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The Ninth Grove Fuel Cell Symposium

BUILDING AND COMMERCIALISATION OF A FUEL CELL INDUSTRY – A PROGRESS REPORT

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The Ninth Grove Fuel Cell Symposium and exhibition was held at the prestigious Queen Elizabeth II Conference Centre in Westminster, London, from 4th to 6th October 2005. This biannual event is now the largest fuel cell gathering in Europe, this one attracting 480 delegates from 38 countries (1, 2). Some 54 papers were presented, and 186 posters were displayed. A further 760 people attended the associated trade exhibition, and a half-day demonstration of fuel cell vehicles and technology was held in Trafalgar Square. The latter attracted considerable public and media attention. Because of the wide range of fuel cell types and applications is now available, this article is restricted mainly to those associated with the utilisation of the platinum group metals.

Facts on Global Warming

Professor Lars Sjunnesson, the Symposium Chairman, welcomed the delegates and introduced Professor Sir David King (Chief Scientific Adviser to the U.K. Government) who spoke on 'The Science of Climate Change: the Challenge of Global Warming' (3). As long ago as the 19th century, noted scientists, such as Fourier and Tyndall, began to speculate about the effects of increased carbon dioxide (CO_2) in the atmosphere, while in 1896 Arrhenius forecast that a doubling of CO_2 levels would result in a 5°C global temperature rise. This agrees well with the latest forecast of a rise of 3 to 7°C. Carbon dioxide levels, having remained stable at 180-270 parts per million (ppm) for millions of years, currently stand at 379 ppm and are forecast to exceed 500 ppm at our current rate of consumption of fossil fuels.

There were an estimated 30,000 fatalities in Europe, in 2003, as a result of high temperatures, but because of global warming, by 2050 the average temperature is likely to equal the 2003 extremes. This is one of the main driving forces for finding more efficient ways to utilise fossil fuels and seek alternative renewable energy sources. Iceland is leading the way: having decided to move to a hydrogen economy. In future all vehicles there will be powered by hydrogen or fuel cells.

Grove Medal Presentation

Professor King then presented the Grove Medal for 2005 to Alan Lloyd (California Environmental Protection Agency) who described himself as "an environmental person with a job to do" rather than specifically a fuel cell advocate. The quality of air in California has improved in recent years, however, particulates have also increased. A number of organisations have been set up to introduce clean energy supplies and clean vehicles. Some 50 stationary fuel cells totalling 10 MW have been installed, and the California Fuel Cell Partnership is demonstrating a fleet of vehicles. The California Hydrogen Highway should result in 50 to 100 hydrogen fuelling stations able to supply 2000 vehicles by 2010. This fuel network is being extended up the west coast of the U.S.A. and into Canada. Other areas, in the U.S.A., Japan and Germany, are being equipped with hydrogen refuelling facilities.

The European Position

Professor Werner Tillmetz (ZSW, Germany) surveyed the technology being developed for fuel cells under the 7th Framework Programme organised by the European Commission. Within the European Union (EU), fuel cells are seen as important for job creation in the longer term, as well as facilitating a change to hydrogen and biomass fuels to safeguard energy supplies. Over 100 light passenger vehicles are in daily use, and 40 fuel cell buses have spent more than 2 years in passenger service. Worldwide, more than 350 vehicles are undergoing fleet tests and product development.

Fig. 1 This ENV motorbike, demonstrated by Intelligent Energy, features a 1 kW PEM-type power pack fuelled by compressed hydrogen. The hybrid design, when used in combination with lead acid batteries, gives a top speed of 80 kmph and a range of over 160 km. The power pack is easily removed for independent use

Early markets are envisaged for fuel cell motor cycles (see Figure 1) and scooters, go-carts, fork lift trucks, uninterruptible power supplies, marine and auxiliary power supplies, while military applications represent early niche markets for similar products. Over 3500 small portable units have already been sold for demonstration and niche markets. More than 100 units, each of 1-5 kW are currently installed in domestic combined heat and power applications within the EU, and many of these are providing over 80% thermal efficiency. These have electricity grid connection.

