Journal of Power Sources, 37 (1992) 81–99

The Tokyo Electric Power Company (TEPCO) fuel cell evaluation program

Kunio Shibata

Fuel Cell Project, Engineering Development Center, Engineering R&D Department, The Tokyo Electric Power Company, Inc., Tokyo (Japan)

Abstract

The Tokyo Electric Power Company (TEPCO) has promoted the development of fuel cells for individual suppliers for installation in buildings having a large heat demand, and for dispersed power sources in re-developed urban areas, utilizing advanced technology associated with phosphoric acid fuel cells. In demonstration testing of two 200 kW water-cooled plants for individual supply, the power generation performance and operating characteristics as a co-generation system are being assessed. Furthermore, construction of an 11 MW fuel cell plant for regional supply was completed. This was followed by the PAC (process and control) test, which led to successfully achieving the plant's rated power output. Although there are some obstacles to be overcome, the present demonstration tests clearly indicate the high potential of fuel cells for full-fledged commercial use. This paper presents an outline of these tests and the interim evaluation results.

1. Introduction

In evaluating plans for introduction of commercial power generation systems utilizing so-called 'new energy', fuel cell power generation is seen as a 'fourth generation technology' following thermal power, nuclear power and hydraulic power. For the PAFC (phosphoric acid fuel cell), in particular, numerous demonstration tests and research have been conducted recently [1, 2]. In Japan, with these development efforts setting the stage, an advisory body to the Ministry of International Trade and Industry has disclosed a plan in its interim report on the Electric Industry for fiscal year 1990 [3], to press forward towards the introduction of approximately 1.05 million kW of fuel cells by the year 2000. Thus, the trends towards commercialization of fuel cells has been steadily enhanced.

TEPCO has been promoting the development of fuel cells for individual supply for installation in buildings having a large heat demand, and for dispersed power sources for installation in re-development urban areas [4]. Although this R&D has been promoted by focusing on PAFC demonstration tests, elemental studies are also being conducted on next generation fuel cells, such as the MCFC (molten carbonate fuel cells) and SOFC (solid oxide fuel cells). This paper, however, is mainly concerned with the PAFC which is nearing the commercialization stage. It gives a brief introduction to its development status and the evaluation of results of its demonstration tests.

1.1. Development program and present status

TEPCO has tackled several problems related to the development of fuel cells as dispersed power sources for a number of years, and has energetically promoted

0378-7753/92/$5.00

demonstration tests and research to firmly establish new technology necessary for achieving the saving of resources. The fuel cell was felt to be attractive because of its unique characteristics:

- high power generation efficiency
- favorable emission characteristics, which are environmentally compatible
- high total thermal efficiency equal to 80% is attainable when utilizing waste heat
- various fuels can be used as the process feed
- no large quantity of cooling water (e.g. sea water) is required
- short-term plant construction is possible

Furthermore, there is a recognized need for the development of fuel cell technology as a dispersed power source for installation near large demand areas to solve the difficulties in siting large capacity power sources and distribution facilities as well as to reduce power transmission equipment and costs.

Table 1 shows the development status of PAFC plants at TEPCO. In regard to large capacity units, a 4.5 MW plant, manufactured by UTC, USA, was installed at the Goi Thermal Power Station in 1981. By the completion of tests in Dec. 1985, the plant recorded a cumulative operation of 2423 h and a cumulative power generation of 5430 MW h, thus demonstrating the possibility of a dispersed fuel cell plant [5].

A water-cooled 11 MW fuel cell plant currently under test is the world's largest to date, and is being developed by TEPCO jointly with Toshiba and IFC Corporation. Construction work commenced in Jan. 1989, and in June 1990 a PAC test was started. The demonstration test aims at examination of its suitability as a dispersed power source for regional supply, ultimately leading to commercialization.

In regard to the fuel cell plant for individual supply, an air-cooled 220 kW plant was jointly developed with the Sanyo Electric Company, and its operational performance was successfully evaluated through demonstration tests [6]. Moreover, in 1988, two units of a 200 kW water-cooled plant (PCX), a compact package type semi-commercial plant, were procured from IFC Corporation to initiate examination of its performance as a commercial plant. The first plant was primarily used for testing to evaluate its power generation performance. The test was completed in Nov. 1990, with the confirmation of plant performance as designed. The second plant was installed in an office building to investigate its adaptability to co-generation systems, and operated in accordance with the power demand of the building for one year. Subsequently, the test location was transfered to a DHC (district heating and cooling) plant, and unit no. 2 has been undergoing co-generation tests in combination with use of a heat pump since Aug. 1990.

1.2. Development status of next generation fuel cells

Next generation type fuel cells are very attractive because of their high electric power generation efficiency, which may surpass that of the PAFC. Also, they enable the use of a variety of fuels, including coal derived gas. To evaluate their many possibilities, TEPCO has pursued studies at its Engineering Research Center.

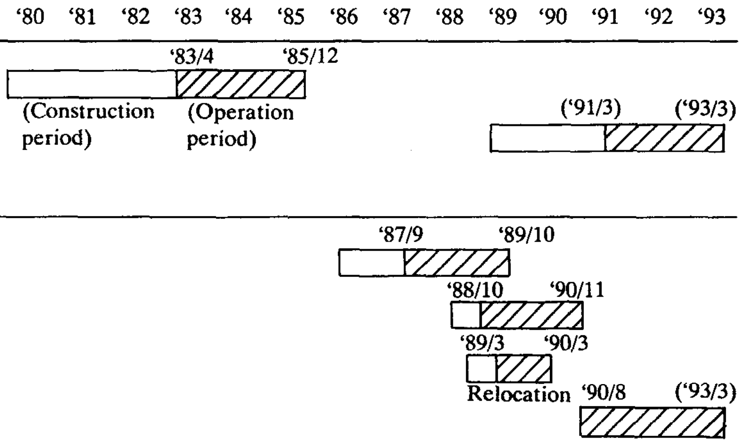
Major tasks in the development of the MCFC are: to suppress dissolution of the cathode catalyst and time-dependent morphology changes of electrodes; to maintain chemical stability of electrolyte-retaining material; to prevent corrosion of metallic materials; to reduce electrolyte migration. Efforts are being made to find viable solutions.

