

Proton Exchange Membrane Fuel Cells

PROGRESS IN COST REDUCTION OF THE KEY COMPONENTS

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Proton exchange membrane fuel cells operating on hydrogen/air are being considered as high efficiency, low pollution power generators for stationary and transportation applications. There have been many successful demonstrations of this technology in recent years. However, to penetrate these markets the cost of the fuel cell stack must be reduced. This report details the progress made on reductions in the stack cost by lowered platinum catalyst loadings in the latest stack designs, the development of lower cost membrane electrolytes, the design of alternative bipolar flow field plates, and the introduction of mass production technology. Despite such advances, there is still a need for further reductions in the stack cost, through improvements in the performance of the membrane electrode assembly. However, improved stack performance must be demonstrated not only with pure hydrogen fuel but also, more particularly, with reformat fuel, where tolerance to poisoning by carbon monoxide and carbon dioxide needs to be improved. Advances that are required in the ancillary sub-systems are also briefly considered here.

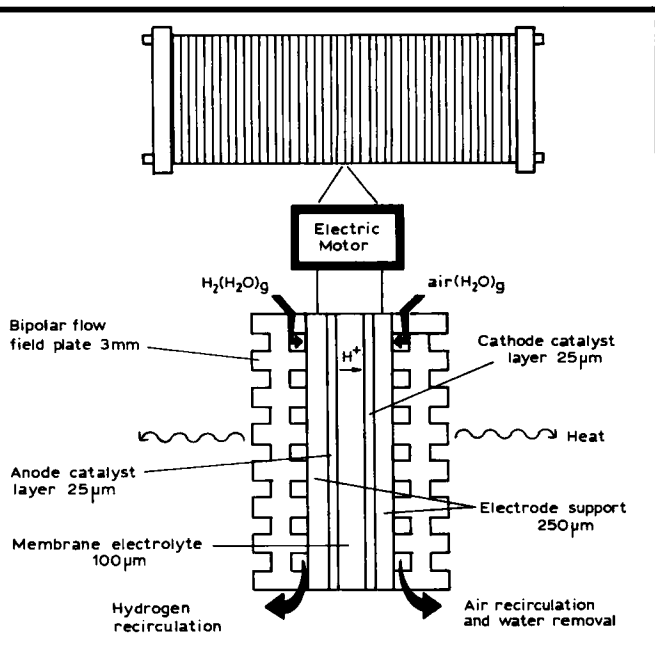
As with all fuel cells, the operating principles of the proton exchange membrane fuel cell (PEMFC) are straightforward. The chemical energy present in a fuel, usually hydrogen, and an oxidant, oxygen, is cleanly, quietly and efficiently converted directly into electrical energy. The hydrogen is oxidised at the anode and the oxygen reduced at the cathode of a single cell. The power requirement in fuel cell technology is achieved by combining a number of single cells in series to produce a fuel cell stack, and a number of stack modules are then combined in series to produce the power plant.

The membrane electrode assembly (MEA) is at the heart of the single cell. It is the critical component of the PEMFC, since it is the site of the fuel cell reactions. The MEA, see Figure 1, is less than a millimetre thick and consists of a solid polymer, proton conducting membrane electrolyte, with a layer of platinum-based catalyst and a gas-porous electrode support material on both sides of it, forming the anode and cathode of the cell. The membrane electrolyte is typically bonded to the electrodes by

hot pressing at a temperature above the glass transition temperature of the membrane. Membranes currently employed are based on perfluorinated sulfonic acid (for example the Nafion[®] range of materials produced by Du Pont) which must be kept in a fully hydrated state during fuel cell operation in order to realise the maximum proton conductivity. This requirement currently limits the temperature of operation of the PEMFC to below 100°C, at moderate pressures.

Hydrogen fuel, supplied either in a pure form from high pressure vessels or metal-hydride storage materials, or diluted with carbon dioxide and other components from a fuel reformer, and the oxidant, usually air, are supplied to the MEA from the flow field plates, see Figure 1. To-date most precommercial stacks have used pure graphite flow field plates with channels machined into their surfaces. The raised landing areas make electrical connection with the electrode support and the channels provide gas access to, and water removal from, the MEA. In most cases the flow field plates are designed

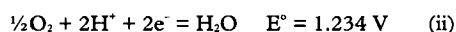
Fig. 1 The fuel cell stack, showing the structure of a typical single cell. The MEAs are located between carbon flow field plates which feed humidified fuel (H_2 or reformat) and air to the MEA. The reactants permeate through the carbon based electrode support structures into the platinum catalyst layers where they react to generate electricity, heat and pure water. The heat is removed via cooling plates, although since the current stacks operate at 80 to 90°C, it cannot be usefully employed. Sufficient MEAs are combined in series to produce stacks which deliver 1 to 25 kW. The stacks are then combined in series to give enough power to drive a car (50 kW), a bus (200 kW) or to provide stationary power (< 1 MW)



to be bipolar, where one side of the plate is the anode of one cell, and the other side is the cathode of the adjacent single cell. The cells are connected in series via the plates. The gases pass from the bipolar flow field plate through the electrode support material to the catalyst layer where they react. Hydrogen is consumed at the anode, yielding electrons to the anode and producing hydrogen ions:



The hydrogen ions are conducted through the proton conducting membrane electrolyte, and are combined at the cathode with electrons and the oxygen from the air supply to generate water:



Thus, the PEMFC combines hydrogen and oxygen to generate electrical power. Pure water and heat are the only by-products:



As long as the single cell is supplied with fuel and oxidant it will generate electrical energy in the form of a direct current. Thus, a fuel cell is better regarded as an electrochemical engine,

where fuel is continuously oxidised by air to produce power, rather than as a form of battery, in which energy is stored.

