

Recent advances in fuel cell technology and its applications

G.J.K. Acres

Johnson Matthey Technology Centre, Blount's Court, Sonning Common, Reading RG4 9NH, UK

Abstract

Currently, there is a good deal of interest in the possibility that fuel cells will make an important contribution to world energy supplies for both mobile and stationary applications. This paper provides an up-to-date review of fuel cell technology. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Fuel cells; Alkaline; Proton exchange membrane; Direct methanol; Phosphoric acid; Molten carbonate; Solid oxide; Prospects

1. Introduction

It comes as a surprise to many people new to the subject of fuel cells and their applications, that although they were invented some 160 years ago by a UK Amateur scientist, Sir William Grove [1], they have taken so long to come to the forefront of energy and environmental considerations.

This has arisen, not so much because their environmental attributes were not known or indeed promoted, but more as a result of the technical challenges to be met in developing a viable power system. Competition from the internal combustion engines and steam turbines has also been a factor. One of the limitations of the Grove cell, as he recognised, was the limited current that it could produce as a result of the small effective area of the Pt electrodes in his cell. Mond and Langer [2] in 1889 were the first to take up the challenge of increasing the 'surface of action', and hence the power density, by using porous electrode structures which could be placed side by side. Thus, they created a structure with all the features of the modern fuel cell. The Mond and Langer cells operated on hydrogen and oxygen at 0.73 V and a current density of 3.5 mA/cm². For comparison, the phosphoric acid fuel cell today operates at a similar voltage but with current densities at least 50 times higher. More advanced systems such as the solid polymer fuel cell developed in the last 10 years [3] can operate at 1000 mA/cm² at 0.7 V. Optimisation of electrode catalysts and structures, together with effective electrolyte and electrode–electrolyte contact continue to be factors where improvements in power density are still sought.

Grove used hydrogen produced by the electrolysis of water or, for example, the dissolution of zinc as the fuel

in his cells. While today, hydrogen or hydrogen rich gas from hydrocarbon or biomass sources are the preferred fuels, the means for using methanol, methane or higher hydrocarbons directly are significant technical challenges, as well as limitations to the wide scale exploitation of fuel cells. In the late 1800s, attempts were made, notably by Jacques [4] and Bacon [5], to utilise carbon in the form of coke. Later, Bacon and Ehrenberg [6] attempted to use coal directly. Not until the work of Bacon, starting in 1933 [7] was a fuel cell developed with the capability of delivering power densities of 1000 mA/cm² at 0.8 V, a performance matched only today by the most advanced fuel cell systems, albeit Bacon used hydrogen and oxygen at elevated pressure. Bacon, the first recipient of the Grove Medal awarded bi-annually and presented at the Grove Fuel Cell Symposium, continued to develop his system up to the early 1960s. The alkaline fuel cell (AFC) system commonly referred to as the 'Bacon Cell' not only provided, after adaptation by Pratt and Whitney, the on-board power system for the Apollo lunar missions, without which the lunar landings would not have been possible, but also stimulated the start of the current interest in fuel cell technology for sustainable stationary and mobile power generation.

It was during the 1960s that the other five fuel cell systems that are the subject of extensive development today were originally conceived. These are the solid polymer fuel cell (SPFC), direct methanol fuel cell (DMFC), phosphoric acid fuel cell (PAFC), molten carbonate fuel cell (MCFC) and solid oxide fuel cell (SOFC). The operating features of these systems are highlighted in Table 1 [8–13].

The AFC, using pure hydrogen and oxygen as is appropriate in space applications, is not compatible with the use of fossil fuels as the carbon dioxide dissolves in the electrolyte impairing the performance of the cell. Until the hydrogen

E-mail address: gary@garyacres.fsnet.co.uk (G.J.K. Acres).

