A perspective on PAFC commercialization by Fuji Electric

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Abstract

The technology development focusing on fuel cell commercialization is progressing at a steady pace in Fuji Electric. Since the start of our PAFC development, we have supplied 27 PAFC demonstration plants with a total capacity of 2100 kW. This includes 1 set of 1000 kW LNG-fueled, 1 set of 200 kW methanol-fueled and 15 sets of 50 kW packaged LNG and naphtha-fueled PAFC plants. An additional 63 plants with a total capacity of 9700 kW and ranging from 50–5000 kW are anticipated.

1. Introduction

The overall activities of PAFC in Fuji are shown in Table 1.

2. 5000 kW PAFC plant

Based on the construction and operation experience of the 1000 kW plant completed in 1989 under the Moonlight Project, Fuji Electronic plans to construct a 5000 kW pressurized plant for electric utilities. The PAFC Technology Research Association has been established to manage the construction and operation of this plant under the control of NEDO (New Energy and Industrial Technology Development Organization).

The plant is based on the following fundamental concepts:

- a dispersed power station in an urban area
- equivalent economic efficiency to the conventional power plant taking into account credit for urban location
- sequential and unattended operation based on WSS (weekly start and stop)
- town gas supplied by pipeline
- environmentally clean plant (low noise, low vibration and low emission)
- compact layout intending to reduced footprint, reduced construction time, reduced siting cost and easy transportation
- co-generation plant
- modular design (unit capacity: 5 MW)

The planned outer view of a 5 MW plant is shown in Fig. 1.

Items to be developed for the early construction of this 5 MW plant are:

- large sized electrode with high performance (1 m^2 size class)
- large capacity reformer
- new air pressurizing and power recovery system
- compact plant design

0378-7753/92/$5.00

TABLE 1

Fuji Electric activities of PAFC

(1) Government project	
1000 kW Kansai Electric	2035 h operation (dismantled)
200 kW Okinawa Electric	8400 h operation
50 kW×14 set Kansai Electric	(some operating, some manufacturing)
5000 kW Kansai Electric	now designing (1995 delivery)
100 kW LPG Center	now designing (1993 delivery)
(2) Gas Company	
50 kW×9 set	now supplying (1990–91 delivery)
100 kW×7 set	now manufacturing (1991–92 delivery)
50 kW×50 set equivalent	now preparing (1991–92 delivery)
(3) Electric Company	
50 kW×6 set	now negotiating
(4) Oil Company	
50, 100 kW×each 1 set	now operating (1990 delivered)
50, 100 kW×each 1 set	now negotiating
(5) Overseas project	
(a) Stack only	
25 kW×2 set	KTI (Netherlands, Italy) (1989 delivered)
80 kW	SWB through KTI (1991 delivered)
(b) Plant	
50 kW×5 set (contracted)	4 European customers (1991–92 delivery) EGAT (Thailand) (1992 delivery)
50 kW×3 set (negotiating)	USA, South East Asia
(c) Bus application	
50 kW×3 set	US-DOE Project (1992, 93) (under planning)

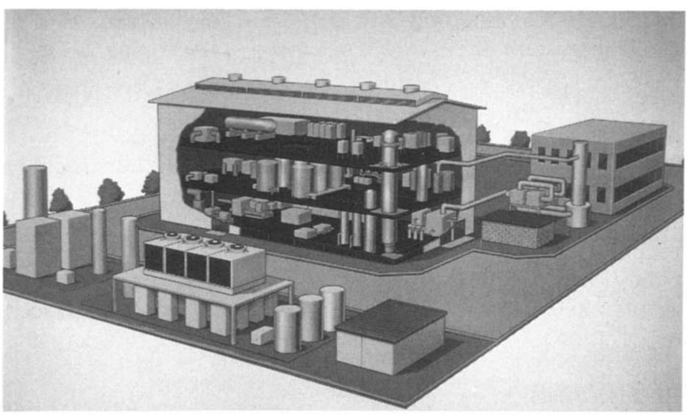


Fig. 1. Artists impression of 5 MW dispersed PAFC plant.

