

# World Developments of Fuel Cells

## MAJOR OPPORTUNITY FOR PLATINUM ELECTROCATALYSTS

By D. S. Cameron

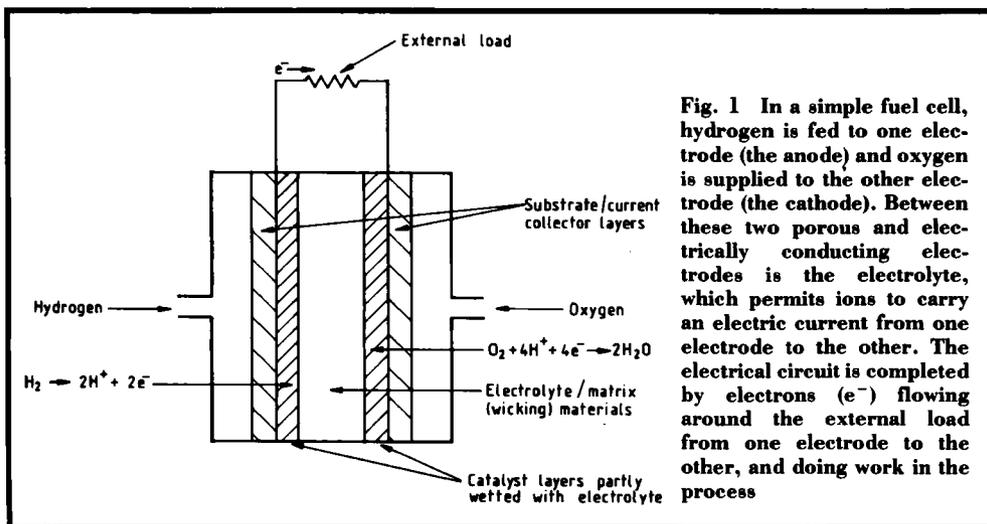
Johnson Matthey Technology Centre

*Writing in this Journal over a quarter of a century ago, the late Dr. L. B. Hunt suggested that a number of different types of fuel cell would be required in the future to meet the varied requirements of auxiliary power sources, communications, specialised military applications and vehicular propulsion, and that it would be further into the future before fuel cells would be used as a means of primary power generation. Since that time several papers and conference reports on this application of the platinum metals have been printed here, and a significant number of abstracts of work that has appeared elsewhere, have been published. An increasing awareness of the environmental costs resulting from the use of fossil fuels has reinforced efforts to use such fuels in more effective and less polluting ways. This review summarises the present situation world-wide regarding developments in fuel cell technology, current and proposed applications and commercialisation.*

Increasing concern with atmospheric pollution and the perceived difficulties associated with the nuclear power industry are causing a re-evaluation of the various means of electric power generation. Fuel cells, which are capable of much higher efficiency than conventional fossil fuelled power stations, while producing

only minimal amounts of polluting gases, offer a viable alternative.

At present the first commercially available fuel cell units, each using a small but vital amount of platinum, are under construction in the United States of America and Japan in sizes ranging from 50 kW to 11 MW. These are



capable of running on a variety of fuels, including natural gas, methanol, liquefied petroleum gas, naphtha, and even waste gases from landfill sites. Their characteristics of compactness, silence and cleanliness make them ideal candidates to replace old urban power stations; while their freedom from pollution is helping to make them economically competitive with existing plants which face huge capital investment to ensure "clean" operation.

## Power Generation

Large power stations use the heat released by the combustion of fossil fuels, or from nuclear reactions to produce steam. This steam is used to rotate turbines and alternators to make electricity. As long ago as 1824, Nicolas Léonard Sadi Carnot (1796–1832) recognised that there is an intrinsic limitation to the efficiency of these thermal processes (1), which means that even the most modern power stations operate at less than 36 per cent overall efficiency. The overall generating efficiency for the United Kingdom, which includes many older power plants, is only 32 per cent; and this is further reduced by distribution losses of perhaps 3 per cent. The unfortunate result of this inefficiency is that the Central Electricity Generating Board wastes more heat from its coal-fired power stations than is produced from the total amount of gas sold for domestic use by the British Gas Corporation (2). However, the very large generating stations producing the bulk of electric power in the U.K. are in isolated locations, where there is no demand for low grade heat.