Cost, Performance and Operating Lifetime Requirements

In addition to space, military and low power (< 1 kW) applications (1), the PEMFC is being considered for two major markets. One essential feature of the PEMFC – its ability to generate much higher power densities at lower temperatures than other fuel cell types – has opened up the potential of fuel cell technology to provide reliable, low cost power for a new generation of non-polluting automotive engines. It is also being considered for more traditional stationary power generation, for distribution or on-site requirements, such as for hotels, hospitals and the home. The drive to reduce pollution levels and to increase the fuel efficiency of the internal combustion engine and of conventional power stations is aiding the adoption of low or zero emission fuel cell technology, and indeed there have now been a significant number of successful demonstration programmes worldwide. But, for this technology to become widely

commercialised cost and, to a lesser extent, performance need to be improved.

In this regard the automotive application is more demanding. The size, weight and cost of the stack are all key issues. Stack power density and energy density targets of 1.0 kW l^{-1} and 1.0 kW kg^{-1} , respectively, at a cost of less than U.S.\$50 kW^{-1} have been quoted for passenger cars (2, 3). To meet this cost target requires both a reduction in material costs and the development of high volume, low cost manufacturing processes for the stack components. Increased power density, achieved by operating at higher current densities while maintaining cell potentials at reasonable levels, will, besides reducing the size and weight of the stack, also have the effect of lowering the stack material costs.

For stationary power applications the size and weight of the stack are generally less of a concern and the cost target is also less demanding at around U.S.\$500 kW^{-1} (3). Improved energy efficiencies, that is higher cell potentials, are more important in this application.

While cost reductions and performance improvements in the PEMFC stack are important, they must be maintained over the operating lifetimes. In this respect, the transportation market is less exacting, with operating lifetimes of some 5000 hours being adequate for a passenger car, compared with operating lifetimes of at least 40,000 hours demanded by stationary power plants.

Progress in Reducing Stack Costs

Over the past five years considerable progress has been made in lowering the cost of PEMFC stacks. This has been achieved largely by reducing the costs of the three critical cell components: the electrodes, the membrane electrolyte and the flow field plate. Some groups are also addressing the cost reductions available from volume manufacture of the stack components.

Lower Platinum Loadings on Electrodes

The leading developer of the PEMFC is the Canadian company Ballard Power Systems. Since the early 1990s several hundred stacks have been produced for a wide range of demon-

stration programmes. Most of these stacks have been rated at a maximum power output of 5 kW (the Mark V type). The loading of platinum black catalyst on the electrodes has typically been 4.0 mg cm^{-2} (4). At operating cell potentials of 0.75 to 0.65 V, the platinum black loading corresponds to 26.7 down to $16.0 \text{ g Pt kW}^{-1}$ of power output. A comparison with the targeted stack costs shows quite clearly that these platinum loadings have to be reduced if the PEMFC is to be developed as a commercially viable product.

When pure hydrogen is used as the fuel almost all of the performance losses occur at the cathode. This is because of the slower kinetics of oxygen reduction, Equation (ii). Despite many studies of this reaction in the PEMFC and other types of fuel cell, platinum-based electrocatalysts remain the only practical catalyst material, since they combine both activity and stability in the fuel cell environment. At the anode, losses in cell potential are usually small (less than 50 mV at 2.0 A cm^{-2}) due to the extremely facile nature of the hydrogen oxidation reaction, Equation (i), on platinum-based catalysts.

Many groups have recently demonstrated very high cell performances from PEMFCs operating on hydrogen/air at substantially lower platinum cathode loadings than the 4 mg cm^{-2} typical of the early prototype stacks. This has been achieved by the successful exploitation of higher surface area carbon supported catalysts, such as 20 weight per cent platinum supported on Cabot Vulcan XC72R carbon black. Central to the development of these electrodes has been the need to impregnate the active catalyst layer with a soluble form of the polymer electrolyte. This significantly increases the protonic contact between the electrolyte and the surface of the platinum catalyst within the porous carbon structure, thus permitting lower platinum loadings on the electrodes to be utilised more effectively. Leading investigators have been the groups at Los Alamos National Laboratories (LANL) (5, 6) and Texas A&M University (TAMU) (7), although similar approaches to electrode design have subsequently been reported by other academic groups around the world (8–10).

Two basic approaches to electrodes have been developed by these groups.

At LANL thin film catalyst layers comprising the carbon supported catalyst mixed with the soluble form of the electrolyte (5 weight per cent Nafion® EW1100 in propan-2-ol and water) are deposited onto the membrane electrolyte. A microporous gas diffusion backing layer, employing a carbon cloth based electrode substrate, is compressed against the catalyst layer in the single cell to provide efficient removal of the product water from the cathode.

At TAMU the catalyst layer is first deposited onto the electrode support structure from a mixture of carbon supported catalyst and polytetrafluoroethylene (PTFE), which binds the layer together. Subsequently, the catalyst layer surface is impregnated with the membrane electrolyte solution.

