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Philosophies and experiences of PAFC field trials

Kunio Shibata and Kenji Watanabe
Fuel Cell Project, Engineering Development Center, The Tokyo Electric Power Company, Inc., Kyodo Building, Jimbo-cho, 4th Floor, 2-30, 2-chome, Kanda Jimbo-cho, Chiyoda-ku, Tokyo 101 (Japan)

Abstract

The development of phosphoric acid fuel cells (PAFCs) accelerated in the 1980s to the point that various demonstration tests of facilities, ranging from small capacity units for on-site use to large capacity units in use for dispersed power generation, have been carried out. These demonstration tests have led to rapid advancement in the technology, though it must also be noted that there still remain many problems prior to commercialization, such as reliability, durability and cost. This paper presents an overview of the status of demonstration tests on PAFC plants and attempts to evaluate the current technology, as well as introducing philosophies for the demonstration tests. In addition, it also includes a discussion of the extent to which the merits of fuel cells have been realized.

Introduction

Our society faces environmental problems on a global scale; the conservation of fossil fuel resources such as oil and natural gas, global warming due to carbon dioxide and so on. As an immediate countermeasure valid for these problems, it is imperative to develop energy conversion devices which offer high efficiency while minimizing the burden on the global environment. With the merits of environmental compatibility and high efficiency, fuel cell power generation plants have come to be regarded as highly attractive in this respect, and more than a decade has passed since full-scale development activities started in the early 1980s in the expectation of producing a new electric power generation device which would meet the afore-mentioned requirements. In particular PAFC (phosphoric acid fuel cell) plants have been consequently placed under demonstration testing, and their practical application is appraised as being imminent. However, there are still problems to be solved: reliability, durability and the cost for full commercialization.

Status of development

The development of PAFC plants was initiated in the USA by the TARGET Program (for the development of small capacity fuel cell plants) and the FCG-1 Program (for the development of large capacity fuel cell plants) which started in 1967 and 1971, respectively. The TARGET Program, undertaken by a group of gas utilities, began with a 12.5 kW system, followed by demonstration of 40 kW units. This led to the development of present-day 200 kW class systems, with mass-production models having been made available since 1992. The FCG-1 Program was undertaken by a group of electric utilities and started with 1000 kW generation system. After dem-

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onstration of a 4500 kW system, the technology was reflected in the development on an 11 MW class system with its demonstrator being in operation in Japan since 1991.

In the early 1980s, a national project in Japan, the Moonlight Project, got underway and as Japanese electrical manufacturing companies began to take part in developing PAFC plants, their participation led to a rapid growth in the installed capacity of demonstration test facilities in Japan. Figure 1 [1, 2] shows trends in the cumulative installed/dismantled capacity of PAFC plants. Although the data only show developments by Japanese gas and electric utilities and oil companies, at present, the installed capacity for small capacity units of less than 1000 kW has reached 5000 kW, and for large capacity units of 1000 kW or greater, 17 500 kW, with further plans for a steady increase in installation capacity in the future.

Table 1 [3, 4] shows the latest status of development of PAFC. For small capacity on-site plants, ONSI completed the production of 56 first-lot PC 25, and their installation and operation have started at various sites. Also, a field test program commenced in Japan, which is aimed at promoting the commercialization of PAFC.

For large capacity units, a TEPCO 11 MW Plant is currently in operation despite encountering system-related troubles during the test. It has recorded a cumulative operation time of 6425 h and a cumulative power generation of 35 444 MWh as of the end of July 1993. In the near future, a 1 MW plant in Italy, and a 5 MW and a 1 MW plant of NEDO with the PAFC Technology Research Association in Japan will become operative.

In other countries, no attempt has been made to develop cell stacks for PAFC, instead efforts were made to put PAFC plants into practical use either by simply introducting entire plants from USA or Japanese manufacturers, or by engineering plant assemblies having purchased cell stacks. As examples, Japanese-made 50 kW plants are being introduced and brought into operation in Sweden, Italy, Spain, etc., while US-made 200 kW plants can be found in Denmark, Sweden, Germany, Italy, Switzerland, etc., since 1992. Also, demonstration tests have been carried out in South Korea and Thailand.

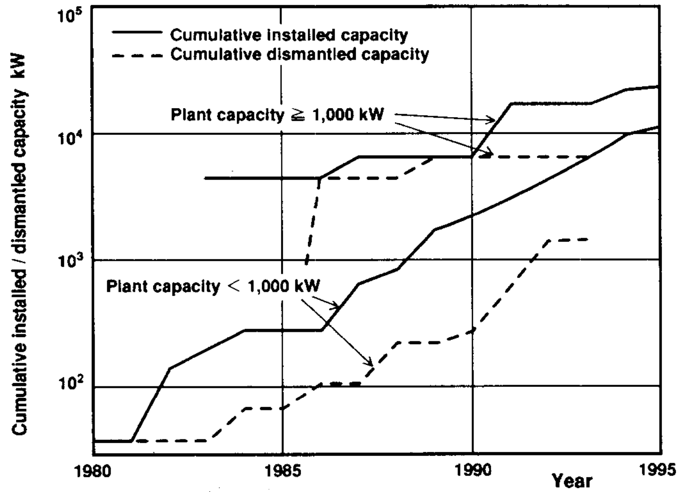

Fig. 1. Trends in installed capacity of PAFC plants in Japan. Data includes plants installed by gas and electric utilities and oil companies.

TABLE 1

Present status of PAFC development [3, 4]

General

Demonstration tests [3]	Europe	4 units/3300 kW	1991–1993 startup
	Japan	128 units/~30000–35000 kW	1992–1994 startup
	USA	19 units/1800 kW	1992–1993 startup

Small-capacity type
- Initiation of Japanese field test project for fuel cell power plants (1992)
- ONSI-completed production of 56 PC 25 first-lot units (June 1993)
  (USA 22 units, Canada 1 unit, Europe 10 units, Japan 22 units, South Korea 1 unit: 27 units in operation as from June 1993) [4]
- Fuji Electric plants (50–100 kW)
  - Installation figures 1989–1993: 50 kW: 53 units, 100 kW: 10 units
- Mitsubishi Electric plants (200 kW)
  - Installation figures 1985–1993: 3 units
- Toshiba 200 kW plant (technical cooperation with ONSI)
  - First unit installed

Large-capacity type
- Start of power generation from TEPCO 11 MW plant (March 1991)
  - Cumulative operation: 6425 h, cumulative power generation: 35444 MWh (as from end of July 1993)
- Japan/NEDO
  - Start of construction of 5 MW plant (June 1992)
  - Power generation test (scheduled to begin in 1994)
- Japan/NEDO
  - Start of construction of 1 MW plant (June 1994, planned)
  - Power generation test (scheduled to begin in Jan. 1995)
- Italy/Milan
  - Start of operation of 1 MW plant (scheduled 1993)

Examples of installed plants

Table 2 lists the major PAFC plants presently available and briefly compares their specifications and performance. For some of these plants, demonstration tests have been already completed, while others are currently in operation or in the preparation stage for demonstration tests.

As major fuel cell manufacturers, there are IFC and ONSI in the USA, and Fuji Electric, Toshiba and Mitsubishi Electric in Japan. They have produced various PAFC plants having their power generation capacity ranging from 50 kW to 11 MW. For on-site type plants, which operate under atmospheric pressure conditions, the electric power generation efficiencies are in a range between 35 and 38% (HHV basis). For dispersed power generation systems, plants are generally operated under pressurized conditions, and their electrical efficiency exceeds 40%, while total thermal efficiencies are generally well above 70%, though the values depend on the way recovered heat is utilized. Indeed, the environmental compatibility of PAFC plants is clear and proven.

