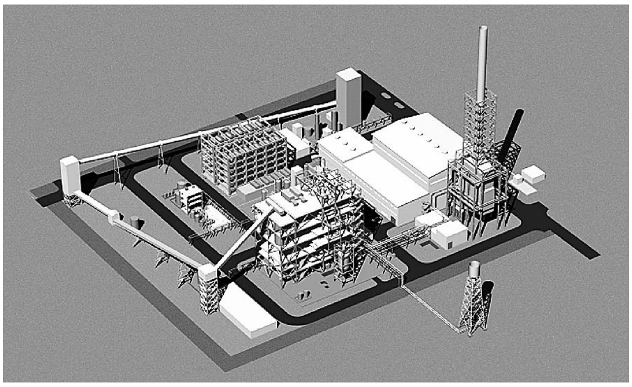

Latest State of Fuel Cells that Open the Way to an Environmentally Friendly Society in the 21 Century

TADASHI GENGO*1
YOSHINORI KOBAYASHI*1
NAGAO HISATOME*2
SHINGO KANEHIRA*3
YOSHIMASA ANDO*1

As part of its research efforts into the development of Solid Oxide Fuel Cell (SOFC) system technology, the New Energy and Industrial Technology Development Organization (NEDO) has been pursuing the development of a micro gas turbine pressurized combined cycle power generation system and 200 kW class co-generation system based on a four-year project started in 2004. A closed loop Polymer Electrolyte Fuel Cell (PEFC) system was installed onboard the "Urashima", a Japan Agency for Marine-Earth Science and Technology (JAMSTEC) autonomous underwater vehicle, which achieved the world's longest continuous cruising distance of 317 km in February 2005. In addition to these projects, efforts are being made to promote the commercialization of environmentally friendly energy systems that meet the needs of the 21st century, such as Mitsubishi Heavy Industries, Ltd. (MHI)'s own solid polymer water electrolysis (SPWE) and SOFC combined cycle power generation systems in conjunction with integrated gasification combined cycle (IGCC) systems, as well as clean combined cycle power generation systems together with the more effective use of renewable energy.

1. Introduction

The need to reduce the amount of greenhouse gas emissions has become particularly urgent with the Kyoto Protocol coming into force in February of this year (2005). However, in order to reduce emissions of CO_2, a greenhouse effect gas, it is necessary, in the short term, to utilize fossil fuels more effectively through the widespread use of high-efficiency power generation systems, while in the longer term, it will become necessary to put into practical use new power generation systems that reasonably combine renewable energy sources and new energy sources, such as hydrogen fuel.

From early on, MHI has focused its efforts on developing fuel cells that make it possible to convert the chemical energy of fuels directly into electric energy, thereby increasing power generation efficiency dramatically. After a steady process of research and development and accumulating relevant expertise, MHI is finally approaching the stage where some of these technologies can be practically applied.

This article introduces an outline of the present state of the development of high-efficiency new power generation systems, which is a key technology for realizing an energy oriented and environmentally friendly society in the 21st century. These systems are based on the Polymer Electrolyte Fuel Cell (PEFC), Solid Polymer Water Electrolysis (SPWE), which MHI is striving to commercialize, and Solid Oxide Fuel Cell (SOFC) technologies.

2. Polymer Electrolyte Fuel Cell (PEFC)

PEFC is a low temperature operating fuel cell with a polymer membrane as an electrolyte. The PEFC is characterized by several advantages as a power source. These include the ability to operate at low temperatures, ease of handling, and excellent start-up, running and operation properties. Furthermore, since the electrolyte used in the fuel cell consists of solid material, it is highly reliable and can be expected to have a long service life. Moreover, it is small and compact, and has high power generation efficiency. As a result, consideration is being given to applying PEFCs as a source of power for vehicles, as well as a distributed power source for co-generation for small commercial and home use, among other applications, taking advantage of these characteristics.

MHI is pursuing the development of these technologies in an holistic, comprehensive manner, from raw materials, such as polymer membrane and catalyst, to components and systems, such as reformers and cell bodies. In 2003, MHI delivered the first unit of the 1 kW town gas co-generation system to the Japan Gas Association as a sample for field testing. Subsequently in 2003, MHI succeeded in developing a compact package unit with a volume of 180 L, verifying the performance of the system with an AC net efficiency of 36% (LHV) and an overall efficiency of 80% or higher (LHV) including heat application.

On the other hand, it was thought that the utilization of PEFCs as a source of power in underwater vehicles would be conceivable, by taking advantage of the special characteristic of the PEFC, including its small and compact size, high efficiency, good running and operational properties, as well as its ability to restrict emissions to only water through the application of pure hydrogen/ pure oxygen fuel. In this case, the PEFC would be used in an enclosed underwater space to which water pressure is applied.