Table 2 shows the planned specification of a 5 MW plant. The plant has 6 stacks having a capacity of 860 kW per stack. The key performance of a stack is shown in Table 3. The cell performance is very much improved and the power density of the

TABLE 2

Planned specification of 5 MW dispersed power plant

Item	Planned specification
Purpose	dispersed power plant
Rated output (MW)	5 (sending end)
Electrical efficiency (%)	41.2 (HHV base) (sending end)
Type	water cooled PAFC
Cell working conditions	200 °C/6 kg/cm^2 g
Range of output (%)	30–100
Start-up time (cold/hot) (h)	6/3
Load response (%/min)	20
Raw fuel	town gas (13A)
Environmental conditions	
NO_x (ppm)	<10 (O_2: 7%)
Noise (dB)	<55 (at plant boundary)
Key components	
No. of stacks	6 (3 series, 2 parallel)
Inverter	5 MW GTO type
Air pressurizing system	motor driven compressor
Layout	indoor type, 3-floor building

TABLE 3

Key performance of proposed stack for 5 MW plant

Stack output (kW)	860
Cell voltage (V)	0.746
Current density (mA/cm^2)	300
Working conditions	6 kg/cm^2 g, 200 °C
Cell size (effective)	8000 cm^2 class
Electrode structure	ribbed substrate
Cooling method	water cooling

new stack is about 1.6 times of that developed in 1986 for our 1 MW plant. By request of the Electric Utility Council, Fuji has been conducting the endurance test for the advanced stack (15 cells, 3600 cm^2 size).

Total operation hours so far are more than 12 600 h including 55 of start and stop cycles, 730 times of load change (as of Mar. 1991). The first addition of acid was performed after 10 000 h operation. The degradation rate for the first 5000 hours was 1/3 of the total expected degradation rate necessary to achieve 40 000 h of life. The rate for the next 5000 h was 1/5. The total of operation hours targeted is about 20 000 hours which will allow a confidence level to estimate life.

This system adopts the new motor driven air compressor and the turbine driven generator to recover the electric power from the exhaust gas of the reformer (see Fig. 2). The compressor and turbo-generator have a separate shaft which differs from that of the common-shafted turbo-compressor system. The advantage of this system

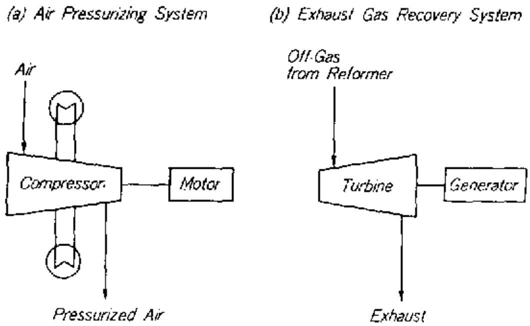


Fig. 2. Air pressurizing system and energy recovery system.

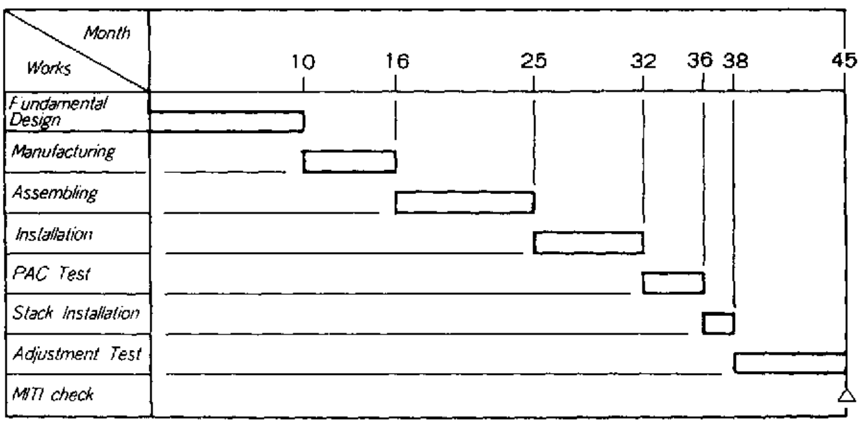


Fig. 3. Proposed construction schedule of 5 MW PAFC plant.

is characterized by the improved controllability of the total plant due to the separation of connections between the reformer loop and the fuel cell loop. Load response is also improved.