## Why Fuel Cells?

The ideal electric generator is one which would be highly efficient, since electricity has roughly three times the intrinsic value of heat. It should also be sufficiently pollution free and compact to be sited close to the user, where waste heat could be used adjacent to the source. Combined heat and power plants are already favoured by industries using gas turbine or diesel power plant, but for environmental reasons it would be impractical to consider

siting such generators in residential areas (3).

Fuel cells are electrochemical devices, and are therefore not limited by the Carnot heat cycle. In theory at least, it should be possible to construct devices of 80 to 90 per cent efficiency (4). Already, units of 40 per cent electrical efficiency plus 45 per cent heat recovery have been routinely demonstrated, and ultimately electrical efficiencies of up to 65 per cent would appear to be practicable. The operation of the fuel cell requires a minimum of rotating machinery in the form of pumps and motors, so that there is little noise or vibration. This freedom from noise, vibration and pollution should facilitate their siting in places not previously considered for power plants. For example, in Japan a 200 kW generator has been installed on the roof of a four-storey office building (5). This has the benefit of not only saving space, valuable in any city centre and particularly so in Japan, but also of providing the building with stand-by power in case of mains failure. Often this emergency supply is provided by a separate diesel generator in the basement, needing care and maintenance, but not normally used, and giving no financial return.

## Fuel Cell Development

The fuel cell was discovered in 1839 by Professor Sir William Grove while working at the London Institution. When carrying out experiments to dissociate water into its component hydrogen and oxygen gases by electrolysis of dilute sulphuric acid between platinised platinum electrodes, he discovered that the process was reversible. The two gases readily recombined to form water and to give an electric current, see Figure 1. He was the first to appreciate the cleanliness and simplicity of this reaction, mentioning it with enthusiasm in a number of papers, as well as building arrays of cells for experimental purposes.

During the next hundred years, many eminent scientists attempted to construct larger and more practical fuel cells. These proved unsuccessful, largely due to the limitations imposed by the materials then available.

It was not until the American space efforts of

the 1950s and 1960s that rapid advances were made. It soon became apparent that manned space flight was not possible without an on-board power source, since far more power would be required than could be provided by batteries. Since liquid hydrogen and oxygen were already carried on the spacecraft, an obvious choice was a device capable of generating power from these gases.

Two types of spacecraft fuel cells were developed independently, the first by the General Electric Corporation (G.E.) for the Gemini missions, and the second by Pratt and Whitney Aircraft Corporation for the series of Apollo missions. The latter was based on cells designed by F. T. Bacon, while working for Marshalls of Cambridge. Further models have been developed for the Space Shuttle Orbiter and other applications. Although dozens of types of cells have subsequently been built, the Gemini and Apollo cells marked the beginning of the fuel cell era. It is true to say that manned space flight has been dependent on the invention of fuel cells.

### Types of Fuel Cells

Space applications represent a limited, highly specialised market, and for terrestrial operation there are very different requirements. At-

mospheric air is the obvious choice of oxidant, while initial cost, and lifetimes measured in years rather than months are other key factors. A number of fuel cell types have been developed to meet these criteria; as can be seen in Table I and Figure 2. These are mainly distinguished by the electrolyte used, and the temperature of operation.