Table 1
Types of fuel cells

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

economy is established, it is widely but not exclusively considered that fuel cells for commercial, industrial and transport applications, must be compatible with the use of fossil fuels and the resulting carbon dioxide. It is primarily for this reason that the low temperature acid electrolyte systems and the high temperature molten carbonate and solid oxide fuel cell systems were derived.

Fuel cell technology would almost certainly have found a place in the energy scene if generally available fossil derived fuels such as petroleum products or natural gas could be used directly. Following the work on coal in the late 1800s [4–6] and more recently, notably by Shell in the 1960s [10], it became obvious from the low current densities achievable with existing electrode catalysts, even when used in high temperature fuel cells, that these fuels would have to be reformed, to produce a hydrogen rich gas, for fuel cells to produce the power densities necessary for commercial applications.

The principal technical challenges resulting from the 1960s developments which have largely determined the direction of research, development and demonstration activities may be summarised as follows:

- electrode materials and cell optimisation to improve power density, durability and resistance to gas impurities;
- scale up of single cells into stacks capable of producing up to 250 kW in a single module;
- reducing the cost of fuel cell stacks by increasing the effectiveness of precious and rarer metal catalysts and other stack components;
- adapting and improving established steam reforming technology for use in both stationary and mobile applications;
- optimising the performance, durability and cost of the system controls generally known as the ‘balance of plant’;
- designing and producing systems for demonstration in selected applications;
- and today
- establishing process and engineering capabilities for the manufacture of fuel cell components, stacks and systems and
- developing improved materials for hydrogen storage.

Work on these aspects of fuel cell technology has been on going since the 1970s with steady rather than spectacular

developments. With increasing resources applied to fuel cell development in the last 10 years, notably by the transport sector, progress towards wide exploitation has accelerated. At the same time, the fuel cell community has expanded with, for example, potential component suppliers taking an active interest as well as the financial investment community.

1.1. Grove Fuel Cell Symposium

How does one best highlight recent advances in fuel cell technology and its applications? Much of a general nature is provided by the many review articles that now appear on the subject or the many workshops, seminars and conferences that take place world wide. However, as this review is included in the 100th volume of *Journal of Power Sources* and it is in this journal that the proceedings of the Grove Fuel Cell Symposium have been published, it is appropriate that these proceedings form the basis of this review.

The first Grove Fuel Cell Symposium was held in 1989 to commemorate the 150th anniversary of Grove’s invention and report on his fuel cell concept [1]. It also coincided with an increase in interest and activity notably in Europe. It has been held bi-annually since, with the objective of reviewing progress in the development and application of fuel cell technology by leading players from Japan, America and more recently Europe [14].

2. Progress in the development and application of fuel cells

2.1. Alkaline fuel cells

While there remains some interest in AFCs for commercial applications, notably by ZeTek as a range extender for battery powered vehicles, this is still at a low level compared with that for SPFC systems for transport applications [15]. A circulating KOH electrolyte is preferred to an immobilised system for transport applications as in addition to providing the means for cooling the stack, it enables the electrolyte to be replaced in the event of substantial CO₂ absorption, without the need to disassemble the stack.

Modified anode and cathode catalysts have now been developed that supersede the high concentrations of Pt and Pt/Au used in the space Orbiter vehicle. However, there is no consensus on whether precious or base metals are the preferred system. The choice depends on the balance between the required performance and acceptable cost. The choices range from low loaded all Pt systems [16] through Ni anodes and silver cathodes to all base metals now being developed by ZETEC.

With increasing interest in the use of hydrogen for fuel cell powered vehicles, interest in the AFC system may increase. On the other hand, it is reported that the new fuel cells for the space shuttle Orbiter vehicles will be SPFCs in preference to the established AFC [17].

2.2. Solid polymer fuel cells

By 1989 and the first Grove Fuel Cell Symposium, the early work by General Electric which established the SPFC system for use on the Gemini space missions [18] had been re-evaluated and developed by Ballard Power Sources [19] to become one of the most significant fuel cell developments of the 1980s.