Concerning the status of plant installation and their utilization purposes, Fig. 2 shows percentages of the number of installed units for various application sectors,

TABLE 2

Specifications and performance of the latest fuel cell power plants[a]

Unit capacity	50 kW	100 kw	200 kW	200 kW	200 kW
Plant	FP-50	FP-100	PC 25	TFC-200/(ST)	NEDO/Plaza
Manufacturer	Fuji Electric	Fuji Electric	ONSI	Toshiba	Mitsubishi Electric
Type	Atmospheric pressure	Atmospheric pressure	Atmospheric pressure	Atmospheric pressure	Atmospheric pressure
Efficiency (%)					
(electrical)	35	38	40	40	36
(total)	72 (HHV)	85 (LHV)	84 (LHV)	84 (LHV)	80 (HHV)
Heat utilization	Hot water, 65 °C 45 Mcal/h	Steam, 165 °C 49 Mcal/h Hot water, 50 °C 58 Mcal/h	Hot water, 90 °C 50 Mcal/h or Hot water, 74 °C 191 Mcal/h	Hot water 191 Mcal/h Temperature Supply 74 °C Return 27 °C Steam 80–90 Mcal/h (Planned)	Steam, 170 °C 18.1% Hot water, 70 °C 26.1%
Fuel	Town gas (NG)	Town gas (NG)	Town gas (NG)	Town gas (NG)	Town gas (NG)
Emission					
NO_x	2 ppm		<2 ppm	<2 ppm	4 ppm
SO_x			<0.01 ppm	<0.01 ppm	
Noise			<60 dB	<60 dB	
Size Lm×Wm×Hm	3.1×1.75×2.3	3.6×2.39×3.18	7.3×3.0×3.5	7.3×3.0×3.5 6.9×2.8×3.5	10×3.1×3.2
Weight (t)	6.5		27.3	27.3	

[a]Note: some of the values indicated in this Table are estimated by the author.

taking the PC 25 first-lot plants as an example. The largest group of the application, apart from the ones installed at R&D facilities or within the utilities own facilities, is those for hospitals and hotels. The percentage decreases in order; for the industrial sector in which plants are installed within works, for plants integrated in district heating and cooling (DHC) plants, for office buildings, and for the commercial sector. The plants installed for verification test purposes account for only 20%, suggesting that commercial introduction of PAFC plants has already taken place. Nearly 90% of the plants are installed outdoors, and there are a few cases in which the plants are installed in the basement floor of buildings.

Philosophies

Characteristics of fuel cells

The characteristics of a fuel cell power generation plant can be summarized in the award ceremony lecture presented at the US Electrochemical Society by Sir Francis Bacon in 1978 [5]. He said, in effect that it has been shown that an overall efficiency, including that of the steam reformer, of 37% can be achieved, and the potential exists

200 kW	500 kW	1 MW	1 MW	5 MW	11 MW
NEDO/Okinawa	Osaka Gas	NEDO-ONSITE	ENEA/PRODE	NEDO/CENTER	TEPCO/GOI
Fuji Electric	Fuji Electric	Toshiba	ANSALDO (IFC)	Fuji Electric	Toshiba (IFC)
Atmospheric pressure	Atmospheric pressure	Atmospheric pressure	Pressurized	Pressurized	Pressurized
39.7	40	36	40	41.2	41.1
	85	71	80	71.4	72.7
(HHV)	(LHV)	(HHV)	(LHV)	(HHV)	(HHV)
Not planned	Steam, >160 °C 23% Hot water, 70 °C 22%	Steam, 170 °C 20~25% Hot water 15~10% Temperature Supply 65 °C Return 50 °C (Target)	1000 Mcal/h	Steam, 324 °C 780 Mcal/h Hot water, 92 °C 357 Mcal/h Hot water, 48 °C 1429 Mcal/h	31.6% (HHV)
Methanol	Town gas (NG)	Town gas (NG)	Natural gas	Town gas (NG)	Natural gas
2 ppm	<10 ppm	<10 ppm		<10 ppm	<3 ppm
		<0.1 ppm		<0.1 ppm	0
		<60 dB		<55 dB	<55 dB
11×3×3.9	5.3×3.2×3.2			45×20×20	
	5.0×3.2×3.2	(<0.1 m^2/kW)			(0.28 m^2/kW)
	~50				

to improve this to 40 or even 45%. However, this novel method of electricity generation has other advantages; the efficiency can be attained using relatively small generators, the efficiency does not drastically drop to about 20% of full load. Further benefits include very low levels of air pollution and relatively noise-free operation, making it possible to place these installations in urban areas. These merits lead to the interesting possibility that the waste heat, which is inevitable in any energy conversion process, can be utilized for building heating, etc.

In addition to the advantages mentioned above, there are other advantages which ease conditions of installation; the variety of usable fuels, the possibility of installation in inland areas as there is no necessity of providing large quantity of cooling water, and the possibility of reducing the construction period due to modular structure (cf., Table 3).

Philosophies on the introduction of fuel cells

Utilities approaches

Invariably gas and electric utilities will play the central role in introducing fuel cells. This will no doubt be the case in any country. As for the needs for fuel cells,

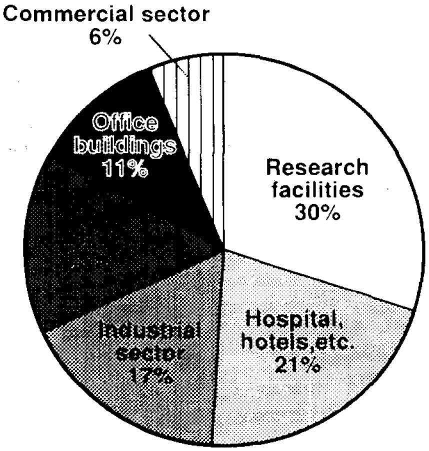

Fig. 2. ONSI PC 25 user categories. The classification of categories was carried out solely by the authors. Several units are not included due to unavailability of information.

TABLE 3

Expected merits of PAFC plants

- High efficiency
  - Power generation efficiency
  - Overall efficiency
  - Efficiency maintained independent of load levels
- *Environmental compatibility*
  - No pollutants (NO_x, SO_x) emitted
  - Low noise or vibration
- Easy installation
  - No large quantity of cooling water required
  - Diversity of fuels
  - Shortened construction period

it is generally regarded, however, that the two utility groups will play different roles; gas utilities will operate the small capacity, on-site type, and electric utilities will operate the large capacity, dispersed power source types. However, this does not mean that their developmental activities and introducing of PAFC will be totally independent.

It is obvious that gas utilities, in view of their primary objective that natural gas be effectively utilized, are encouraging the development of fuel cells and are placing emphasis on expanding their market. Therefore, the division between on-site and dispersed type plants is not a conflicting issue when seen in terms of the role as primary fuel suppliers.

Although electric utilities will ultimately place emphasis on utilization of large-capacity, dispersed type plants of multi MW or greater, they will also promote the development of small-capacity on-site types due to the following reasons:

(i) to obtain fuel-cell related know-how prior to introducing large-capacity units, and to collect information regarding heat utilization;

(ii) to identify potential problems for the introduction of large-capacity, dispersed type fuel cell plants leading to practical application;

(iii) to encourage fuel cell manufacturers to promote development;

(iv) to investigate the influence of on-site type power sources when/if they are connected to the commercial grid system, and

(v) to support the large-capacity plant technology indirectly by promoting the development of a common technology basis.

Thus, through demonstration tests and active market introduction programs for PAFC by users, including the oil industries, general contractors, electrical contractors, and other independent industries, the realization of this new technology is being accelerated.