Michael Fübi (RWE Fuel Cells, Germany) provided an overview of the stationary fuel cell market. There is increasing interest in utilising renewable energy, with manure, sewerage and farm wastes, coal mine and landfill gases representing huge untapped energy resources, as well as presenting critical disposal problems. Molten carbonate fuel cells can utilise hydrogen derived from these sources. Several 250 kW plants built by MTU CFC Solutions have been extensively demonstrated, and one has been operating on natural gas in Magdeburg, Germany, since December 2002, accumulating over 23,500 hours of power generation. As operation on natural gas has been successfully demonstrated, a plant running on biomass anaerobic digester gas was begun in July 2005. Applications for these combined heat and power units include hospitals, telecommunications companies, the food industry and sewerage works. For smaller generators of up to 10 kW, there is an estimated demand for 50,000 units per year in the EU alone for commercial applications, while a much larger market exists for smaller fuel cells for residential use.

William Ernst (Plug Power, U.S.A.) described an early market for small fuel cells in his talk entitled 'Small-Scale Dispersed Stationary Systems - a Status Report'. Generators of 1-20 kW, most of which are based on polymer electrolyte membrane (PEM) fuel cells catalysed by platinum, are rapidly finding an increasing range of uses for cell-phone network supplies, microwave repeater stations, pipeline monitoring stations, and cathodic protection. Plug Power have produced over 500 systems to date, and the eventual market for this type of device was quoted as \$3.6 billion. Even at the current cost of \$3000 kW^{-1}, economic niche markets are beginning to emerge as fuel cells can provide unique solutions for standby and auxiliary power supplies. In the United States, a Federal tax credit of 30% (up to \$1000) of the capital cost is helping to develop a market that is expected to mature between 2010 and 2020.

Road Vehicles and Auxiliary Power Supplies

Yuji Kawaguchi (Honda Fuel Cell Power, Japan) gave details of their passenger vehicle development programme. This was begun in the 1980s, and has culminated in the latest Honda FCX which is now fully certified for road use, and offered for public rental. The high power density fuel cell

Fig. 2 This DaimlerChrysler Citaro bus was used at the Symposium for taking delegates on tours of London sights. There are three such fuel cell buses in service in London. In total, 30 such buses are being evaluated in European cities under CUTE, the European Union sponsored Clean Urban Transport Experiment

developed by Honda for the purpose is suitable for volume production.

For peak power it is augmented by an ultracapacitor giving a total of 80 kW. The fuel cell develops 50 kW, has a volume of 33 litres and a weight of 48 kg. It operates at 95°C and is capable of start-up from -20°C. This platinum-catalysed fuel cell has an aromatic electrolyte membrane containing sulfonate groups, providing conductivity twice that of conventional proton exchange membranes at -20°C. The stamped metal separator plates have a stainless steel base with an oxidised surface containing electrically conductive inclusions to provide contact resistance of less than one quarter of equivalent carbon plates, and weighing 20% less. Using the stamped separators halves the thickness of the cell compared to standard construction methods. Their inherent springiness means that fewer compression components are required. The Honda FCX vehicle has a weight of 1670 kg, and range of 430 km on hydrogen compressed to 350 bar, with a top speed of 150 km h^{-1}. The first models were delivered in 2002, in Japan and the U.S.A., and one vehicle is in use in California for personal daily commuting.

Massimo Venturi (NuCellSys, and formerly of Ballard Power Systems, Germany) described the progress made for buses during various demonstration programmes. The EU sponsored Clean Urban Transport Experiment (CUTE) trials involves 30 buses, see Figure 2. By July 2005 this fleet had operated for 60,000 hours and 850,000 km. The trials have shown that fuel cell engines have proven functionality and availability in commercial use. Reliability has been dramatically improved, with mean times between failures now about 3 times longer than at the start of the trials due to implemented improvements. For example, start-up times have been improved simply by making changes to computer software. Improvements still needed for a fully viable commercial product include longer fuel cell lifetimes (at least 5000 hours), increased power density and competitive cost.

Power for Consumer Electronics

According to George Apanel (SRI Consulting, U.S.A.) consumer electronics could provide one of the first large markets for fuel cells and provide a revolution in personal devices. Costs are already competitive – with rechargeable batteries for many applications – and, on a cost per watt basis, are up to 80% lower. At equal weights, fuel cells can provide 5-10 times the operating time of an advanced battery. However, the main advantage is the ability to recharge fuel cells instantly with a cartridge of liquid fuel, such as methanol. Commercially viable direct methanol fuel cells (DMFCs) are expected to be widely available within 2 years, and there is a huge opportunity provided by the 470 million consumer electronic devices sold worldwide. This market is growing at 10% per annum. A DMFC for portable use is in Figure 3.