The total construction period is proposed to be about 45 months as shown in Fig. 3.

3. 50 kW/100 kW on-site PAFC plant

The number of 50 kW and 100 kW packaged co-generation plants to be demonstrated and planned is more than 70, including four sets of 50 kW for European countries. The total capacity which can be realized for pre-commercial demonstration is about 5350 kW.

The development of the co-generation packaged plants was initiated and supported by Tokyo Gas Company. Encouraged by promising operating results of the first plant, there are currently ten such units under operation in gas and electric companies in Japan.

Figure 4 shows the 6 sets of 50 kW plants installed in the Rokko Testing Station, Kansai Electric Company, near Osaka. These plants are now in operation under various

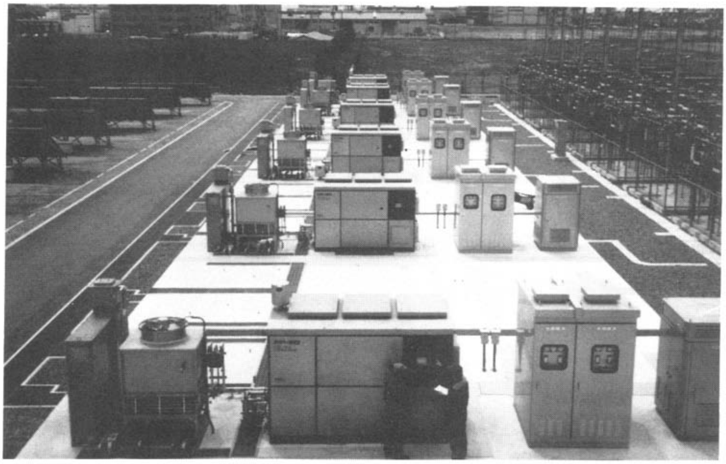


Fig. 4. General view of 50 kW PAFC plants at Rokko Testing Station (near Osaka).

TABLE 4

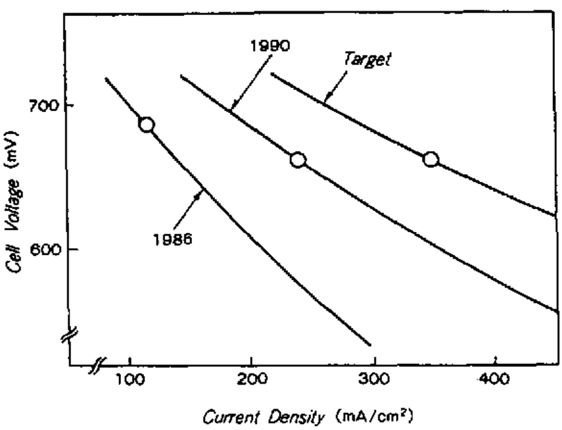
Key specifications of 50 kW PAFC on-site plant

Item	Specification
Purpose	on-site co-generation
Type	water cooled packaged type PAFC (indoor/outdoor)
Output (kW)	50 (net)
Electrical efficiency (%)	40 (LHV) (net)
Total efficiency (%)	80 (LHV)
Heat recovery (°C)	65 outlet/40 inlet water
Fuel	town gas (13A) (LNG) inlet pressure 100 ~250 m/m Aq
Operation	unattended fully automatic operation independent and/or grid connected
Load response (%)	±50 (instantaneous)
Start-up time (cold) (h)	3 (with electrical heater) 1.5 (with start-up boiler)
Start-up power (kW)	30–35 (with electrical heater) 7 (with start-up boiler)
Range of output (kW)	0–50
Water supply	not necessary
NO_x (ppm)	<10
Weight (ton)	5
Dimension (m)	2.9 (l)×1.6 (w)×2.2 (h)
Footprint (m^2/kW)	0.09
Power density of plant (kW/m^3)	4.9