For the SOFC, efforts have been made to establish basic technology. A cylindrical cell, with an unit output of 35 W, was developed under joint research with Mitsubishi Heavy Industry, and power generation testing over more than 5000 h has been successfully

TABLE 1

Demonstration test of PAFC power plants at Tokyo Electric Power Company

Plant		Installation site
Large capacity plants	4.5 MW (water cooled)	Goi Thermal Power Station
	11 MW (water cooled)	Goi Thermal Power Station
Small capacity plants	220 kW (air cooled)	Shin Tokyo Thermal Power Station
	200 kW (water cooled) no. 1	Shin Tokyo Thermal Power Station
	200 kW (water cooled) no. 2	Shibaura Kandenko Building
		Shibaura district heating/ Cooling Plant (Shibaura Square Building)



Item	4.5 MW	11 MW	220 kW	200 kW/no. 1	200 kW/no. 2
Power generation efficiency (power generation terminal) (%)	37.8	42.9	35	37	37
Working pressure/ temperature	2.5 kg/cm^2 G/191 °C	7.4 kg/cm^2 G/207 °C	atmospheric pressure/185 °C	atmospheric pressure/213 °C	atmospheric pressure/213 °C
No. of cells	439 cells × 20 stacks	469 cells × 18 stacks	330 cells × 4 stacks	320 cells × 1 stack	320 cells × 1 stack
Manufacturer	UTC(IFC)	Toshiba	Sanyo	IFC	IFC
Remarks	world's largest fuel cell plant which has generated electric power	(fuel cell stacks manufactured by IFC)	world's largest air-cooled type	world's first 200 kW packaged plant	world's first plant installed inside a building

completed. Based on the results obtained, a test generator comprising 48 cells was manufactured, and a maximum output of 1.3 kW has already been achieved. In addition, a flat plate SOFC is being studied as part of the basic research activities.

Note that no mention of the details of these results is made in this paper. For detailed information, see refs. 7–10.

2. Demonstration test of water-cooled 200 kW fuel cell plant

2.1. Outline of demonstration test

The water-cooled 200 kW fuel cell used in the demonstration test is called PCX, or power cell X, which is a pre-prototype of IFC's PC-25. It is ranked as a semi-commercial plant, and its compactness is made possible by the introduction of high performance cells and simplification of the plant system. Table 2 shows an outline of the plant specifications. The configuration and other details of the PCX have already been reported in the literature [4].

Unit no. 1 was installed outdoors at the Shin-Tokyo Thermal Power Station to examine primary basic power generation characteristics, safety and durability. The plant demonstration test was completed and recorded a cumulative power generation of 6762 h and cumulative generated power of 1032 MW h. The demonstration test of unit no. 2 was designed to obtain operation and maintenance experience for underground building installation and to acquire valuable data necessary for co-generation operation. This plant established a world record equal to maximum continuous operation of 3246 h. In late June 1991, cumulative power generation time reached 10 000 h. Table 3 outlines the records of generation by units no. 1 and no. 2.

2.2. Evaluation of power generation performance

Measurement of plant initial performance revealed that the net power generation efficiency measured at the transmission end for both units no. 1 and no. 2 satisfied the design value of 35% (HHV basis). Figure 1 shows the generation efficiency of unit no. 1. The minimum output is 50 kW. At such low output range, the cell temperature is maintained at a constant level by electrical heating, thus resulting in a decreasing net efficiency. For further improvement, the efficiency in the low output range should be increased.

TABLE 2

Outline of 200 kW water-cooled plant (PCX)

Rated power (kW): gross	200
net	190
Power output range (%)	25–100
Power generation efficiency (%)	35 (HHV)
Waste heat recovery rate (%)	45 (HHV)
Fuel	natural gas
Load change rate (50–200 kW) (s)	15
NO_x (ppm)	<25
Harmonic distortion (voltage) (%)	<3

TABLE 3

Operation records of PCXs[a]

Plant unit	No. 1	No. 2		
		Site A	Site B	Total
Cumulative operating hours (h)	6752	3509	7188	10697
Longest continuous operating hours (h)	1393	417	3246	
Cumulative power generated (MW h)	1032	382	635	1017
No. plant start-up/shutdown	56	31	12	43

[a] As of Aug. 31, 1991.

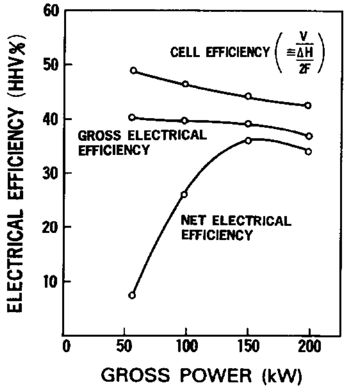


Fig. 1. Power generation characteristics for PCX no. 1.

