The Grove Fuel Cell Symposium

POLLUTION-FREE POWER SOURCES ATTRACT WORLDWIDE INTEREST FOR STATIC AND TRANSPORT APPLICATIONS

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Commemorating the one hundred and fiftieth anniversary of the first exposition of the fuel cell principle by Sir William Grove, over two hundred delegates gathered at the Royal Institution, London, for a four day conference, from 18th to 21st September, 1989. Twenty papers, six short contributions and three panel discussions addressed the historical context, environmental implications and national efforts for each type of fuel cell in turn. Applications for centralised and dispersed power generating plants were considered, including operation in the combined heat and power (CHP) and cogeneration modes. In the transport sector, fuel cells were predicted to have an important role for road vehicles, marine vessels and in space. Phosphoric acid (PAFC), alkaline (AFC) and solid polymer (SPFC) fuel cells rely on noble metal, mainly platinum, electrocatalysts at present. The Symposium heard of the imminent availability of commercial units, suggesting that if widespread introductions could be achieved, then a considerable new market would open up for these metals and would lead to a cleaner, more efficient world.

The conference was convened by an ad hoc steering committee, drawn mainly from British industry but with academic, establishment and government support. The aims were to provide a platform for international leaders in this promising new technology to explain the present status of fuel cell development in order to provide the United Kingdom, in particular, with the necessary background to worldwide developments in the field. U.S. and Japanese speakers predominated; other contributors came from the Netherlands, Italy, Germany and Canada. Some twenty delegates came from Japan, with an equal number from the U.S.A., and the remainder from Europe. Thus, the attendances well-represented current world interest and commitments to the technology.

His Royal Highness the Duke of Kent, President of the Royal Institution, opened the proceedings on the Monday evening. He briefly referred to the historic context surrounding the work on electricity of William Grove and Michael Faraday at the Royal Institution. He explained how fuel cells offered the prospect of providing a cleaner, more efficient future. He then introduced Professor J. M. Thomas, F.R.S., Director of the Royal Institution, who presented the Grove Anniversary Fuel Cell Lecture. Professor Thomas began by outlining the rich history of the Institution, where no less than fifteen Nobel Prizewinners had worked. He dwelt extensively on the remarkable career of Grove, the Swansea-born, privately educated "amateur" scientist and professional jurist. Many slide copies from the extensive archives of the Royal Institution were shown of original, often handwritten, letters and manuscripts by the great man; these included the first drawing by Grove of a four cell fuel battery. Professor Thomas then provided delegates with a series of spectacular demonstrations, in keeping with the Royal Institution tradition, illustrating the logicality of scientific thought which had led William Grove to seek out the fuel cell as the "theoretically more perfect (battery) . . . (which) exhibits such a beautiful instance of the correlation of natural forces". First he demonstrated the development of electric arc and filament lighting; then illustrated the explosive combination of hydrogen and oxygen which could be initiated by a flame or a precious metal catalyst. Continuing this theme he showed that a controlled flame could be lighted at a jet of hydrogen, again using a platinum catalyst (incredibly, the basis of one early gas lighter!). Finally, the cool, controlled and continuous electrochemical combination of these gases at an electrocatalytic surface was exhibited in the first public demonstration of a small 500 W Ballard SPFC, supplied with hydrogen and oxygen, and having virtually instantaneously available power sufficient to drive an outboard motor.

Why Fuel Cells?

The technical sessions on the Tuesday morning were opened by Professor R. Parsons of Southampton University who asked the question "Why fuel cells?". Professor A. J. Appleby of Texas A. & M. University began to answer this question in his Keynote Address. First, he traced the origins of Grove's fuel cell (having only about 10 mm^2 of effective area at the meniscus of his platinised platinum plate), Ostwald's vision of a clean, electrochemically-based 20th Century, the decline of interest in the field at the turn of the Century, through to the triumph of Dr. F. T. Bacon, who was present in the audience, in the 1950s, with the first engineered working fuel cell which used nickel electrodes. Then followed the Gemini and Apollo missions which depended on fuel cell power. Meanwhile, in the Netherlands, Ketelaar and Broers had laid the foundations for molten carbonate devices (MCFC), while other workers developed ion-conducting zirconia for solid oxide fuel cells (SOFC). Although modern electrodes with highly dispersed noble metals supported on non-wetting PTFE substrates have revolutionised PAFC and SPFC technologies, the slow electrocatalytic reduction of oxygen was still disappointing. In closing, Appleby emphasised the importance that sound and innovative engineering had made, and is making, to the development of these high efficiency power generators. He suggested that the prospect of a "Hydrogen Economy" could still be achieved in time to allay the "greenhouse effect"; electric vehicles would have a major impact in reducing urban pollution.