testing conditions including some fault or transient operations (operating hours are now 1500 h–6000 h). Table 4 shows the key specifications of this 50 kW PAFC plant. The power density of 4.9 kW/m^3 is one of the highest attained in the world. Such a high power density is achieved mainly by the compact design of the fuel cell stack, reformer and inverter. As to the fuel cell stack, the power density was doubled compared to the first prototype delivered to Tokyo Gas in 1984 (see Fig. 5). This was obtained through the improvement of a high performance electrode and separator, and by decreasing the number of cooling plates.

Improvement of the reformer is another important factor in reducing the plant size. Figure 6 shows the comparison of reformer size between the first model (1988 technology) and the second model (1990). The volume and weight of the second model was reduced to one-half and one-third, respectively. The comparison of key performance and compactness of these two models is shown in Tables 5 and 6, respectively. The endurance test of this second model reformer combined with the fuel cell stack has been conducted under various operational conditions in our research facility.

The compact design of the inverter offers a substantial reduction to plant size. The second generation inverter is based on a high frequency system using a high frequency d.c.–d.c. convertor and IGBT. Through these modifications the volume and weight of the second generation inverter was reduced to one-third and one-fifth compared to the first model. This high frequency inverter also contributes to substantial noise reduction. Figure 7 shows a non-interrupting switchover from independent operation to grid connected operation demonstrated in this inverter system.



(Normal Pressure)

Performance	Current (mA/cm²)	Voltage (mV)	Power Density (mW/cm²)	Ratio —
1986	115	683	80	1
1990	240	660	160	2
Target	350	660	230	3

Fig. 5. Increasing of cell power density.

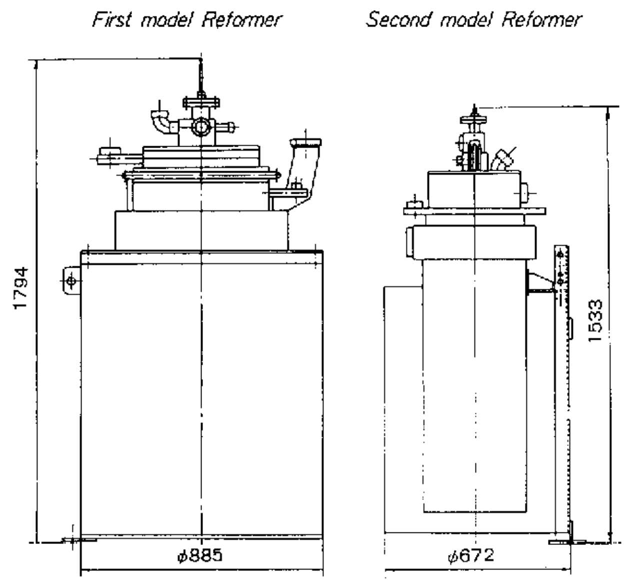


Fig. 6. Comparison of reformer size.

TABLE 5

Comparison of key performance of reformers

	First model (1988)	Second model (1990)
Raw fuel	town gas 13A	town gas 13A
Process	steam reforming	steam reforming
H_2 generation (Nm^3/h)	50	50
Reaction temperature (°C)	700	710
Working pressure	atmospheric	atmospheric
Steam carbon ratio	3.25	2.5

TABLE 6

Comparison of compactness of reformers (%)

	First model (1988)	Second model (1990)
Footprint	100	59
Weight	100	37
Volume	100	52
Thermal load	100	148
Catalyst quantity	100	24

In addition to the substantial size reductions of key components, system simplifications were also realized through integral design of many other components such as heat exchangers.

