making it necessary to ensure adequate heat transfer. Using the condensed-type cartridge mentioned above, we estimated the distributions of generation room temperature and oxygen concentration under elevated pressure and verified that the required heat transfer was maintained even at 2 MPa-a. Also, the cartridge was confirmed to have a temperature distribution appropriate for power generation, and the minimum oxygen concentration in the vicinity of the cells was affected little by pressure (**Figure 12**).

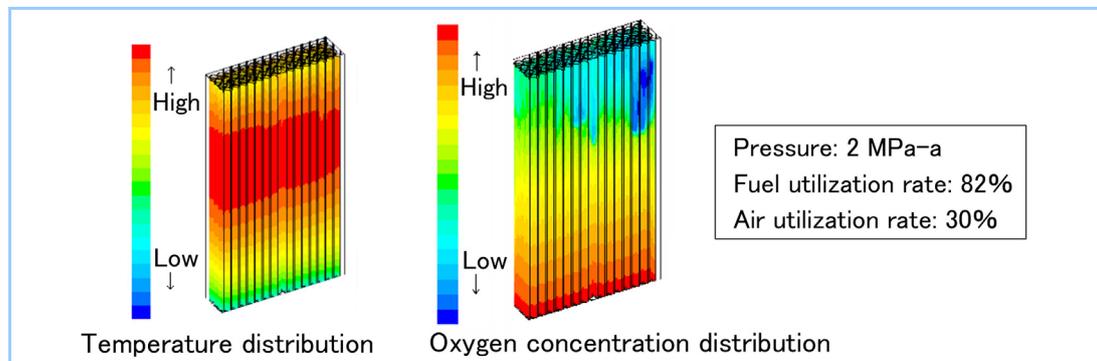


Figure 12 Estimation of temperature and oxygen concentration distributions under elevated pressure

3.4 Planned SOFC-MGT Combined-cycle System Demonstration

In view of our accomplishments thus far, MHI plans to manufacture and demonstrate a 250-kW class SOFC-MGT combined-cycle system (**Figure 13**) as part of the NEDO project scheduled for fiscal year 2011–2012 and to put it on the market.

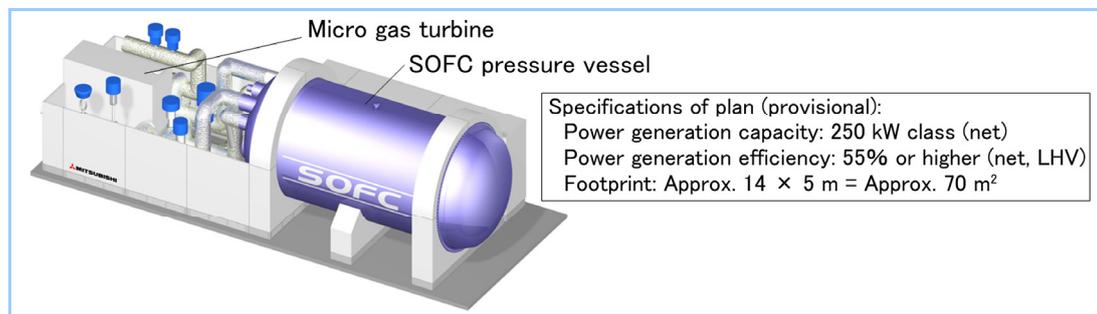


Figure 13 Plan for 200-kW class SOFC-MGT combined-cycle system demonstration

4. Toward Practical Application of the Triple Combined-cycle System

Figure 14 shows a road map for the development of the SOFC power generation system. We will launch 200-kW to megawatt-class generation facilities for distributed power sources (including combined heat and power) after the demonstration period so that they can continue to be evaluated by users.

For the practical application of triple combined-cycle power generation, we plan to start with relatively small systems because the initial phase will entail the establishment of a mass-production system for SOFC manufacturing equipment.

Figure 15 shows an 800-MW class triple combined-cycle system to be adopted in the future. The system operates on natural gas and generates power with maximum efficiency based on a triple combined cycle using SOFC, GT, and ST. This is the ultimate goal of our SOFC product concept.

In a several hundred megawatt-class natural gas-firing triple combined-cycle system, the net power efficiency is expected to reach 70%-LHV or higher. A combination of a several hundred megawatt-class integrated coal gasification combined cycle (IGCC) and SOFCs (**Figure 16**) is also expected to be capable of ultra-high-efficiency power generation, with a net power efficiency of 60%-LHV or higher.