Market directions

There is a possibility in the future that the energy market will become diversified and have a different structure from that of today. Also, it will certainly reflect the needs of the times; particularly overall efficiency improvement. However, it is generally accepted that the market for fuel cells continues to exist in the conventional on-site cogeneration market as well as in the large-scale, dispersed type power source market.

For example, in North America, utilization of fuel cell plants as dispersed type facilities is now attracting keen atttention in order to control environmental problems and to minimize the expansion of power transmission facilities, and there are expectations that fuel cell plants can be utilized as power source or in a manner which will combine heat utilization.

Meanwhile, in Europe, expectations are being placed on cogeneration systems using fuel cells which enable the effective utilization of natural gas, in line with the enforcement of various regulations on environmental issues [6]. It is considered, for the time being, that small-capacity fuel cell plants will spread and enter into the market for cogeneration applications, followed by the introduction of large-capacity plants as dispersed power sources from the second half of the 1990s. Also, the general view expresses that, in the initial stage, the introduction of fuel cells will be mainly led by PAFC [7].

As for on-site cogeneration, one prevailing view is that introduction should be made by differentiating from conventional cogeneration systems, taking advantage of the fact that the heat and electricity ratio for fuel cell plants is small. However, to this end, it will be just as important to ascertain application targets after gaining an adequate understanding of the operating characteristics of fuel cell plants, and to establish standard specifications of fuel cell plants that are suitable to proposed application targets. In this sense, the demonstration tests being conducted in various countries should be expanded further into field test projects such as those being carried out in Japan [8].

On the other hand, a gas utility in The Netherlands expressed its opinion that the cogeneration market expansion using conventional devices is a precursor to the market penetration of fuel cells.

As a specific example of an application target, NTT (Nippon Telegraph and Telephone Corporation) in Japan is considering the application of fuel cells to their telecommunication facilities, whereby the direct current electricity generated by fuel cells can be used for telecommunication devices, while the heat produced is used for air conditioning the telecommunication facility. Since such facilities require air conditioning throughout the year, with the preferably long annual operating time using waste heat, this is an extremely suitable case as an application target [9, 10].

Forming an application group of this kind would enable plant standardization and lead to considerable merits, as the number of plants under identical conditions of use would be large.

As for large-capacity dispersed type plants, apart from electric utilities, it is considered that they can be utilized as independent power generation plants for industrial use. Also, it may be possible to adopt them for the effective use of by-product gas and unutilized fuel gas from chemical industries, such as oil refineries and soda plants.

What we can expect from demonstration tests?

Most users and developers concerned with fuel cell demonstration tests are greatly attracted to the environmental compatibility of fuel cells and their potential for conserving resources. Therefore, they are redoubling their efforts towards achieving these goals. As seen in many past examples of developing a new technology, the development and demonstration processes of fuel cells involve several stages during its course.

The first stage is to ascertain feasibility such that a practical scale fuel cell plant can be constructed as a system; the second stage is to grasp the operating characteristics of the plants while establishing durability and reliability along with the necessary improvements to be made; and the third stage is to supply the market with a system that can be operated continuously with a certain degree of confidence from the technical point of view, though the high cost still remains.

For both small-capacity on-site type plants and large-capacity dispersed type plants, one may consider that the first stage hurdles have been cleared, with the possibilities of the system being confirmed and the limitations of using current technology being clarified. Moreover, even conservative views allow to say that the development of PAFC has passed the midpoint in the second stage.

The most important element in the second stage is improving reliability and durability. Assuming the expected lifetime of the cell stack is 5 years of continuous operation, a nominal target of 40 000 h has been set from the early stage of the development. However, as no cell stack has actually been operated for 40 000 h under actual operation conditions, it has not yet been possible to conclude whether the target can be reached. In this respect, it is necessary to keep updating the records of continuous operation time and cumulative operation time.

Although the reliability of cell stacks is vitally important for the reliability of the entirety of fuel cell plants, it is equally important to maintain the reliability of equipment other than the cell stacks. Therefore, it is necessary to confirm that a sufficient degree of reliability can be guaranteed not only for main reactors such as the steam reformer, but also for conventional machineries when operated under actual conditions in fuel cell plants.

In the early period of the second stage, various problems can be identified during demonstration tests and their solutions can be studied, leading to preparation of data to be firmly reflected in future plants. This type of database can be established comparatively quickly when operating several units of the same type in parallel. Thus, the pace of development for small capacity plants should be faster than that for large-capacity plants, as there are a great number of demonstration test plants for small units.

In terms of the above-mentioned objectives of demonstration test in the second stage, troubles should not necessarily be regarded as matters of despair. On the contrary, one can expect that more fruitful results may be obtained from plants with troubles than from those without troubles just by incident or luck. The important thing at this stage of the development is to clearly identify the problems that users experienced during demonstration tests, and to reflect them in future improvements. In addition, there is an absolute need for studies to develop easy-to-use plants that allow end users to operate them with confidence. Also, users who implement demonstration tests must clarify the requirements of the end users after having grasped the characteristics of fuel cells.

In the third stage, fuel cells can be virtually used for practical application, and reliability can be established to a fairly high degree of certainty. Also, the operability of fuel cell plants should be refined even further by users, and attention should be shifted towards activities for opening up markets comparable with the cogeneration market. Since the introduction of fuel cell plants at this stage greatly depends on preceding introduction activities encouraged by policy incentive schemes and the initiatives of major users, greater efforts will be needed for cost reduction by manufacturers so as to make fuel cells economically compatible. For some small-capacity on-site type plants, it is regarded that the development has just proceeded into this third stage.

Evaluation of the characteristics of fuel cells by demonstration tests

In the previous section, the characteristic merits of fuel cells are reviewed. The present section is devoted to study how far these merits have been realized. Here, it is intended to grasp the status of current technology levels by reviewing officially published data, rather than evaluating individual technology, in order to maintain impartiality of the description.

Power generation efficiency

Although fuel cells offer much promise as high efficiency energy conversion devices, the transmission-end efficiency of PAFC plants (HHV basis) is reported to be approximately 35–38% for atmospheric pressure types and 41–43% for pressurized types, respectively. Electrical efficiencies at rate power for various PAFC plants are plotted in Fig. 3. For large-capacity plants of 1000 kW or greater, that are commonly of pressurized type, a transmission-end efficiency of 41.3% has been recorded in recent demonstration tests with a TEPCO 11 MW plant. In addition, the Japanese PAFC Technology Research Association planned a design value of 41.2% for its 5 MW plant. For small-capacity plants, efficiencies of 35–38% have been demonstrated, implying that the efficiency for fuel cell plants is higher than those for rotating-type generators of the same capacity.

Figure 4 shows the load characteristics of power generation efficiency. Although each characteristic curve shows a different profile from that of others, in general there is a tendency for electrical efficiency to decrease at low load conditions. In particular, for some types, it is possible to maintain a constant efficiency for load conditions of 60% or greater, though notable reductions in efficiency occur at levels lower than 60%. It is considered that this efficiency reduction at low load conditions is attributed to the loss due to heating necessary for maintaining the temperature of the cooling water, and to the increase in the ratios of heat loss from the entire plant surface and of required power for the reaction air blower relative to the total thermal input. However, amongst those designed recently, there have emerged some plants that exhibit almost no drop in efficiency, even at partial load.