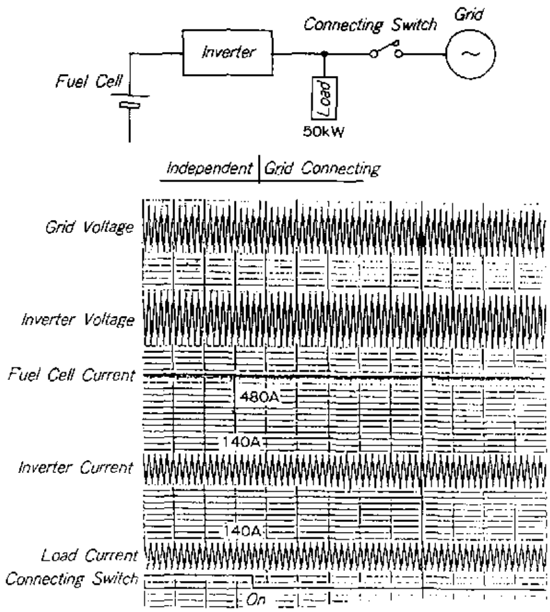


Fig. 7. Non-interrupting switchover of independent/grid connected operation.

TABLE 7

Standardization of plant capacities

Application	Type	Output (kW)
On-site use (atmospheric pressure system)	FP-50 FP-100 FP-500	50 100 500
Dispersed station use (pressurized system)	FPD-5 FPD-20	5000 20000

4. Cost reduction

The cost reduction aspect for the packaged type PAFC is of prime importance. Substantial cost reduction, however, can be achieved via technical improvements, standardization and mass production. To reach the cost target goal, Fuji has standardized all cell sizes to 2000 and 8000 cm^2 (effective cell area), and plant capacities as shown in Table 7.

Modular design can be achieved generally at a slightly high unit cost in comparison to large systems. However, this increase in cost can be offset by mass production of standard plants, short construction period etc. The final step to cost reduction is mass production. Fuji Electric has installed a semi-mass production facility with an annual capacity of 15 MW per year for producing on-site power plants and stacks for dispersed power plants. Figure 8 shows an assembly line of on-site packaged plants equipped in this semi-mass production facility.

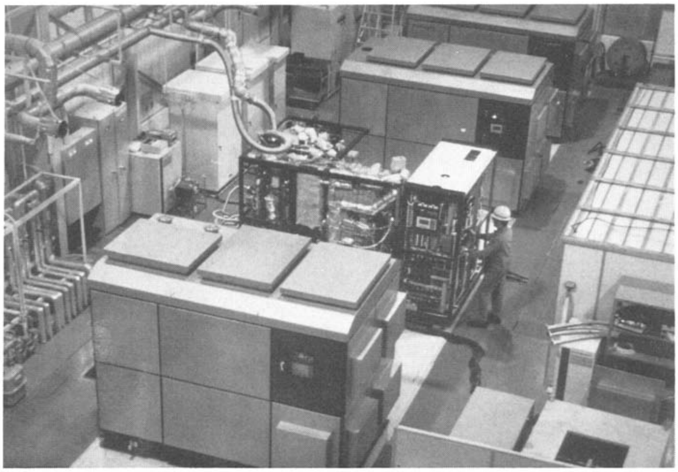


Fig. 8. Assembly line of on-site package PAFC plants.

TABLE 8

Methanol reforming PAFCs

Capacity (kW)	No. of sets	Customer	Delivery	Remarks
4	2	Electric Utility Companies	1986–7	research
4	3	Oil Companies	1988	research
25	1	US DOE (Bus Project) (Phase I)	1989	oil cooling
50	3	US DOE (Bus Project) (Phase II)	1992–3	oil cooling
200	1	Okinawa Electric PC	1989	NEDO Project

5. PAFC plants using various fuels

Other than natural gas-fueled power plants described above, Fuji Electric has been developing various type of PAFC plants using methanol, LPG and naphtha.

The following gives a very brief description of these various PAFCs.

Methanol reforming PAFC plants.