It is suggested that General Electric chose not to pursue commercial applications for the SPFC as, in its then existing form, it required high Pt metal loaded electrodes and was more sensitive to CO poisoning than the established PAFC system. In addition, it was potentially more expensive as a result of the cost of the proton conducting polymer electrolyte and the high Pt metal loaded electrodes.

While the sensitivity to CO poisoning remains, but less so with anode catalysts such as Pt/Ru, rapid developments were achieved in improving the power density while at the same time reducing Pt metal electrode loadings. For example, Nafion had been identified as a suitable proton conducting membrane electrolyte. By substituting other sulphonated fluorocarbon polymer materials, a four-fold increase in current density could be achieved at the same operating cell voltage. Further, by optimising catalyst and electrode structure, Pt metal loadings were reduced from a high of 28 to 0.4 mg/cm² and recently to 0.2 mg/cm² while maintaining current densities in excess of 1 A/cm² at 0.7 V [19]. The details of what, at the time, were unexpected but exciting developments are described in a paper given by Pratter at the first Grove Fuel Cell Symposium [20].

2.3. SPFC fuel cells for transport applications

These developments attracted the interests of the major car companies who were seeking ways to eliminate CO, HC and NO_x emissions from vehicles, while at the same time reducing fuel consumption and the associated CO₂ emissions [21,22].

In 1994, California introduced the 'zero emissions mandate' which required that 2% of all new vehicles sold in 1998 should produce no emissions, rising to 5% by 2001 and 10% by 2003. These time scales have now been relaxed, largely as a result of the failure of battery powered vehicles to meet the required performance and range targets. However, the ZEV standards, together with the US Government's PNGV (Partnership for a New Generation of Vehicles) initiative to develop light duty vehicles with a fuel economy of 80 miles/gal by 2004 remain.

Together, they have provided the stimulus for major investments by the car companies in fuel cell technology for both cars and buses.

Developments in the technology of SPFC systems and their application to vehicles has been rapid in the last 10 years. In 1993, Ballard demonstrated an SPFC powered bus. Following the announcement of the first fuel cell stack with a power density of 1 kW/l [23], a Ballard phase 2 bus was

demonstrated powered entirely by a 200 kW unit. This bus had no reduction in passenger seating or on road performance compared with the standard bus. Today, XCELLSIS, the Daimler Chrysler/Ballard/Ford consortium has now developed and is demonstrating buses in Canada, America and Europe with the aim of making them commercially available by 2005.

Progress in developing fuel cell powered light duty vehicles has been equally impressive [24], but there remain significant technical challenges to be addressed. These include the fuel such vehicles will use and the cost of the fuel cell system and drive train.

Pure hydrogen is the preferred fuel for SPFC fuel cells but it is debatable whether this is a realistic choice for widescale consumer use in the short to medium term [25]. Hydrogen storage on vehicles has been demonstrated and includes high pressure light weight cylinders, cryogenic liquid systems and solid state metal hydride stores. Although substantial progress [26] has been made with these systems to a level that, for example, compressed hydrogen may be acceptable for use on buses, they are generally considered not to meet volume and weight criteria for light duty vehicles. Following reports on high levels of hydrogen adsorption in carbon nanotubes [27], this, together with improvements to metal hydride systems are being actively sought by the research community [28].

A liquid-fuel-based system with on-board reforming would be the preferred choice as the existing production and distribution system could be used or easily adapted with minimal additional investment. However, with today's on-board reformer technology, methanol is the preferred choice and has been demonstrated by Daimler Chrysler in their prototype NECAR3 vehicle [29]. Although gasoline or other petroleum derived fuel is significantly more difficult to reform for on-board fuel cell applications, the challenge to solve the problems is being addressed with the aim of bringing fuel cell vehicles into widespread use prior to the dawn of the 'hydrogen economy' [30].

