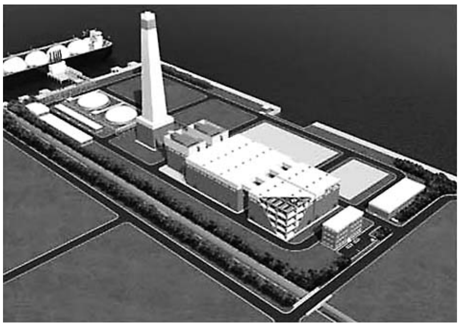

Development of SOFC for Products

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Mitsubishi Heavy Industries, Ltd. (MHI) succeeded for the first time in Japan in 1990 in electric power generation with a 1 kW module of domestic SOFC using tubular type SOFC. MHI achieved continuous generation of electric power for 7 000 hours using a pressurized 10 kW module in 1998. In MOLB type, MHI succeeded in generating 15 kW electric power for a total generation time of 7 500 hours in 2000 using 3 pieces of 200 mm x 200 mm x 100 cells stack. Thus, the MHI SOFC is on the way to technical verification and commercialization as a power generation system. We are currently developing the atmospheric pressure 50 kW type, the MOLB type cell closest to the stage of commercialization. In the tubular type modules, development is under way for the pressurized 100 kW unit. We are also planning a micro-gas-turbine (MGT) and a hybrid system aiming at a combined cycle power system.

1. Introduction

As fuel cells do not involve combustive reaction and can generate power directly from the fuel, and compared with the conventional power generating systems using fossil fuels, the fuel cells are highly efficient and friendly to environment; their development is promoted both in Japan and overseas. Among many of such cells, the Solid Oxide Fuel Cell (SOFC) has high power generation efficiency, high working temperature and allows effective utilization of exhaust heat, and is therefore expected to be applied widely for small-scale capacity to large-scale capacity.

MHI has been making joint study on tubular type SOFC with Electric Power Development Co., Ltd since 1989, and on MOLB (MOno-block Layer Built) type SOFC with Chubu Electric Power Co., Inc. since 1990. In 1992, MHI was entrusted with the research and development of SOFC, a national project, by the New Energy and industrial technology Development Organization (NEDO).

This paper describes the details of the research and development so far made in this field and the activities thereof for SOFC commercialization.

2. Aim of SOFC Development

Although various fuel cells have been developed as shown in the **Table 1**, the SOFC, with its operating temperature standing somewhere at 1 000 °C, ensures

Table 1 Comparison of basic features of various fuel cells

Type of fuel cell	Fluid electrolyte type fuel cell		Solid electrolyte type fuel cell	
	Phosphoric Acid Fuel Cell (PAFC)	Molten Carbonate Fuel Cell (MCFC)	Solid Oxide Fuel Cell (SOFC)	Polymer Electrolyte Fuel Cell (PEFC)
Electrolyte	Phosphoric acid (fluid)	Molten carbonate (fluid)	Fully-stabilized zirconia (solid)	Polymer membrane (solid)
Conductor ion	H^+	CO_3^{2-}	O^{2-}	H^+
Working temperature (°C)	150–200	600–650	900–1 000	20–100
Reactive substance	Hydrogen	Hydrogen, CO	Hydrogen, CO	Hydrogen
Fuel	Natural gas, methanol, LPG, naphtha and kerosene	Natural gas, methanol, LPG, naphtha, kerosene and coal	Natural gas, methanol, LPG, naphtha, kerosene and coal	Natural gas, methanol, LPG, naphtha and kerosene
Electrode	Porous carbon (platinum catalyst)	Porous nickel, etc. (platinum catalyst not needed)	Nickel oxide, etc. (catalyst not needed)	Porous carbon (platinum catalyst)
Feature	Use of platinum catalyst, With limited CO content	Inclusion of CO allowed, Internal reformation of fuel possible	Inclusion of CO allowed, Internal reformation of fuel possible	Strict limitation of CO content, Low working temperature
Main applications	Cogeneration, Distributed generation	Cogeneration, Distributed generation, Large scale power plant (substitute for thermal power plant)	Cogeneration (With higher Power/Heat ratio), Distributed generation (medium - large capacity), Large scale generation (substitute for thermal power plant)	Cogeneration, Distributed generation (small - medium capacity), Portable power supply