Shimshon Gottesfeld (MTI Microfuel Cells, U.S.A.) explained that battery technology has traditionally lagged behind telecommunications technology. Ideally, power supplies with a five-fold power density are needed for devices such as wireless local area networks, digital television, hard disk drives and radio tuners. MTI have developed a method of operating DMFCs to overcome some of the limitations of this system. By running these cells at high current density, the methanol oxidation reaction reaches zero order. The Pt/Ru catalysed anodes can be fed with concentrated methanol, which is consumed before it has the opportunity to diffuse to the air cathodes (which have 6 mg cm^{-2} platinum loadings), where it would otherwise cause mixed potentials. In addition, there is a spontaneous transfer of water from the cathode to the anode helping to suppress methanol diffusion. The cells provide power of 35 mW cm^{-2} with 30% conversion efficiency of the fuel. These Mobion® cells are being used by an industrial customer to power a radio frequency identity (RFID) tag reader. The fuel cell has an output of 1 W for 35 hours (that is 35 W h), compared to the 8 Wh provided by the normal Li-ion battery.

The high energy density of methanol as an energy store explains the huge increase in interest in these devices in the past few years. The Mobion® cells yield around 1100 Wh l^{-1} at 30% conversion efficiency, compared to 200 Wh l^{-1} for advanced lithium prismatic batteries. This provides an enormous incentive and an opportunity for electrical device manufacturers to utilise this higher available power in an even wider range of devices. In the immediate future, the military domain is seen as the first large niche market for DMFCs from a cost point of view, in applications such as cord-free rechargeable power pack technologies. Hybrid battery/fuel cell applications are ideal since DMFCs are able to provide relatively low power outputs for long periods with high ampere-hour capacities.

Methanol is a high energy density store

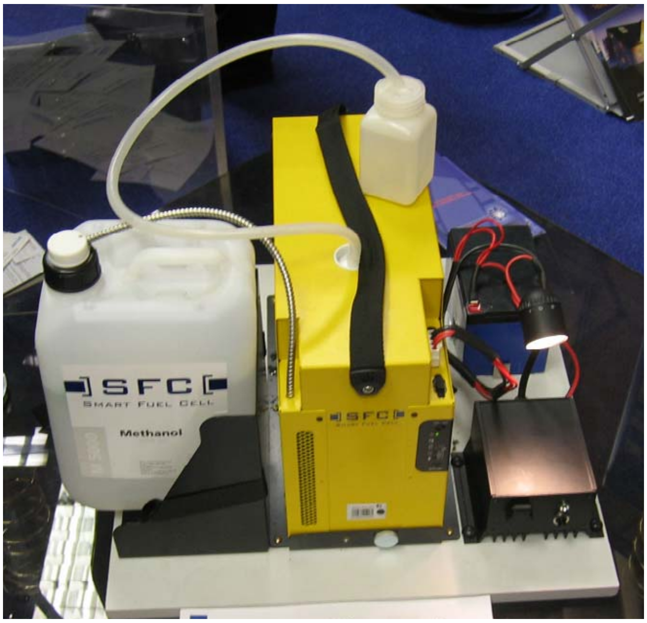

Fig. 3 A direct methanol fuel cell produced by Smart Fuel Cell. This was operated at the exhibition alongside the Symposium. Its output is 50 W at 4 A; methanol consumption is 1.3 l kWh^{-1}; and its overall weight is 8 kg

Peter Gray (Johnson Matthey Fuel Cells, U.K.) reviewed some of the advances made in catalysts and membrane electrode assemblies (MEAs) for DMFCs, and explained how these are underpinning development of devices for portable power and consumer electronics. Applications being considered for DMFCs include recreational vehicles, boats and isolated dwellings, as well as remotely located telecommunications stations, traffic signs, weather stations, pipeline monitoring, etc. There are huge numbers of devices requiring less than 25 W, including laptop computers, personal digital assistants, camcorders and mobile telephones. These require MEAs giving high performance at temperatures close to ambient, and self regulation of water and fuel, as well as being of low cost. Activation polarisation at the methanol electrode is still the main performance limitation of DMFCs, despite the availability of catalysts, such as carbon supported Pt/Ru with upwards of 100 m^2 g^{-1} surface area, and self-supported Pt/Ru alloy catalysts with 70 m^2 g^{-1}. MEAs have demonstrated lifetimes in excess of 4000 hours and power densities of 100 mW cm^{-2}. This equates to 500 mV at 200 mA cm^{-2} at 60ºC - a relatively high operating voltage that is desirable for good energy conversion efficiency.