Using these approaches LANL and TAMU have reported performances comparable to platinum black based cathodes, but with cathode catalyst loadings as low as 0.12 mg Pt cm⁻² and 0.05 mg Pt cm⁻², respectively. Assuming a negligible anode loading (reasonable for pure hydrogen operation) the noble metal usage is reduced, from 13.4 down to 8.0 g Pt kW⁻¹ for platinum black cathodes to less than 0.4 g Pt kW⁻¹ of power output at operating cell potentials of 0.75 to 0.65 V. Based on a platinum price of about U.S.\$12 g⁻¹, this represents a cost of less than U.S.\$5 kW⁻¹ for the noble metal, which is compatible with all PEMFC applications.

Other methods of achieving high performance cathodes with low platinum loadings have been demonstrated. Notable is work by PSI Technology using cathodes formed from uncatylsed carbon black impregnated with a soluble form of the membrane electrolyte and then electro-deposited with platinum at loadings as low as 0.05 mg cm⁻² (11). The aim of this approach was to deposit platinum only in regions of the electrode which were both in electronic contact with the carbon support and protonic contact with the membrane electrolyte, again ensuring efficient use of very low platinum loadings.

Other groups have deposited the platinum catalyst directly into the polymer membrane

electrolyte by chemical reduction of platinum salt solutions, see for instance (12). Loadings deposited in this way tend to be higher than with other methods (> 1 mg Pt cm⁻²). It appears that platinum can be isolated within the membrane in regions where it cannot be contacted electronically. This, coupled with the much lower platinum dispersions achieved on the membrane, has meant that the effective catalyst surface areas are inferior to those in electrodes employing carbon supported platinum catalysts.

Electrodes Manufactured in Volume for Advanced Stack Designs

The above studies have largely been at the laboratory scale. Electrodes have been fabricated using manual techniques which do not necessarily lend themselves to scale-up to high volume production and MEAs have been evaluated in small (< 50 cm² active area) single cells. Cell performances have often been measured in cells functioning at high gas stoichiometries. This cannot be justified economically and performances can be raised on air operation, particularly at higher current densities (13). In addition, there have been few evaluations of operating lifetime data. Both LANL and TAMU are now, however, beginning to address these factors. LANL are examining the principle of ink jet printing the electrodes by modifying a chart recorder (14) and TAMU have investigated spraying and rolling the catalyst layers (15). Performances are being evaluated in larger single cells (50 to 100 cm² active area). The success in reducing the platinum loadings has led other academic and industrial groups to focus on mass production techniques suitable for electrodes and MEAs. However, testing has mostly been restricted to single cells, often with only 5 cm² active area, see for example (16).

One major target of a joint programme between Ballard Power Systems and Johnson Matthey has been the development, for full size PEMFC stack hardware, of low platinum loading electrodes prepared in high volume. An electrode manufacturing process based on screen printing has been developed (17) and a small pilot plant facility has been established at Johnson

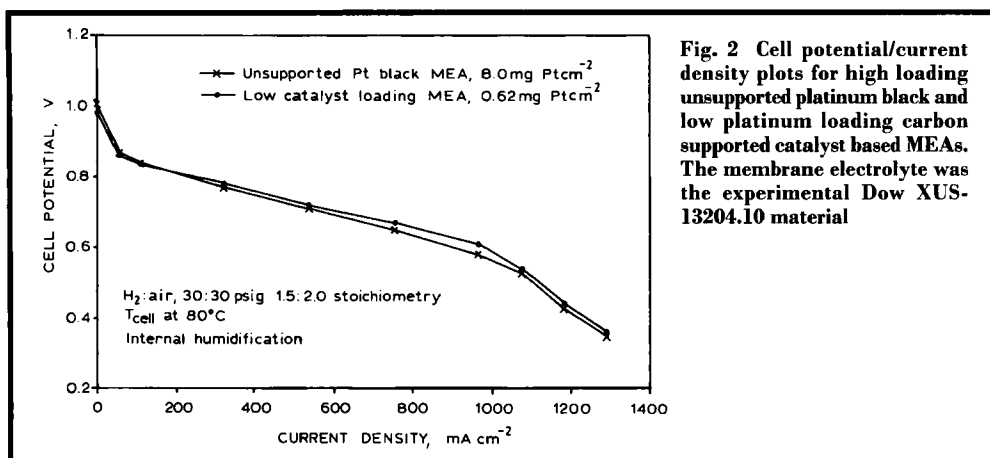


Fig. 2 Cell potential/current density plots for high loading unsupported platinum black and low platinum loading carbon supported catalyst based MEAs. The membrane electrolyte was the experimental Dow XUS-13204.10 material

Matthey. The plant currently produces around 50,000 electrodes per annum, but has the potential for scaling-up as demand rises. Electrodes have been produced from inks comprising carbon supported platinum catalysts and solutions of the polymer electrolyte. For high volume production it was deemed unsuitable to use the organic solutions of Nafion[®] employed by LANL, TAMU and others to impregnate the catalyst (5–11). Besides not wanting to handle large volumes of organic solvents in a production environment, there is a possibility of interaction between the solvents and the high surface area platinum catalysts, which could result in the production of organic by-products in the inks and, with high solvent concentrations, possibly combustion. Thus, a method was developed to remove the alcohols from 5 weight per cent Nafion[®] solution to give an essentially 'aqueous' Nafion[®] polymer solution (18), which has been used for routine manufacture of electrodes with catalyst loadings of 0.1 to 1.0 mg Pt cm⁻².