high-efficiency power generation system through effective utilization of exhaust heat. First of all, the SOFC + heat recovery system in **Fig. 1** enables recovery of higher quality steam, ensuring net power generation efficiency of 45% (same as below the LHV <Lower Heating Value>) and overall efficiency of 80% for a town-gas fired 50 kW class system. In the case of SOFC + gas turbine system as shown in **Fig. 2**, the net power generation efficiency for natural-gas fired 20 MW-class plant is 60%, making it a suitable power plant for inland areas where boiler water and cooling water are not easily available. Further, in the case of a combined cycle power system of SOFC + gas turbine + steam turbine as shown in **Fig. 3**, the net power generation efficiency for natural-gas fired 700 MW-class plant can be expected to be as high as 70%.

In the case of a combined cycle power system of coal gasifier + SOFC + gas turbine + steam turbine as shown in **Fig. 4**, the net power generation efficiency of 60% can be expected.

In this way, since SOFC is expected to ensure high power generation efficiency in a wide range of capacity from small and medium capacity to large capacity as a substitute for thermal plant, using various fuels from natural gas to coal, MHI has engaged itself in the development program for commercialization of the SOFC.

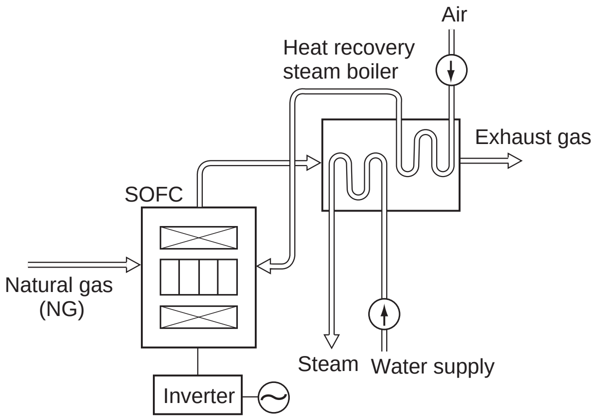

Fig. 1 SOFC + Heat Recovery System
Indicates the co-generative system composed of SOFC and heat recovery.

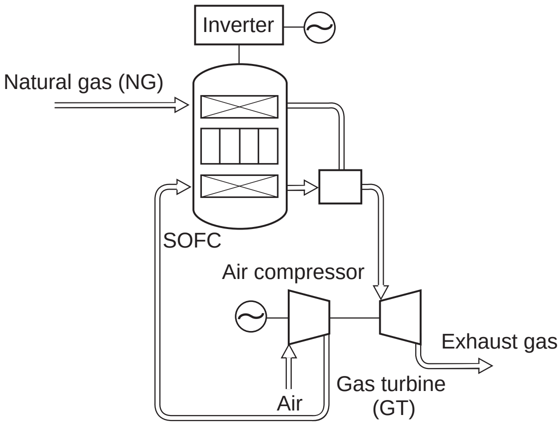

Fig. 2 SOFC + Gas turbine System
A power generation system for inland use, a system using only SOFC and gas turbine and needing no cooling water

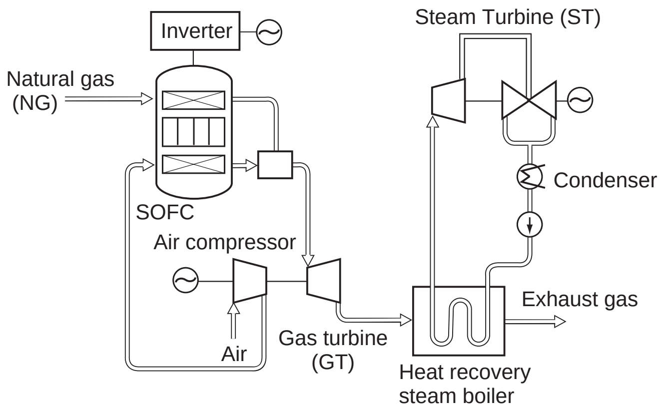

Fig. 3 Combined Cycle Power System of SOFC + Gas turbine + Steam Turbine
SOFC is installed as a topping to the gas turbine combined cycle power plant to ensure power generation efficiency of 70% LHV.