### Alkaline Fuel Cells

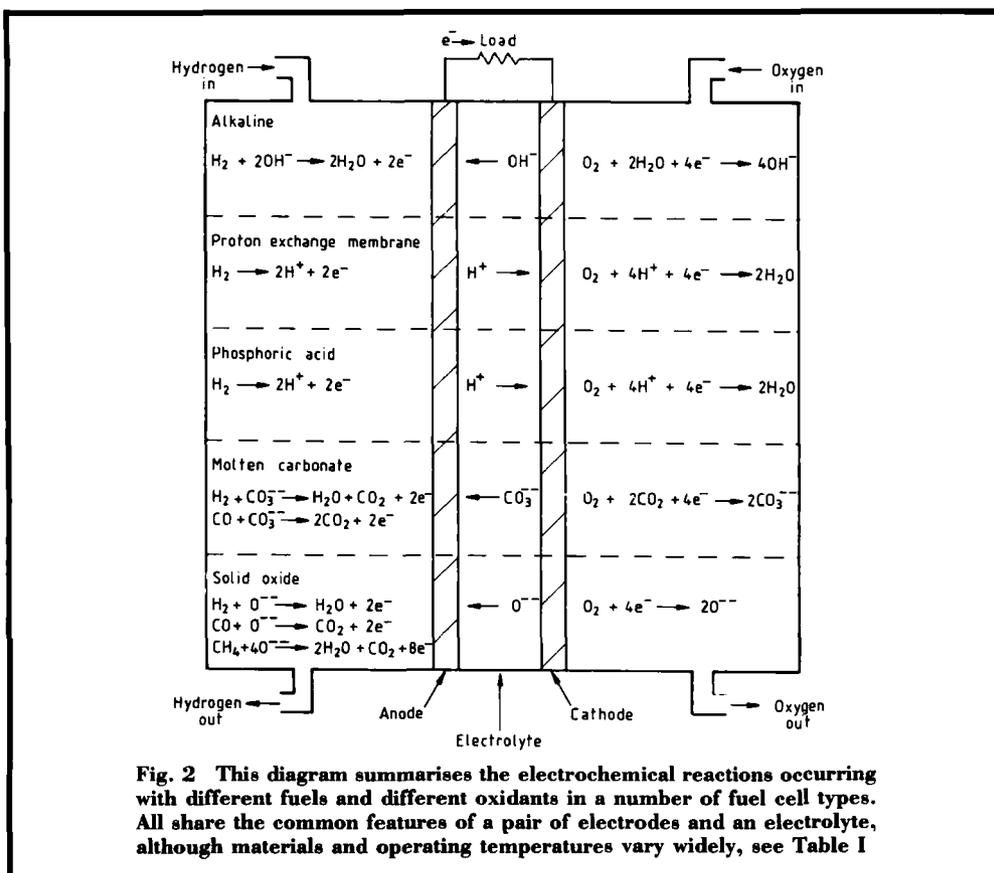
From an engineering point of view, alkaline fuel cells are the easiest types to build, since a wide variety of materials are stable in this electrolyte. Two main types of cell have evolved, one using re-circulated electrolyte, and the other with the electrolyte trapped in a "matrix" or wicking material, such as asbestos paper.

Alkaline fuel cells will operate satisfactorily at quite low temperatures, 50 per cent of rated output being available at ambient temperatures, 20°C, and with optimum temperatures ranging up to about 90°C. Since the electrolyte has good conductivity, very high current densities may be employed, up to 8 A/cm<sup>2</sup> being claimed (6). The use of platinum catalysts enables high power densities to be obtained, as required for aerospace and military applications.

The necessity to remove product water has

**Table I**  
**Types of Fuel Cells**

Type	Electrolyte	Operating temperature, °C
Alkaline	Potassium hydroxide	50-90
Proton exchange membrane	Polymeric	50-125
Phosphoric acid	Orthophosphoric acid	190-210
Molten carbonate	Lithium/potassium carbonate mixture	630-650
Solid oxide	Stabilised zirconia	900-1000
Biological	Sodium chloride	Ambient
Direct methanol	Sulphuric acid or polymer	50-120



given rise to a number of ingenious solutions, including re-circulating the hydrogen gas supply and condensing out the moisture, and forced evaporation of water from the re-circulated electrolyte. This water by-product was, and still is, the sole source of potable water for the Apollo and Space Shuttle crews. Apart from the space applications of alkaline fuel cells built by Pratt and Whitney, now part of United Technologies Corporation (U.T.C.), others are being developed by Siemens, Germany and Elenco N.V., Belgium, for the European Space Agency. Recently Siemens together with Howaldtswerke-Deutsche Werft (H.D.K.), Ingenieurkontor Luebeck G.m.b.H., (I.K.L.) and Ferrostaal A.G. have announced the availability of a submarine with enhanced cruising capabilities provided by fuel cells (7). Elenco have a separate programme to develop fuel

cells, of 50 to 70 kW, to provide motive power for both passenger buses and lorries (8).