*1 Power Systems Headquarters
*2 Nagasaki Shipyard & Machinery Works
*3 Kobe Shipyard & Machinery Works

This would necessitate the need to meet additional technical challenges, such as fuel supply system, operation temperature retention, high air tightness, among other unique factors that are not normally required for vehicles. Overcoming these technical challenges, MHI manufactured a 4 kW class closed loop PEFC as a source of power for "Urashima", an autonomous unmanned underwater vehicle built for JAMSTEC (**Fig. 1**, **Fig. 2**, and **Table 1**). In February 2005, JAMSTEC carried out sea trials in the Suruga Bay and achieved the longest continuous cruising distance of 317 km, rewriting the world record for autonomous underwater vehicles.

A PEFC is a device which extracts chemical energy (that fuel has) in the form of electric energy. It utilizes the chemical reaction where fuel hydrogen and air (oxygen) are made to flow to produce water with a solid polymer membrane placed between them. Conversely, if water is made to flow on both sides of a solid polymer membrane and a voltage is applied, water is decomposed by the resulting electric current to produce hydrogen and oxygen. SPWE is a hydrogen production technology that utilizes this principle.

Fig. 1 "Urashima", an autonomous underwater vehicle
Achieved the longest continuous cruising distance of 317 km, rewriting the world record for autonomous underwater vehicles powered by PEFC.

Table 1 Principal Specifications of PEFC

Output	4 kW (2 kW X 2)
Operation temperature	60^oC
Power generation efficiency	54% (gross LHV)
Fuel used	Pure hydrogen / pure oxygen

Table 2 Results of SPWE Electrolysis Tests

Operating Conditions				Result	
Current density (A/cm^2)	Pressure (MPa)	Temp. (^oC)	Average cell voltage (V)	Current efficiency (%)	Energy efficiency (%)
1	0.1	80	1.6	100	91
1	0.7	80	1.6	98	89
2	0.7	83	1.9	98	77

Current efficiency = Energy of generated hydrogen/Energy put into cell
Energy efficiency = Energy of generated hydrogen/Energy put into electrolytic device

Compared with other types of hydrogen production technologies, SPWE has the characteristic of being able to obtain highly pure hydrogen at a high energy efficiency. It is possible to produce such highly pure hydrogen because the polymer membrane also functions as a gas barrier. Further, since cell resistance is low, operation at large current density is possible, and as a result, the device is compact.

MHI has been working on the development of a SPWE device since 1993 for hydrogen stations with the aim of contributing to the realization of a future hydrogen oriented society as part of the WE-NET project, a research project entrusted to MHI by NEDO.

Since 2003, MHI has participated in the "Development for Safe Utilization and Infrastructure of Hydrogen Project", another research project sponsored by NEDO, and has pursued studies into reducing the costs of this technology. With the goal of concurrently overcoming challenges in hydrogen production technology, while achieving ever higher efficiencies, and lower costs, MHI has developed a natural circulation type device that circulates water based on the void ratio of generated H_2/O_2 gas. This has eliminated the need for water circulation pumps. Furthermore, based on the extensive expertise and knowledge regarding boiler technologies that MHI has accumulated over the years, MHI has succeeded in realizing this natural circulation type device through improvements in a separator incorporating results obtained in the WE-NET project.

As a result, since 2004, MHI has developed an integrated natural circulation system (**Fig.3**) and carried out preliminary tests (**Table 2**). Since 2005, MHI has pursued further development with a central focus on improving reliability with a view toward product commercialization.

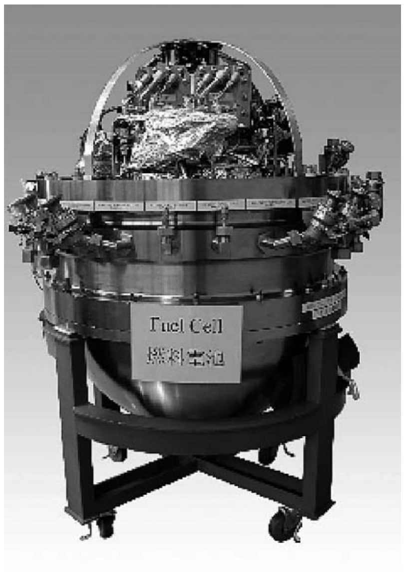

Fig. 2 The PEFC installed onboard the "Urashima"
Employs a 4 kW-class closed loop system due to its use in an underwater enclosed environment.