Steam reforming of natural gas or liquid hydrocarbon fuels is the established technology for producing hydrogen rich gas for stationary fuel cells. Such systems are not suited to the requirements of vehicle applications where space, weight and in particular fast start up and response are essential. Auto thermal reforming, while intrinsically less efficient than steam reforming, does provide the basis for a mobile system. A successful development of auto thermal technology is the Hot Spot reactor demonstrated by Johnson Matthey [31,32]. Starting from cold, with vaporised methanol, 100% output is achieved in 50 s; subsequent changes in through put result in instantaneous changes in output.

2.4. SPFC fuel cells for stationary applications

In the early 1990s, as interest in SPFC systems for transport applications gathered pace, it became apparent that the performance and cost objectives set by the car

manufacturers would provide an attractive and competitive fuel cell system for stationary applications, albeit with a limited temperature heat output.

A 250 kW unit has been developed by Ballard Generation Systems operating on natural gas. Other versions are planned which will operate on propane, hydrogen or anaerobic digester gas. Demonstration units in America, Japan and Europe are now in place with some having achieved over 1 year of operation. Cell voltage decay rates are reported to be <0.3% per 1000 h [33].

The applications for 250 kW units in distributed power systems are well established. An exciting and potentially new development with major implications for reducing energy consumption in the housing sector, is the adaption of the SPFC units for mobile applications to smaller systems in the 2–10 kW range. Units in this capacity range were considered to be impractical until the advent of the SPFC fuel cell. Up to 100 units have now been built and demonstrated by companies such as Plug Power, H Power and Sanyo [34,35].

2.5. Further developments in SPFC technology

SPFC fuel cell developments and technology have been particularly rapid during the 1990s. However, there is scope for further improvements notably concerning the proton conducting membranes presently available. In addition to the cost, existing materials such as Nafion need to be hydrated to be effective proton conductors. This limits their operating temperature to 90°C and adds further complications to the design of the fuel cell stack and system. For these reasons, a material with an operating range up to 200°C would be beneficial. In addition, the higher temperature operation would result in an increase in the CO tolerance of the anode catalysts and extend the range of applications where high grade heat is a requirement. Proton conducting membranes with a 200°C operating capability and no hydration requirement have recently been announced by Celanese [36].

An extensive review of SPFC technology and its applications has been published by Hoogers [37].

2.6. Direct methanol fuel cells

Fuel cell technology, particularly for transport applications, would take a leap forward if a viable system were to be developed that could use a liquid fuel without the need for reformation. The prospects for anode catalysts being developed having the activity to operate on petroleum derived hydrocarbon fuels are poor. However, Shell and others in the 1960s [10] established that Methanol, with anode catalysts such as Pt/Ru, had some potential. The early work utilised sulphuric acid as the electrolyte.

With the introduction of proton conducting membranes, interest in DMFC systems in the 1990s has been renewed with projects in America, Japan and Europe. Of particular

significance has been the work of Los Alamos National Laboratory [10].

If the power density required for vehicle applications are to be achieved, further improvements to anode catalyst performance are necessary. In addition, existing membrane materials are subject to what is known as ‘methanol cross-over’, which in turn contributes to poor cell performance. In this context, it is interesting to speculate on how high temperature membranes such as that developed by Celanese would perform in a DMFC fuel cell [36].

In addition to transport applications for DMFC fuel cells, there are also defence requirements and with appropriate technology, consumer applications such as laptop computers, video cameras and mobile phones. In other words, any small scale applications dependent upon rechargeable batteries.

2.7. Phosphoric acid fuel cells

Following the successful development of AFCs for space exploration, attention turned to commercial applications, initially in American in 1967 with the TARGET programme for small scale units, followed in 1971 with the FCG1 programme for large scale multi-MW units. The phosphoric acid system using Pt metal containing electrodes was chosen as the most viable technology at the time for use with hydrocarbon fuels such as natural gas. Similarly, established steam reforming technology was adapted to provide hydrogen rich gas for the fuel cell.