### Proton Exchange Membrane Fuel Cells

The first fuel cell used in space was built by G.E., for the Gemini missions and incorporated a solid electrolyte made from ion-conducting polymers. These solid polymers were further developed by DuPont Chemicals into a material called Nafion, based on perfluorosulphonic acid. The latter has subsequently enjoyed great success as a separator material in electrolyzers used in the chlorine/sodium hydroxide manufacturing industry. Other materials have now appeared on the market, but all have the common feature of carrying current in the form of charged hydrogen ions (protons). They are acidic—or at least become so during operation,

due to ion concentration changes—so they are not susceptible to absorbing atmospheric carbon dioxide. Being a solid the electrolyte is robust, inherently free from possible leakage, and able to withstand differential gas pressures. However, it is necessary to keep the electrolyte moist since ionic conductivity is lost if it dries out. This requirement must be incorporated into the engineering of the cells, and restricts operating temperatures to below the boiling point of water at any given pressure.

Early proton exchange membrane cells for aerospace application were built using exotic construction materials, such as platinum coated tantalum, for current collectors and heat exchangers. Now, however, experience gained from engineering phosphoric acid fuel cells has enabled the substitution of inexpensive carbon materials. Early cells also incorporated very high platinum catalyst loadings of 8 mg/cm<sup>2</sup> although these have been reduced to less than half. Indeed, work at Los Alamos National Laboratory has shown that platinum loadings of 0.45 mg/cm<sup>2</sup> or less are quite feasible using carbon supported platinum catalysts, similar to those used in phosphoric acid fuel cells. Proton exchange membrane fuel cells operate at relatively low temperatures, with 50 per cent of rated power available at room temperature (9).

### Commercial Developments

Proton exchange membrane cells are currently being built and sold by Ballard Technologies Corporation of Canada, who are also collaborating with Vickers Shipbuilding and Engineering Limited (U.K.) to study their application in submarines (10). The original solid electrolyte fuel cell technology developed by G.E. has been acquired by the Hamilton Standard Division of U.T.C., and also licensed by Siemens of Germany.

Ballard Technologies and Dow Chemical have a joint programme to build and demonstrate two 10 kW proton exchange membrane cells. Vast amounts of waste hydrogen result from the production of chlorine and caustic soda by the electrolysis of brine, an energy intensive process. These fuel cells,

designed to run on by-product hydrogen from this process will be installed at the Dow chloralkali plant in Sarnia, Canada. They are the first of a number of 10 to 50 kW installations planned for the U.S.A., Canada, Europe and Japan over the next 18 months. The system has considerable potential benefits for energy conservation, enabling otherwise waste hydrogen to be used to regenerate direct current, which can be fed back into the electrolyzers. In Japan, Fuji Electric have developed 7.5 kW alkaline fuel cells also designed to operate on waste hydrogen from the same source.

A two-man submarine, powered by a 4.5 kW Ballard cell is currently undergoing sea trials, having been installed by Perry Engineering Systems in Florida. A 2 kW Ballard cell is also being evaluated by Daimler Benz in Germany, who have also carried out extensive trials of hydrogen-powered vehicles with internal combustion engines, where hydrogen fuel was carried in hydride stores.

A joint programme sponsored by the U.S. Department of Energy has recently been announced between Los Alamos National Laboratory and U.T.C. This project is intended to develop a road vehicle powered by a proton exchange membrane fuel cell. The A.C. Delco Division of General Motors Corporation is also carrying out preliminary fuel cell work aimed at vehicular applications. This includes designing compact, lightweight reformers to enable vehicles to operate on liquid fuels such as methanol or liquid petroleum gas.

### The Phosphoric Acid Fuel Cell

Orthophosphoric acid was the electrolyte chosen by Pratt and Whitney in the late 1960s, when they began constructing fuel cells for terrestrial applications. Although this acid has rather poor ionic conductivity, it has the major advantages of good stability and low vapour pressure. To enable the fuel cell to operate on natural gas or hydrocarbon fuels, a system was evolved consisting of three major components: [a] A fuel processor, which consists of a reformer/water-gas shift reactor, converts

fuels to hydrogen-rich gas. This is an endothermic process, some of the heat for the reaction being provided by steam, and some by the combustion of waste gases returned from the fuel cell.

- [b] A power section, consisting of the fuel cell stack (or multiples of stacks), fed with atmospheric air and hydrogen-rich gas from the fuel processor. These reformate gases consist of a mixture of hydrogen, with some carbon dioxide, traces (1 per cent) of carbon monoxide, and some inert gases such as nitrogen. The fuel supply passes through the fuel cells where about 80 per cent of the available hydrogen is consumed. The waste gas is then returned to the reformer and burned to provide heat.
- [c] Direct current from the power section is converted to alternating current using a device called an "inverter" or power conditioner. Alternatively, it may be used immediately by the consumer, for example in a chloralkali electrolyser or to drive DC motors.