Traditionally, the platinum metals industry has responded to increased demand for materials by increasing production. The emergence of the automotive catalyst industry posed no problems, and similarly, steadily growing demand for fuel cells should create no difficulty. Gray emphasised that there are substantial reserves of platinum available for fuel cell development, and also the fact that at the end of life, over 90% of the platinum group metals can be recovered and recycled. Products can be designed for ease of metal recovery as well as efficient manufacture. In fact, according to Philip Crowson, formerly Chief Economist of RTZ, at current rates of use, two-thirds of the metals in the Periodic Table will run out before platinum.

Military Applications

The power and energy demands for future U.S. Army programmes, such as Future Force Warrior and Future Combat System, require a revolution in power supplies, and fuel cells are viewed as a technology that may meet many of the military's power needs. Chris Bolton (U.S. Army Research, Development and Engineering Command (RDECOM)) outlined three applications where fuel cells are being evaluated for possible military use. These are soldier and sensor power (under 100 W), man-portable power sources (100-500 W) and small mobile power units (0.5-10 kW). Fuel cells larger than 10 kW face competition from other power sources, such as diesel and Stirling engines. RDECOM are evaluating fuel cells supplied by a number of manufacturers and has drawn up preliminary specifications for a 20 W tactical power system for the Land Warrior Program, with a goal of 600-700 Wh kg^{-1} (including fuel) for a 72-hour mission. However, the life of competing rechargeable batteries is reduced by high ambient temperatures, experiencing up to a 2-3 fold decrease in extreme environments, which further renders fuel cells even more economic as battery replacements.

George Cipriano (Protonex, U.S.A.) outlined some of their work on direct and reformed methanol fuel cells. Most of these are hybrid systems with batteries providing peak power, in a size range of 10-500 W. One 30 W continuous PEM fuel cell man-portable system designed for a 72-hour mission operates on sodium borohydride fuel which is decomposed to provide hydrogen when required. This provides an energy density of 380 Wh kg^{-1}, compared to 150 Wh kg^{-1} for lithium batteries and 130 Wh kg^{-1} for rechargeable cells. Further developments are projected to increase the fuel cell energy density to 800-1000 Wh kg^{-1}. One major contrast with battery power is that for missions of longer duration, the fuel cell unit remains the same, and only additional fuel cartridges need to be carried.

The use of portable fuel cell battery chargers for frontline soldiers is also being evaluated by the British Ministry of Defence, according to Angus Johnson (Thales Ltd., U.K.). Typically, a company of soldiers requires 183 batteries for a 48-hour frontline mission on the battlefield, under a wide variety of environments.

Navies using fuel cell submarines

Great advances in reliability and safety enable fuel cells to be the sole power source for a new generation of submarines. S. Krummrich (HDW Fuel Cell Systems GmbH, Germany) stated that at least 16 Type U212A boats are being supplied to a number of navies, including those of Germany, Greece, Italy, Portugal and South Korea. These boats use platinum-catalysed PEM fuel cell modules, each of 72 cells, made by Siemens. Nine of these provide around 30 kW each, operating at 70-90ºC with fuel conversion efficiencies of 72% at 20% of rated load and 62% at full load. Hydrogen fuel is stored on board the vessel in the form of hydrides, while the oxidant is liquid oxygen. The whole propulsion system must be self-contained, with provision for disposing of waste heat, product water, purge gases, etc. Product water, for example, is used during the whole mission for the sanitary equipment on board. The fuel cell modules are connected in series by diodes using double bus bars to eliminate magnetic fields, and a hybrid arrangement with conventional lead-acid batteries is used for high speed operation. The propulsion load defines the main bus bar voltage, and the system normally operates using only the fuel cell assembly. For high current demands, as the bus bar voltage falls, an increasing load is taken from the batteries in combination with the fuel cells.