The decision, by Pratt and Whitney to use phosphoric acid as the electrolyte and adapt steam reforming technology to produce hydrogen were ground breaking at the time. For these developments, Mr. William Podolni, head of fuel cell development at Pratt and Whitney, later to become United Technologies, was awarded the Grove Medal in 1995.

Much of the technology relating to SPFC systems originates from the development of the PAFC units and their demonstration in a variety of on-site locations. Notable in this, is the use of highly dispersed Pt metal catalysts, Teflon bonded electrode structures, graphite bipolar plates and last but by no means least, reformer technology and the associated balance of plant.

PAFC systems such as the ONSI Corporation PC25 200 kW CHP unit are still the only units that are commercially available, albeit at a price that is still not competitive with established CHP systems. They have established the viability and reliability for on-site electricity and heat generation with the added feature, where appropriate, of absorption chilling for air conditioning applications.

There are now some 65 MW of PAFC systems worldwide. Most of the plants are in the 50–200 kW capacity range but large plants of 1 and 5 MW have been built including an 11 MW plant for Tokyo Electric Power. Details on performance, reliability and cost reduction initiatives are contained in several reviews [38–40].

Despite extensive fuel cell and systems development and widespread demonstration in a wide range of potential

applications, the PAFC system has not yet achieved the commercial goals to fulfil projections of 2000 MW of installed capacity by the year 2000 [41].

2.8. Molten carbonate and solid oxide fuel cells

These high temperature fuel cells operating at 650 and 1000°C, respectively, were developed largely with the intention of overcoming the limitations of the low temperature SPFC and PAFC systems. Their two main advantages are that their performance is not affected by carbon monoxide and the residual heat, which is available at temperatures in excess of 600°C, makes them applicable to industrial as well as commercial uses.

Although neither system with existing anode catalyst technology is capable of truly operating in a direct fuel mode and hence hydrocarbon reforming is necessary, the stack operating temperatures are such that internal reforming is possible. In fact, the systems which today have been developed and demonstrated all employ internal reforming either directly within the cell [42] or in a separate reformer contained within the stack module [43]. This basically simplifies the system with benefits in terms of cost and power efficiency.

Despite the benefits of these high temperature systems, their development and demonstration is still at a comparatively early stage compared with that of PAFC.

2.9. Molten carbonate fuel cells

The largest demonstration of a MCFC system was a proof of concept natural gas fuelled 2 MW unit which was operated from 1996 to 1997 at Santa Clara, CA. The plant was built by Energy Research Corporation (now Fuel Cell Energy Inc.) and incorporated internal reforming in what is known as the Direct Carbonate Fuel CellTM (DFC). The plant achieved a maximum output of 1.93 MW AC at an electrical efficiency of 43.6% and operated grid connected for 4100 h. One of the problems during the extended run was attributed for the decomposition of thermal insulation materials which caused deposition of carbon and short circuits in electrical components including the stacks [42]. Based upon the technology and experience gained from the 2 MW demonstration, 250 kW units have been designed and demonstrated by FCE and their partner, MTU, in Germany. Several MCFC developers are also active in Japan and Europe including BCN in The Netherlands, Ansaldo (Italy), Hitachi, IHI, Mitsubishi Electric and Toshiba in Japan. Interestingly, recalling early attempts to use coal in fuel cells, a 250 kW DFC unit will be installed at the Harrison Mining Corporation coal mine in Cadiz, OH, USA to demonstrate the feasibility of fuelling an MCFC with coal mine methane emissions.

The recent progress in demonstrating MCFC systems is being supported by an extension to the existing FCE production plant to increase its annual production capacity from 50 MW in 2001 to 400 MW in 2004.

2.10. Solid oxide fuel cells

Last but by no means least of the six fuel cell systems that make up today's range is the SOFC. Less developed than the rest of the fuel cell range, but possibly having more and wider potential. Until recently, the SOFC was seen as only having application in large scale multi-MW stationary plants. Now, SOFC systems have been developed and demonstrated by Sulzer Hexis Ltd. at the 1 kW level for residential CHP applications. These are primarily intended to be fuelled with natural gas but have been demonstrated using low sulphur home heating oil [44]. The maximum electrical efficiency of these demonstration units that has been achieved so far is 36% (LHV) [45].