3. Solid Oxide Fuel Cell (SOFC)

SOFC also has excellent characteristics among fuel cells. Since the power generation efficiency of a cell itself is high and, further, the operation temperature is as high as 1000°C, it is possible to achieve a high power generation efficiency of more than 60% by making a combined cycle power generation system utilizing high temperature exhaust gas. Furthermore, since internal reformation of fuel is possible and it is permissible for CO to be contained in the fuel, a wide variety of fuels from natural gas to coal gas can be used in the cell. Moreover, because the electrolyte consists of a solid material, the cell can be expected to enjoy a long service life. Taking advantage of these characteristics, it is anticipated that it will be possible to apply SOFCs to a wide range applications, from small-to-medium scale co-generation systems to large-scale capacity systems capable of replacing thermal power plants. Therefore, MHI has been working on the development of the practical and widespread use of SOFC technology.

3.1 Development of tubular type SOFC

MHI has been collaborating with the Electric Power Development Co., Ltd. (EPDC) to develop a pressurized tubular type SOFC module in 1998, achieving a maximum output of 21 kW and a continuous operation time of 7 000 hours. In 2001, using a cell manufactured with the sintering method, MHI developed a pressurized 10 kW class module based on the internal reforming method, achieving a continuous power generation time of 755 hours. At present, EPDC is working on a 150 kW class system planned to be installed and operated in 2006, with a view to establishing the SOFC at an early stage.

In the four-year project starting in 2004, on the other hand, MHI has been developing one of the largest pressurized combined cycle power generation systems in the world in combination with a micro gas turbine (MGT) in a research project entrusted to MHI by NEDO (**Fig. 4**).

The tubular type SOFC is a fuel cell in which thin films of a fuel electrode, electrolyte and air electrode are laminated on the external surface of a substrate tube to form a power generation part to which adjacent power generation parts are connected in series by an inter-connector. The external appearance of a tubular type cell tube is shown in **Fig. 5**. MHI has worked on the realization of higher output of this tubular type cell in the development of advanced tubular type cell, a research project entrusted to MHI by NEDO. In a tubular type cell, an electric current is made to flow in the longitudinal direction. Consequently, reduction of the resistance value of the boundary face between the air electrode and electrolyte as well as reduction of the resistance value of the air electrode is effective for improving cell performance. Thus, higher output is realized through an improvement of the electrode materials and joint parts used. **Fig. 6** shows the results of power generation tests on the cell tube in the pressurized state. An output density of 0.21 W/cm^2 has been achieved at a pressure of 0.4 MPa, which is the SOFC operation pressure in a combined cycle system operating with a MGT. MHI continues to pursue the development of cells with higher output levels in the future.

Engineering development of cell module design and construction has been carried forward since 2001 to improve the reliability of module. Tubular type cell tubes are bundled to form a cartridge that serves as a minimum unit for supplying fuel and air and for extracting an electric current. Several cartridges then are placed to form a submodule and electrically connected in series for extracting an electric current. Furthermore, several sub-modules are placed in the longitudinal direction of the pressure vessel to form a highly scalable module.

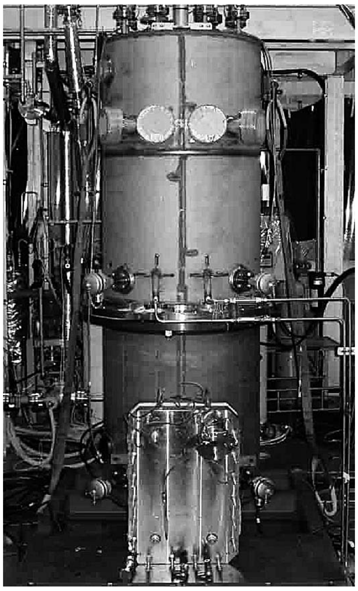

Fig. 3 Integrated natural circulation water electrolysis system
Adopts natural circulation in which water is circulated based on the void ratio of generated H_2/O_2 gas, achieving both high efficiency and low cost at the same time.

Fig. 4 MGT combined power generation system
One of the largest class pressurized combined power generation systems in the world based on the incorporation of a micro gas turbine.