TABLE 4

Electrical efficiency variation with operating hours: PCX no. 2

Operating hours (h)	Power output (%)		
	100 kW	150 kW	200 kW
500	29.0	36.8	35.4
2500	28.9	32.5	31.6
5000	28.4	32.4	

It is unavoidable that cell voltage will decrease with time, and this was the case for the PCX. Table 4 shows the drop in efficiency as a function of lapsed time for unit no. 1. For unit no. 2, this tendency continued. After operation of 8000 h, the gross power generation efficiency at 100 kW, which was initially 40%, dropped to 34%. It is, therefore, desirable that cell durability should be improved.

2.3. Evaluation of heat utilization characteristic

Consideration is given here to the utilization of waste heat from unit no. 2 which is presently installed in the DHC plant of the district heat supply center at Shibaura (see Fig. 2). The DHC plant satisfies the heating and cooling demands of 11 adjacent buildings. The electric power generated by the fuel cell plant covers approximately one fifth of the power required by the DHC plant. Furthermore, heat recovered from the fuel cell plant is temporarily accumulated in the heat storage reservoir of the DHC plant, and then used mostly as the heat source for hot water supplied from the DHC plant. This thermal energy accounts for approximately 10% of the total amount of heat supplied from the DHC plant. The output voltage of electricity generated by the fuel cell plant is stepped up to the grid interconnection voltage of 6.6 kV by an output transformer.

Utilization mode and total efficiency

Although, theoretically, the fuel cell plant can recover 45% of the input fuel energy as waste heat, the quantity of recoverable heat in practice varies depending on the methods of its utilization. In this system configuration, for example, waste heat can be utilized for heating, cooling and hot water supply. However, since the level of the recoverable temperature from the fuel cell plant is low when used for cooling purposes, the waste heat recovery rate is higher if used for hot water supply or heating. Table 5 outlines the set of test data in various heat utilization modes in the case of 100 kW load operation. The modes of utilization considered are as follows.

(i) Utilization exclusively for hot water supply. This mode is solely used for hot water supply. Hot water is supplied at a temperature of 60 °C.

(ii) Utilization exclusively for warm water. This mode is solely used for warm water. Warm water is supplied at a temperature of 47 °C. Though the total thermal efficiency is the highest among all modes, its utilization is limited to winter seasons.

(iii) Utilization for hot water supply and warm water. As both pumps for hot water and warm water supply are operated, the net efficiency lowers as compared with the cases of sole utilization for hot water supply or warm water.

(iv) Utilization for cold water and hot water supply. An adsorption type refrigerator was used on a trial basis for the supply of cold water, as the temperature level attainable by the PCX heat recovery system is as low as 85 °C (at the highest). Furthermore, heat source water discharged from this refrigerator can be utilized for hot water supply.

The degree of power generation efficiency varies slightly for each mode. It is considered that this variation reflects changes due to measurement errors, as the mode of utilization itself should not affect power generation efficiency.

System improvement and operational characteristics

According to the original design of PCX, the heat from the fuel cell cooling water is to be absorbed by the auxiliary cooling water system, and then transported to the loop of the heat utilization system by a customer heat exchanger. Furthermore, the temperature of the auxiliary cooling water returning to a heat exchanger, having cell cooling water as heat source, is controlled at a temperature of 41 °C (by rejecting