By way of a thought-provoking scenario, M. P. Walsh, formerly of the U.S. Environmental Protection Agency, suggested that homo sapiens might be engaged in a massive global experiment to change the entire planetary ecosphere—irreversibly! So far the experiment appeared to be proceeding successfully; one side-effect, of course, could lead to the extinction of the investigators. Expanding on the theme of global warming as well as tropospheric pollution, Walsh highlighted the presently inadequate attention being paid to the lowering of carbon dioxide emissions produced by fossil-fuel devices, particularly vehicles. Fuel efficiency was the key and fuel cells had an important role to play. Various scenarios were indicated. However, in order to redress the balance, a combination of strategies, including a 3 per cent switch to fuel cell vehicles, starting at the turn of the century, would be required. By inference, these would most probably be low temperature fuel cells (LTFC) units and would incorporate noble metal electrocatalysts, at least initially.

Professor N. Itoh of the National Energy Development Organisation (N.E.D.O.), Tokyo, explained that although fuel cell research had been underway in Japan for a quarter of a century, it was the intervention of M.I.T.I. in 1981 under the "Moonlight Project" which elevated the scale of development towards viable, large-scale demonstrators. Presently, 1 MW PAFC plants are being constructed and installed with considerable early successes. These units are aimed at the electric utility markets, whereas a parallel programme is developing 200 kW PAFC units fuelled on either reformed methanol or syngas for on-site applications. An important example included the imminent installation and development of a 200 kW PAFC type in the leisure complex at Rokko Island. Slides from several Japanese speakers showed how compact on-site PAFC units were being located in/on city centre buildings; some were already operating. Meanwhile, N.E.D.O. is directing the development of MCFC stacks, currently operating at the 10 kW level but with a target of demonstrating 100 kW stacks by 1991, and 1 MW plants by 1995. Elsewhere, the Electro Technical

Laboratory (E.T.L.) is attempting to develop 500 W tubular SOFCs, while the National Chemical Laboratory (N.C.L.) is studying planar and monolithic configurations. Apart from these government supported efforts, Japanese industries, including the utilities, were engaged in constructing and demonstrating both their own and foreign plants, mainly PAFC and MCFC types.

The market opportunities for fuel cells were highlighted by K. A. Trimble of the Gas Research Institute, Chicago, who stressed their inherent advantages of efficiency, modularity, site flexibility and environmental acceptability. In the U.S.A. alone, 4 million sites representing 175,000 MWe peak load were in prospect with further growth potential of 2 to 4 per cent per annum, all in the commercial sector. These would comprise on-site CHP units from 25 kW to 1 MW size, for offices, stores and apartments. In the industrial sector 300,000 sites in the chemical, metal and food industries, for example, offered scope for up to 15,000 MWe peak demand, although PAFC technology would face stiff competition in some applications.

Long lead times for the construction of conventional plant, demand growth at 2.6 per cent per annum, increasingly severe environmental constraints all conspired to favour fuel cell introductions in the 1990s. However, if they can be developed in time, larger MCFC and perhaps SOFC plants could absorb much of the demand, especially for coal gas operation as the coal:oil/gas price ratio widens.

D. M. Rastler, of the Electric Power Research Institute (E.P.R.I.), California, outlined the historical context of that organisation's $70m venture on, mainly, PAFC technology, culminating in the 4.5 MW demonstrations and the design of an 11 MW system, by United Technologies Corporation. Support was also provided for the development of the Westinghouse air-cooled PAFC units. Although recent attempts to begin commercialising PAFC technology had proved unsuccessful, E.P.R.I. continues to monitor Japanese and European demonstrations. Simultaneously they are now directing attention towards MCFC technology as well as tubular SOFC development. Closer studies of market trends worldwide were underway.

