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1,000 kW PHOSPHORIC ACID FUEL CELL POWER PLANT (MOONLIGHT PROJECT)

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1. INTRODUCTION

The research and development of a 1,000 kW phosphoric acid fuel cell power generation system has been promoted from 1981 as a part of "Moonlight Project" by New Energy Development Organization.

In the meantime, Fuji Electric Co., Ltd., Fuji Electric Corporate Research and Development Ltd. and Mitsubishi Electric Corp. were jointly entrusted with "the research and development of the dispersedly located type fuel cell system," and we completed the design, manufacture and installation of the equipment in 1985. We started test operation with a dummy stack in place of the fuel cell in May, 1986 to confirm the performance of the natural gas reformer unit and the adjustment and safety of the plant control and protection.

Then, we carried out power generation tests with the cell connected and succeeded in the first 1,000 kW generation with a domestic product in September, 1987. At present, the plant is under aging characteristic tests and provisional tests for the official witness test. The environmental measurement of NO_x and noise carried out during the operation test proved that the plant satisfied the target values. This article gives an outline of the principal design specifications of the plant and the results of the tests.

2. PRINCIPAL SPECIFICATIONS OF THE POWER PLANT

2.1 Basic configuration of the plant

Fig. 1 shows the basic flow diagram of the 1,000-kW phosphoric acid fuel cell power plant.

The plant consists of five principal subsystems: a natural gas processing subsystem where natural gas produces hydrogen necessary for reaction in the cell by adding steam, fuel cell stacks which produce electricity, inverter units which convert the DC produced in the cell into commercial frequency AC, an air subsystem which supplies reactant oxygen, i.e. air, by means of turbocompressors, and a water/steam subsystem which consists of a steam separator for the supply of steam for natural gas reforming and water treatment equipment for the supply of high-purity demineralized water for cell cooling.

2.2 Basic specifications of the power plant

The fuel cell power generating system has well-known features as follows:

1. High-efficiency power generation of 40 to 50%
2. High environmental accessibility owing to low NO_x and noise.
3. The ratio of electric output and exhaust heat is nearly 1 suitable for cogeneration, and the overall efficiency is as high as about 80%.
4. Less limitation of location due to no need of a large supply of cooling water.

Table 1 shows the actual design target of the 1,000 kW power plant.