Although an SOFC system operating at 1000°C is not an initial first choice for transport applications, in fact, small scale systems are now being developed in Europe and America for use as auxiliary power units (APU) in cars. A dual fuel hydrogen/gasoline vehicle with a SOFC auxiliary power unit is being demonstrated by BMW [45]. The unit provides electric power for on road use as well as for accessories, heating and cooling when the car is stationary. Fuel cell APUs with larger capacities are also being developed to replace engine driven generators and refrigeration units on trucks.

The first demonstration of a SOFC system for cogeneration was carried out at Westervoot in The Netherlands. The 100 kW unit built by Siemens Westinghouse and operated by Elsam and EDB (a consortium of Dutch utility companies) began operation in 1998. At the end of the demonstration project in December 2000, the plant had accumulated a total of 16,612 h.

The fuel cell stack used the Siemens Westinghouse tubular cell system and was shown to be reliable under plant operating conditions which included several thermal cycles and sulphur contamination. The plant had an electrical efficiency of 46% (net) and a total energy utilisation of 75% [46].

2.11. Hybrid SOFC–gas turbine (GT) developments

The electrical efficiency of fuel cell plants are often compared with that of combined cycle gas turbine units (CCGT) with electrical efficiencies of up to 50%. While high temperature fuel cells such as the MCFC and SOFC, in the early stages of their development, are capable of a similar performance, the question is frequently raised as to what benefits fuel cells offer over and above the established CCGT systems.

It is now widely believed that a hybrid SOFC–GT system could achieve electrical efficiencies of up to 70% in a system where the GT combustor is replaced with a SOFC fuel cell. A proof of concept 220 kW demonstration has been carried out at the National Fuel Cell Research Centre, Irvine, USA [47].

Further demonstrations of SOFC–GT hybrids are planned in America and Europe including a 1 kW unit.

In a further development of the SOFC hybrid concept, a study has been made of combining SOFC and SPFC fuel cells in a single system. In this system, the SOFC is used to produce electricity and carry out reforming simultaneously. The exhaust stream from the SOFC is passed through shift converters and is supplied to a low temperature SPFC unit. It is predicted that the overall efficiency of the hybrid system will be significantly higher than the separate fuel cell units with additional benefits to capital and running costs [48].

2.12. Future technical developments

Although SOFCs have the potential for a wider range of applications than any of the other fuel cell systems, there remain significant materials as well as cell and stack assembly challenges to be met before confidence in the technology is justified. Experience from more advanced systems such as PAFC and MCFC, has shown that extensive demonstrations in real situations are required before operating deficiencies become apparent. This is particularly true with balance of plant components and materials.

As far as materials are concerned, there remain three principle areas of research and development. They are:

- the manner in which cells are constructed and stacks assembled;
- the development of interconnect or bipolar plate materials for 1000°C operation;
- the development of electrolyte and electrode materials compatible with a reduced operating temperature of 600–800°C.

Three types of cell/stack assembly have been identified, namely, the tubular, planar and monolithic [49]. The tubular system, developed by Siemens Westinghouse, is to date the most advanced and demonstrated system [50] but it remains to be seen how successful further scale up and cost reduction programmes prove to be. Others, notably Sulzer Hexis Ltd., Global Thermalelectric Inc., Rolls Royce Plc. and Ceramic Fuel Cell Ltd., are actively developing innovative versions of the planar system for use in single or hybrid systems [51].

Although the monolithic cell structure offers significant advantages, little progress has been reported, possibly as a result of difficult materials and application technology.