More details of the Westinghouse achievements with air-cooled PAFC were provided by J. M. Feret, the goal being to offer plants in the 3 to 50 MW range, initially fuelled by natural gas, but eventually with fuel flexibility. Individual modules are based on the 375 kW stack, but a steam-bottoming cycle would boost an installation to 13 MW nominal. In early tests, the 690 mV/cell target had been met or surpassed; in small stacks, an 8 mV per 1000 hour voltage decline had been approached over 16,000 hours of operation. However, the 4 mV per 1000 hour decay goal for larger stacks had been improved upon over 4000 hours of testing. In a single 100 kW stack, performance objectives were being exceeded during 2000 hours of operation. Commercialisation of the 3 MW prototype is planned for the mid-1990s. However, all aspects of stack performance, stability and cost are presently being reviewed against considerations of market expediency.

L. J. M. J. Blomen and H. N. Mugerwa of K.T.I., the Netherlands, described their company's cautious approach to developing and marketing 25 kW and 80 kW PAFC plants. Reliability and economics, including risk sharing, were seen as key strategies to successful introductions. The use of standard proven components from existing hydrogen plants, would aid the development of larger plants. Designs should aim at optimum rather than maximum current density, in order to achieve the best compromise between investment costs and the ultimate cost of the electricity produced.

P. H. van Dijkum and K. Joon from Novem and E.C.N., respectively, outlined the Dutch MCFC development programme. Although Hoogovens had withdrawn from the programme, it was still hoped to build 100 kW stacks by the mid-1990s after completing trials of 10 kW, 25 cell stacks by 1991. Present efforts focused on improved performance, the introduction of new materials and the development of internal reforming units, the latter with British Gas.

Concluding the first day the Panel Discussion centred around the need and justification for fuel cells, with aspects of availability, timing, cost and opportunities for market introductions being considered. In a provocative contribution, Professor A. Ascoli of C.I.S.E., Italy, suggested that politicians should immediately abandon excessively expensive fusion research—which led to as much radioactive contamination (sic dirty) as in fission—and plough those resources into (sic clean) fuel cell development. Elaborating, he pointed out that fuel cells uniquely avoid the production of nitrogen oxides emissions, since electrochemical processes can be conducted below those temperatures which lead to this highly undesirable pollutant. These comments drew a sustained and enthusiastic round of applause! Similar sentiments were recorded upon Professor Appleby suggesting that fossil fuels should, in future, be reserved for making chemical feedstock and for the conversion of water into hydrogen for efficient production of power, by way of fuel cells.

The Commercialisation of Fuel Cells

Opening the proceedings on the second day, N. Hashimoto of Osaka Gas set out their plans to bring PAFC technology to fruition from 1993, followed later by SOFC. Presently, they were aiming to demonstrate 50 kW to 200 kW PAFC units for on-site applications using Japanese, mainly Fuji and Mitsubishi, and International Fuel Cells Corporation's (I.F.C.) PC25, plant.

Demand for these types of plant was assessed at 1000 units per annum, each rated at 100 kW, by the mid-1990s with a cost target of $1400–2000/kW. Some details of the testing of Westinghouse 3 kW SOFC units were also provided; durability, thermal cycling and 6 per cent performance decline were of concern, but 25 kW internal reforming generators would be tested by Osaka and Tokyo Electric Power Company (TEPCO) within the next two years.

The extensive involvement of TEPCO with PAFC, MCFC and SOFC trials, dating from the late 1970s, was described by T. Asada and Y. Usami. This work included 2423 hours of demonstration with the United Technologies Corporation's 4.5 MW prototype, leading to the commissioning of an I.F.C. 11 MW stack scheduled to start-up in January, 1991. Sanyo 200 kW air-cooled PAFC and I.F.C. 200 kW PC25 units were presently under test. In common with statements by many other contributors, TEPCO considers that an eventual move towards MCFC or SOFC technology would depend upon the prior successful introduction of PAFC equipment. This suggests, perhaps, that it could be worthwhile for the platinum industry to redouble its short and medium term efforts in order to establish this early market opportunity in the fuel cell industry, even if a redirection of strategy is called for in the longer term. Usami reported details of the early performance data emerging from PC25 trials—most goals are being achieved or exceeded. As well as setting out TEPCO programme objectives for the PC-23, Usami addressed the broader expectations of lifetime extension to 40,000–60,000 hours, reduced footprint of 0.1 m^2/kW down from 0.3 m^2/kW and cost reduction from 1 million ¥/kW to 200–300 ¥/W. He stressed the need for an accurate market-assessment based strategy. Again echoing other speakers, international co-operation was seen as an essential requirement.