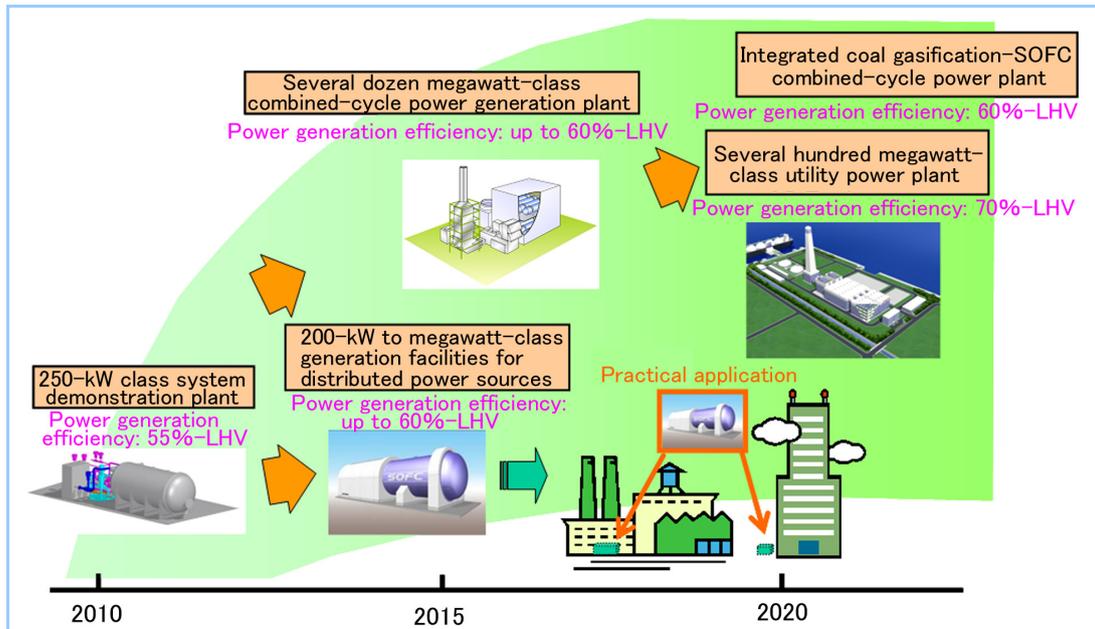


Figure 14 Road map for SOFC power generation system development

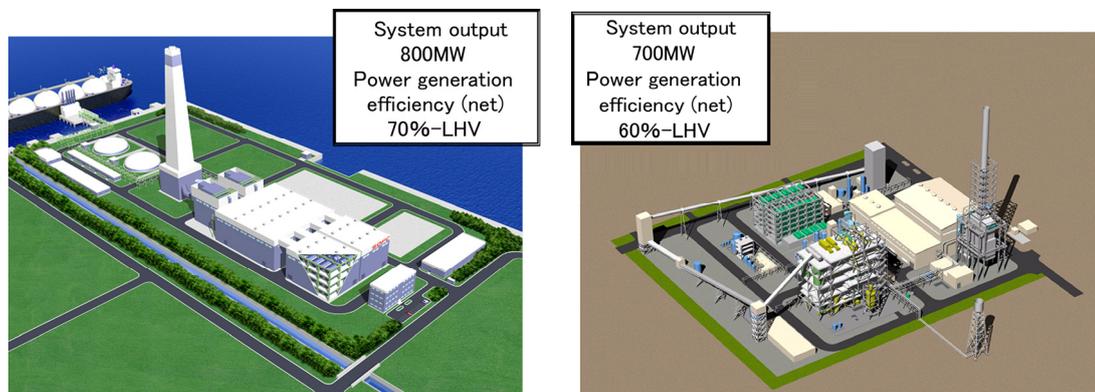


Figure 15 800-MW class natural gas-firing triple combined-cycle plant

Figure 16 Coal gasification-SOFC triple combined-cycle plant

5. Conclusions

High expectations are placed on the early implementation of a fossil fuel-firing ultra-high-efficiency power generation system because it has recently become imperative to develop an effective technology to reduce CO₂ emissions and simultaneously secure a stable power supply. We regard the SOFC triple combined-cycle power generation system as one of the most effective existing measures for the electrical business sector to reduce CO₂ emissions. We are determined to make a significant contribution to the establishment of a safe society with a sustainable energy environment in the 21st century by continuously developing our technologies and striving to put this system into practical use as soon as possible.