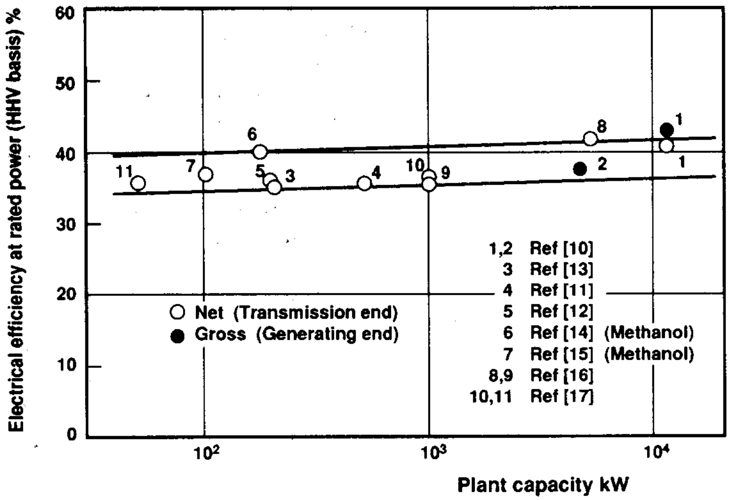

Fig. 3. Electrical efficiency at rated power.

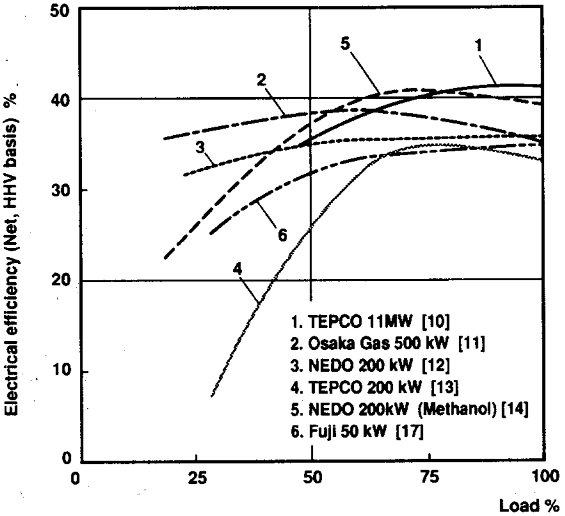

Fig. 4. Electrical efficiency trends as to various demonstration plants.

As the power generation process in fuel cells is of electrochemical reaction, the time-lapse deterioration of fuel cell plants is inevitable, and is more noticeable than those of conventional heat engines. Figure 5 presents examples of time-lapse reduction in fuel cell stack voltage. The most commonly accepted cell-life target in Japan sets the reduction in cell stack voltage at no more than 10% of the initial voltage value even after 40 000 h of operation, though no clear conditions of operation are specified. This is regarded as a technical target for the present moment with the operation condition generally interpreted as that the plant is continuously operated at the rated power condition.

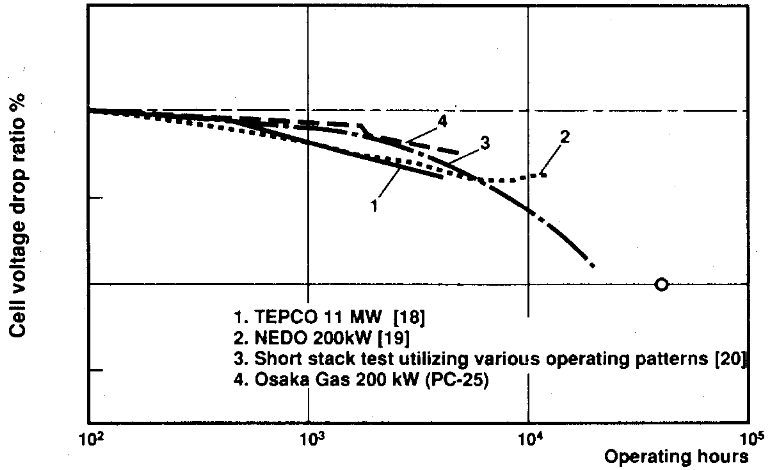

Fig. 5. Durability of cell stacks. Cell voltage drop normalized by initial voltage measured at a cumulative operation time of 100 h.

Officially published data on the time-lapse characteristics of cell stack voltage are limited, and in general the rate of voltage reduction is said to be affected considerably by factors such as operation conditions. These facts make accurate assessment of the data difficult. As can easily be seen from the curves in Fig. 5, the voltage drop process is not simple and is not merely a function of the elapsed time. It can be considered that this is due to combination of influencing factors, as variable elements, such as the number of plant startups and shutdowns and the operating load levels. Therefore, the estimation of the cell stack lifetime at present has a high degree of uncertainty and, thus, a highly accurate prediction method is considered necessary in order to speed up the cycle of developing fuel cell stacks. Ultimately, of course, it is necessary to confirm in actual demonstration tests that the target time can be achieved.

Overall efficiency and heat utilization

For PAFC plants, it is a common practice to utilize high temperature heat discharge from cell cooling water or CO shift converter cooling water (as steam: 160–170 °C) or low temperature heat discharge from cathode exhaust air or reformer combustion exhaust gas (as hot water: 60–70 °C). The utilization of this heat enables the overall heat efficiency to reach 70–80%. However, it is true of any cogeneration system in general, that this can only be realized when the heat demand change occurs in an ideal pattern along with power demand change.

The following are examples of the method to introduce fuel cell power plants at demonstration test sites where heat utilization is considered:

(i) to design the capacities of electric power and heat output from fuel cells smaller than the minimum demands at the site, and

(ii) to install fuel cell plants in a district heating and cooling supply plant in which the existing heat storage tank can be utilized.

Some application examples are given below. Osaka Gas has installed a 500 kW plant by Fuji Electric at their Torishima Works, with a view to targeting both industrial and district cooling applications in the future. This plant covers approximately 5% of the contracted electric power capacity of the entire works, and the steam generated is supplied to the existing steam supply line and utilized within the works. However, the hot water produced is not utilized at present.

Tokyo Gas has introduced a PC 25 from ONSI, and integrated it into a cogeneration system for the Tokyo East 21 Project, which aims at district heating and electricity supply. In the development area of this project, there are office buildings, a hotel, a department store and a shopping mall. The power generation capacity is 800 kW in total, with two 300 kW gas-engine generators and a 200 kW PAFC plant. The waste heat from the fuel cell plant is recovered for hot water supply [21].

Figure 6 shows the load characteristics of thermal efficiencies for three on-site type fuel cell plants. As almost no data on heat utilization have been published, the presented data here may not be regarded as representative of general characteristics for fuel cell plants. The data consist of groups of three curves for total thermal efficiency including both heat and electricity generation, total heat utilization efficiency, and high temperature heat utilization efficiency. Here, the total heat utilization efficiency is a sum of the low-temperature and high-temperature heat utilization efficiencies.

In general, as the heat utilization efficiency tends to drop at low load conditions, operation at near rated load conditions is required in order to maintain a high total thermal efficiency. This tendency is interpreted as being that the decrease in the amount of heat carried by fuel cell cooling water occurs as a result of reduced heat generation in the electrode reaction at a low load condition. For such a low load condition, which is equivalent to a low current density condition, various resistance losses in the electrode decrease.

In addition, when considering cases of heat utilization primarily made up of cooling demands, recovering high-temperature waste heat becomes important. Also, it must be noted for such cases that, in fact, hardly any high-temperature heat discharge at low load and that the obtainable high-temperature heat discharge is only about 10–20% of the total thermal input even at a rated load condition.