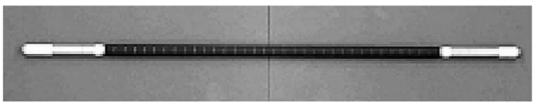

Fig. 5 Tubular type cell tube; 1500-mm long cell tube

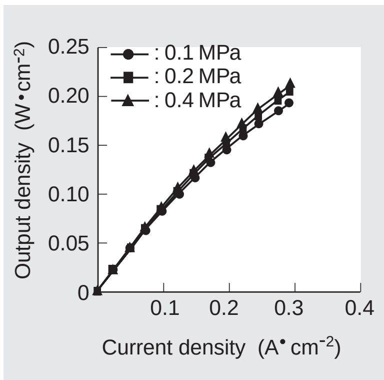

Fig. 6 Results of pressurization tests on tubular type cell tube
An output density of 0.21 W/cm^2 was achieved at 0.4 MPa, which is the SOFC operation pressure in a combined cycle with a micro gas turbine.

Low-calorie fuel (1/10 the heating value of town gas) remains after most of the chemical energy has been consumed in the SOFC. As a result, a technology is required to burn this low-calorie fuel stably at the MGT combustor. At MHI, however, a technology for burning low-calorie gases, such as blast furnace gas, accumulated with industrial gas turbines is applied. In addition, when SOFC and MGT are linked to each other, a control technology such as a pressure and temperature control system is also an important challenge. In the MGT pressurized combined cycle power generation system, a power generation efficiency of 50% or greater (LHV) is aimed for in terms of performance.

3.2 Development of MOLB type SOFC

With regard to the MOLB (MOno-block Layer Built) type SOFC, MHI developed a 5 kW class cell with 200mm x 200mm x 40 stages x 2 stacks in 1996 in collaboration with the Chubu Electric Power Company, Inc., achieving an output density of 0.23 W/cm^2. In 2001, MHI developed a train connection of MOLB type (T-MOLB) stack, which was an improvement over the cell lamination method, and achieved a cumulative power generation time of 7 500 hours with a maximum output of 15 kW and an internal reforming operation time of 2 473 hours.

At the Aichi Expo held from March through September 2005, MHI carried out a verification test on a co-generation system, which was the first one of its kind in Japan, in the Wonder Circus Electric Power Pavilion. At the same time, MHI also exhibited the MOLB type SOFC as one of the power sources for the micro grid power network in a research project entrusted to MHI by NEDO, achieving a power generation output of 30 kW, which was the world's highest output for the planner type SOFC, with 100% internal reforming (**Fig. 7**).

In other projects, MHI has been developing a 200 kW class co-generation system, one of the largest ones in the world as the planner type, in a four-year project starting in 2004 as part of a research project also entrusted to MHI by NEDO.

The cell consists of a power generation stack made up of an active layer (fuel electrode / electrolyte / air electrode) that engages in a power generation reaction, an inter-connect for collecting current and connecting the different parts, gas sealing material, and a manifold that supplies fuel and air to the cell. **Fig. 8** shows the MOLB type SOFC stack. The active layer, which adopts a high-performance three-dimensional dimple shape manufactured with concavity and convexity, is made to function so as to secure a gas flow channel for both the fuel and air. This approach has also made it possible at the same time to construct a compact system. In addition, in order to make the module even more compact relative to the present 200 mm x 200 mm cell, MHI is pursuing the development of a larger cell with a larger size. **Fig. 9** shows the result of power generation tests on this large cell. The cell achieved an output of 2 kW at an electric current of 300 A, confirming that it is possible to realize higher output with this design.

MHI participated "Engineering development of thermally self-supporting module" project, a research project entrusted by NEDO in 2002. MHI started to carry out a heat cycle test on the module using a 200 mm x 200 mm cell with an output density of 0.35 W/cm^2, and an operation control method verification test. After obtaining data on the temperature follow-up properties of each component of the cell and module as well as on the control characteristics, MHI fabricated a 10 kW class module adopting a digital control system (DCS). The module structure was such that basic unit modules were cut out based on the conceptual design of a several hundred kW class module, and in consideration of the future need for scalability to larger capacities.

At present, MHI is implementing a study on a module structure for a 200 kW class co-generation system based on the results obtained from these various studies. The 200 kW class co-generation system is also aiming at the small-to-medium sized distributed power source markets. The performance goal to be achieved is a power generation efficiency (LHV) of 45% or higher and in an overall efficiency (LHV) of 80% or more.

Fig. 7 40-kW-class co-generation system for the Aichi Expo
Exhibited as one of the power sources for the microgrid power network in a research project entrusted to MHI by NEDO at the Aichi Expo.

Fig. 8 MOLB type SOFC stack
200 mm x 200 mm power-generation stack made up of active layer, interconnect, gas sealing material, and a manifold.