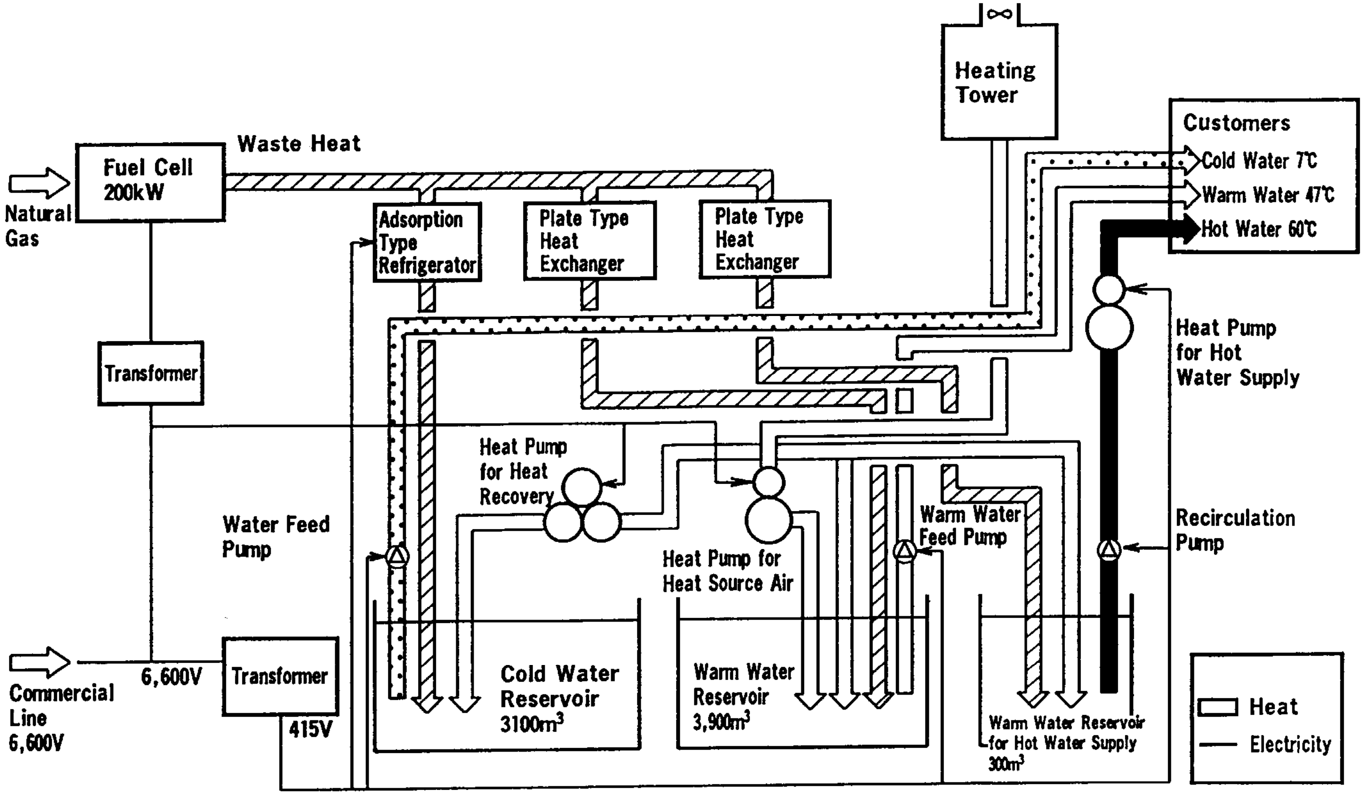


Fig. 2. DHC plant system combined with PCX no. 2 (in case of winter operation).

TABLE 5

Results (%) of heat utilization test at DHC plant (operating at 100 kW)

Test item	Hot water supply	Hot water heating	Hot water supply and heating	Cold water and hot water supply	Hot water supply[c]
1. Electrical efficiency (a.c.)	34.1	34.3	33.0	34.6	34.7
2. First electrical efficiency[a]	28.1	27.5	28.3	28.1	28.2
3. Second electrical efficiency[b]	21.9	24.3	21.0	20.7	24.7
4. Heat produced	41.2	42.1	37.8	39.9	39.2
5. Heat utilized	38.1	42.1	37.0	23.9	39.2
6. Total efficiency (3+5)	60.0	66.4	58.0	44.6	63.9
7. Heat loss (cooling tower)	3.1	0	0.8	6.1	0
8. Heat loss (exhaust gas)	22.8	21.7	27.2	23.6	26.1

[a] Parasite power is subtracted from the gross a.c. power generated.

[b] Electric power required for heat utilization facility and plant security system is subtracted from the first electrical efficiency.

[c] Auxiliary cooling water (glycol/water) is returned to the fuel cell system without cooling the water.

heat) using a dry cooling tower integrated in the auxiliary cooling water loop system (see Fig. 3(a)).

Upon installation of the fuel cell plant at the DHC plant the customer heat exchanger was however omitted, and the auxiliary cooling loop was directly connected to the loop for heat utilization in an attempt to reduce heat loss and pump power, as shown in Fig. 3(b).

With respect to the return temperature of the auxiliary cooling water, the temperature of the heat accumulating reservoir for warm water and hot water supply ranges from 45–50 °C, levels that are higher than the return temperature. According to operation guidlines, it is necessary to reduce the range through heat rejection by the DHC's cooling tower facility, as harmful effects may cause damage to the fuel cell stack. However, it was confirmed that no such influence could be identified, even when no control of the return temperature was made, so that the heat rejection process can be omitted. As a consequence, it became possible to reduce the electric power required for the pump in the heat rejection loop system, thereby resulting in improved efficiency. Figure 4 shows the energy balance of the fuel cell plant in the case of hot water supply after the above-mentioned system modification was made. Figure 5 presents the operational characteristics in the case of hot water supply, also. Due to reduction of the said power, total efficiency at 100 kW output was improved by about 4%.

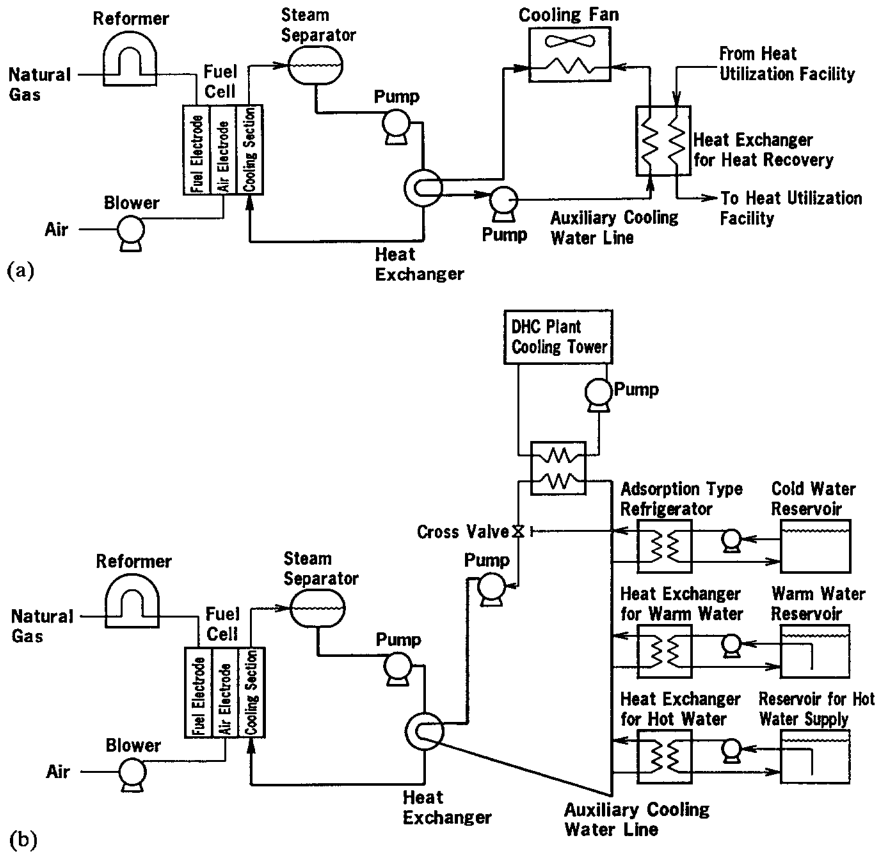


Fig. 3. Utilization of heat from fuel cell. (a) Outline of heat recovery system for original PCX design. (b) Arrangement of heat utilization facility for fuel cell at Shibaura DHC plant.