Fuji Electric has supplied many methanol reforming PAFCs as shown in Table 8. Methanol is liquid at ambient temperature and is appropriate for plants installed in isolated areas, remote islands or vehicular applications where methanol is the fuel of choice. Since the reforming temperature of methanol (about 300 °C) is much lower than natural gas (about 800 °C) a methanol reforming fuel cell plant has generally better efficiency and a shorter start-up time. The 200 kW PAFC plant shown in Table 8, installed on a detached island in Okinawa Electric Power Company, has been constructed and operated for more than 8300 hours very successfully under the NEDO Project.

Table 9 and Fig. 9 show the key performance and general view of the 200 kW methanol reforming PAFC plant, respectively. This plant entered into operation in

TABLE 9

Key performance of 200 kW methanol reforming PAFC plant for detached island

Items	Performance (test results)
Rated output	215 kW (generating end)
	202 kW (sending end)
Efficiency (%)	39.7 (HHV) at rated load
	40.6 (HHV) at 75
	36.7 (HHV) at 50
Stack working conditions	190 °C, 1 atm.
Cooling	water cooling
Cold start-up time (h)	3
Minimum load (%)	20
Response time (s)	25
NO_x (ppm)	<2 (O_2: 7%)
Operation mode	full automatic operation

Fig. 9. General view of 200 kW methanol reforming PAFC plants installed on detached island.

Jan. 1990 and supplied electric power to the grid network of the island in parallel operation with existing diesel generators of 1400 kW capacity. After successful operation under very severe weather conditions including a typhoon, the plant stopped its operation at the end of July 1991, due to the project budget limitation.

A 25 kW brassboard experimental PAFC plant manufactured under the Phase I bus contract of US DOE also proved its successful operation in the USA. This is a typical example of fuel cell for vehicular application. The project is entering into the next phase, under which three sets of 50 kW PAFC plants will be on board the three demonstration buses. The test result of the 25 kW brassboard plant and specification of the 50 kW on board plant are shown in Tables 10 and 11, respectively. Details of this project were reported to the Fuel Cell Seminar held in Phoenix during the Fall of 1990.

TABLE 10

Test results of 25 kW brassboard plant (Phase I)

Item	Results
Output (kW)	
at generating end	25 (d.c. 52.8 V×480 A)
at chopper end	23.2
Efficiency (%)	38.0 (LHV, excluding auxiliary power)
Exhaust gas (ppm)	
CO	30
NO_x	0.5
CmHn	not detected

TABLE 11

Specification of 50 kW on-board plant (Phase II)

Item	Specification
Plant output (kW)	50
Efficiency (%)	38 (LHV)
Fuel consumption (kg/h)	methanol: 23.6
	pure water: 26.0
Start-up time (min)	<25
Dimension (mm)	1300 (l)×2100 (w)×1450 (h)
Weight (kg)	1200

LPG reforming PAFC plants

Fuji has an trial operation experience of LPG reforming 50 kW PAFC plant for Tohoku Electric Power Company and is also developing a LNG/LPG reforming 50 kW PAFC plant (nine sets) for domestic gas companies. Furthermore Fuji Electric will start the development of a comprehensive LPG reforming 100 kW PAFC plant under a government contract. This 100 kW project will start in 1991 and finish in 1994. The purpose of this project is to expand the fuel cell market because the LPG supplied area in Japan is much greater than the LNG supplied area. As a result, the applicability of LPG reforming plant might be larger than that of LNG.

Naphtha reforming PAFC plants

Fuji is developing naphtha reforming PAFC plants under close cooperation with PEC (Petroleum Energy Center) and has supplied two sets of these PAFC plants to Idemitsu Oil Company in 1989 and 1990, respectively. Basically the construction of the plants is similar to our 50 kW prototype plants but the catalyst of naphtha reformer is developed and supplied by Idemitsu. These plants are now being tested at the Research Center of Idemitsu Oil Company. These developments should contribute to expanding the marketability and applicability of PAFC plants.

6. Environmental conditions

Worldwide concerns for environmental and energy are stimulating the urgent development of fuel cell power plants. It is worthwhile discussing the environmental characteristics of Fuji's fuel cell power plants and comparing these performance to that of the conventional generating plants.