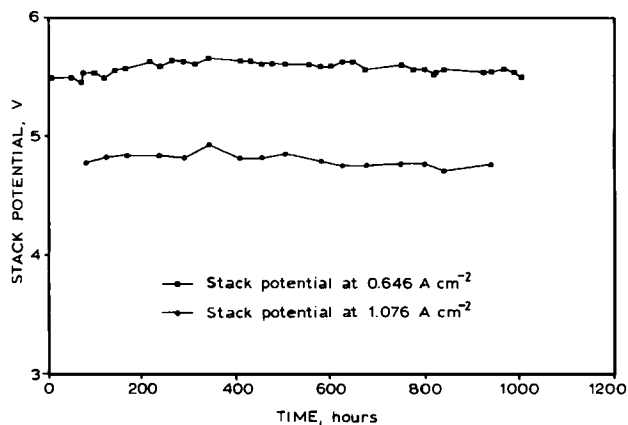
Comparison of Electrodes

Figure 2 shows the "beginning of life" cell potential versus current density plot of a low catalyst loading MEA (0.62 mg Pt cm⁻²), compared with the higher loading unsupported platinum black MEA (8.0 mg Pt cm⁻²) in a Ballard Mark V single cell of 240.2 cm² active area. The performances are comparable. The cathode comprises 40 weight per cent platinum on

Vulcan XC72R at a loading of 0.37 mg Pt cm⁻² and the anode 20 weight per cent platinum-10 weight per cent ruthenium (Pt/Ru) on Vulcan XC72R at a loading of 0.25 mg Pt cm⁻². At a cell potential of 0.75 to 0.65 V the MEA generates 0.4 to 0.8 A cm⁻², equivalent to 0.3 to 0.5 W cm⁻². This translates to a much reduced catalyst requirement of 2.0 down to 1.2 g Pt kW⁻¹ compared to 26.7 to 16.0 g Pt kW⁻¹ for the platinum black MEA. This reduced loading shows considerable progress towards a platinum catalyst cost compatible with the stack cost targets for stationary and vehicle applications.

The "beginning of life" performances of the low platinum loading MEAs have been retained in the advanced Ballard stack technology being developed for submarine, bus, automotive and utility applications. With pure hydrogen fuel and air as oxidant, stable long term performance has been demonstrated in 4 and 8 cell sub-stacks and in full stacks. Figure 3 shows the performance of Dow membrane MEAs with anode and cathode catalyst loadings of 0.25 mg Pt cm⁻² and 0.50 mg Pt cm⁻², respectively, in an 8 cell stack representative of the Phase 2 bus stack hardware. This hardware is being developed for the forthcoming precommercial transit bus fleet trials in Chicago and Vancouver. Transit buses offer an early market opportunity for fuel cell power plants as cost targets are less demanding than for small vehicles and there is space to store sufficient hydrogen fuel on-board to give a range

Fig. 3 Durability of low platinum loading MEAs in an 8 cell Ballard stack, using Dow XUS-13204.10 membrane electrolyte. The stack construction is typical of the hardware employed in the precommercial transit buses being supplied to Chicago and Vancouver



comparable to current diesel-fuelled engines. After 1000 hours at 0.646 A cm⁻², with 5-hour excursions to 1.076 A cm⁻², the degradation rate of below 4 μV h⁻¹ was well within target levels.

Reproducible Cell Performance

Particularly important in volume manufacture is reproducible performance. The low catalyst loading MEAs exhibit excellent cell to cell reproducibility in full stacks. In Figure 4 consistent

cell potentials produced by the individual cells in an 80 cell stack built for an air-independent submarine propulsion application are shown. The MEAs comprise cathodes with 0.6 mg Pt cm⁻², anodes with 0.25 mg Pt cm⁻² and Nafion[®] 117 membrane. The minimal variation in cell performance achieved over a range of current densities represents the highest level of cell to cell consistency that has recently been reported in the literature for PEMFC stacks, see for

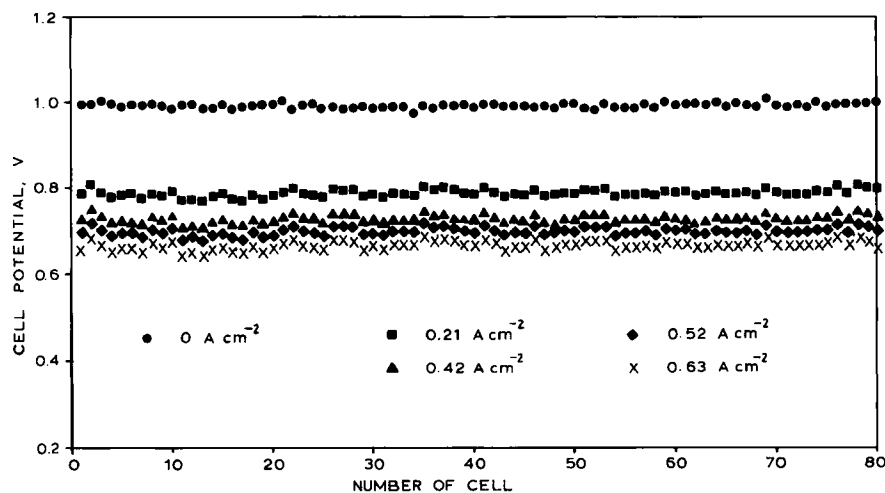


Fig. 4 Individual cell potentials in a full 80 cell stack for submarine propulsion. The low platinum loading MEAs contain Nafion[®] 117 membrane electrolyte. The high consistency of the cell potentials is a reflection of the control of operating conditions through the stack and the ability of the pilot plant at Johnson Matthey to manufacture reproducible electrodes. Uniformity in cell performance is of prime importance in the development of PEMFC technology