Operation of the phosphoric acid fuel cell at elevated temperatures ensures adequate tolerance of small amounts of carbon monoxide from the fuel processor section, and provides waste heat at a sufficiently high temperature to enable efficient transfer to the reformer. It will be appreciated that the integration of the three major components of the system are essential to give good overall efficiency. The latter is typically 37 to 38 per cent from natural gas to bus-bar for electrical efficiency, with a further 40 to 45 per cent of waste heat available from the fuel processing and the power sections together.

Most phosphoric acid fuel cells operate at 190 to 205°C, depending on size and application, the larger scale units being pressurised at up to 8 bar, and run at 205°C. Carbon is used extensively for construction, being virtually the only inexpensive material not readily attacked by hot phosphoric acid. Platinum and more recently platinum/base metal alloy catalysts, supported on carbon powders are used as the catalysts, which are in turn supported on carbon elec-

trodes, in the form of paper, felt or foam, with graphite plate intercell separators. Currently, there is great emphasis on the reduction of the capital costs of phosphoric acid fuel cells to improve their commercial prospects. However, there are considerable incentives to at least maintain platinum metal loadings, the cost of platinum being more than outweighed by improved performance of the fuel cell stack components (11). Moreover, the platinum metal content is recoverable at the end of the life of the cell, and can be recycled.

Individual phosphoric acid fuel cells range in scale from a few kilowatts up to 1 MW, with "stacks" of over 450 electrode pairs connected in series (12, 13).

### Cells in Use

The phosphoric acid fuel cell was brought to an advanced state of development by U.T.C. in two major programmes. The first of these was started in 1967, in association with a consortium of U.S. gas supply utilities. Under this TARGET programme (Team to Advance Research on Gas Energy Transformation), 65 fuel cells, each of 12.5 kW, were demonstrated at 35 sites in the U.S.A., Canada and Japan.

Following these trials, the Gas Research Institute (G.R.I.) and U.T.C. jointly developed and demonstrated a series of forty-six 40 kW power plants. These were able to convert almost 40 per cent of the energy in natural gas into electricity and heat. Installation and operation of the units were carried out by various participating utilities, at sites of their choice. Applications included greenhouses, hotels, laundries, restaurants, sports complexes and a telephone exchange. Geographical locations varied from Alaska to Southern California, and from Tokyo to the eastern United States. Operation of the units was carefully monitored, and provided a wealth of practical experience and education. One of the most significant findings was the low level of exhaust emissions, the fuel cells operating with less than 10 per cent of the Environmental Protection Agency limits for small stationary generators. At present, a new series of 200 kW (electrical) output

**Table II**  
**Phosphoric Acid Fuel Cell Trials in Japan**

Organisation	Size of cell and manufacturer
Chubu Electric Power Co.	1 MW (Toshiba/Hitachi)
Tokyo	4.5 MW (U.T.C.), 11 MW (I.F.C.), 220 kW (Sanyo), 200 kW (I.F.C.) (× 2)
Kansai	1 MW (Mitsubishi/Fuji), 200 kW
Tohoku	50 kW (Fuji)
Hokkaido	100 kW (Mitsubishi)
Hokuriku	4 kW
Shikoku	4 kW (Fuji)
Okinawa	200 kW (Fuji)
Tokyo Gas Company	40 kW (U.T.C.), 200 kW (I.F.C.), 50 kW (Fuji), 100 kW (Fuji)
Osaka Gas Company	200 kW (I.F.C.), 200 kW (Mitsubishi), 50 kW/100 kW (Fuji)
Toho Gas Company	50 kW (Fuji), 100 kW (Fuji), 200 kW (I.F.C.)
Nippon Mining Co. Ltd.	100 kW (Sanyo/Toyo)

combined heat and power units are under construction by International Fuel Cells (I.F.C.), a joint venture between U.T.C. and Toshiba. Some of these units are now operational and monitoring is proceeding.