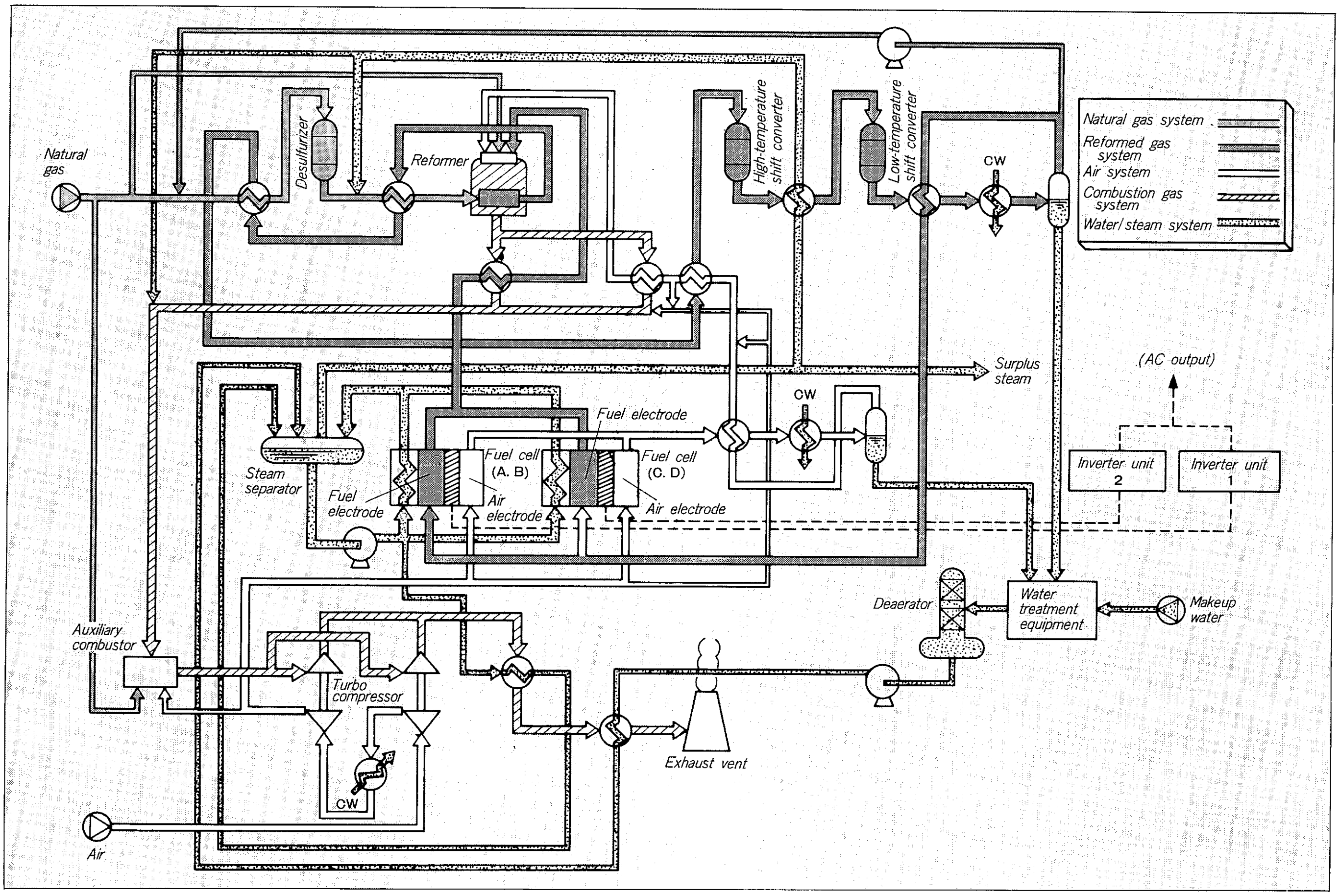
2.2.1 Fuel cell

The 1,000 kW fuel cell consists of four 260-kW DC

Table 1 Design target of the low-temperature low-pressure demonstration plant

Item	Object
(1) Electric output	1,000 kW (AC output)
(2) Gross generation efficiency	40% or more, (Higher heat value base)
(3) Cell operating pressure/ temperature	4 kg/cm²G 190°C
(4) Operating mode	Full automatic operation (manned monitoring)
(5) Inverter	Self-excitation
(6) Fuel	Natural gas (equivalent to city gas)
(7) Cell cooling method	Water cooling
(8) Exhaust heat	Not recovered
(9) Starting time	4 h (Cold start)
(10) Load follow-up characteristics	25% to 100% within 1 min
(11) Environmental conditions	NO_x<20 ppm SO_x<0.1 ppm Noise<55 dB (at the plant boundary)
(12) Plant shutdown time	1 h Within 1 min for emergency fuel stop
(13) Expected life	40,000 h

Fig. 1 Basic flow diagram of the 1,000 kW phosphoric acid fuel cell power plant



output stacks. Each two stacks connected in series generate 520 kW DC output, which is converted into 500 kW AC output by the inverters connected to the cell.

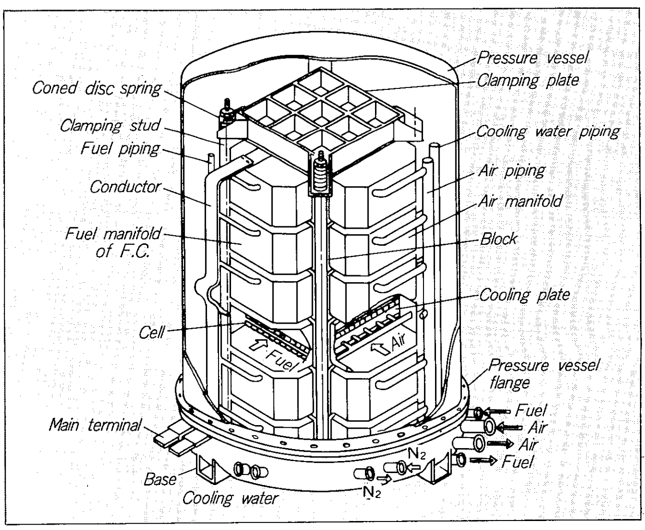
The fuel processing system and the air system are single each; fuel or air is distributed into each stack by the control valves at the cell inlet. The cooling water system is also single; cooling water sent from a steam separator by a fuel cell cooling water circulating pump flows through the cooling pipes into the four stacks in parallel and returns to the steam separator. The specifications of the fuel cell is as follows:

Type	: Phosphoric acid electrolyte fuel cell
Rated output	: 520 kW DC (two 260 kW stacks; the other two were made by Mitsubishi Electric.)
Rated voltage	: 680 V DC
Rated current	: 765 A DC
Operating pressure	: 4 kg/cm^2·G
Operating temperature	: 190°C
Cooling method	: Water cooling
Vessel	: Vertical cylinder nitrogen filled type

The configuration of the fuel cell stack is shown *Fig. 2.* The features of the configuration are outlined below.

(1) Stack

Fig. 2 Configuration of the fuel cell stack



The rated output of a fuel cell stack is 260 kW. The stack is housed in a pressure vessel as shown in *Fig. 2.* The pressure vessel is 1.7 m diameter, 1.8 m in height, and can be disassembled into three parts longitudinally.

(2) Block

For the purpose of making stack assembly easy, stacking the cells fully checked for characteristics, and enabling uniform reactant gas distribution, the cells in the stack are divided into six blocks.

Fuel manifolds and air manifolds for distributing reformed gas and reactant air uniformly into cells are mounted on the sides of each block with seals inserted, so that each block can be put to various operation tests individually.

(3) Catalyst

For high activation of electrode with a minimum quantity of catalyst, we have developed high specific surface, corrosion-resistant platinum-base catalyst supported by acetylene black.