R. Anahara indicated that Fuji Electric had concentrated on the development of PAFC technology, targeting mass production towards commercialisation in 1994. Both stationary (on-site, co-generating and dispersed power plants) and transport applications were envisaged across the kilowatt to megawatt spectrum. Notwithstanding, other work was continuing on AFC, MCFC and SOFC stacks. The company has accumulated many thousands of hours of PAFC operating experience with 1 MW, 200 kW and 50 kW plants. A compact 50 kW PAFC design is destined for sites in Japan, Europe, the U.S.A. and S. E. Asia. The smaller 4 kW methanol-reforming device continues to be available. For vehicles, the 5 kW PAFC fork-lift truck power unit will spearhead attempts at market penetration, but cost reduction is the major goal. These units will be used as the basis for 50 kW bus motive power packs; a half-size 25 kW unit has already been supplied to Chrysler and is under trial. Environmental concerns were considered to be a strong driving force for market development, but Anahara re-emphasised the need for international collaboration.

Turning again to market opportunities, J. A. Serfass of Technology Transition Corp., Washington, D.C., wondered whether even the presently available fuel cells might not be the solution to problems as yet poorly defined—at least in the U.S.A. He considered that the characteristics offered by fuel cells would be desirable in the longer term, however. Simplification of designs would convince early users that cost reductions would be achievable. A clearer identification of present market trends seems essential in the near-term. The American Public Power Association (A.P.P.A.) had taken the initiative by calling for small, municipal units. While public power accounted for only 15 per cent of the U.S. market, this still represented 1–2 GW per annum for 15 years! Markets exist today in Europe, Asia and N. America for early fuel cells in constrained areas and these cells would find willing buyers if the $1100/kW barrier could be met.

Closing the morning session, during the Panel Discussion, N. Hashimoto, in response to a question, indicated that the next major strategic programme evaluation and decision to continue (or otherwise) with fuel cell demonstrations would occur in about 2 to 3 years; R. Anahara remained confident for the future. Discussion ensued on early market costs and niche markets; J. A. Serfass warned that while in the U.S., at least, users could not expect to include cost-reducing credits on the basis of environmental factors, there were still some A.P.P.A. clients who could bear present fuel cell prices with more in prospect at lower mature-market costs. R. Anahara explained that cost depended on many factors, market size being the most important. Professor Appleby suggested that best investment policy would be obtained by having a broad portfolio of power generating options of which one might be fuel cells. Trimble advised that, in the U.S.A., 1994 emission-control standards could not be met unless new technology were introduced. Professor Ascoli referred to niche markets, such as historic city preservation, where costs were not the primary consideration; these might well take advantage of fuel cells at an early stage. Attention was also focused on the intended introduction of electric vehicles in Los Angeles, for example, the through-life costs of their batteries, their rechargeability and the scope for fuel cell only or fuel cell-battery hybrid vehicles according to usage and location.

European Fuel Cell Interests

The Commission of the European Communities (C.E.C.) was concerned to see the urgent introduction of more efficient, less polluting power sources, according to P. Zegers. Fuel cells with battery storage seemed attractive. Power plants, co-generation systems and electric vehicles could all help to lower the net carbon dioxide per calorie rate. In Europe, PAFC, MCFC and SOFC were being actively pursued, both nationally and with C.E.C. collaboration. In MCFC technology, the C.E.C. particularly wished to promote a 1 kW internal reforming demonstration by 1992. Elsewhere, it was developing two 1 kW SOFC stacks to be operational within the same timeframe. For vehicle development, long term research on direct methanol fuel cells (DMFC) had been undertaken under C.E.C. programmes, while the Italians were investigating PAFC and SPFC plants as well as methanol reforming.