Military propulsion systems

Darren Browning (DSTL, U.K.) outlined their programme on fuel cells for a variety of military applications, including propulsion systems for unmanned underwater vessels, unmanned aerial vehicles, sonobuoys and army equipment. Their target specification is 600-1000 Wh kg^{-1}, which is 5 to 6 times the energy density of silver-zinc or lithium-ion batteries. For a variety of reasons, direct borohydride fuel cells have been selected for development. Sodium and potassium borohydrides are stable in highly alkaline solution, and these are used in alkaline electrolyte fuel cells with Pt/C catalysts for the cathode and an anion exchange membrane. For the anode catalyst, several materials have been evaluated, the optimum being high surface area gold dispersed on carbon, which exhibits good electrochemical activity, but low rates of spontaneous borohydride hydrolysis. In comparison, Pt/Ru or Au/Pt catalysts provide higher anode activity than gold, but hydrolyse the reagent. Work is underway to synthesise and evaluate suitable anionic membrane materials to minimise borohydride migration to the cathode.

Residential military uses

A fleet of residential proton exchange membrane fuel cells, produced by manufacturers in the U.S.A., is being evaluated at military and civil facilities by the U.S. Army Engineer Research and Development Center/Construction Engineering Research Laboratory (ERDC/CERL). These premises include office buildings, hospitals, industrial facilities, barracks and gymnasiums, etc., all of which can benefit from improved power generation efficiency and security of supply. M. White (Jones Technologies, Inc., U.S.A.) introduced some of their preliminary findings. Domestically-produced proton exchange membrane fuel cells of 1-20 kW output are being evaluated at various U.S. military installations and embassies. Their manufacturers include Idatech, Plug Power, Nuvera, ReliOn, and Logan Energy. One fuel cell will be installed in the U.S. Embassy in Grosvenor Square, London. A great diversity of installations is being sought; units are required to provide a minimum of one year of fuel cell power with at least 90% availability. Although the program has been running for 4 fiscal years, delays in implementation mean that results are only available from the first two years. A total of 92 fuel cells will be sited at 56 DoD facilities. Results from 34 fuel cells at 24 sites are so far available.

The fuel cell units have achieved 82–90% reliability, although not all the units have completed the one-year demonstration. Overall, the project has accumulated 115,000 operating hours, with an average conversion efficiency for natural gas of 31.7%. The most commonly replaced components were steam filters, pumps, and supply lines, while the second most common were water filters, including reverse osmosis units, carbon filters, deionising units and other associated parts. Fuel cell stacks were replaced on average after 2485 hours, although 4 of the 11 natural gas fired units that ran for over a year did not require replacement stacks. One stack has operated for over 10,250 hours to date. All of the stack replacements took place before they failed completely. However, it has been concluded that the weakest parts of the installation are the steam and filtration systems. The study will continue for at least another two years, and improvements in designs resulting from information feedback should considerably improve the systems during this time.

Residential Combined Heat and Power

Small fuel cells are being demonstrated as a prelude to commercial exploitation. J. Heinen (RWE Fuel Cells GmbH, Germany) explained they are one of the companies active in this field, with partners BBT Thermotechnik (Germany) and IdaTech

LLC (U.S.A.). Currently, twelve 4.6 kW units are being evaluated in multi-family houses and small commercial applications, with a further 25 units planned for the end of the year. Operating on natural gas, they provide 30% conversion of natural gas to electricity, with an overall 80–83% efficiency including heat recovery. The devices can be connected to the electric utility grid to enable optimum utilisation of the generating capacity. RWE is exploring the possibility of acting as an energy service supplier who owns and maintains the devices, selling electricity and heat to the consumer.

Individual Homes

The single family house is also a possible market for fuel cells. In his talk entitled 'Micro Combined Heat and Power Generation', G. Gummert (european fuel cell gmbh, Germany, now part of the Baxi Group) detailed their programme to develop residential fuel cells. The potential scale of this market is illustrated by the fact that Baxi produce 800,000 central heating boilers and 500,000 water heaters annually. A 1.5 kW reformer/proton exchange membrane fuel cell system has been developed, and provides an additional 3 kW of recovered heat. Natural gas, their preferred fuel, is now supplied to 75% of new houses in Europe. While 1.5 kW represents 70% of the total power requirements, 3 kW provides 65% of the need for heat.