example the 50 cells in (19). This highlights the excellent degree of consistency achieved in MEA production and the efficient control of operating conditions throughout the stack.

Based on the large volume of data now available, it is clear that achieving economical platinum loadings on electrodes is no longer a barrier to the commercialisation of PEMFCs. The reduced metal loadings are clearly compatible with the cost targets for stationary power generation and are close to the levels required for passenger cars. Indeed, rather than pursuing further cost reductions by lowering the electrode platinum loadings in stacks to the lowest levels studied in small cells ($0.05 \text{ mg Pt cm}^{-2}$), greater attention should be paid to improving cell performance at slightly higher, total MEA loadings (about 0.2 to $0.35 \text{ mg Pt cm}^{-2}$ for automotive applications, and 0.5 to $1.0 \text{ mg Pt cm}^{-2}$ for stationary power plants). This would reduce the cost of all other stack materials and improve stack efficiencies.

Improved cell performance may be achieved by developing electrode structures in which the platinum catalyst is still more efficiently utilised. Even with the high performances discussed here, there are still performance losses due to oxygen and proton diffusion limitations in the electrode structures. Modelling and practical studies have indicated that even in the low platinum loading electrodes, only a limited thickness of the catalyst layer is being utilised. LANL have estimated this to be as little as $5 \mu\text{m}$ in their structures (20) and TAMU estimate a $10 \mu\text{m}$ thick active layer for their electrodes (21). While this suggests there is scope for maintaining performances as catalyst loadings are reduced – to the order of $0.1 \text{ mg Pt cm}^{-2}$ and below – it also indicates enhanced performance is attainable.

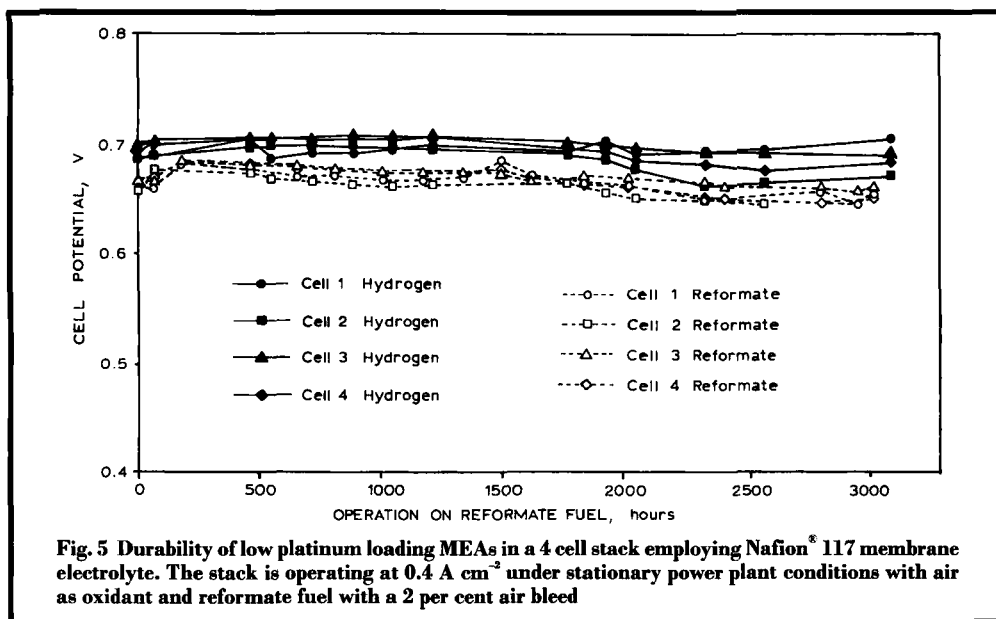
Low Platinum Loading Anodes for Reformate Operation

There is no great technical challenge in lowering platinum loadings on anodes operating with pure hydrogen fuel; anode catalyst loadings as low as $0.025 \text{ mg Pt cm}^{-2}$ are sufficient for high current density operation (22). However, for stationary power plant and light

duty vehicle applications, the anode fuel will almost certainly be impure hydrogen (reformate) produced via reforming carbon-containing fuels, such as natural gas, methanol, petrol or diesel. Achieving satisfactory performance and durability with these fuels is much more difficult, because the anode is poisoned by trace levels of carbon monoxide present in the reformate. Carbon dioxide poisoning and dilution effects also reduce performance. But, even using impure hydrogen and with lowered anode platinum loadings the tolerance to poisoning has been increased. Unsupported platinum black catalyst has been replaced by higher surface area and more poison tolerant Pt/Ru catalyst supported on Vulcan XC72R, and the catalyst has been impregnated with the soluble form of the polymer electrolyte to increase the number of active catalyst sites in the anode.