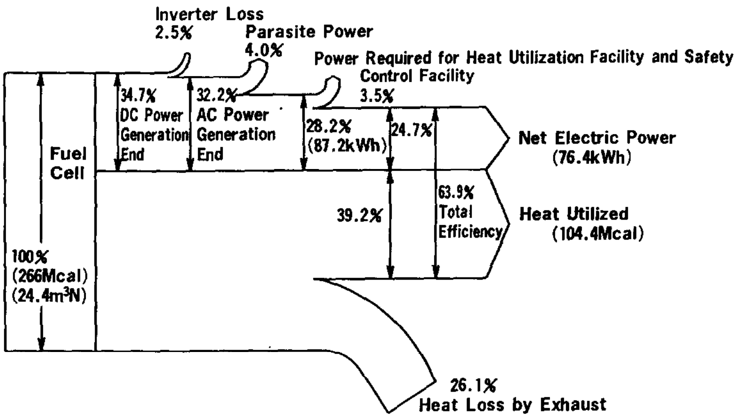
In combination with DHC plant

Integration of PCX to a DHC plant allows effective utilization of waste heat from the fuel cell plant, as the waste heat can be accumulated in the heat storage reservoir of the DHC plant. It is necessary, however, that the heat demand of the DHC plant be in conformity with the quality (temperature) and the quantity of waste heat supplied from the fuel cells. Nevertheless, despite its high total energy efficiency, the feasibility of this arrangement, as compared with competitive systems, requires further study on its economics.

With the recent increase in office automation devices, the power demand for cooling has increased in office buildings. Consequently, generation of high temperature steam suitable for use in absorption type refrigerators, which allows a high COP value, will become a key concern for users of fuel cell plants.

Further improvements desired

In the original PCX design, several waste heat takeoff ports are attached to a single pipe for the purpose of simplifying the system layout. In the improved plant design currently considered, however, provision is made of for extraction of waste heat at different temperature levels.



Plant Power Output : 100kW
Heat Utilization : Hot Water Supply (After plant modification)

Fig. 4. Example of energy balance.

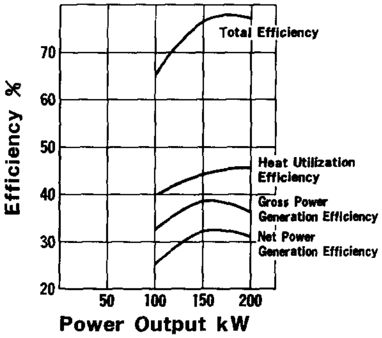


Fig. 5. Total thermal efficiencies.

2.4. Others

Operational characteristics

Start-up time from a cold state takes approximately 3.5 h. This is governed by the heating-up time of the cell cooling system. Although 3.5 h is shorter than the designed value, further reduction of start-up time is desired.

Environmental characteristics

The concentration of NO_x in exhaust gas from PCX is less than 3 ppm (7% O_2 equivalent) at rated output, and the emission of other pollutants, such as SO_x and particulates, are not detected. These results attest to the superiority of the fuel cell plant in terms of adaptability to the environment.

Maintainability

Major troubles which occurred in the early stage of the demonstration tests were the breakdown of sensors and controllers, and leakage of gas and steam from piping. In case of the reformer, trouble points were defective flame detection and gas leakage

TABLE 6

Summary of evaluation results of PCXs

Item	Evaluation	Future improvement objectives
Power generation characteristics	Satisfactory performance achieved – initial design performance achieved – cumulative operation hours of more than 10000 recorded – cell voltage drop due to time passage	– cell stack durability must be improved – electrical efficiency at a lower output range must be improved – endurance test must be continued
Heat utilization characteristics	Satisfactory performance achieved – total thermal efficiency in various heat utilization modes verified	– heat utilization system must be modified so as to extract heat simultaneously at different temperature levels
Operational characteristics	Satisfactory performance achieved – start-up time is shorter than as designed	– shortening of start-up time is necessary
Grid connection characteristics	No problems encountered – harmonic destortion characteristics were satisfactory	– no problems
Emission characteristics	Satisfactory results – low level NO_x emission – SO_x and dust were not detected	– no problems
Maintainability	Some sensors and control-related trouble occurred	– reliability of control system must be improved – amount of replaced resin for WTS must be reduced – nitrogen consumption for start-up/shutdown operation must be reduced

from flanges, etc., similar to problems experienced with other plants. Although no serious trouble occurred, further improvement of reliability is necessary.

Concerning plant maintenance, replacement of resin for the water treatment system is necessary: note that the maintenance period varies in accordance with the quality of water. Approximately 1.6 kg of resin was consumed in a year. Furthermore, a certain amount of nitrogen is required at the time of start-up and shutdown. Lower nitrogen consumption is desired to reduce the quantity used in the future.

2.5. Comprehensive evaluation

Demonstration tests have been conducted by installing two units of 200 kW water-cooled plants at different test sites. As described in the preceeding sections, it can be concluded on an interim evaluation basis that satisfactory results were obtained in consideration of the original plant design and test plan. The tests also revealed that there are several problems requiring solution, such as durability of the fuel cell stack. For commercialization of fuel cell plants, it is necessary to continue operation over a longer period of time. An outline of comprehensive evaluation results is presented in Table 6.