(4) Electrode and matrix

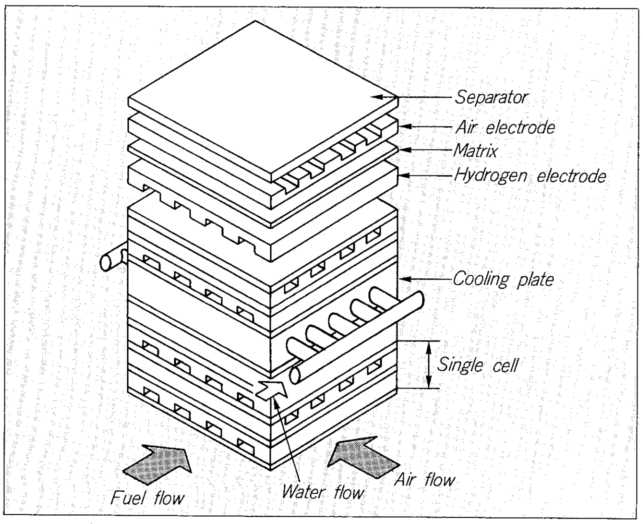
The construction of the electrode is of a ribbed electrode is of a ribbed electrode type because it can realize larger area (in the 3,600 cm^2 class) and has high phosphoric acid retaining capability. The ribbed electrode is a porous carbon plate of high gas permeability with gas passing grooves on one side and with a catalyst layer formed on the other side. Reformed gas and reactant air flow at right angles to each other. *Fig. 3* shows the configuration of the fuel cell.

The electrolyte matrix is a porous film made of SiC by means of fluororesin. The separator is used for preventing reformed gas and reactant air from mixing and is made of glassy carbon which is superior in nonpermeability to gas, corrosion resistance to phosphoric acid, electric conductivity, thermal conductivity, and strength.

(5) Cooling plate

It is desired that the temperature distribution should be as uniform as possible to operate the fuel cell for long time at high efficiency. For this purpose, cooling plates are inserted every five cells to keep temperature difference low in the stacking direction and on the cell surface. The cooling plate is made of a sintered carbon plate from the viewpoint of thermal resistance, thermal expansion, heat-resisting property, and corrosion resistance, and has a stainless tube with phosphoric acid resistant coating buried inside.

Fig. 3 Configuration of the phosphoric acid fuel cell



2.2.2 Reformer

The reformer for the phosphoric acid fuel cell power generating systems is different from that for chemical industry in the following points:

1. Good follow-up characteristics to load change
2. High environmental accessibility
3. Compactness particularly for on-site use
4. Use of fuel cell exhaust gas as fuel

The reformer was developed on the basis of the results of pressurized combustion tests of burners and dynamic characteristic tests with a small-scale system. *Fig. 4* shows the section of the reformer in the 1,000 kW class.

(1) Burner

The burner has to burn lower heat value fuel (about 1,000 kcal/Nm^3 at L.H.V. base) with low-concentration-oxygen air (about 9%) at a comparatively lower air ratio to be stably in a wide range of combustion.

We adopted the circular burner which showed good combustion stability during the preceding elementary research. *Fig. 5* shows the burner portion of the reformer unit.

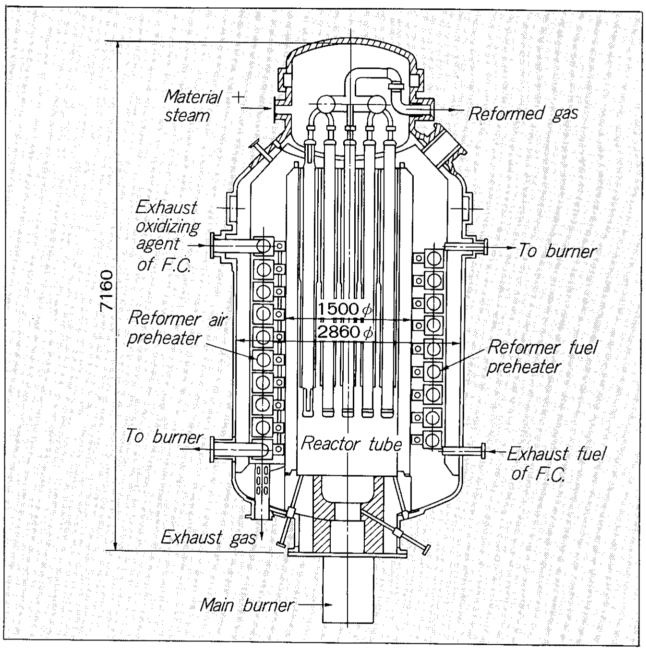
(2) Material of the reformer tubes

The material of the reformer tubes has been selected to be excellent in high-temperature strength, especially in creep rapture strength to withstand the high tube surface temperature of about 1,000°C. The centrifugally cast tube HK40 is widely used in the petroleum and petrochemical industries and officially qualified. Considering the experiences in the past fuel cell power generating systems together with the above, we decided to adopt HK40.

(3) Thermal insulation material

The heat capacity of the combustor had to be as

Fig. 4 Reformer in the 1,000 kW class



small as possible to make starting time shorter and to make load follow-up speed higher. To meet these requirements, ceramic fiber type material was used for thermal insulation.