The favoured catalyst for tolerance to both carbon monoxide and carbon dioxide is Pt/Ru at 50:50 atomic per cent (23–25). Wilkinson and colleagues have confirmed that with Pt/Ru catalysts a higher catalyst dispersion and an increased protonic contact between the platinum and the membrane electrolyte improves the poison tolerance by increasing the number of non-poisoned catalyst sites within the anode (23). The best results have come from Iwase and Kawatsu, who showed that with Pt/Ru anodes containing $0.4 \text{ mg Pt cm}^{-2}$ there is complete tolerance to 100 ppm carbon monoxide in hydrogen, at 80°C and 7 psig (24).

The long term performance of a 4 cell Ballard sub-stack, with Johnson Matthey/Ballard Power Systems low platinum loading MEAs is shown in Figure 5. The MEAs contain Pt/Ru at $0.25 \text{ mg Pt cm}^{-2}$ in the anode, Pt at 0.55 mg cm^{-2} on the cathode and Nafion[®] 117 membrane electrolyte. The stack is operating at a constant current density of 0.4 A cm^{-2} under typical stationary power plant testing conditions. The oxidant is air and the reformate fuel contains 70 per cent hydrogen, 25 per cent carbon dioxide and smaller quantities of other contaminants, including 10 ppm carbon monoxide. A 2 per cent air bleed was also directly passed into the anode chamber to promote gas-phase



oxidation of carbon monoxide to carbon dioxide (26). Compared with pure hydrogen operation, the loss in performance at a current density of 0.4 A cm^{-2} is less than 30 mV. This loss is due principally to the effect of diluting the fuel to 70 per cent. By thus combining the effects of the intrinsically more poison resistant Pt/Ru anode electrocatalyst and a low level air bleed, tolerance to carbon monoxide and carbon dioxide poisoning has been achieved. Significantly, after 3000 hours of continuous operation an acceptable decay rate of only $4 \mu\text{V h}^{-1}$ was measured at this current density, see Figure 5. This durability has now been extended to over 5000 hours of reformate operation, demonstrating that stable performance can be achieved with reformate fuel using a Pt/Ru catalyst, even in the presence of an air bleed.

At current densities much higher than 0.4 A cm^{-2} there are performance losses due to the effects of carbon dioxide, which are not overcome, principally because the poisoning does not respond to the air bleed technique. A typical loss is 50 mV at 1 A cm^{-2} . This suggests that while these Pt/Ru anode loadings may be acceptable for stationary applications where the reformate fuel is cleaned by the water-gas shift

reaction and selective oxidation, a more poison tolerant anode catalyst may be required for automotive use to achieve high power densities at the required platinum loadings.

In both applications, an anode catalyst that is much superior to Pt/Ru would allow lower anode platinum loadings and put less demand on the fuel processing system. Ideally, removing or simplifying the selective oxidation reactor would benefit the overall system design, but anode tolerance would need to be increased to a level close to 1000s of ppm of carbon monoxide. Such improved anode catalyst tolerance could also be used to eliminate the need for the air bleed, which adds to the complexity of the system and raises concerns over safety, heat management and losses in efficiency because of the possibility of hydrogen and oxygen recombining.

Proton Exchange Membrane Electrolytes

The most widely used membrane electrolytes are based on Nafion® type since these are known to offer a long lifetime in aggressive environments (50,000 hours). Nafion® is a perfluorinated sulfonic acid polymer consisting of a fluoropolymer backbone, similar to Teflon, to

which sulfonic acid groups are chemically bonded (27). The sulfonic acid groups are fixed in position, but the associated protons are free to provide conduction. These membranes are commercially available for around U.S.\$ 700 m⁻². Figure 6 shows the performances of a range of Nafion[®] membranes and of the experimental Dow XUS-13204.10 membrane in a Ballard Mark V single cell. The electrodes, from Johnson Matthey/Ballard Power Systems, have low platinum loadings. The membrane resistance controls the single cell performance in the pseudo-linear region of the plot. The thinner Nafion[®] membranes give enhanced performance particularly at higher current densities (Nafion[®] 112 > Nafion[®] 115 > Nafion[®] 117) although the thinner membranes are less durable and more difficult to handle in mass production. The Dow membrane is close to the thickness of Nafion[®] 115, but gives superior performance due to a lower equivalent weight (defined as: gram of polymer/mole of sulfonic acid group).

Based on the superior performances of the Nafion[®] 112 and Dow membranes the electrolyte costs translate to about U.S.\$ 135 kW⁻¹ at 0.65 V and U.S.\$ 230 kW⁻¹ at 0.75 V, which is closer to the operating potential of a stationary power plant. This is perceived to be too costly, particularly for widespread application of PEMFCs in passenger cars.

It has been quoted, however, that with an increase in demand of two orders of magnitude – a market of 1 million cars per year – membrane costs could be reduced by an order of magnitude (2). But, from a commercial viewpoint, it is likely that a range of products and suppliers will be necessary to drive the costs down, particularly to the levels required for automotive applications.