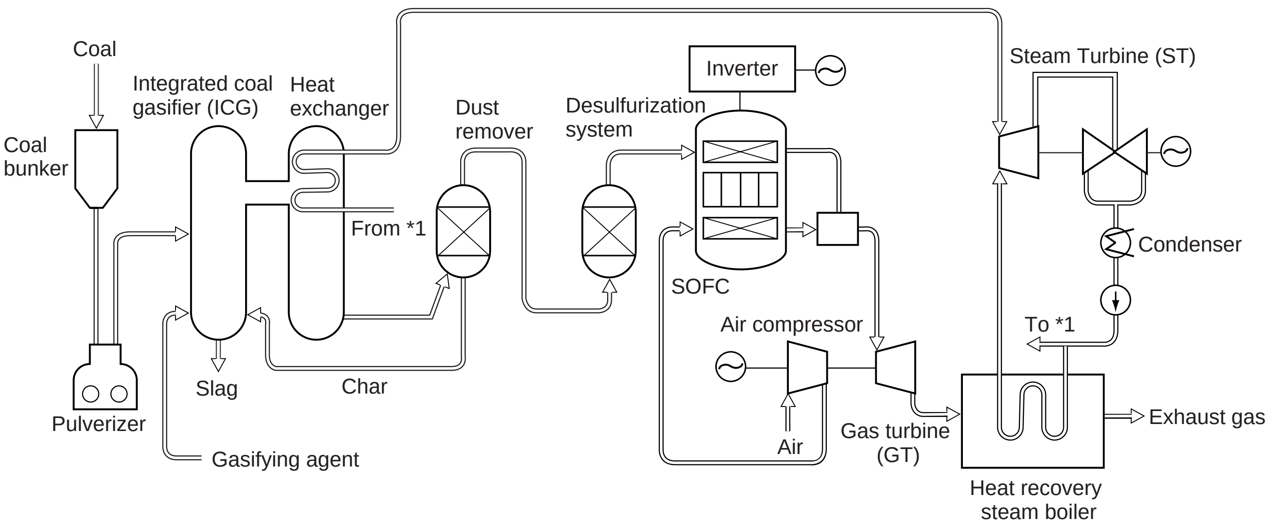

Fig. 4 Combined Cycle Power System of Coal Gasifier + SOFC + Gas Turbine + Steam Turbine
Ensures power generation efficiency of 60% LHV, the highest of a coal-fired power generation plant

3. State of Development

3.1 Tubular type SOFC

The tubular type SOFC is composed of the fuel electrode, the electrolyte and the air electrode laminated to the surface of a tubular ceramics tube (substrate), and several such cells are arranged on the substrate through the electro-conductive inter-connector. (**Figs. 5** and **6**). The cell is manufactured by drying the extruded substrate before successively printing the slurry of ceramics (the cell raw material) dissolved in solvent on the surface of the substrate, with the slurry as well as the substrate subjected to baking at 1 400 °C. Since the cell unit including the substrate gets shrunken at the time of baking by 30%, the development of SOFC calls for high performance of materials as well as optimization of materials, cell structure and manufacturing method in order to ensure uniform expansivity.

The tubular type SOFC succeeded for the first time as a domestic made SOFC in power generation using a 1 kW class module in 1990, and in 1995 a continuous power generation for 5 000 hours was carried out using an atmospheric pressure 10 kW module. MHI further carried on development of pressurization technology indispensable to a hybrid system with the gas turbine, achieving success for the first time in the world in continuous power generation for 7 000 hours using a pressurized 10 kW module in 1998.

The fuel electrode in SOFC is composed of nickel having the function of reforming catalyst (for steam reforming) for methane gas. This results in simultaneous occurrence of the methane reforming reaction, i.e., the endo-thermal reaction and the power generating reaction of the cell, i.e., the exothermal reaction in the cell unit (internal reforming), needing no installation of a separate reforming device, thus contributing to a drastic simplification of the system and improvement in power generation efficiency. MHI worked on the development of internal reforming technology and tested its pressurized internal reforming 10 kW module in 2001.

The specifications and the appearance and structure of the module are given respectively in **Table 2** and **Fig. 7**. A tubular vertical type pressure vessel was used as the module container; with the internal structure composed of a fuel feed chamber, a fuel exhaust chamber, a reaction chamber and an air preheater.

Fig. 8 shows the result of continuous operation of a pressurized internal reforming 10 kW module in EPDC Wakamatsu Site. The module output of 10.2 kW and the system power generation efficiency of 45.6% were achieved, with the module brought to a planned stop after a continuous internal reforming power generation for 755 hours.