R. Vellone of E.N.E.A. explained how, since 1983, that organisation had co-ordinated all national fuel cell interests under the "Volta Project". Italy wished to reduce dependency on imported oil and to improve pollution levels in their dense urban communities. Large savings could be achieved by any fuel cell introduction scenario, but these savings could be trebled if cost-reduction targets, legislative support and an indigenous producer industry could be arranged. However, in view of the technical maturity of PAFC, no further Italian effort was envisaged, rather demonstration programmes were planned using U.S. or Japanese stacks with Italian peripherals. R. Dufour of Ansaldo, in an unscheduled supplementary comment, indicated that Milan would install a 1 MW PAFC capacity for 1991 using I.F.C. 670 kW units with Ansaldo engineering and A.E.M. monitoring. Bologna will install a 25 kW PAFC on-site plant for 1990 with Fuji stacks and K.T.I. engineering, with a similar configuration to follow at Casaccia, Rome, both with C.E.C. support. Options for an I.F.C. 200 kW PAFC purchase are being examined. Smaller, portable 1 kW and 5 kW stacks are being developed for E.N.E.A. and the Italian Ministry of Defence using both foreign and Italian stack technology. A second aspect of the "Volta Project" is to develop MCFC technology; a foreign collaborator is being sought. At present Ansaldo has built and tested small cells; C.N.R.-T.A.E., Messina, has acquired 30,000 hours of experience testing I.G.T. single cells and has developed an internal reforming catalyst. C.I.S.E. is developing novel cathodes. Supporting activities are underway elsewhere. Further, an E.N.E.A./De Nora initiative is planning a 10 kW SPFC stack for 1990, while several organisations are commencing SOFC studies with C.E.C. support. Overall, about \$28.5m is being earmarked for Italian fuel cell programmes, some 63 per cent from E.N.E.A.

Future Prospects

B. Riley of Combustion Engineering, Connecticut, U.S.A., briefly outlined the three main SOFC configurations, their component parts, materials of fabrication, and performance targets. Against these considerations, it was possible to match types and sizes with the likely "commercial window" in the 1990s. Both present and future fabrication procedures were described. All these factors are interactive, but target costs should meet \$1500/kW installed, \$350–400/kW stack and \$50–70/kW materials. Quality control should dominate throughout and critical areas for attention were highlighted, especially with regard to scale-up. Allied Signal apparently have developed some very advanced designs for internally-manifolded flat plate devices.

Considerable excitement was generated by K. Strasser of Siemens AG who described their recent successes with the 6 kW AFC modules. Apart from space application, alkaline cells have tended to receive less attention recently. Using silver cathodes and nickel anodes and a recirculating potassium hydroxide electrolyte at 80°C, cells can provide 0.8V at 400mA/cm^2 at approximately 2 bar; thus a 60 cell stack provides 6 kW at 46–48V and with an efficiency of 61–63 per cent (71–72 per cent at 20 per cent load). Detailed performance data was discussed, including load following and start-up. Some 20,000 hours experience has been gained with an 8 × 6 kW assembly giving approximately 50 kW output; performance decline had been negligible. Most recently, a 100 kW system had been tested successfully in a submarine.

At this point, the format of the symposium was modified to accommodate six short contributions. However, the first two of these from W. Kumm of Arctic Energies and V. W. Adams of the U.K. Ministry of Defence both echoed the theme of marine applications. Substantial fuel savings were apparently in prospect for shipping. PAFC might have a role, but MCFC and SPFC are potentially more competitive than diesel-electric. SOFC might be viable, if successfully developed. For best advantage a diesel fuel reformer would be needed to permit hybrid power operations from the single currently available fuel. For military and submarine applications, LTFCs offer low noise and low infrared signature profiles. Next, G. Thomas of D.T.E., outlined the earlier fuel cell involvements of the Royal Navy, and offered opportunities for future collaborative ventures. The reticence of the Royal Navy in respect of fuel cells was puzzling in the context of the papers from Strasser, Kumm, Adams and Thomas. Certainly, if LTFC were adopted for military vehicles, this would represent a considerable requirement for noble metal electrocatalysts.

Two further short contributions by M. Washay of NASA-Lewis and H. Van den Broeck of Elenco considered AFCs for space and ground transport, respectively. The regenerative space module, essential for extended lunar and Martian missions, was highlighted later. The 70 kW hydrogen-oxygen cell of Elenco had now completed the design phase with EUREKA support, and construction would begin soon. A consortium had been assembled to oversee the introduction of a fuel cell city bus for Amsterdam. Cryogenic hydrogen storage was being adopted.

Further excitement was generated by the final contribution from C. Dyer of Bellcore, who described a recently patented novel "fuel cell". The device consisted of thin film overlays of metal/membrane/metal laid down upon an insulating substrate. The membrane material did not seem to be critical, both oxidant and reactant gases were present in the same gas stream with separation occurring within the membrane; invariably, the oxidant was partitioned and appeared to interact with the inner electrode, contrary to expectation. The assembly could be produced in a continuous strip in a back-to-back configuration and rolled between spacers to form gas channels. In this way larger currents could be generated; a 1 volt per cell output was typical. Although different polarities and voltages could be obtained by using different electrodes, best performances were evident if both were platinum, suggesting, perhaps, that the adoption of modern alloys and commercial dispersions of noble metals might be advantageous.