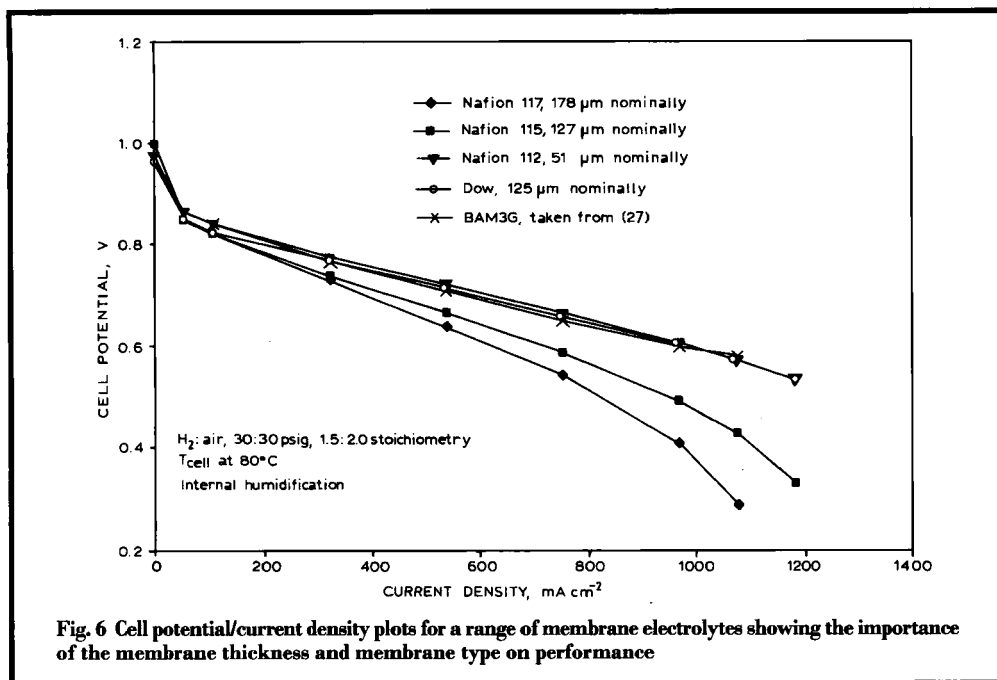
It is also likely that different membrane electrolytes will be employed in automotive and stationary power plants. For stationary application, where 40,000 hours of operating lifetime is required but high power densities are less important, a thicker more durable membrane may be used, for instance a Nafion[®] type membrane which, with cost reductions from volume demand and increased competition, could be

compatible with the cost target for this use, particularly with improved performance. In contrast, a thinner higher power density membrane, which may be less durable than the perfluorinated sulfonic acid membranes but have an operating lifetime of 5,000 hours, will probably be used in passenger cars. Steck has reviewed studies on preparing intrinsically lower cost membranes, many of which are hydrocarbon based or partially fluorinated (27). Most do not have the necessary stability or the low specific resistance shown by Nafion[®] membranes.

New Ballard and Other Membranes

Recently Ballard Advanced Materials have developed a membrane material that is not fully fluorinated and which may be suitable for automotive applications (3, 27). The membrane shows at least equivalent “beginning of life” performance to the Dow XUS-13204.10 and Nafion[®] 112 membranes in a Ballard Mark V single cell, Figure 6, (27). The Ballard membrane has demonstrated this performance for over 4500 hours – almost sufficient for an automotive application (3). Since the preparation of this membrane is cheaper and since it produces more quantitative yields of partially fluorinated polymer, it is anticipated that with volume demand the membrane costs will be reduced to as little as U.S.\$ 50 m⁻². This translates to U.S.\$ 10 kW⁻¹ at 0.65 V and U.S.\$ 17 kW⁻¹ at 0.75 V with current performance levels, based on the low projected costs with volume demand.

In an alternative approach to preparing electrolytes for a wide range of applications, W. L. Gore & Associates have produced low platinum loading electrodes and MEAs based on very thin (5 to 40 μm) composite membranes, by impregnating a PTFE support with perfluorinated sulfonic acid membrane electrolyte solution. The PTFE support is claimed to provide mechanical strength and dimensional stability in the thin membranes (28). Studies at LANL have shown that these Gore-Select[™] membranes give high performance both with LANL “thin film” electrodes and Gore’s own cathode, in small (5 cm² active area) single cells operating on hydrogen and air (28). The performance is not, however,



as high as projected for a homogeneous Nafion[®] membrane of similar thickness, since the specific resistance of the Gore membranes is higher. At 0.75 to 0.65 V, power densities of 0.3 to 0.5 W cm⁻² are generated, similar to the power density produced by existing precommercial stacks. Potential cost savings are still available by using these thinner membrane materials. A material cost reduction to around U.S.\$ 100 m⁻² for a 20 μm thick membrane, based on the list price of the membrane electrolyte solution for the chloroalkali industry, has been quoted (29).

Recently, the performance of Gore MEAs was examined in a 50 cell stack manufactured by Energy Partners (19). The lower power density than observed in small single cells (0.24 W cm⁻² at 0.6 V) was limited by a few cells. This was attributed to difficulty in controlling the water content in the MEAs resulting in flooding and gas diffusion limitations at the cathode.