The principal specifications of the reformer are as follows:

(1) Type : Vertical vessel, external firing type

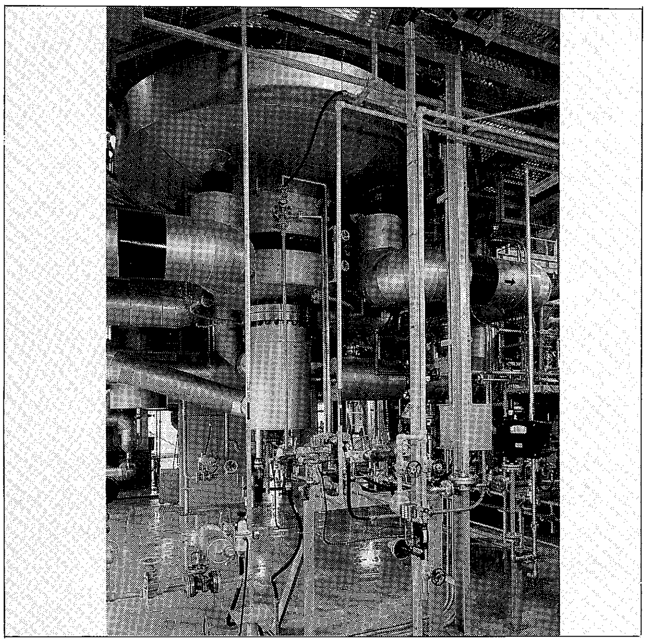
(2) Burner : Bottom firing, premixed fuel, forced ventilation type

(3) Fuel : Natural gas and fuel cell exhaust gas

(4) Preheater : Built-in fuel and air preheater

The other features are reactor tube monitoring in the vessel with a fiberscope and burner combustion monitoring with an ITV. Tube surface temperature and catalyst layer temperature are also monitored. A rapture disk and combustion gas detector as well as a safety valve are equipped to secure full safety even if combustion gas leaks.