3. Demonstration test of 11 MW fuel cell plant

3.1. Outline of the plant

The Goi 11 MW plant is based on the design of PC-23, a standard unit for the American market, although design review was performed by TEPCO and Toshiba prior to its introduction. The plant specifications were set so as to meet conditions necessary for installation in Japan, and were based on technology and experience accumulated from the demonstration test of the 4.5 MW plant at Goi. Figure 6 outlines of the system diagram of this plant.

Plant characteristics

Principal plant design performance is as shown in Table 7. Natural gas is used as the process feed. The electric power generation efficiency of this plant is considerably improved when compared with that of the 4.5 MW plant. The waste heat utilization rate was held to a low level, as heat recovery at the blowdown cooler and the inter-cooler of turbo-compressor, as well as utilization of heat from turbo-compressor exhaust gas are not called for in the present demonstration tests. For waste heat utilization, the plant is equipped with an absorption type refrigerator and a heat exchanger for utilization of warm water. Their planned purpose is to provide cooling and heating of the building for plant control. Figure 7 shows that the balance of energy at rated output is as designed.

Circumstances leading to PAC test

The plant consists of so-called 'pallets' on which devices and pipings are factory assembled to shorten the period of construction at site. Transportation from the factory was conducted by shipping these pallets in units as seaborne freight, excluding some plant components. A construction period of approximately 15 months was required from commencement of civil work for the foundation to completion of installation of pallets and other plant components. After the subsequent period of about two months for adjustment and checkout of individual devices, the PAC test, or process and control test, was started in June 1990.

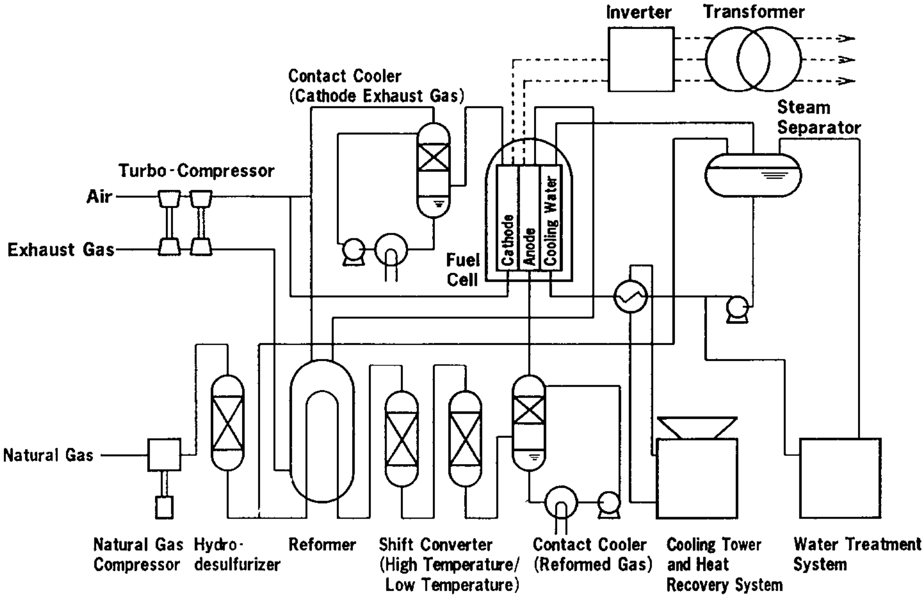


Fig. 6. Outline of plant flow diagram for 11 MW plant.

TABLE 7

Design performance of 11 MW plant

Rated power (a.c., net) (MW)	11
Output voltage (kV)	66 (50 Hz)
Power output range (%)	30–100
Power generation efficiency (net, HHV basis) (%)	41.1
Waste heat recovery rate (%)	31.6
Fuel	natural gas
NO_x (ppm)	<10

Purpose of demonstration test

The present demonstration test was intended to achieve the following:

- to demonstrate the potential of the fuel cell plant as a combined heat and electricity supply system
- to clarify the operational characteristics of the plant
- to verify performance of principal plant components, such as fuel cell stack and reformer
- to establish technology necessary for highly reliable operation ultimately aiming at automatic operation
- to confirm favorable environmental adaptability

3.2. Results of the PAC test

The PAC test was conducted, prior to power generation, with the fuel cell stacks isolated from the plant. The test purpose was to adjust the plant sub-systems and

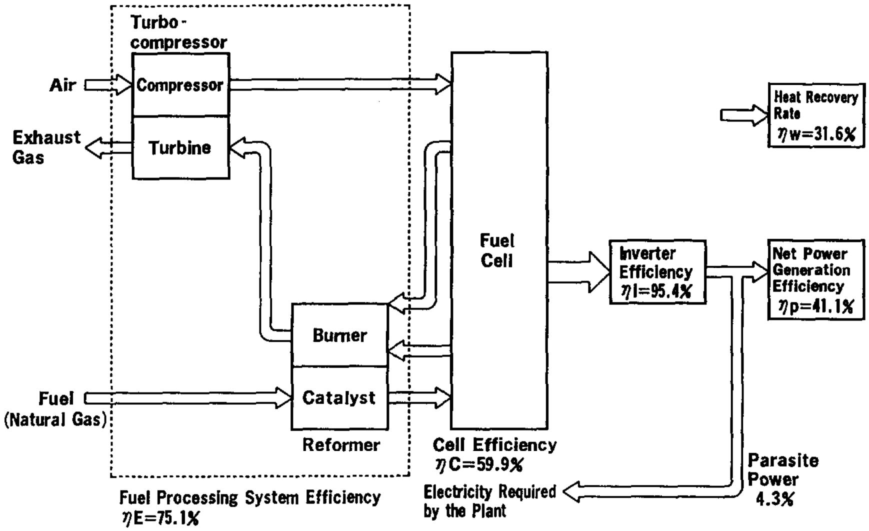


Fig. 7. Energy balance at rated power for the 11 MW plant (design values).

controlling system, so that proper plant control could be ensured. Executed were a series of start-up operations, from heating up and pressurization of the plant to hydrogen production by steam reforming reaction, as well as transition to simulated load operation.