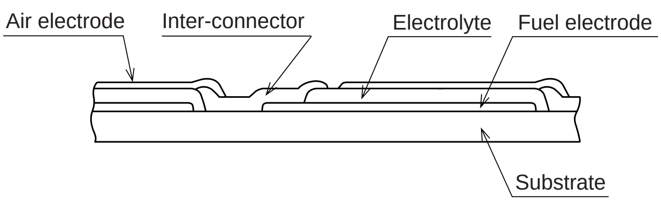

Fig. 5 Tubular Sintering Type SOFC Cell Tube Structure
Indicates the sectional structure of tubular sintering type SOFC

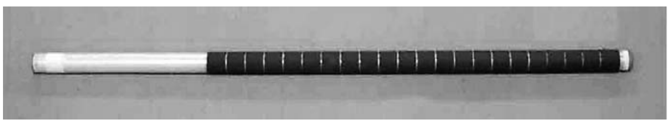

Fig. 6 Appearance of Tubular Sintering Type SOFC Cell Tube
Shows the photograph of the external view of the tubular sintering type SOFC, with the cells (section in black color) arranged in series.

Table 2 Specifications for Pressurized Internal Reforming 10 kW Module

Type	Tubular type
Operating temperature (°C)	900
Operating pressure (MPa)	0.39
Fuel	Natural gas
Power (kW)	10
Power generation efficiency (LHV) (%)	≧45

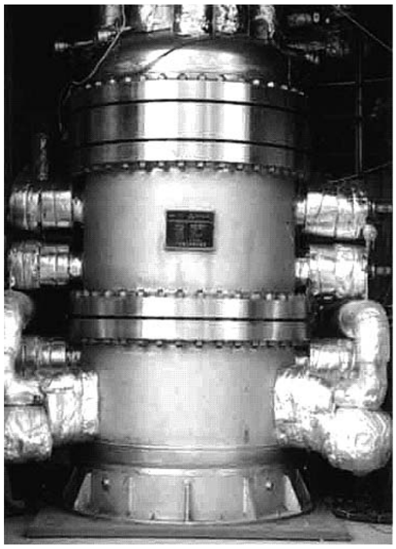

Fig. 7 Appearance of Pressurized Internal Reforming 10 kW Module

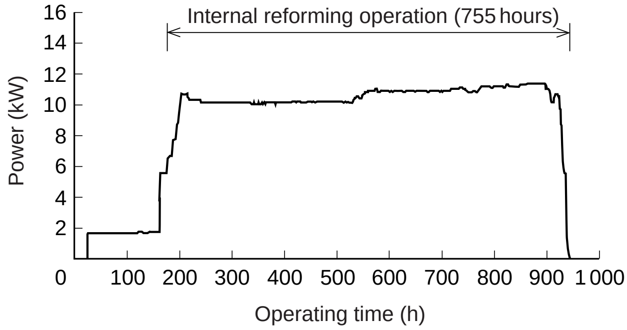

Fig. 8 Result of Pressurized Internal Reforming 10 kW Module Operation: Continuous operation for 755 hours with methane reformation using internal heat generation

3.2 MOLB (MO no-block Layer Built) type SOFC

Fig. 9 shows the structure of the MOLB type SOFC, with the cell composed of active layer (fuel electrode/electrolyte/air electrode), inter-connector to connect the active layer in series and seal material to seal the gas in the cell terminal. The acitve layer is molded unevenly in three-dimensional dimple shape to ensure the effective power generation area twice as large as the projected area. Further, the dimple structure of the active layer itself provides the film with the combined function of fuel and airflow path, making the cell compact.

Initially the MOLB type SOFC was composed of plane active layer instead of the dimple structure. In 1992, MHI succeeded for the first time in the world in generating 1 kW class power using planner type SOFC by using 3 pieces of 150 mm x 150 mm x 40 cells stack. Later, we launched development program on large-size cells and dimple structure. In 1996, MHI was successful in generating 5.1 kW power, the highest level of power so far generated by a planner type SOFC in the world, by using 2 pieces of 200 mm x 200 mm x 40 cells stack. MHI further developed the combination type cell (T-MOLB type) shown in **Fig. 10** in order to enable easy multi-layer lamination, which is indispensable to manufacturing large-capacity cells. MHI was successful for the first time in the world in the field of planner type SOFC in generating 15 kW power by using T-MOLB type SOFC with 3 pieces of 100 cells stack in 2000, with the total power generation time being 7 500 hours (including atmospheric pressure internal reforming power generation for 2 473 hours).