Fig. 5 The reformer unit



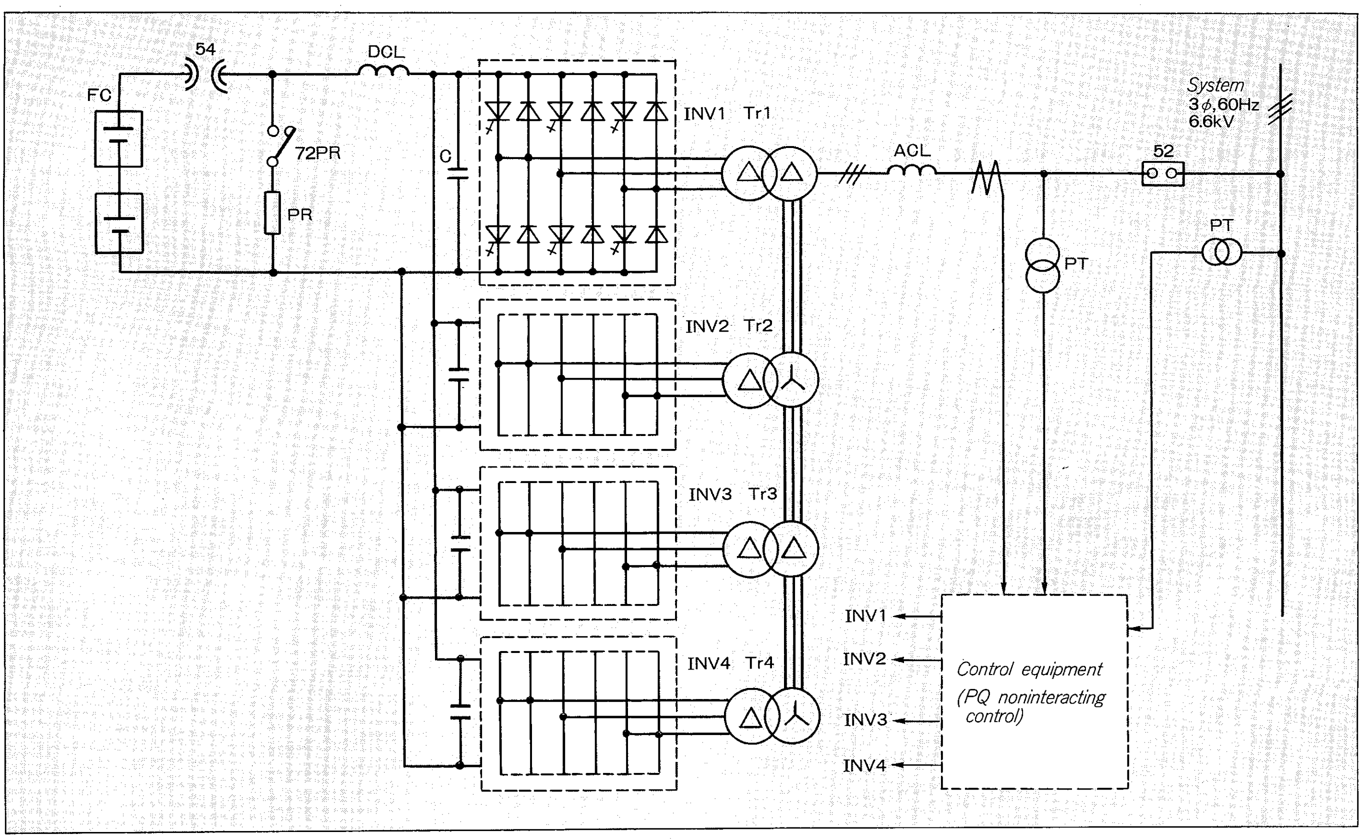
2.2.3 Inverter unit

The inverter unit, as the interface of the fuel cell and power system, has to follow up the voltage drooping characteristics of the fuel cell and system fluctuation and

Table 2 Specification of the inverter unit

Item	Specification/characteristics
Type	GTO inverter air-cooled, indoor
DC input	520 kW
AC output	3-phase, 6.6 kV, 60 Hz, 500 kVA
Efficiency	96% (at rated output)
Distortion factor	Each harmonic 1%, overall 2%
Operation	(1) Individual operation · Constant voltage control (5.0%) · Constant frequency control (0.5%) (2) Interconnecting operation · Effective power control (25–100%) · Reactive power control (±100%)

Fig. 6 Basic configuration of the inverter unit



to have less reactive power and harmonics in output. We have developed a quasi-24 phase, phase-controlled voltage type GTO inverter for the purpose. The principal specification of the unit is shown in *Table 2*, and the basic configuration, in *Fig. 6*. The DC power generated in the fuel cell is conducted to the inverter through a DC high-speed circuit breaker for protection against cell short circuit and through a DC smoothing circuit composed of a DCL and capacitors for limiting cell current pulsation.

The inverter, applying GTO thyristors, is composed of four 3-phase 180°C conducting voltage type inverter bridges commutated only once a cycle to reduce loss. These bridges are in pairs connected by a transformer on AC side to form two 12-phase inverters. Therefore, quasi-24-phase superposed AC output of the two 12 phase inverters is obtained with reduced higher harmonics. This superposed output is supplied to the power system through an ACL with necessary inductance for control, protection and higher-harmonics suppression and through an AC circuit breaker for system short-circuit protection.

2.2.4 Water treatment equipment

It supplies high-purity demineralized water for fuel cell cooling; the principal specification is as follows:

(1) Type : Cartridge ion-exchange resin
(2) Capacity : 1,648 kg/h
(3) Quality of outlet water : Electrical conductance < 0.1 $\mu S/cm^2$
TDS < 0.02 ppm
$SiO_2 < 0.02$ ppm
Dissolved oxygen < 0.1 ppm

Besides, there are a hot-water generator for startup steam supply, an exhaust vent (used also as a flare stack), a cooling tower, a nitrogen storing facility, an instrumentation air compressor, an fleon fire extinguisher, and hydrogen

Fig. 7 Basic layout of the plant

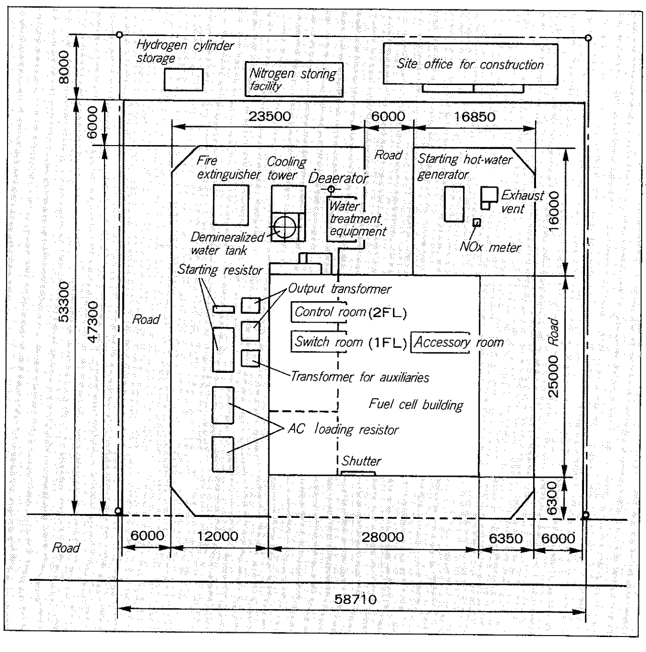
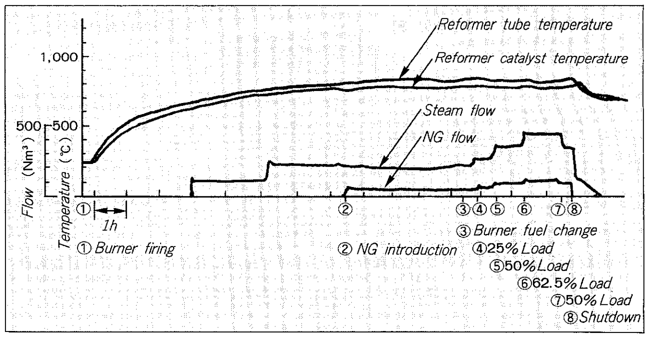


Fig. 8 Operating characteristic of the fuel processing sybsystem



cylinder storage. *Fig. 7* shows the whole layout.