Features of the plant

The following improvements were made for this plant, by incorporating the experience gained in the PAC test for the aforementioned 4.5 MW plant.

- The plant sub-systems can be operated independently so that system adjustment can be made without interfering with other sub-systems.
- As the plant operation sequence can be maintained in any state upon occurrence of trouble, thus making shutdown unnecessary, testing can be efficiently carried out.
- Manual operation is possible during each operation sequence.

The word ‘sub-system’ here implies a unit of functional groups that comprise the entire plant. Examples are FPS (fuel processing sub-system) and APS (air processing sub-system). A unique feature of the present PAC test is that activation of catalysts for four reactors incorporated in the plant (hydro-desulferizer, reformer and high/low temperature shift converters), was conducted at site.

Test items

The followings items were checked in the PAC test:

- clean-up and system checkout for contact cooler systems at the anode inlet and cathode outlet
- clean-up of the cell cooling system, followed by system heating up and checkout
- activation of catalysts for reactors
- heating up, reforming and fuel transition test for fuel processing system
- simulated load test and overall adjustment and checkout

Comprehensive evaluation

In the PAC test, the static- and dynamic-state characteristics and controllability of the plant were examined to ensure that they conform to the design characteristics. It was also confirmed that the plant was in a state ready for transition to power generation, with a 30% simulated load operation achieved.

Troubles occurring during the PAC test were mostly those requiring minor adjustments, so that the test program could be smoothly completed. Consequently, the actual number of days required for the PAC test was shortened to 82 as against the plan of 128 days. This fact can be considered as a great step forward toward shortening of the preparation period at site, and can be evaluated as indicating that the design of the operation monitoring system and quality control of the software were satisfactorily performed. As for major devices, such as the reformer and inverter, tests were carefully performed by respective manufacturers beforehand using devices identical to actual items. This also contributed to the rapid improvement in reliability of such devices. Some of these test results are reported in the literature [11, 12].

3.3. Power generation test

Initial power generation was successfully achieved in Mar. 1991 shortly after completion of installation and adjustment of the cell stacks, followed by the then world's largest output for a fuel cell of 5 MW being recorded on Mar. 25. With careful observation of plant conditions, the output was gradually increased during subsequent days, with the rated output of 11 MW attained on Apr. 26. Table 8 presents a comparison of measurement and design data for some characteristic values at rated power output, together with the operating records as of Aug. 31, 1991.

Power generation efficiency

The measured efficiency exceeds the design value, implying that the cell stacks are in extremely good condition. It can be concluded that the initial plant performance fully satisfies the design values. The variations in power generation efficiency as against

TABLE 8

Initial performance of 11 MW plant[a]

	Designed	Measured
Gross power generation efficiency (HHV) (%)	42.9	43.6
Net power generation efficiency (HHV) (%)	41.1	41.3
Total harmonic distortion rate (%)		
Voltage		1.5–1.7
Current	5	4.3
NO_x ($O_2=7\%$ equivalent) (ppm)	<10	1
Cumulative generating hours (h)	10000	1414
Longest continuous operating hours (h)	3000	875
Cumulative power generated (MW h)		10263
No. of start-ups		11

[a] As of Aug. 31, 1991. Efficiencies defined at rated power. NO_x emission measured at rated power.

load change are as shown in Fig. 8. Also, it was found that the balance of cell stack voltage for the 18 stacks, the differential pressure between electrodes, static and dynamic characteristics of the plant at each load range and plant controllability, were all satisfactory.

Operational characteristics

It was confirmed that the plant can maintain stable operation at a constant output level, indicating that operational characteristics are satisfactory. However, as the operation is in its early stages, continued examination is required for this evaluation to be conclusive.

Environmental characteristics

The excellent environmental compatibility of the fuel cell was confirmed. NO_x in the plant exhaust gas satisfies the design value, and SO_x and dust were not detected.

Grid interconnection characteristics

Satisfactory results were confirmed with respect to the overall waveform distortion rate, or harmonic distortion rate, as well as both the voltage and current waveform distortion rates.

Maintainability

Some initial trouble in peripheral devices has been experienced to date. Examples are damage of the impeller of the cathode recycle blower and leakage from flanges around the cell stack and the turbo-compressor. In the case of the former, reinforcement was made by increasing the impeller thickness. In case of the latter, the packing material was changed, and additional tightening was given to flanges.

3.4. Interim evaluation and test plan

Interim evaluation

As described, during the initial stages of the demonstration tests, from construction to power generation through to the PAC test, everything proceeded smoothly. This was due to the fact that the results and experience gained from past demonstration tests were fully reflected in the present test. Another contributing factor was improvement in plant reliability, leading to initial power generation being successfully attained in a relatively short period. That the plant exhibited satisfactory performance is indeed

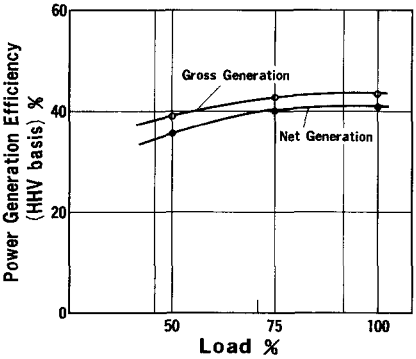


Fig. 8. Power generation characteristics for 11 MW plant.