MHI has been promoting development of "thermally self-supporting module" since 2001, when MHI together with Chubu Electric Power Co., Inc. was jointly entrusted by NEDO with the "development of 10 kW class module", a national SOFC project, aiming at the development of a practical (commercial) unit.

The fuel cell generates heat at the time of generation reaction, and needs to be cooled in order to maintain the reaction temperature of the cell. However, since excessive cooling results in the failure of keeping the reaction temperature, it is indispensable to establish an air cooling system. The "thermally self-supporting module" refers to a module structure including the startup, operation and shutdown temperature control. The appearance of the module is shown in **Fig. 11**. The module, equipped with 200 mm x 200 mm x 100 cells, was put to verification test in fiscal year 2002 for startup, operation, shutdown operations, with the test results given in **Fig. 12**. In fiscal year 2003, we are planning to conduct power generation test on the newly developed 10 kW class module.

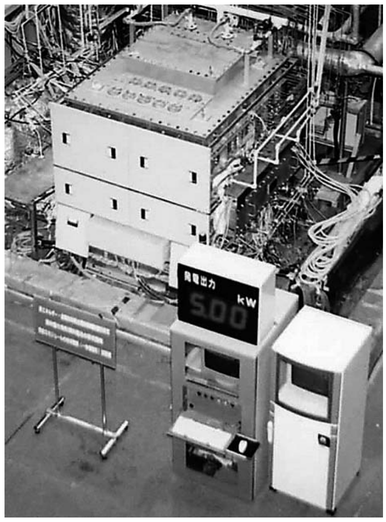

Fig. 11 Appearance of "Thermally Self-supporting Module"
Shows the photograph of the external view of the several dozens kW class test power generation system

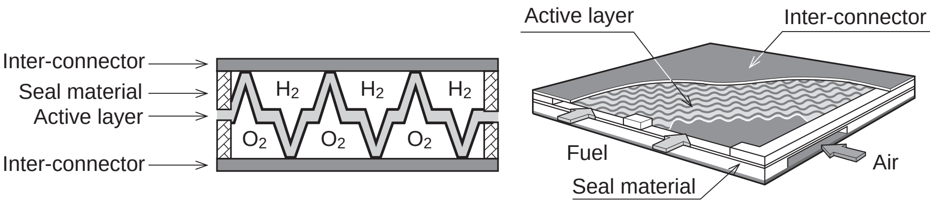

Fig. 9 Structure of MOLB Type SOFC
Indicates the appearance and sectional structure of MOLB type SOFC

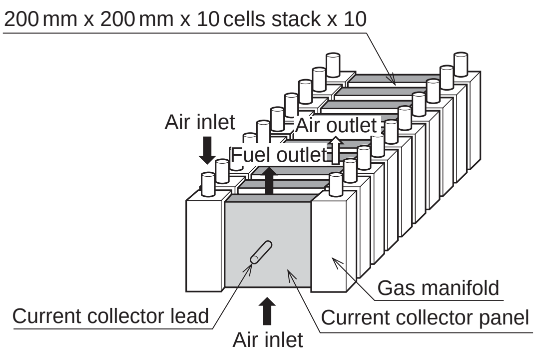

Fig. 10 Structure of MOLB Type SOFC
Shows MOLB type SOFC with 10 pieces of 200 mm x 200 mm x 10 cells arranged in train type

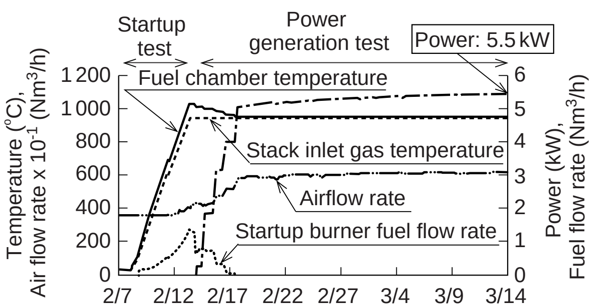

Fig. 12 Test Results of "Thermally Self-supporting Module"
Indicates the verification results of automatic operation during test of 5 kW class power generation