In order to meet the demand for cooling purposes, it is considered that the steam used for the fuel reforming process can be reduced, with the saved steam being

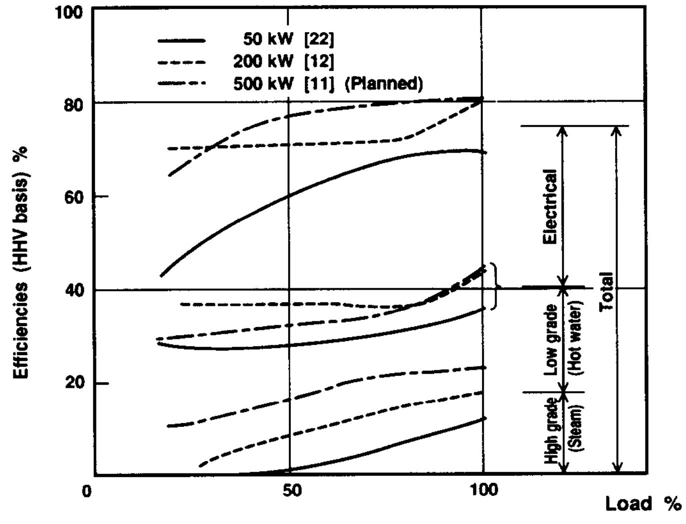

Fig. 6. Combined heat and electricity utilization.

allocated to the high-temperature heat for heat utilization instead. Normally, for natural gas as primary fuel, the steam reformer is operated at a steam/carbon ratio or S/C, of 3.5/4.0 so as to avoid carbon formation inside the reformer tubes, while a reforming catalyst enabling operation at S/C of 2.5 has been recently developed [23].

Environmental adaptability of fuel cells

NO_x

As shown in Table 2, the amount of NO_x emission is small with values never exceeding 10 ppm under rated conditions. This can be explained by the fact that most of the oxidation reaction takes place in fuel cells and that formation of thermal NO_x in the reformer combustor is suppressed by reduced flame temperature due to low-calorie, low-oxygen combustion using anode exhaust gas consisting of unreacted hydrogen and cathode exhaust air with a depreciated oxygen content.

For pressurized systems such as the Goi 11 MW plant, the origin of NO_x generation in addition to that of the reformer is an auxiliary burner for the turbocompressor system, though the emission can be still maintained at a sufficiently low level even with inclusion of this burner.

SO_x

The emission of SO_x is extremely low, and is normally at a level below the detectable limit. This is due to the fact that natural gas having a low sulfur content is widely used, and that desulfurization treatment is performed as a countermeasure against the sulfur poisonning of reformer catalyst.

CO_2

As long as hydrocarbon fuels are used as primary fuel, the amount of CO_2 produced is inversely proportional to power generation efficiency. Accordingly, the fuel cells are superior to gas turbines and gas engines that give lower efficiencies. Also, when heat utilization is considered, CO_2 production by a cogeneration system based on fuel cells becomes smaller compared with those by the combined utilization of both commercial electric power and boiler-supplied heat.

Soot and dust

As the fuel used for combustion in the reformer combustor is mainly composed of hydrogen, soot generation rarely occurs. Also, a filter installed at the air intake protects the fuel cells from being contaminated by airborne dust. These facts result in substantially no soot or dust emission from the plant.

Noise and vibration

For atmospheric pressure type plants, the air blower is the only rotating machinery in the plant. Even for the pressurized type, as the capacity of rotating machinary for air compression per unit power generation is much smaller than that of turbine generators, noise and vibration problems are less significant.

Diversity of fuels

It has been pointed out that various gaseous and liquid fuels can be used as primary fuel for PAFC plants. The majority of demonstration tests have used natural gas, which is commonly supplied as city gas. With a view to installing fuel cells to areas without access to city gas, studies are being made on the utilization of liquid fuels such as kerosene, methanol and naphtha. Also, utilization of unused resources, such as land-fill gas and biogas, is being considered. Furthermore, the use of hydrogen produced by electrolysis of water using electricity from photovoltaic power generation is being studied. So far, no research work is available for non-LNG-type city gas or byproduct gas from chemical plants.

Although the steam reforming process is used for the production of hydrogen from hydrocarbon fuels, the reaction for some fuels takes place at low temperatures (250–300 °C), and for others at high temperatures (700–800 °C). Depending on the reaction temperature and the potential of hydrocarbon fuel to form carbon deposit, either nickel, copper or rare metals are selected as the reforming catalyst. The sulfur content in primary fuel must be reduced as sulfur poisons-reforming catalysts and decreases catalyst activity.

Although the structure of the fuel processing system varies depending on fuel handling procedures, examples of demonstration tests already exist for principal fuel types. Therefore, it can be considered that the introduction of a diversity of fuels is possible by selecting an appropriate fuel processing system already available, cf., Table 4.

As for higher hydrocarbons contained in LPG, such as butane and propane, the fuel processing system for LNG can be used without modification, though utilization of rare metal-based catalysts are being studied with a view to reducing the occurrence of carbon formation on the catalyst surface [24]. In tests of a 50 kW plant at the Tohoku Electric Power Company, it is reported that the thermal efficiency for an LPG system was identical with that for an LNG system [25].

As methanol contains no sulfur compounds, no desulfurizer is necessary. Also, as the steam-reforming reaction can take place at low temperatures (250–300 °C), CO concentration in the reformed gas is low as can be explained from the equilibrium compositions. Therefore, CO shift converters may be omitted. However, care must be taken in controlling the catalyst temperature; for this reason the heating method using heat carrier is adopted [26]. As examples, in Japan, the Hokkaido Electric Power Company demonstrated this with a 100 kW plant [15] and the Okinawa Electric Power Company with a 200 kW plant installed on an offshore island [15].

The utilization of oil products as fuel is considered as follows. The problem with kerosene is reducing its sulfur content (typically 10–100 ppm). In research conducted at the PEC (Petroleum Energy Center), the sulfur content was successfully reduced to 0.1 ppm with an in-house fuel processing system. In addition, for naphtha it is possible to use a conventional desulfurizer–reformer system; the Nippon Oil Company has already demonstrated this with their 200 kW plant [28].

The Solar–Wasserstof–Bayern (SWB) Research Institute, in Germany, is carrying out a demonstration test on a fuel cell system combined with photovoltaic power generation. Hydrogen is produced by electrolysis of water using power generated by solar energy, with the produced hydrogen utilized in the fuel cells [29]. However, it is questionable whether PAFC would be suitable for this purpose.

Land-fill gas [30] and biogas [31] are being studied. In the former, the removal of halogens and dust is an important consideration, besides the necessity of desulfurization.

NTT has developed and demonstrated a multi-fuel system which enables the use of three different fuels: city gas, LPG, and methanol [32].

Reliability and maintainability

Status of plant reliability

Figure 7 shows the average monthly operating hours during a demonstration test period as against the year of plant installation. Here, the average monthly operating

TABLE 4

Diversity of fuels used in PAFC plants[a]

Type of fuel	Desulfurizer	Reformer	Shift converter	Features	Examples of demonstration test
Hydrogen	–	–	–	Hydrogen-energy utilization technology (solar power generation/hydrogen production by water electrolysis)	Solar–Wasserstof–Bayern, Research Center, Germany, 80 kW stack
LNG	○	○	○	High-temperature steam reforming using Ni catalyst Odorizer–desulfurization required For pressurized system, high- and low-temperature shift converters are needed Supplied by LNG base or city gas pipelines	Many cases for on-site type Pressurized type, TEPCO 11 MW
LPG	○	○	○	High-temperature steam reforming using Ni or rare metal catalyst Used in non-city gas areas Measures to avoid carbon formation required	Tohoku Electric Power Company, 50 kW Showa Shell Sekiyu, 100 kW
Methanol	–	○	–	Low-temperature steam reforming using Cu catalyst Fuel vaporizer and heat-carrier heater needed Indirect heating of the heat carrier generally applied	Hokkaido Electric Power Company, 100 kW Okinawa Electric Power, 200 kW
Naphtha	△	○	○	Simple desulfurizer possible due to small amount of sulfur	Nippon Oil, 200 kW
Kerosene	○	○	○	Fuel supply possible with existing distribution system Desulfurization necessary due to sulfur content	Nippon Mining, 100 kW

Others: City gas (non-LNG), land-fill gas, biogas, byproduct hydrogen, etc.