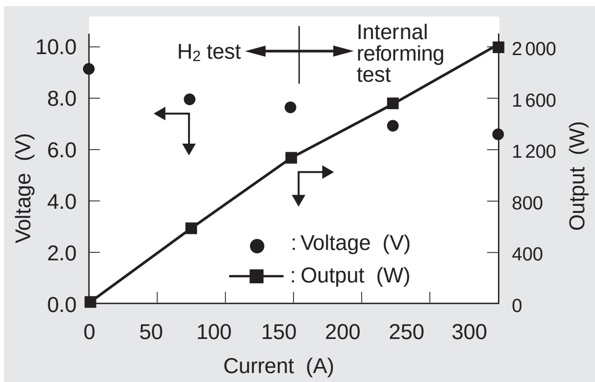

Fig. 9 Result of power generation test on large cell
An output of 2 kW was achieved with an electric current of 300 A.

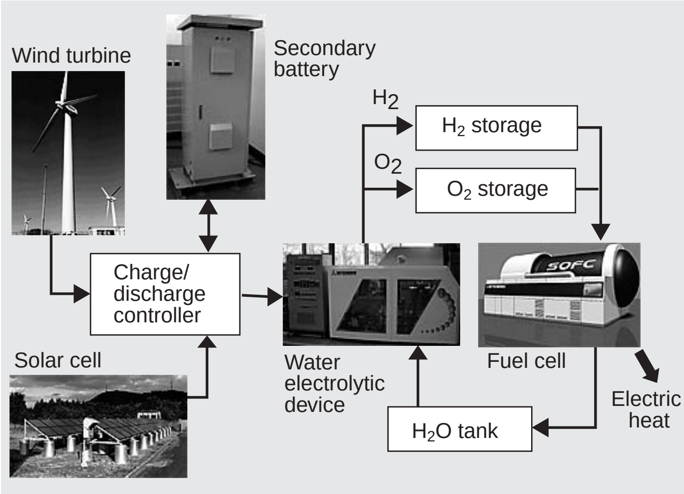

Fig. 10 Example of configuration of clean combined power generation system
A fuel production system and power generation system built with a renewable energy supply system.

3.3 Efforts toward practical application

Up to now, MHI has pursued development of SOFC at a stead pace. MHI now believes that it has approached a stage where it should work on engineering verification of SOFC as a power generation system and on product commercialization for widespread use.

As a replacement model for large thermal power plants in the future, a combined cycle power generation system that combines SOFC, gas turbine and steam turbine technology from which high efficiency can be expected is just the ultimate SOFC product concept that MHI should aim for. However, when also taking into account mass production and other systems required for realizing effective SOFC manufacturing facilities at the initial stage of development, MHI is looking at a market which it can enter, first of all, with small systems. Further studies would also be carried out of how best to improve the efficiency of existing facilities, while at the same time also exploring the feasibility of cultivating markets for atmospheric pressure systems and promoting their widespread use.

Combined cycle power generation systems that combine natural gas-fired, several hundred MW class SOFCs together with gas turbines and steam turbines can be expected to achieve new power generation efficiencies of 70% or more, well positioning them as a model to replace large thermal power plants in the future. Furthermore, MHI also expects to achieve net power generation efficiencies of 60% or more with combined cycle power generation systems that combine a several hundred MW class coal gasifier (IGCC) using coal as fuel, SOFCs, gas turbines, and steam turbines. In the future, MHI intends to establish an effective process for systematizing these various technologies at an early stage and to push forward vigorously towards product commercialization.

4. Conclusion

Given the urgent need today to reduce CO2 emissions, practical application of high efficiency power generation systems utilizing fossil fuels is expected in the short term, while in the longer term, the practical application of clean combined cycle power generation systems (**Fig.10**) is expected. A clean combined cycle power generation system can be built by combining systems that supply renewable energies, such as solar energy and wind power. Such systems would support the needs of an ever more energy oriented society after fossil fuels have been depleted. Such systems would include a water electrolytic device that is a fuel production system which makes it possible to store energy in the form of hydrogen, and a fuel cell that is a system capable of generating power on demand as it is needed.

MHI has already commercialized wind turbines and solar cells. MHI is also working to establish the technology and carry forward early product commercialization of fuel cells and water electrolytic devices. MHI strongly feels that the introduction of such technologies can significantly contribute to facilitating the establishment of an energy oriented and environmentally friendly society in the 21st century.

Finally, these product technologies and expertise have been fostered and accumulated in the course of various entrusted research or joint research projects undertaken by MHI and other interested parties. MHI would like to take this opportunity to express its deepest gratitude to all parties who have entrusted these research projects to MHI and to the many parties who carried out or cooperated in research and development projects jointly with MHI.

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Tadashi Gengo


Yoshinori Kobayashi


Nagao Hisatome


Shingo Kanehira


Yoshimasa Ando