4. Activity for Commercialization

As mentioned above, until the last fiscal year MHI had been engaged in the development of the SOFC cell unit and had been developing module structure with built-in cell for power generation and current collection. We have at last come to the stage to strive for technical verification and commercialization of the cells as a power generation system. We are presently engaged in the development of the MOLB type atmospheric pressure 50-kW unit which is closest to commercialization. The first commercial unit as a co-generator is planned to be launched in the market in the next fiscal year. The specifications and appearance of the 50 kW unit are given respectively in **Table 3** and **Fig. 13**. Our future plan is to develop a high-efficiency unit ensuring power generation efficiency of 50%.

As for the tubular type SOFC, the pressurized 100 kW unit is under development, with a hybrid system through combination with micro-gas turbine (MGT) being planned, aiming at a combined cycle power system. In order to get a hybrid system of SOFC and MGT, it is necessary to extract the air almost entirely from the outlet of MGT air compressor before feeding the air back to the combustion chamber through SOFC, and to burn a low-calorie gas as a fuel after the reaction in SOFC, so that the existing MGT cannot be used as it is. Further, the MGT available in the market is hard to reform the structure so as to be applicable to SOFC. Thus, we are thinking of a hybrid system with the MGT currently being developed by MHI, in which case the net power generation efficiency of 57% can be expected by using a 400 kW class system. The image diagram of the system is shown in **Fig. 14**. The SOFC is installed inside a cylindrical vessel, with the cabinet containing MGT and control system arranged in the side.

Since fiscal year 2001, MHI has been engaged in improving the power of the cell itself as a part of the NEDO's national project "Development of advanced Tubular Type SOFC." If the power of the cell itself is improved, it will be possible to generate a power of 1 MW using only one unit of SOFC module. A hybrid system made up of several dozen units of 1 MW modules and MHI's 10-MW class gas turbine "MF-111" (**Fig. 15**) can probably be verified to ensure a 50 MW power plant with the net power generation efficiency 65%. The image diagram of this system is shown in the title figure. The SOFC module is built indoors.

5. Conclusion

With the power generating temperature in SOFC reaching 1 000 °C, a lot of time was needed to improve the material, structure and manufacturing method of the cell itself in addition to the piled-up problems such as upgrading the scale of the cell, development of module vessel, and other technical problems. However, the prospects for the commercialization are at last well on the way to realization. We are determined to establish the systematization technology in an early date in the future to move forward toward commercialization of the system.

Finally, we would like to express our heartfelt gratitude to all concerned people since MHI's technology for SOFC development has been obtained through the joint research with Electric Power Development Co., Ltd. and Chubu Electric Power Co., Inc. under NEDO's national SOFC project.

Table 3 Specifications for Atmospheric Pressure MOLB Type 50kW Unit

Power (kW)	50
Power generation efficiency (LHV) (%)	45
Overall efficiency (LHV) (%)	80
Fuel	Town gas

Fig. 13 Appearance of Atmospheric Pressure MOLB Type 50 kW Unit
Shows the external view of the atmospheric pressure MOLB type 50 kW SOFC unit

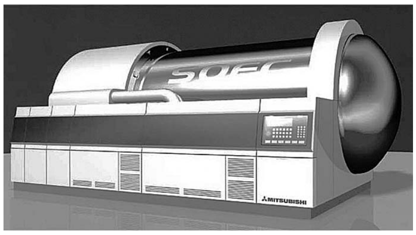

Fig. 14 Appearance of 400 kW Class SOFC + MGT System
Indicates the external view of the 400 kW class system using the tubular type SOFC

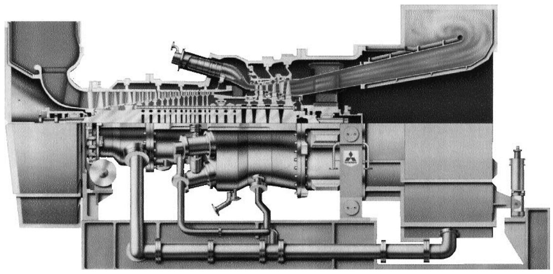

Fig. 15 10 MW Class Gas Turbine (MF-111)
Indicates the structural diagram (photograph) of the MHI 10 MW class gas turbine MF-111


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