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[a] Symbols: (○) necessary; (△) necessary, but simplified, and (–) unnecessary.

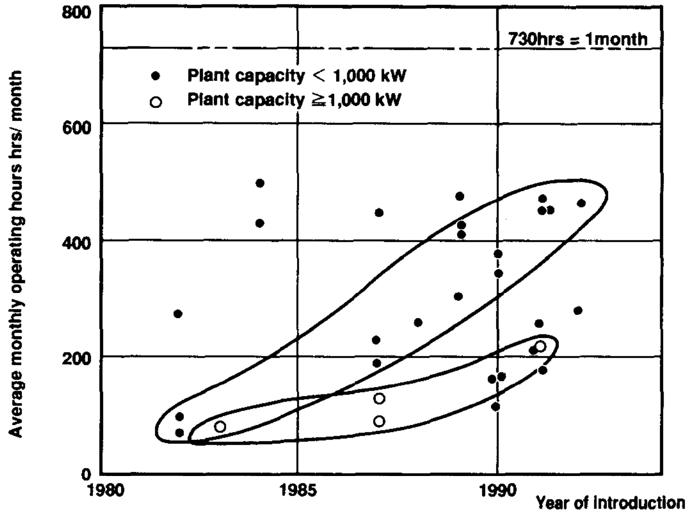

Fig. 7. Relationship between average monthly operating hours and year of introduction.

hours was obtained simply by dividing the cumulative operation hours by the number of months in a power generation test period. Also, the test period here includes periods of scheduled shutdown for plant inspection purposes as well as periods of plant shutdown due to breakdowns and troubles. Although, for this reason, care must be taken in adopting this characteristic value as an absolute index for plant reliability, it may be observed that there has been a general tendency towards increasing reliability over the past ten years.

For small-capacity plants of less than 1000 kW, the Figure shows that some plants were in operation for approximately 70% of the test period, and the rate of increase in the average monthly operation hours is larger than that of large capacity plants. We may conclude that the rate of development is faster for small-capacity units due to the large number of demonstration test opportunities available, and that we may envisage, with reasonable confidence, that their introduction for practical use will be realized in the not too distant future.

Figure 8 shows plots of the latest data for continuous operation times and average operating load levels, respectively. We can observe a tendency in the continuous operation time to be proportional to the average monthly operation hours. The average operating load level here is calculated by dividing the amount of generated power by the product of the cumulative operating hours and the rated power generation capacity. Described is the load level at which operation is performed on average. In most demonstration tests, although the average load level exceeds 50%, it can be considered that plants were at partial load operation for a considerable number of hours.

As for ONSI PC 25, a 200 kW plant, a number of 27 first-lot production units were placed in operation in various locations as of the end of June, 1993, and recorded an average plant availability of more than 90%, excluding times of scheduled shutdown periods [2]. Also, the maximum cumulative operating time of ~7000 h and the maximum continuous operating time of ~5000 h have been reached.

Osaka Gas has installed a PC 25 at Umeda Center Building. The plant recorded the cumulative operation time of 6003 h and the continuous operation time of 5122 h as of July 12, 1993, with operation being continued after this time. Accordingly,

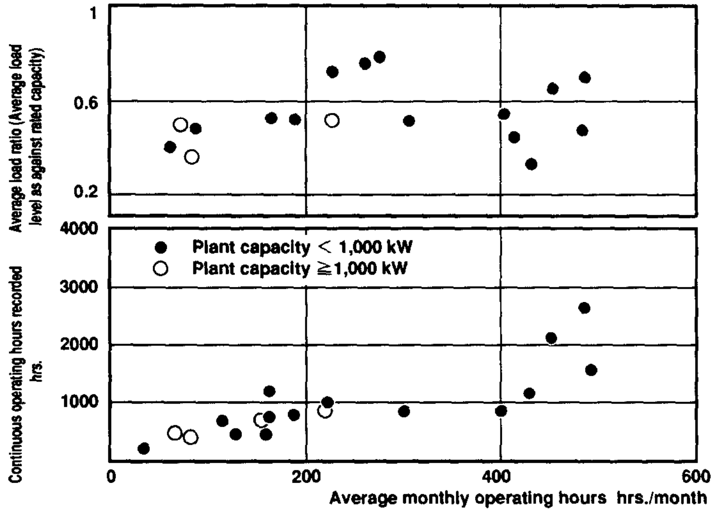

Fig. 8. Continuous operating hours recorded and average operating load levels.

this maximum continuous operation time record surpassed the previous record of 4230 h, which Kansai Electric Power Company achieved with its Fuji 50 kW plant installed at the Rokko New Energy Center in April 1993. Thus, the reliability of small-capacity plants is progressively being improved.

Troubles and their eradication

The number of troubles occurred can be used as a reliability index. The New Energy Foundation in Japan carried out a survey on plant troubles and found that the number of occurrences was considerably reduced for units installed in 1992 when compared with those installed before 1989, i.e., the average number per one unit was 43.3 previously, while reduced to 3.3 in 1992. Also, the number of troubles occurred per 1000 h of operation decreased from 5.6 to 2.2, indicating that plant reliability has improved. Also, it is reported that the equipment prone to troubles is changing from the cell stack and reformer at the initial stage to peripheral equipment and system related matters.

Table 5 shows the causes of breakdown and troubles occurring in fuel cell plants. These are all technically soluble, and no serious breakdown exists.

An example of breakdown statistics is given in Table 6. The data were taken from the demonstration testing of IFC-made PCX, a 200 kW plant for on-site use, conducted by the Tokyo Electric Power Company. Partially due to the fact that the PCX is a prototype model, a number of initial troubles occurred at the beginning of the operation. However, the frequency of trouble occurrence has decreased in proportion to the increased operating hours, and the number of occurrences per 1000 h has decreased from 5 to 1.9. As a whole, many instances of breakdowns and troubles stem from instrumentation, steam leakages and electrical parts. Also, there occurred a decrease in the performance of cell stacks and the corrosion of heat exchangers, which are considered unique to PAFC plants. Though the occurrence of the same troubles being repeated tends to decrease due to the countermeasures taken, new problems are beginning to arise as the hours of operation are further extended.

TABLE 5

Potential causes of breakdowns

Electrical	
Fuel cell stack	Leakage, material breakage, operation, handling and deteriorated characteristics
A.c./d.c. converter	Cooling fan breakdown, d.c. ground fault
Control system	Sensor breakdown, control software changes, faulty parts
Process devices	
Fuel processing system	Reformer durability, catalyst life, faulty flame detection, faulty valves
Peripheral devices/piping	Faulty valves, pipe leakage, machinery breakdown, clogged filter mesh, rotor vibration
Cooling water system	Poor water quality

Of the breakdowns occurred at TEPCO's 11 MW plant, 25% are due to leakage of fluids from flanges, valves, main devices, etc., 19% are due to the vibration of rotating machineries, and 18% are due to faulty sensors in the control system and breakdowns related to control valves. Thus, there are few phenomena which are unique to fuel cell plants. As for main troubles relating to cell stacks, there was an incident in which a part of the corners of cell stack were damaged electrochemically. As this was attributed to the composition of combustion exhaust gas from the reformer, which was used as purge gas for the containment vessels of the cell stack, plant operation resumed after improving the vessel purge system.