3. PROVISIONAL OPERATION TEST

The installation, piping and wiring of all the equipment except the fuel cell had been completed by the end of April, 1986, and operation tests were started in the middle of May. During the construction, pipe-welding inspection and gestightness tests were carried out on key equipment, auxiliaries, and pipings. The substation equipment was subjected to official inspection on the withstand voltage test, insulation resistance test, phase check and so on, and was put to use.

In addition, a dummy cell in place of the actual fuel cell was used from May, 1986, to make adjustment of system control and protection and to carry out operation tests of the fuel processing, air, and water/steam subsystems. *Fig. 8* shows the operating characteristics of the fuel processing sybsystem.

The environmental measurement carried out at 90% load during the operation test showed a good result of 18 ppm computed in terms of 7% O_2 concentration as against the NO_x target value of 20 ppm.

4. OVERALL OPERATION TEST

After the provisional operation test, the fuel cells were shipped and installed in the Sakaiko PS site of the Kansai Electric Power Co., Inc. From the middle of January, 1987, overall inspection, complementary work, and gas permeability tests were carried out, followed by the power generation test. It includes the tests of air and gas introduction to the fuel cell, measurement of open circuit voltage and closing test of the DC resistor, closing test of the inverters and changeover test for cell exhaust gas application to the reformer burner, and also adjustment of automatic sequences and fuel cell differential pressure control.

From the middle of June to the beginning of August, 1987, 25% load was applied; then, load was gradually increased to 50% and to 75%. In the middle of September, 1,000 kW generation was achieved. Now operational research is continued to obtain data necessary for the future.

5. RESULTS OBTAINED FROM OPERATIONAL RESEARCH AND FUTURE SUBJECTS

The 1,000 kW power plant is now under operational research, and will successively be put to the tests of the aging characteristics of the fuel cell, the starting characteristic of the system, load follow-up characteristic and overall performance. This paper gives an outline of the results obtained from the overall operation test and operational research up to now and future subjects as well.

5.1 Fuel cell

(1) Initial characteristics

The target values for the current and voltage at 100% load is 200 mA/cm^2 and 0.7 V per cell. The actual average cell voltage at 100% load was 0.71 V. The voltage difference between cells was small enough. Also it was confirmed that the target overvoltage of not more than 0.8 V at low load was fully satisfied.

The insulation resistance of the fuel cell and the leakage of hydrogen and oxygen into the outlet gas and vessel did not exceed the allowable values.

(2) Cooling

The cooling method is water cooling, and was designed so as to apply two kinds of cooling: boiling water cooling in which partly vaporized water flows through the cell cooling tube (having an advantage of making temperature distribution flat) and pressurized cooling in which the temperature rise of cooling water cools the fuel cell. Both methods were tested and both were proved satisfactory for cell cooling.

(3) Differential pressure control

Since the blow-through of hydrogen and oxygen across the matrix will make fuel cell voltage lower and makes life shorter because of local heating, it is necessary to control electrode differential pressure in either normal or abnormal operation within 50 to 400 mmAq. Satisfactory results were obtained by controlling the control valves and shut-off valves equipped at the cell inlet and outlet. Further, water sealing was provided as a protection against excess differential pressure. It proved to be effective as a kind of safety valve. Future subjects are the researches into the voltage-current characteristic change with the passage of time and the timing and effect of phosphoric acid replenishment. *Fig. 9* shows the flow diagram of the fuel cell subsystem at 100% load.

5.2 Reformer unit

Since the reformer unit was put into operation in June, 1987, about 100 times startup and shutdown and about 1,200 hour operation have been achieved. At the start of the operation, we had some trouble in refractories breaking off, but no particular problem has occurred after improvement of the installing method.

(1) Composition of reformed gas

The planned composition of the reformed gas at the cell inlet at 100% load was hydrogen 76%, carbon monoxide 1% or less, and residual methane 2% or less, and the test result was as good as 77%, 0.2%, and 3.2%, respectively. Though the residual methane was a little excessive, it is not an obstacle to cell operation. The subjects from now on are the research into gas composition change at a sudden load change and the analysis of reforming performance. *Fig. 10* shows the flow diagram of the fuel processing subsystem at 1,000 kW generation.