Flow Field Plates

The bipolar plate is the third high-cost component in the fuel cell stack. The machined graphite flow field plates currently used are

estimated to account for as much as 60 per cent of present stack costs (29). As the plates are the heaviest and thickest stack components – and there are over two plates per MEA when additional cooling and humidification plates are considered – their replacement offers great potential for reductions in stack size and weight. Two main approaches to fabricating flow field plates are being examined: thin metal plates and composite carbon plates; but there is little information in the literature as much of the work is industry led. While both approaches could lead to cheaper and lighter plates, there are problems with maintaining low specific resistances in alternative materials. This will require much thinner plates to minimise ohmic potential losses, particularly for an automotive application.

Stainless steel plates have been examined by ECN (30) and LANL (14), and LANL have also investigated metal meshes; in general, cell potentials were lower due to higher contact resistances probably as a result of surface oxide films. LANL also noted that the cost of machining the metal plates was prohibitively high (14). Several companies are investigating the use of thin metallic

plates fabricated from a low cost base metal with a thin protective coating to provide the necessary stability to oxidation in the fuel cell environment. With such substrates it may be possible to press or stamp out the flow fields.

The second approach is to fabricate moulded carbon black-polymer composite flow field plates. International Fuel Cells hold a patent on this concept (31). Thin, flexible graphite sheets with flow fields punched or stencilled in place have also been patented by Ballard (32, 33).

Remaining Technical Challenges and A Look Forward

While there has been considerable progress in recent years in reducing the stack costs, a number of technical challenges remain. Improvements in performance are necessary to increase cell efficiency and power density at total MEA loadings of $< 0.35 \text{ mg Pt cm}^{-2}$ for passenger cars and slightly higher for stationary power plants. At the cathode, improved oxygen reduction catalysts and improved cathode designs to utilise the platinum catalyst more fully are desirable. At the anode, besides greater utilisation of the catalyst in improved electrode designs, greater intrinsic catalyst tolerance to carbon monoxide and carbon dioxide is needed.

The development of membranes which can operate above 100°C would be of significant benefit in reducing carbon monoxide poisoning, improving the electrochemical kinetics and mass transport processes in the MEA, and allowing water removal in the vapour phase. A wider selection of membrane electrolytes from different suppliers is needed to reduce costs, particularly for automotive use. Membranes with resistances lower than those of Nafion[®] 112 or Dow XUS-13204.10, and with low gas transfer rates and durability of at least 5000 hours would clearly be beneficial for an automotive stack.

MEAs will have to be manufactured using high volume technology, and cheaper bipolar plate materials need to be developed. The resultant low cost MEAs and flow field plates then have to demonstrate the required operating lifetimes in the advanced stack hardware.

Among the stack ancillaries, the air delivery

sub-system is a major drain on power. Air compressors consume 10 to 15 per cent of the fuel cell output (2). Consequently there is a trade-off between improved stack performance at higher air pressures and the power required for compression. A low cost highly efficient air compressor is needed. In fact, many groups are developing electrodes, MEAs and stacks that function at ambient pressure (3), generally employing passive water and thermal management. Although small ambient pressure systems are attractive for low power applications it remains to be seen if compact ambient pressure systems can be developed for major multi-kilowatt applications.

The recent progress in developing lower cost PEMFC stack components has created confidence that the remaining challenges can be successfully overcome. This view is supported by the increased attention being paid to fuelling and fuel infrastructure issues for vehicle applications. While in the longer term the production of hydrogen fuel for PEMFCs from renewable sources, such as solar energy, allied to the development of more efficient hydrogen storage materials is clearly desirable, early commercialisation will require hydrogen from fossil fuel sources. There is a major need to produce high performance, compact, fast start up, responsive, and fuel flexible, reformer systems, and Johnson Matthey, besides working to develop lower cost, higher performance catalysts, electrodes and MEAs, have produced a compact (0.25 l) autothermal reformer (HotSpot[™]) (34). This converts methanol selectively to hydrogen to produce a high output per unit volume – 2.5 kW of fuel cell power per litre of reactor – by a combination of steam reforming and partial oxidation. Heat transfer between the two reactions occurs over microscopic distances within the catalyst, avoiding the need for complicated heat-exchange engineering. Scale-up is achieved by feeding the appropriate number of individual reactors from a central manifold.

Thus all aspects of fuel cell development are under intensive investigation and with the savings achieved in the key components successful commercialisation is much more certain.

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Platinum Increases Hydrogen Photoproduction

Platinum group metal complexes find extensive use as sensitisers, photocatalysts and photoelectrodes in harvesting sunlight to produce electricity or hydrogen by the electrolysis of water (1). Hydrogen is usually photoproduced from water using semiconductors and catalysts, and polymer semiconductors combined with ruthenium chloride can produce hydrogen effectively.

Now scientists from the Tokyo Institute of Technology (2) report a photocatalytic system which produces hydrogen from the electrolysis of water using a semiconducting chelating π -conjugated polymer poly(2,2'-bipyridine-5,5'-diyl), which has a strong affinity towards metals,

and [Pt(bpy)₂](NO₃)₂ (bpy = 2,2'-bipyridyl) as photocatalyst in aqueous NET₃ solution.

When irradiated with light, the system produced hydrogen with a turnover number of H₂: [Pt(bpy)₂]²⁺ of 490 and maintained this activity over several cycles. This is thought to be related to the ability of the polymer to trap platinum as [Pt(bpy)]²⁺ on its surface.

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