By conducting demonstration tests, the cause of breakdowns and troubles are steadily being removed. Also, as problems that were not considered at the time of design are manifesting themselves, this data can also be reflected in future designs having improved reliability.

Cell stack improvements

Requirements from users regarding the cell stack are described below. The first item is to increase the power output per cell stack, taking into account the scale limits upon transportation. Reducing the number of cell stacks is considered important for improving compactness and reliability. For example, the power output of a cell stack was 240 kW for the former 4.5 MW plant, while it is now 670 kW for the latest 11 MW plant. Also, the Amagasaki 5 MW plant uses 860 kW stacks.

The key issues in developing cell stacks are to increase the power output density, or current density, and to prevent cell performance from deteriorating. Increased power output density enables a compact and lightweight cell stack design, and thus leads to cost reduction. Therefore, fundamental research work has been carried out for this purpose and countermeasures have been implemented [33, 34].

In Fig. 9, current densities at rated output for cell stacks used in some plants are plotted as against the year of installation. Note that some of the plots are target values. As there are differences in pressure conditions and the definition of the effective cell area, it is not appropriate to compare and evaluate individual data, though as an overall trend certain improvements can be observed.

TABLE 6

Breakdown of trouble areas of TEPCO PCX in Shibaura DHC

Period	Mar. 1989–Mar. 1990	Aug. 1990–June 1991	July 1991–July 1992	Aug. 1992–Jan. 1993
Electrical equipments				
Instrumentation sensor	11	6	1	2
Control device	7	2	4	0
Controller	4	1	0	2
Inverter	2	1	2	3
Electrical parts	2	1	3	1
Heater, short circuit	0	1	0	0
Faulty wiring connection	2	2	0	0
Process equipments				
Gas leakage in pipe joint, etc.	6	0	0	0
Water leakage in pipe joint, etc.	6	4	5	0
Rotating machineries	4	0	0	0
Flame extinction, ignition failure	2	0	2	0
Deterioration of cell stack	0	1	1	0
Reactor catalyst	1	0	0	0
Internal leakage of heat exchanger	0	0	1	0
Drop in quality of cooling water	0	0	1	0
Total	47	19	20	8
Number of times per 1000 h	5.0	2.4	2.3	1.9

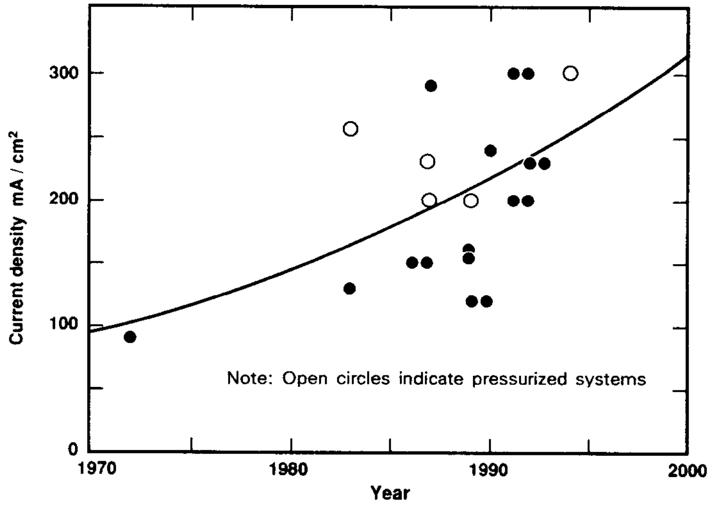

Fig. 9. Status of increasing current density.

TABLE 7

Means of improving cell output current density and durability

- Improving cell output current density
  - Reducing activation polarization
    - High activation of electrode catalyst, particularly for air electrode
    - Optimizing hydrophobicity of electrodes
  - Reducing internal resistance
    - Lowering resistance of material and reducing thickness of electrodes
    - Reducing resistance at contact surface
- Improving life characteristics
  - Preventing catalyst sintering
    - Use of platinum alloy as electrode catalyst
  - Preventing corrosion of carbon materials
    - Creating a favourable operating atmosphere by improving gas flow, fuel starvation and increasing steam quantity avoided
  - Preventing phosphoric acid deficiency
    - Controlling of phosphoric acid, controlling stored volume, and distribution of phosphoric acid
  - Improving gas sealing

At present, cell performance has reached a current density of 200–250 mA/cm^2 and an output density of 0.13–0.16 W/cm^2 for small-capacity plants, and 200–300 mA/cm^2 and 0.15–0.22 W/cm^2 for large-capacity plants, respectively. It is considered that more emphasis will be placed on extending cell life and improving its stability from now on, rather than improving the current density performance. Means of improving cell characteristics are shown in Table 7, though more detailed descriptions are available in the literature by cell manufacturers [33–36].

In relation to reducing activation polarization, the effects from the type of air electrode catalyst on cell performance is presented in Fig. 10. The increase in cell voltage due to changing the catalyst type implies that higher current density can be obtained for that type when the cell voltage level is fixed. However, high-activity cells does not mean that a longer cell life can be obtained. Also, the hydrophobicity of electrodes has an undeniable influence on cell performance [34].

In order to reduce the height of the cell stacks, the effective cell area must be increased, the cell elements must be made thinner and the number of cooling plates must be minimized. For the latter, it is required that an electrode material be created, which has high thermal conductivity so as to remove the heat generated in the electrode reaction, as well as realization of high gas transmittance necessary for maintaining high current density. For this reason, high performance electrode materials are being developed and the status of their development, as an example, is shown in Fig. 11 [36].

It is also important to obtain a uniform temperature distribution within the cell stack. Figure 12 shows an example of computer analysis for cell temperature distributions [35].

Note that, in order to increase the perfection of cell stack, some other elemental development activities are required, and that the development of cell stack will be eventually carried out by integrating the elemental studies and developments.

Reformer improvements

The steam reformer is regarded as an important reactor in the fuel processing system, and the major development items are to increase its thermal efficiency and compactness. Although the steam-reforming process is considered as an established technology in the chemical industry field, there are some additional restrictions when applying the technology to fuel cell plants. For example, there are the facts that a high response to load change is required and that anode exhaust fuel and cathode exhaust air are used for combustion in the reformer burner.

There are two different types of reformer; the multi-tube type having multiple reaction tubes contained in a reactor vessel, and the single-tube type having one single large diameter reaction tube, though most reformers are of the multi-tube type. The

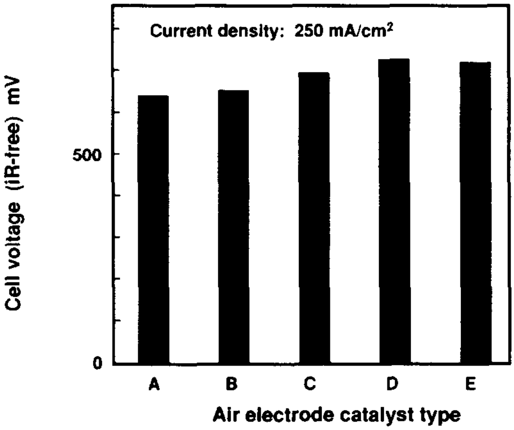

Fig. 10. Effect of air electrode catalyst type on cell characteristics. IR-free: cell voltage corrected for internal resistance [36].