(2) Starting time and load follow-up characteristics

Introducing natural gas for reforming requires the catalyst temperature of about 800°C. It takes about eight hours to raise temperature from the cold state. The starting

Fig. 9 Flow diagram of the fuel cell subsystem at 100% load

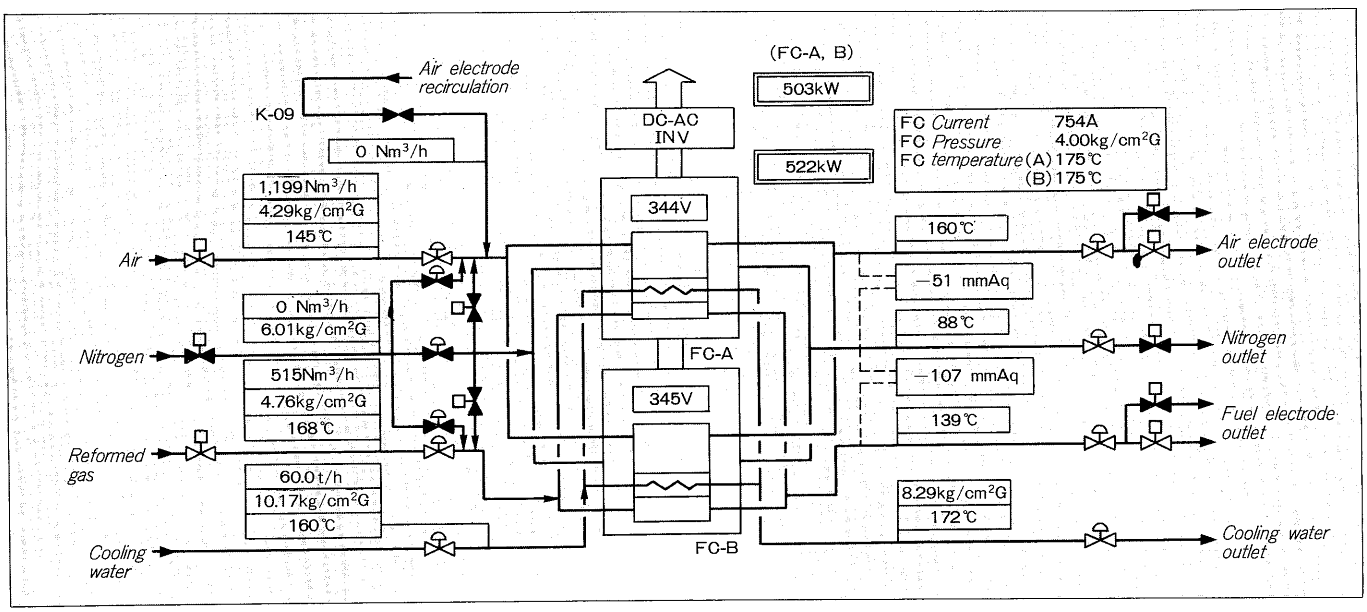


Fig. 10 Flow diagram of the fuel processing subsystem at 1,000 kW generation

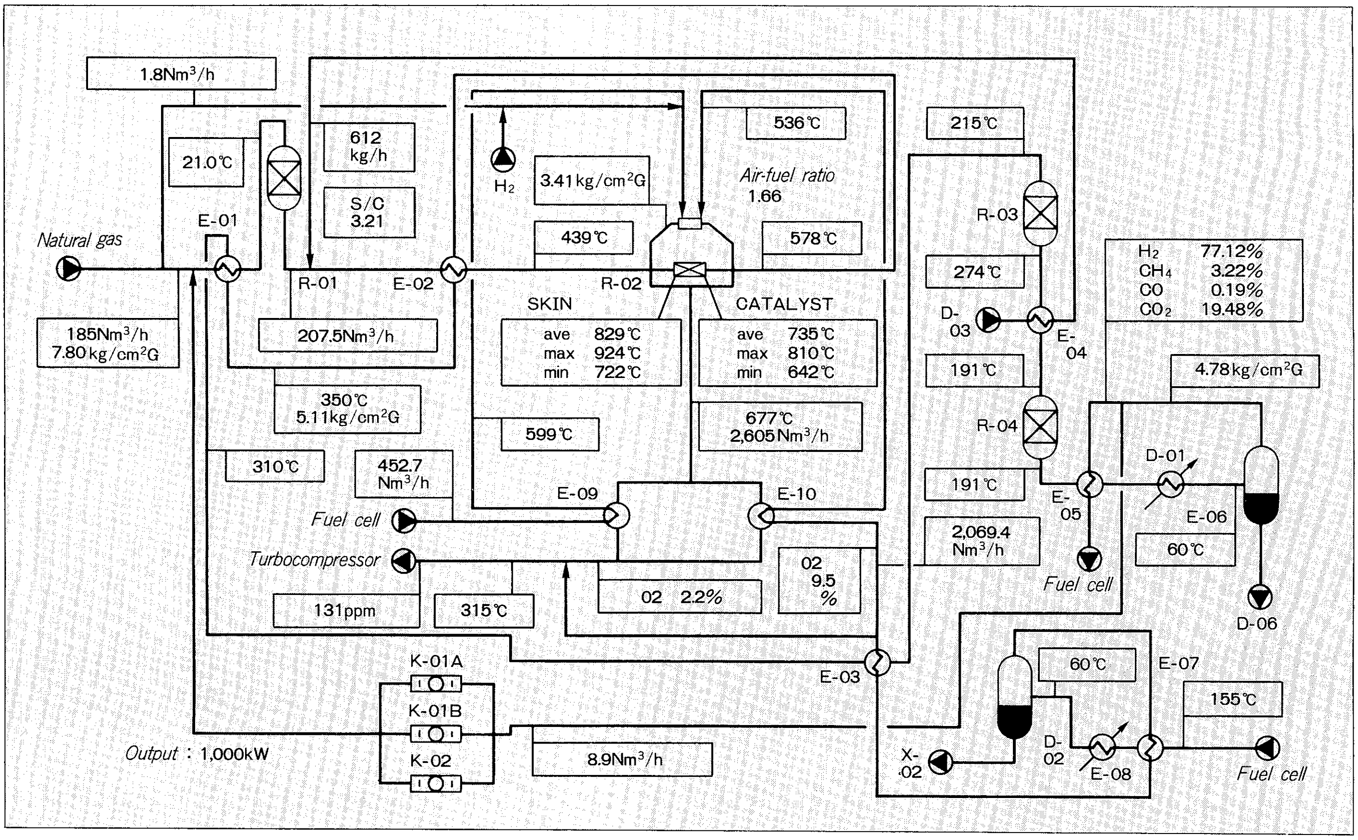
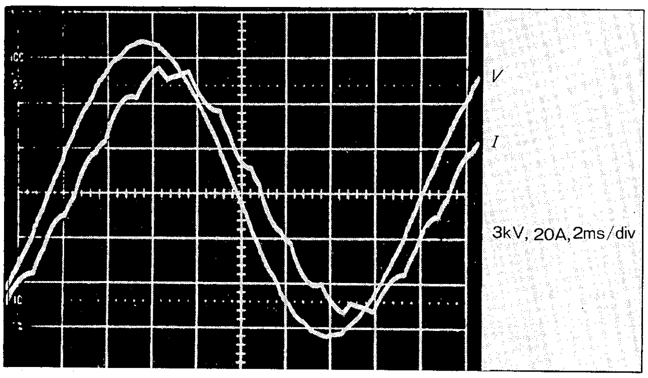