A second series of programmes, started in 1971, was undertaken by U.T.C. in collaboration with various electric utilities and the Electric Power Research Institute (E.P.R.I.), with the support of the U.S. Department of Energy. A 1 MW pilot plant was demonstrated in 1976, supplying electricity to the grid, and two 4.5 MW generators were installed, one in New York by Consolidated Edison, and the other in Tokyo by Tokyo Electric Power Company (T.E.P.Co.). The latter plant was built in truck-transportable modules, being constructed, shipped to Tokyo and commissioned in less than three years.

A further plant rated at 11 MW is currently under construction by I.F.C. for T.E.P.Co. and will be demonstrated at the same site. Toshiba have acquired the rights to construct

further such generator plants in Japan.

Other American companies developing phosphoric acid fuel cells include the Energy Research Corporation and Westinghouse Electric. The latter are planning a 7.5 MW power plant using air cooling for the fuel cell stack. The Japanese have organised the "Moonlight Programme" sponsored by the Ministry of International Trade and Industry to improve the efficiency of utilisation of fossil fuels. As part of this programme, two fuel cell generators, each of 1 MW have been built by consortia of Hitachi and Toshiba, and Mitsubishi and Fuji Electric, respectively. Despite some initial teething troubles, these generators are now said to be working satisfactorily. Each of these large companies, together with Sanyo, have separate programmes to build phosphoric acid power plants in sizes ranging from a few kilowatts to 5 MW. Most of the Japanese electricity generating companies and several of the gas supply utilities, are collaborating to evaluate these devices, see Table II. A list of industrial

and utility companies participating in the Japanese fuel cell programmes is published annually with details of their efforts (14).

In Japan, a country where all fuel has to be imported, and where city environments are extremely crowded, the potential benefits of fuel cells are greatly appreciated. In addition, of course, there is a huge potential export market for fuel cells, with a demonstration programme already being organised in Thailand, and others planned for South East Asia.

### **The Molten Carbonate Fuel Cell**

Pioneering work on molten carbonate fuel cells was carried out by Broers and Ketelaar in the 1950s at the Central Technical Institute (T.N.O.) in Holland. Although the problems associated with the use of molten salts at 650°C are considerable, the potential rewards offered by success are enormous. These include the possibility of using carbonaceous fuels, and even of reforming these internally to give a relatively simple, low cost generator. At this high temperature, it becomes much easier to integrate the fuel cell with the fuel processor. High grade steam is available, which can be used either to run steam turbines in a "bottoming cycle" which raises the possible overall efficiency to between 60 and 65 per cent, or to provide steam which can be used for chemical processes (15).

The main problems associated with the molten carbonate fuel cell are due to corrosion and sintering of the materials of construction. In order to obtain a high area of interface between the gases, the electrodes and the electrolyte, a careful gradation of pore structures is required, with the electrolyte held in a central matrix of an inert porous material such as lithium aluminate. Corrosion, or sintering of the major components can result in the electrodes becoming de-wetted or flooded. Considerable effort has been devoted to finding materials resistant to corrosion. Presently favoured are 10 per cent nickel-chromium for the anode or hydrogen electrode, with lithiated nickel oxide for the air cathode. The inter-cell separator plates are made from high quality

stainless steel, (such as Incolloy 825, 310S or 316L stainless steels) faced on one side with nickel to improve conductivity. Some of the few materials with proven resistance to molten carbonate electrolytes are the platinum group metals, which may find application as construction materials or catalysts (16).

Although great progress has been made in developing molten carbonate fuel cells with power outputs of up to 10 kW, and even towards 100 kW in recent years, there are still doubts about their durability, due to the high operating temperatures employed. Apart from corrosion, other problems include the preferential evaporation of lithium salts, giving changes in electrolyte concentrations, and a slow but definite tendency for the electrolyte to migrate through the fuel cell stack. Most tests carried out to date indicate that the system is extremely sensitive to sulphur impurities in the fuel stream, as well as to other contaminants such as halogens. Thus, coal derived fuels will require considerable cleaning before use.

### **Development Work in Progress**

A large number of organisations are developing molten carbonate fuel cells, although so far none has offered a commercial product. In the United States these include U.T.C., Energy Research Corporation, and the Institute of Gas Technology. In Japan, Hitachi, Mitsubishi, Toshiba and Ishikawajima Harima Heavy Industries are co-ordinated under the Moonlight Programme. In Europe, the main developers are in Holland (T.N.O. and E.C.N., Petten), and in Italy. The Italian programme is co-ordinated by the state electricity company E.N.E.A. together with various universities, C.I.S.E. (Milan), C.N.R.-T.A.E. (Sicily) and Ansaldo (Milan). The Italian objective is to develop a 50 to 100 kW unit by 1992 (17).