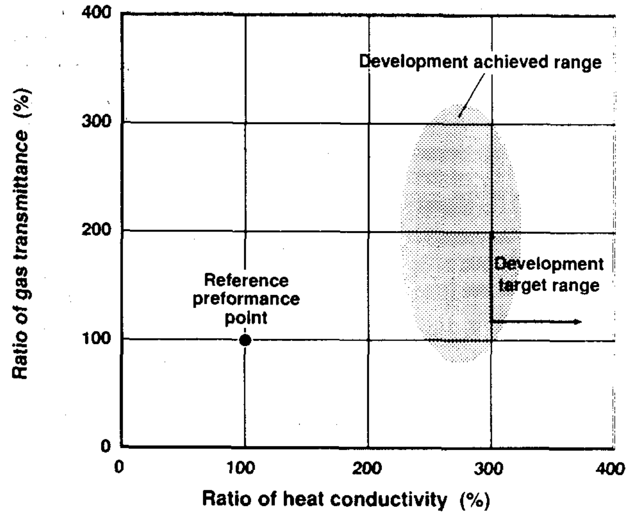

Fig. 11. State of electrode substrate development [37].

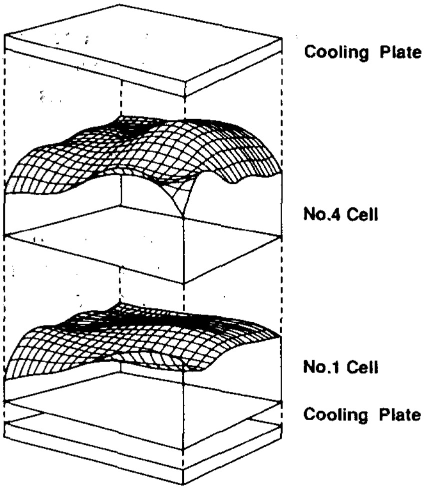

Fig. 12. Results of calculation of cell temperature distribution in planes (670 kW stack) [35].

single-tube type was designed by Haldor–Topsøe of Denmark, and has been adopted in the 1 MW plant in Milan, Italy, and in the 5 MW plant in Amagasaki (Japan). Although this type is highly compact in terms of vessel volume, it is considered that accommodating such a tall reactor inside buildings and scaling up to a larger capacity unit are problematical points. For the multi-tube type, it is vital to maintain a uniform temperature level for all reformer tubes.

Figure 13 shows the compactness factor of the reformer vessel which is defined as the vessel volume per unit power generation capacity. It is apparent that compactness increases in proportion to the plant power generation capacity. However, experience

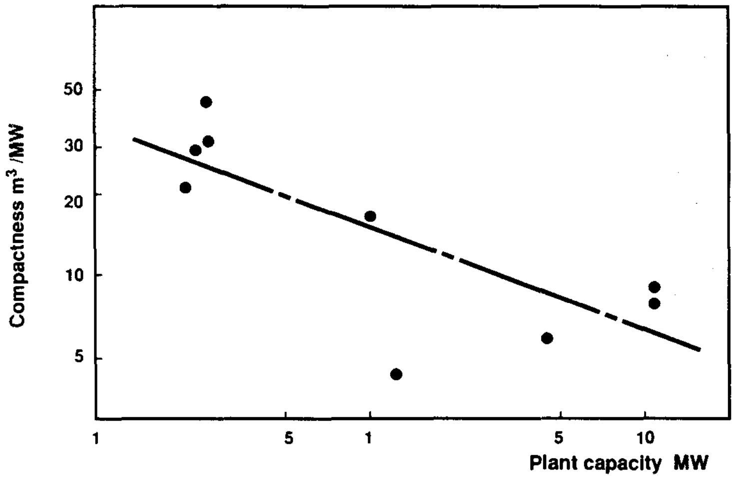

Fig. 13. Compactness factors of reformer vessel: vessel volume/plant capacity.

has shown that when compactness is pursued excessively the reformer tubes tend to undergo thermal damage.

As for the durability of reformer catalyst, provided that the sulfur content of primary fuel is sufficiently removed and no drastic deterioration due to mis-operation occurs, considerably long hours of catalyst life can generally be expected. However, in the TEPCO 200 kW plant, a reduction in methane conversion has been observed as the cumulative operation hours increase, so that the evaluation of catalyst life must be carefully made based on field data covering a sufficiently long period.

As the compactness and the catalyst life are in a trade-off relationship in some respects, the evaluation of compactness is possible only after catalyst life is ensured.

Technical problems

Although small-capacity PAFC plants are considered to have been in approachable level of practical application in terms of technology, there are still several problems to which solutions must be found. The technical problems generally quoted are listed in Table 8. Though these problems have existed since the initial stage of development, they remain items of consideration for further improvements.

The reliability of small-capacity plants has been improved to a considerable extent as described so far, so that it is important at present to concentrate on reducing their cost and assessing long-term operation data continuously. Large-capacity plants are less reliable than the smaller units and require further improvements. For this purpose, demonstration tests should be carried out with a view to seeking out trouble areas and finding their solutions, and eventually verifying plant reliability.

Also, progress must be made in the optimization of the plant system so as to simplify plant equipment and thereby achieve further increases in efficiency for dispersed power plants. As concrete proposals, a fuel cell power plant combined with a newly developed gas turbine [29] and a large-capacity atmospheric pressure system enabling system simplification [37] have been presented. For the latter, bottoming cycle power generation is also proposed as an option in order to utilize heat from plants installed in locations where no heat demand exists. For on-site type plants, there is a strong

TABLE 8

Technical matters for improved PAFC plants

Reliability
Extending cell stack life
Improving reformer reliability, extending reformer tube life
Reducing number of plant breakdowns
Operability
Shortening startup time
Improving response to load changes
Maintainability
Establishing a preventive safety system
Simplification and shortening of maintenance and checkout, (maintenance-free operation)
Economy
Improving plant efficiency
Reducing equipment and maintenance costs

demand for a reformer to operate at a low steam/carbon ratio, in order to extract larger amounts of steam.

As for the basic technology, there is a need to establish methods of evaluating the lifetime of fuel cells. In order to realize this, close cooperation among users and manufacturers and data publication are necessary. This type of collaboration would effectively provide data necessary for clarification and description of the cell deterioration mechanisms, and defining the typical operation conditions of the atmosphere in which fuel cells are actually used. Furthermore, with a view to practical application, it is important that the requirements by end users be clarified and reflected in improvements.

Conclusions

The technical level of PAFC plants is now becoming clearly outlined, and the expectation for fuel cells has turned into a more realistic and concrete image than before. Despite some technical problems still remaining, there has been an accumulation of data as to the know-how on the possible application targets and the method of operation, now that we have a better understanding of the potential of current PAFC technology.

An engineer from a construction company has expressed his thoughts on fuel cells in that: '...intuitively, there is a very good match between general construction and fuel cells'. By this, he means that fuel cells are endowed with noise-free operation and cleanliness, while for conventional heat engines noise and vibration are suppressed by force. We may consider that time has progressed to a point whereby the technology, especially for on-site plants, is ready for being given the shape leading to actual use by users who are not specialist of fuel cells.

Although it is always challenging to introduce a new technology to the existing market using traditional technology, fuel cells can make the best use of their merits over conventional equipment such as heat pumps and gas-turbine generators. One should remember this when developing fuel cell plants.

In order to realize the installation targets being set by various organizations, it is necessary to repeat the sequence of setting interim targets, which are achievable based on the current technology, and achieving them. Therefore, sufficient understanding of the status of the technology at the time, is required. By clearing these intermediate hurdles, the technology should be able to move on to the final goal.

For small-capacity units, it is vitally important to maintain the number of units manufactured and installed so that the fuel cell market can be firmly established. This should also help indirectly the development of large-capacity plants.

Emphasis should also be placed on the promotion of information exchange among users and manufacturers, as this is one of the most effective means of enabling the early realization of the new technology which is necessary for the preservation of our environment and resources. In conclusion, it is our responsibility to hand on this new technology to the next generation.

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