Opening the final session, F. Baron of the European Space Agency described the development of regenerative AFCs for the Hermes and Columbus projects. Two 4.6 kW units were required for the twelve-day Hermes mission, and Dornier were engaged in development with Aerospatiale. Suppliers under consideration included Elenco, Siemens and Varta. Much detailed performance goal data was illustrated; both static and recirculating electrolyte configurations had been considered, but the former was presently favoured. Other designs incorporating proton-conducting membrane electrolyser—AFC hybrids had proved less effective in trials. A bread-board approach to development was being adopted, with feasibility being demanded by the end of 1990 in time for first flights in early 1997.

The inherent advantages of all-solid state, low temperature SPFCs, were outlined by K. Prater of Ballard Technologies, Vancouver, Canada, who traced their development from early General Electric devices used in Gemini missions. The advent of Nafion had provided impetus to SPFC development and the new Dow membrane appeared to offer further improvement. Ballard efforts had begun in 1984 in response to Canadian Defence requirements. A 54-cell stack capable of operating on air or oxygen had been developed, and was very tolerant of carbon dioxide; pretreatment of the gas stream to selectively oxidise carbon monoxide had proved possible. Cost reduction was being achieved by the use of low cost graphite plates, and by substantially reducing the platinum loading from 8 mg/cm^2 perhaps to 0.7 mg/cm^2. A 2 kW device had recently been installed in a manned submarine with outstanding performance, including a dramatic extension of duration by more than one order of magnitude; a 10 kW hydrogen-air unit would be hybridised into a Dow chlor-alkali plant. Major motor manufacturers as well as defence contractors were becoming interested in SPFC technology and new market opportunities could arise. Concern was expressed that membrane cost and availability could be limiting factors, but recent assurances had been received from Dow. Further noble metals loadings reductions were in prospect, perhaps to 0.1 mg/cm^2.

In the final paper, R. Lemons of the Los Alamos National Laboratories highlighted the problems of transport dependence on petroleum supply (62 per cent of U.S. consumption) and the concommittant pollution that arose therefrom. Although alternative fuels, including renewable fuels, were being scrutinised for this use, the combination of methanol (reformed) in a fuel cell vehicle appeared particularly attractive, giving a doubling of range over an internal combustion engine, with a consequent lowering of carbon dioxide emissions. Due to the stringent specifications to be met in this market sector, fuel cell types needed to be carefully matched to the application. Thus, for road vehicles SPFC and AFC types of LTFC offered the best start-up and wide power band performances. A SOFC monolith might prove viable. At Los Alamos, major progress had been achieved with SPFC technology; platinum loading had been reduced to $<0.5 mg/cm^2$ and power densities $>0.9 W/cm^2$ had been achieved with experimental membranes at current densities of $2 A/cm^2$. Recent work had shown that a performance recovery from carbon monoxide poisoning could be obtained by air-injection at the anode. The U.S. Departments of Energy and of Transport were initiating co-operative development programmes with industry to explore fuel cell-battery hybrid systems for urban buses. Initially PAFC units would be used. Much research and development remained to be undertaken if maximum benefit were to be obtained from fuel cell introductions in the transport field.

Summary and Conclusions

A final Panel Discussion reviewed the way forward for fuel cells, followed by a summary and closing remarks by Professor Appleby.

Global warming and tropospheric pollution were identified as issues of current concern. Significantly, the Japanese had gained considerable operating experience with fuel cells already and apparently had a clear commitment for their future manufacture, demonstration and commercialisation. Likewise, U.S. Agencies had a long track record of commitment to fuel cells. The Dutch, who had initially researched the MCFC two decades ago, had made outstanding progress with these systems in the last three and a half years by purchasing United States know-how to incorporate into their own programmes. Now, the Italian fuel cell effort was intensifying. Materials research and development in Europe was strong.

Ultimately, Appleby envisaged a diverse range of fuel cell applications due to their low environmental impact. Elenco had identified liquid hydrogen as the best method of fuel storage for the vehicle and this would power their alkaline cell stack in the Amsterdam bus project. The promise of $1 MW/m^3$ SPFCs, representing 700 W/kg, could lead to viable traction power plants (volume to power to weight 50 litres, 60 kW and 90 kg, respectively).