### **Solid Oxide Fuel Cells**

In the past few years solid oxide fuel cells have advanced from small laboratory single cells to 3 kW power plants, several of which have been sold by Westinghouse, the principal developers, for evaluation. Since conduction is

dependent on solid state diffusion of oxygen ions through the electrolyte, the system must operate at around 1000°C. Performance has been improved by perfecting methods for depositing extremely thin layers of electrolyte (about 40µm) together with conducting oxide and metallic nickel electrodes. Typical electrolytes are zirconia stabilised with yttria, while porous anodes are made from metallic nickel on an yttria/zirconia skeleton, to minimise sintering. Air cathodes are porous conducting oxides such as strontium-doped lanthanum manganite. With any system operating at 1000°C, it is vital that all the materials should resist oxidation and inter-diffusion, and also that they have carefully matched coefficients of thermal expansion.

### Industrial Evaluations

The first solid oxide fuel cells were successfully developed by Westinghouse using a system of hollow tubes, connected in series and parallel by strips of nickel felt. Although the system is not compact, it is able to accommodate thermal expansion.

Alternative designs, for which power densities of up to 1 MW/m<sup>2</sup> have been claimed, are dependent on packing cells into honeycomb or flat plate structures. These designs are being studied at Argonne National Laboratories, Ceramtec Inc., Combustion Engineering, I.F.C., and Ztek Corporation. In Japan, initial work by the Government Electro-technical Laboratory is being followed up by Mitsui Engineering and Shipbuilding, Fuji Electric Co., The National Chemical Laboratory for Industry, and T.E.P.Co. in collaboration with Mitsubishi Heavy Industries. In Europe, the Commission of the European Community are sponsoring exploratory research on advanced solid oxide fuel cell designs and manufacturing methods. Dornier in Germany are carrying out some solid electrolyte fuel cell work as part of a programme mainly on high temperature electrolyzers.

The exacting demands of perfectly matching the thermal expansion characteristics of materials must be overcome to enable scale-up.

At 1000°C, it would be perfectly feasible to consume natural gas in the fuel cell stack to give an extremely elegant design with high efficiency.

Westinghouse 3 kW solid oxide fuel cells have been evaluated by the Tennessee Valley Authority, Osaka Gas Company (18) and Tokyo Gas Company (18). A total of 12,000 hours of operation have been accumulated with three units in Japan. A joint test is being organised by Westinghouse, together with Kansai Electric Power, Osaka Gas and Tokyo Gas for a 25 kW solid oxide fuel cell generator which will consume natural gas, with testing due to commence in 1990.

### Other Fuel Cells

Power generation by the direct oxidation of hydrocarbons and alcohol fuels would be highly desirable, and has been widely investigated (19). Catalysis of the oxidation reaction is very slow compared to that of hydrogen. The only commercial uses to date are for analysis of oxidisable organics, such as ethanol, methanol and formaldehyde in gases, the breathalyser being one example.

Small biological fuel cells have been proposed for directly monitoring glucose levels in blood, for the treatment of diabetics.

### Conclusions

Fuel cell design continues to make rapid progress, led by the phosphoric acid fuel cell which is now becoming available commercially. As with any new technology, the initial pace of development has been relatively slow, with the need to educate potential customers on the safety and general viability of the devices. In general, electricity and gas supply companies that have participated in trials have been keen to evaluate more advanced designs.

The latest models of 200 kW combined heat and power phosphoric acid fuel cells, being marketed separately by I.F.C. and Fuji Electric Company, are said to be almost at commercially acceptable prices, especially for the Japanese market, where fuel costs are high. Although phosphoric acid fuel cells are at a high level of

technical development, capital cost is still the main obstacle to be overcome. Longer production runs should provide much of the cost reductions needed. Improvements in platinum catalyst technology are playing an important part, both by providing better utilisation of the noble metals, and by increasing the power out-

puts of the fuel cell assemblies. The successful commercial development of second generation concepts such as molten carbonate and solid oxide fuel cells are likely to be dependent on the effective exploitation of phosphoric acid fuel cells, and the establishment of a market for such devices.