An area that has received considerable research interest in the last 10 years is the development of what is generally described as the ‘low temperature’ SOFC operating in the range of 600–800°C. At these temperatures, cheaper materials may be used for stack components as well as heat exchangers used in the balance of plant. Success depends upon using thinner electrolyte layers of established materials such as yttria-stabilised zirconia or mixed oxides such as ceria, gadolinia. This and other materials including electrodes with low temperature activity have been presented at several Grove Fuel Cell Symposia [52–54].

3. Conclusions

Since the first Grove Fuel Cell Symposium was held in September 1989, progress in developing fuel cell technology for both stationary and mobile applications has been steady if not spectacular. The most significant has been the rapid development of the SPFC system for transport applications, together with the realisation that success in this field would provide the basis of a low temperature stationary unit for combined heat and power applications (CHP).

Following the successful demonstration of fuel cell powered buses and light duty vehicles by all of the major vehicle manufacturers, attention has now turned to choice of fuel and fuel infrastructure. Technical solutions to two challenging areas will, I predict, go a long way to resolving the question. First, the development of a hydrogen storage system. It should provide a vehicle range of at least 300 miles with no significant increase in volume or weight compared with that of the equivalent gasoline tank. Second, a reformer and gas clean up system for use with gasoline with a start up and response time giving a fuel cell powered vehicle similar performance to that of the conventional ICE vehicle.

In the 1980s, projections for stationary fuel cells anticipated there being at least 2000 MW of capacity in use by 2000. Not only have these projections been over optimistic, but also opinions on the size of the units have changed. For example, much of the market was seen to require large stationary multi-MW units. The smallest size that was thought to be commercially viable was 200 kW. While this may still be the case in some circumstances, both low-temperature and high-temperature micro-CHP fuel cell units are seen to have wide scale application in domestic applications.

Why these changes of direction? What are the driving forces? In part, interest in micro CHP fuel cell units results from technical developments in stack and reformer systems. However, deregulation of the energy utilities and environmental issues, including Kyoto climate change aims, have stimulated a rethink of the relative benefits of large base load power stations versus distributed power, including heat, power and cooling for individual buildings.

In all, the drive to develop the zero emission vehicle with improved fuel economy, together with the contribution fuel cells have long been predicted to make to stationary applications should this time truly see a significant start to their commercialisation in the next 5–7 years.

References

- [1] W.R. Grove, *Philos. Mag. Ser. 3* 14 (1839) 127.
- [2] L. Mond, C. Langer, *Proc. R. Soc. London* 46 (1889) 296.
- [3] K.B. Prater, *J. Power Sources* 61 (1966) 105.
- [4] W.W. Jacques, *Harper's Mag.* 94 (1896–1897) 144.
- [5] E. Bacon, *Z. Elektrochem.* 16 (1910) 300.
- [6] E. Bacon, H. Ehrenberg, *Z. Elektrochem.* 18 (1912) 1002.
- [7] A.M. Adams, F.T. Bacon, R.G.H. Watson, in: W. Mitchell Jr. (Ed.), *Fuel Cells*, Academic Press, New York, 1963, p. 129.