Both engineering and materials development were central to the success of fuel cells. However, political factors and legislation were equally determining. Their inherent efficiency implied a reduced environmental carbon dioxide impact; coupled with their very low "classical" pollutant emissions, notably nitrogen oxides, they would commend themselves strongly to the general public. Presently, it was necessary to address cost and reliability matters, while identifying early market niches. Increased power densities, reduced weight of repeat-parts and improved gas distribution networks, constituted areas for detailed development. The high power of AFCs appeared attractive, as well as their capability for instantaneous start-up, provided gas-scrubbing could be economically addressed. SPFCs needed to achieve substantial cost-reduction, particularly regarding presently available membranes. Furthermore, SPFCs might lose their performance edge if pressurisation was needed. This would account for as much as 150 mV-equivalent from the available output of approximately 0.7 V at $300 mA/cm^2$.

In essence, PAFC required manufacturing cost reduction, improved engineering and improved performance; MCFC needed materials development, in particular, cathode integrity improvement. For SOFC, lightweight, low cost targets had to be met and innovative manufacture was called for.

Professor Appleby saw hydrogen as the natural fuel of the future and fuel cells represented the only logical conversion devices. However, methanol should not be overlooked.

Overall, the symposium was well planned and co-ordinated and it attracted the correct balance of speakers and delegates. Clear market opportunities were evident across many industrial and governmental interests, including the platinum industry.

In summary, the symposium had heard about the present developments and commercial availability of fuel cells. Notably, the demonstrations of 200 kW on-site PAFC units was to proceed. Major advances were being made in MCFC technology and these devices still offer perhaps one of the best options for fuel cell power production. SPFC technology had shown dramatic progress through lower noble metal electrocatalyst loadings, and with increased current densities being reported. SOFC still required much research and development but could represent a serious option later.

With so much demonstrable progress evident, albeit predominantly in the U.S.A. and Japan at present, the promise for fuel cells in a cleaner, more efficient future is still as bright as Grove foresaw so long ago.

The full proceedings will be published in the *Journal of Power Sources.*

Thermomagneto-Optical Recording Materials

COBALT/PLATINUM LAYERED STRUCTURES OFFER ADVANTAGES

Rewritable optical storage technology offers an attractive alternative to current magnetic recording, particularly with a capability to store 10^8 bits of information for each square centimetre of media material, together with remote optical reading, writing and erasing procedures. To date, the most promising candidates for magneto-optical recording are based on rare earth-transition metal (RE-TM) alloys deposited as thin amorphous layers on a variety of substrates. Such materials include variants of GdTbFe and TbFeCo.

Two recent publications by scientists at the Philips Research Laboratories, Eindhoven, and at the Central Research and Development Department of E.I. du Pont de Nemours, Wilmington, have highlighted both the deficiencies of current magneto-optic media based on RE-TM materials, and their advantages (1, 2). However, investigations by these researchers into the magnetic and magneto-optic characteristics of cobalt/platinum layered structures are clearly pointing the way to new magneto-optic media with enhanced properties, many of which overcome the deficiencies of current RE-TM based materials. For example, the cobalt/platinum layered structure media have excellent corrosion and oxidation resistance which eliminates the need for protective coatings. Also perpendicular magnetic anisotropy, a pre-requisite for advanced magneto-optical systems, has been achieved in these layered structures without the need for high temperature annealing, as in the case of proposed oxide candidates.

The authors in their respective papers present and discuss recent research findings on the magneto-optical Kerr effect of various cobalt/platinum layered structures, with differing thicknesses of cobalt and platinum. Preferential magnetisation perpendicular to the film planes has been shown for media having cobalt thicknesses <1.2 nm, with 100 per cent perpendicular remanence at cobalt thicknesses <0.45 nm. A multi-layer system having 25 layered structures of 0.41 nm cobalt and 1.9 nm platinum was used to demonstrate thermomagneto-optic writing. This media system proved to have good perpendicular magnetic anisotropy, 100 per cent remanence and a coercive field of 76 kA/m, at room temperature.

Environmental stability tests were carried out on unprotected cobalt/platinum layered structures stored at ambient for several months. No sign of oxidation or corrosion, and no corruption of the magnetic and magneto-optical data was apparent on these media, which are considered to be promising candidates for magneto-optical recording.

Attention is drawn to another informative paper on the magneto-optical properties in ultra-thin cobalt/platinum and cobalt/palladium multilayer films, from the Sony Corporation Research Center, Yokohama, Japan, which is abstracted on page 222 of this Journal.

I.R.M.

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