M. Kawamara (Tokyo Gas, Japan) described the Japanese national effort to develop proton exchange membrane fuel cell systems for residential applications. One was installed in the Japanese Prime Minister's official residence in April 2005. The units, built by Matsushita Electric Industrial Co. Ltd. and Ebara Ballard Corporation, consist of a 1 kW reformer/fuel cell unit and a hot water unit. The device is grid connected, with an inverter to provide AC mains power for the consumer. A 200 litre storage tank provides hot water for domestic use. Over 400 units have been built this year; 175 were installed in the first 6 months. It is planned to build up to 10,000 units by 2008, and tens of thousands of units after 2010. Ultimately, the Japanese market is seen as up to 1.5 million units per year at prices of less than $10,000 each.

The Future of Fuel Cells and Hydrogen

The final session of the Symposium looked forward to the challenges and future prospects for hydrogen and fuel cells. Pablo Fernandez-Ruiz, a member of the Advisory Council of the Hydrogen and Fuel Cell Technology Platform of the European Commission in Belgium, stressed that the EU currently imports 50% of its energy needs, which is forecast to rise to 70% by 2030. In an effort to stem this rise, under the 7th Framework Programme for 2007-2013, EU funding for energy research will be doubled to 10 billion Euros, with basic research attracting 1.5 billion per year.

Valri Lightner (U.S. Department of Energy) detailed the Hydrogen Fuel Initiative which commits $1.7 billion for the first five years (2004-2008) of which $1.2 billion is for the realisation of the hydrogen economy and fuel cells. The United States is focusing on energy supplies, particularly the energy needs for transportation, as two-thirds of oil is used for this purpose. Surprisingly, heavy vehicles and light trucks account for higher fuel usage than private cars. Natural gas is one of the best distributed and cheapest sources of energy for hydrogen production in the U.S.A., while coal (combined with CO_2 sequestration) is also regarded as a potential fuel. Fuel cell costs need to be reduced to a target of around $\$30\ \text{kW}^{-1}$, compared to a current estimated cost of $\$110\ \text{kW}^{-1}$, when a production rate of 500,000 units per year is assumed. The barriers to achieving wide scale deployment of fuel cells are thought to be codes and standards, the investment required for a hydrogen generation and distribution network, and educating the public, rather than any technical hurdle.

Summary

A host of manufacturers of fuel cells, components and associated equipment is emerging, and many of their products were exhibited at the Symposium. Small fuel cells of up to 5 kW are already finding niche markets as standby generators in residential combined heat and power applications and consumer electronics. In the latter example, there are considerable incentives for con-

Fig. 4 This DaimlerChrysler F-Cell A-Class vehicle was driven around in London. It is one of 60 such vehicles already in use

sumers, and customers are likely to be willing to pay a premium price. However, it is evident that costs must be substantially reduced for widespread transport applications to emerge, even for buses. But for stationary applications, increasing manufacturing capacity is likely to reduce costs considerably.

Associated Exhibitions and Demonstrations

On the afternoon preceding the Symposium, a demonstration of fuel cell technology was held in Trafalgar Square. This attracted wide public and press interest, and included an Intelligent Energy motorcycle (Figure 1), a DaimlerChrysler Citaro fuel cell bus (Figure 2), a DaimlerChrysler F-Cell A-class car (Figure 4), a BOC Echo2O car, a Microcab fuel cell taxi, and a Ballard Airgen unit, and on a trailer the London Hydrogen Partnership fuel cell, and a Tees Valley fuel cell powered mobile information sign. The exhibition included a large marquee open to the public containing a host of displays and smaller exhibits including: MTU CFC Solutions, Baxi Group, siGEN, Johnson Matthey, three U.K. universities, Ceres Power, Voller Energy, the London Hydrogen Partnership, and Transport for London. Fuel Cells Canada featured a Scalectrix miniature racetrack which the adults present reluctantly allowed children to use.

The Trafalgar Square exhibits were later moved to the Queen Elizabeth Conference Centre where the exhibition attracted over 85 organisations, including fuel cell manufacturers (many with working demonstrations), component suppliers and users. The DaimlerChrysler bus proved very popular, taking delegates for regular sightseeing tours around London.

A special edition of the *Journal of Power Sources*, will carry the full papers.

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The Reviewer

Don Cameron is an Independent Consultant on the technology of fuel cells and electrolysers. He is a member of several Working Groups of the International Electrotechnical Commission, Technical Committee 105 on fuel cell standards. He is also Secretary of the Grove Symposium Steering Committee.

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