### References

- 1 [N.L.] S. Carnot, "Réflexions sur la Puissance Motrice du Feu", Bachelier, Paris, 1824
- 2 "Digest of United Kingdom Energy Statistics 1989", Department of Energy, H.M.S.O., London, 1989
- 3 R. Forrest, "Small Scale Combined Heat and Power", Energy Technology Series 4, Energy Technology Support Unit, AERE, Harwell, 1985
- 4 K. Kinoshita, F. R. McLarnon and E. J. Cairns, "Fuel Cells, A Handbook", DOE/METC-88/6096, U.S. Department of Energy, Morgantown, 1988
- 5 N. Hashimoto, The Grove Anniversary Symposium, London, September 1989; Proceedings to be published in *J. Power Sources*
- 6 J. K. Stedman, "Program and Abstracts, Fuel Cell Seminar", Tucson, Arizona, May 1985, p.138
- 7 G. Sattler, in a supplement to "Naval Forces", 1989, "HDW Supplement", Mönch Group, pp. 71-80
- 8 H. van den Broeck and D. S. Cameron, *Platinum Metals Rev.*, 1984, 28, (2), 46
- 9 E. A. Ticianelli, C. R. Derouin and S. Srinivasan, *J. Electroanal. Chem. Interfacial Electrochem.*, 1988, 251, (2), 275
- 10 K. Prater, The Grove Anniversary Symposium, London, September 1989; Proceedings to be published in *J. Power Sources*
- 11 P. Hite, "Fuel Cell Technology and Applications—Extended Abstracts International Seminar", The Netherlands, October 1987, organised by PEO (Management Office for Energy Research, The Netherlands)
- 12 W. H. Johnson and T. G. Schiller, "Program and Abstracts, Fuel Cell Seminar", Long Beach, California, October 1988, p.213
- 13 D. S. Cameron, *Platinum Metals Rev.*, 1989, 33, (1), 10
- 14 "Fuel Cell R&D in Japan 1989", Fuel Cell Development Information Center, The Institute of Applied Energy, SY Bldg., 1-14-2, Nishinbashi, Minato-ku, Tokyo 105
- 15 A. J. Appleby and F. R. Foulkes, "Fuel Cell Handbook", Van Nostrand Reinhold, New York, 1989
- 16 M. Wyatt and J. M. Fisher, *Platinum Metals Rev.*, 1988, 32, (4), 200
- 17 P. Zegers, The Grove Anniversary Symposium, London, September 1989; Proceedings to be published in *J. Power Sources*
- 18 Y. Mori and M. Harada; also Y. Yamamoto, S. Kaneko and H. Takahashi, "Program and Abstracts, Fuel Cell Seminar", Long Beach, California, October 1988, p.18 and p.25, respectively
- 19 D. S. Cameron, G. A. Hards, B. Harrison and R. J. Potter, *Platinum Metals Rev.*, 1987, 31, (4), 173

## A New Process for Direct Coal Gasification

It is known that fuel cells can be used to co-generate electricity and useful chemicals, and also that there are important technological advantages in gasifying coal in a molten metal bath. The latter is a relatively new process which has attracted significant attention, particularly in Japan. Now I. V. Yentekakis and P. G. Debenedetti of Princeton University and B. Costa of Naples, Italy, have reported a novel concept for coal gasification, which involves the simultaneous gasification of coal and the generation of electrical power in a single reactor which is a combination of a high-temperature solid electrolyte fuel cell and a fused metal gasifier (*Ind. Eng. Chem. Res.*, 1989, 28, (9), 1414-1424).

Finely divided carbon is carried in an inert gas flow to the molten iron which serves as the anode. The cathodic compartment of the cell consists of yttria stabilised zirconia, and the inner walls of the electrolyte are coated with a porous platinum film which has high catalytic activity for the dissociation of oxygen.

The process combines the advantages associated with coal gasification in a molten metal bath, namely high gasification efficiency and low sulphur content in the gas, with the thermodynamic efficiency of high temperature fuel cells. A lumped parameter model is presented. Calculations support the opinion that the fused iron bath fuel cell concept is an attractive idea, worthy of experimental testing.