Table 12 shows the results of our PAFC plants. By comparing the NO_x contents in the exhaust gas of conventional diesel plant, gas engines and gas turbines which are 2000–4000, 2000–4000 and 200–600 ppm, respectively, the exhausted NO_x contents from PAFC plants are two orders of magnitude lower. The low NO_x level of the PAFC plant comes from the low combustion temperature of the lean reformer burner. The SO_x contents in the exhaust gas of the PAFC plant are practically zero because of the internal desulfurizer in the PAFC plant package. There are no regulations for

TABLE 12

Results of exhausted NO_x from PAFC plants

Customers	Output (kW)	Fuel	NO_x (ppm)[a]
Kansai Electric Power Company (NEDO project)	1000	LNG	10
Tohoku Electric Power Company	50 (pressurized)	LNG	45
Tokyo Gas Company	50	13A (town gas)	2
Shikoku Electric Power Company	4	methanol	~0[b]
Forklift Truck Application	5	methanol	~0[b]
Okinawa Electric Power Company (NEDO project)	200	methanol	<2

[a]At rated power, 7% O_2 base.
[b]Less than detection limit.

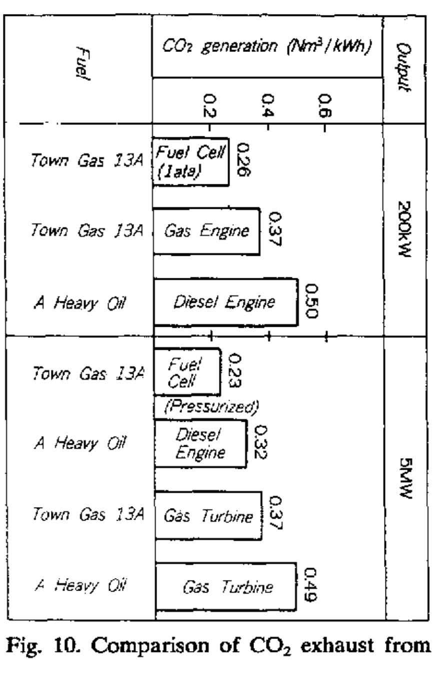


Fig. 10. Comparison of CO_2 exhaust from variow generating plants.

TABLE 13

MITI's prospect for fuel cell power plants (MW)

	Year 2000	Year 2010
Electric utilities	1050	5500
Private uses	1200	5300
Total	2250	10800

CO_2 exhaust, although worldwide control is necessary to protect global warming. Effective means to reduce CO_2 exhaust from generating plants other than using fuel of lower C content per unit heat output are to increase the electrical conversion efficiency or overall fuel efficiency by adopting a co-generation system. Figure 10 gives a comparison of the CO_2 content of exhausts from various generating plants. The CO_2 exhaust from the fuel cell is the lowest compared to other conventional generating plants. The proper choice of fuel and the high conversion efficiency of PAFC contribute to this reduction.

In summary it is very clear that the environmental benefits of PAFC plants are superior and are a key factor in stimulating the development and for expanding the market.

7. Conclusions

MITI published in 1990 a Long Term Energy Supply and Demand Prospects which included fuel cells. Coupled with the Japanese Government intention to further support the private sector via favourable regulation and an attractive financing offer, there is a bright future for fuel cells in Japan. MITI's concrete target capacity of fuel cell plants is summarized in Table 13.

Both the electric and gas utilities are taking aggressive steps to accelerate the commercialization of the PAFC and other types of fuel cells, stimulated by the superior environmental benefits and high energy saving characteristics.

Fuji Electric fully intends to work cooperatively with the electric and gas utilities and government agencies to help contribute to the meeting of the national long term energy supply goal. As we move closer to commercialization and with an increasing number of pre-commercial PAFC plants achieving satisfactory operation, Fuji is confident that the PAFC will become a commercially viable product in the not too distant future.