Fig. 11 Waveforms of the output line voltage and output current



time is prolonged not only by the reformer but also by the time necessary for introducing gas and air into the fuel cell, changing over the resistor and changing fuel, and it is a theme of researches concerning the whole system to shorten the time required.

The load follow-up characteristic is now about 10%/min at low load, which is affected by the load follow-up characteristics of the compressors and the like. It is also a theme of the researches like the starting time, and should be shortened in near future.

5.3 Inverter unit

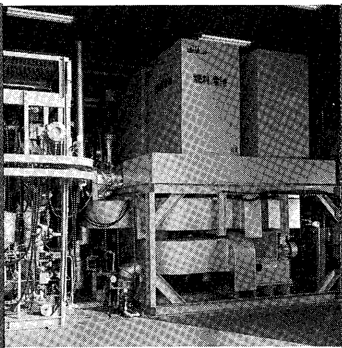
The inverter is a record capacity unit for power system use, and the target efficiency was as high as 96%. The test gave a good result of 97% at 100% load. *Fig. 11* gives an example of the output voltage and current waveforms in steady interconnecting operation. It was confirmed that protection properly operated against system abnormality (e.g. power failure, over- or under-voltage, short circuit, ground fault), fuel cell abnormality (e.g. voltage drop, ground fault) and inverter fault (e.g. commutation fault).

6. ACKNOWLEDGEMENTS

The 1,000 kW fuel cell power generating system is put to a long test as described above, which should bring us valuable experiences for commercial introduction of fuel cells in future. The authors gratefully acknowledge the guidance and cooperation given by Agency of Industrial Science and Technology, New Energy Development Organization, the Kansai Electric Power Co., Inc., Mitsubishi Corp. and JGC Corp.

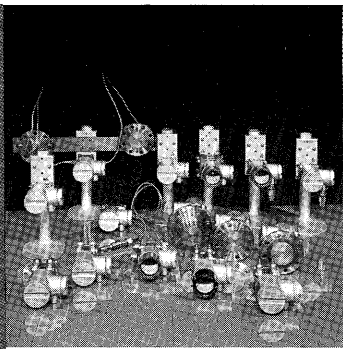
Outline of Products

Power and Industrial Electrical Machinery



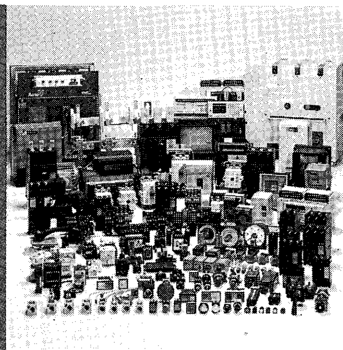
- Nuclear Power
- Power Generation and Distribution
- Transportation
- Environmental Equipment
- Industry
- Electrical Installation
- Mechatronics Equipment

Instrumentation



- Industrial Instrumentation
- Water Treatment
- Data Process Engineering

Standard Electrical Products



- IC (Integrated Circuit)
- Semiconductors
- Rotating Machines
- Standard Electrical Equipment

Vending Machines and Specialty Appliances

- Vending Machines
- Freezing & Refrigerating Open Showcases
- P.O.S. for Versatile Purpose Appliances
- Air Conditioning