TABLE 9

Summary of evaluation results of 11 MW plant (Interim)

Item	Evaluation	Future improvement objectives
Power generation characteristics	Satisfactory performance achieved – initial design performance achieved – higher power generation efficiency obtained as against the design value – good balance of stack voltage for 18 stacks achieved – static- and dynamic-state characteristics were satisfactory	Performance tests must be continued
Heat utilization characteristics	Test not started	To assess results when data are obtained
Operational characteristics	Satisfactory operability confirmed – stability of plant operating condition confirmed	Performance tests must be continued
Grid connection characteristics	No problems encountered – harmonic distortion verified	No problems
Emission characteristics	Satisfactory – low NO_x level emission – SO_x and dust were not detected	Monitoring of emission level must be continued
Maintainability	Initial troubles occurred – peripheral devices (damaged blower impeller, leakage from flanges, etc.)	Countermeasures taken Performance test must be continued

promising, even though the test program is only in its initial stage. Table 9 summarizes the interim evaluation results.

Test schedule

It is planned in the present demonstration program to continue power generation tests for further evaluation of the plant. A period of two years is assigned for power generation testing so as to achieve the goals of continuous operation of 3000 h and a cumulative operation of 10 000 h. During this period, investigations will be made as to the reliability as a dispersed power source for regional supply, adaptability to the environment, and characteristics for heat utilization. Also, operational performance will be assessed from the standpoint of the user, and to establish the technology necessary for highly reliable performance which will eventually lead to automatic operation.

4. Concluding remarks

It may be concluded from the results of evaluation and examination through these demonstration tests that the potential for practical use is high as far as technical feasibility is concerned. The future task will be to push forward with improvements in reliability and durability, and to make possible introduction of a compact and low-priced plant.

In the case of the 11 MW plant, for example, the construction cost per kW amount to approximately Y900 000 at present. To compete with a gas turbine system, the cost will have to be cut down to at least below Y250 000 per kW. As the Goi 11 MW plant is regarded as a prototype, auxiliary devices are used to control certain equipment so as to increase system reliability. In commercial plants, however, these devices will have to be minimized or simplified to achieve cost reduction. Moreover, the price of the cell stack itself will have to be reduced to a range from one-third to one-fourth of the present cost, thus requiring further technological innovation.

In practice, methods of cost reduction include improvement in cell stack performance, such as increasing current density; more compact design of principal devices, such as the reformer and inverter; and simplification and standardization of plant subsystems. Also, substantial cost reductions will have to be made through mechanization and automation of production facilities as well as the introduction of mass production techniques.

For the improvement of operational reliability, it is essential to establish a long-term operation to demonstrate the true reliability of fuel cell plants. In this context, as already described, a cumulative operation of 10 000 h has been recorded for the PCX, together with some other encouraging results. These achievements can be regarded as the foundation for further progress.

TEPCO considers it necessary to continue identifying technical problems from the standpoint of the user and to promote technical innovation in cooperation with manufacturers. In order to put fuel cell plants into practical use by the late 1990s, it is indispensable to further deepen the international cooperation among parties and individuals concerned with the fuel cell plant development.

The emerging age of fuel cell technology is of necessity as one of the leading power generation systems in view of today's urgent need to preserve our global environment. As described herein, the commercialization of a phosphoric acid type fuel cell has been a possibility now well conceived, with the establishment of this technology an essential step for the development of next generation type fuel cells. In this respect, it is important to continue our efforts and accumulate experience for this challenging technology.

References

1 A. J. Appleby and F. R. Foulkes, *Fuel Cell Handbook,* Van Nostrand Reinhold, New York, 1989, pp. 131–145.

2 T. Sugimoto, *Fuel Cell Seminar, Phoenix, AZ, 1990,* Courtesy Associates, pp.1–2.

3 Advisory Organ for MITI on Electric Industry, *Interim Rep. for Fiscal 1990,* 1990.

4 T. Asada and Y. Usami, *J. Power Sources, 29* (1990) 97–107.

5 A. J. Appleby and F. R. Foulkes, *Fuel Cell Handbook,* Van Nostrand Reinhold, New York, 1989, pp. 69–73.

6 N. Funahashi, T. Okamoto, R. Saito and O. Tajima, *Fuel Cell Seminar, Long Beach, CA, 1989,* Courtesy Associates, pp. 222–225.

7 Y. Watanabe, H. Sotouchi, T. Kobayashi and M. Murai, *31st Battery Symp., Osaka, Japan, 1990,* pp. 203–204.
8 Y. Watanabe, H. Sotouchi, T Kobyashi and M. Murai, *31st Battery Symp., Osaka, Japan, 1990,* pp. 205–206.
9 F. Umemura, H. Ohta, K. Amano *et al., Fuel Cell Seminar, Phoenix, AZ, 1990,* Courtesy Associates, pp. 127–130.
10 F. Umemura, K. Amano and Y. Ochiai, *2nd SOFC Symp. (Int.) Athens, Greece, 1991.*
11 T. Okamoto, Y. Itakura, Y. Nagata and M. Watanabe, *Inst. Electrical Engineers of Japan, Ann. Meet., Kanazawa, Japan, 1991,* Vol. 12, pp. 169–170.
12 K. Mochizuki, A. Tajima, T. Amamiya and M. Watanabe, *Inst. Electrical Engineers of Japan, Ann. Meet., Kanazawa, Japan, 1991,* Vol. 12, pp. 171–172.