- [8] H. Maget, et al., G.E. Tech. Inf. Serv. Rep. 64DES, Lynn, MA, 1964
- [9] M. Clark, et al., in: Proceedings of the 18th Annual Power Sources Conference, Red Bank, NJ, 1964.
- [10] X. Ren, *J. Power Sources* 86 (2000) 111.
- [11] H. Liebhafsky, et al., *Fuel Cells and Fuel Batteries*, Wiley, New York, 1968.
- [12] G. Broers, et al., *Fuel Cells*, Vol. 1, Rheinhold, New York, 1960.
- [13] J. Weissbart, et al., *J. Electrochem. Soc.* 109 (1962) 723.
- [14] N. Itoh, *J. Power Sources* 29 (1990) 29.
- [15] V. Hacker, et al., in: Proceedings of the 3rd International Fuel Cell Conference, Nagoya, Japan, November 1999.
- [16] J. Larminie, A. Dicks, *Fuel Cell Systems Explained*, Wiley, New York, 2000.
- [17] M. Warshay, et al., in: Proceedings of the Intersociety Energy Engineering Conference, Lucerne Vol. 1, 1996, p. 1717.
- [18] M. Warshay, et al., *J. Power Sources* 29 (1990) 193.
- [19] T. Ralph, et al., *J. Electrochem. Soc.* 14 (1997) 3845.
- [20] K. Pratter, *J. Power Sources* 29 (1990) 39.
- [21] M. Walsh, *J. Power Sources* 29 (1990) 13.
- [22] R. Lemons, *J. Power Sources* 29 (1990) 51.
- [23] K. Prater, *J. Power Sources* 61 (1996) 05.
- [24] F. Panik, *J. Power Sources* 71 (1998) 36.
- [25] W. Hever, *J. Power Sources* 86 (2000) 158.
- [26] J. Zieger, *Hydrogen Energy Progr.* 10 (1994) 1427–1437.
- [27] A. Dillon, et al., *Nature* 386 (1997) 377.
- [28] 'FUCHSIA', EC Energy Project No. NNE5-2000-00255.
- [29] F. Panik, *J. Power Sources* 71 (1998) 36.
- [30] W.R. Grove, in: Proceedings of the Grove Fuel Cell Symposium, London, 2001.
- [31] N. Edwards, et al., *J. Power Sources* 71 (1998) 123.
- [32] S. Golunski, *Platinum Met. Rev.* 42 (1998) 2.
- [33] K. Washington, in: Proceedings of the Fuel Cell Seminar, Portland, USA, October 2000.
- [34] M. Sperry, M. Torpeg, in: Proceedings of the Fuel Cell Seminar, Portland, USA, October 2000.
- [35] D.J. Edlund, et al., in: Proceedings of the Fuel Cell Seminar, Portland, USA, October 2000.
- [36] J. Pawlik, in: Proceedings of the European Fuel Cell Group Workshop, Ulm, Germany, 2001.
- [37] G. Hoogers, *Phys. World* (1998) 3.
- [38] A.J. Appleby, F.R. Foules, *A Fuel Cell Handbook*, 2nd Edition, 1996.
- [39] L. Blomen, M. Mugerwa, *Fuel Cell Systems*, Plenum Press, New York, 1993.
- [40] M. Ishizawa, et al., *J. Power Sources* 86 (2000) 294.
- [41] W.P. Teagan, et al., in: Proceedings of the 4th European Solid Oxide Fuel Cell Forum, Lucerne Vol. 2, Switzerland, July 2000.
- [42] P. Eichenberger, *J. Power Sources* 71 (1998) 95.
- [43] B. Baker, *J. Power Sources* 86 (2000) 9.
- [44] A. Schuler, et al., in: Proceedings of the 4th European Solid Oxide Fuel Cell Forum, Lucerne Vol. 1, Switzerland, July 2000.
- [45] R. Piethelm, et al., in: Proceedings of the 4th European Solid Oxide Fuel Cell Forum, Lucerne Vol. 1, Switzerland, July 2000.
- [46] J. Sukkel, in: Proceedings of the 4th European Solid Oxide Fuel Cell Forum, Lucerne Vol. 1, Switzerland, July 2000.
- [47] S. Vora, in: Proceedings of the 4th European Solid Oxide Fuel Cell Forum, Lucerne Vol. 1, Switzerland, July 2000.
- [48] A. Dicks, et al., *J. Power Sources* 86 (2000) 501.
- [49] B. Riley, *J. Power Sources* 29 (1990) 223.
- [50] R. George, *J. Power Sources* 86 (2000) 134.
- [51] B. Godfrey, *J. Power Sources* 86 (2000) 68.
- [52] B. Steele, *J. Power Sources* 49 (1994) 1.
- [53] J. Huijsmans, *J. Power Sources* 71 (1998) 107.
- [54] T. Inagaki, *J. Power Sources* 86 (2000) 347.