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Conference Report

First European Solid Oxide Fuel Cell Forum: A Platform for Science, Engineering and Technology, 3–7 October 1994, Lucerne, Switzerland

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For a number of years the development of solid oxide fuel cells 'SOFC' had been interrupted in Europe because of energy policies resulting from the shock of the first oil crisis. In 1988 the Commission of the European Communities, Switzerland and Norway took initiatives to revive the promising technology. In 1989 Switzerland organised the first SOFC workshop of the International Energy Agency. Subsequently, an international co-operation was formed. Under the leadership of Switzerland scientists and engineers of Italy, Germany, The Netherlands, United Kingdom, Denmark, Norway and Japan started a programmed exchange of SOFC research results. Workshops were organised at least once a year to document progress in the field. One of the outcome of this fruitful joint effort was the Swiss initiative to host the First European Solid Oxide Fuel Cell Forum in Switzerland. From 3 to 7 October 1994 about 190 scientists and engineers from 20 countries including Australia, Japan, Korea, USA, Russian Federation and Brazil gathered in Lucerne for a highly successful meeting on SOFC engineering, systems and science. The First European SOFC Forum, organised and chaired by the author of this review, addressed itself to the conversion of natural gas into electricity. It was supported by the Swiss Association of Gas Industry and the Swiss Federal Office of Energy and endorsed by the European Fuel Cell Group, Ltd. and the IEA Advanced Fuel Cell Programme.

The field of solid oxide fuel cells is characterised by the large number of materials for use as electrolyte, anode, cathode or interconnect. There are about 20 elements which may be blended in many ways to form ceramic structures whose properties not only depend on the material composition, but also on such things as fabrication procedures or sintering temperatures. No wonder that previous international SOFC meetings had been dominated by papers on the ionic or electronic conductivity of such substances. The European SOFC Forum was therefore designed to address engineering aspects, system designs, ceramic fabrication procedures, system and component optimisation, modelling of cells, stacks or systems, applications related to natural gas and market aspects. Materials' aspects were surveyed in only two of the twelve technical sessions. All in all, 94 papers were presented orally or as posters and published in the Proceedings which were on hand at the time of registration.

Following the welcome speeches the presentation 'The Unique Features of the SOFC in a Hydrocarbon Energy World' by Paul Stonehart (USA) revealed the complexity of today's natural gas distribution and how much the gas industry would appreciate to have a simple fuel cell like the SOFC which does not require complex ancillary systems for gas conditioning or electrolyte maintenance.

This paper was followed by the presentation 'Fuel Cells, Gas Engines or Gas Turbines? Perspectives of the Natural Gas Industry' of Frank Blaker (Norway), a representative of Statiol, the largest gas producer in Europe. The audience was reminded that the SOFC has to compete not only with other types of fuel cells, but also with established generating technologies.

In the international survey of SOFC programmes and the most significant developments of the four main geographic regions were presented by Charles E. Pax (USA), Masayuki Dokiya (Japan), Sukhvinder P. S. Badwal (Australia and New Zealand) and Pieter van Dijkum (Europe). It became obvious that European groups, what planar SOFC configurations are concerned, had closed the gap to R&D efforts in the USA and Japan.

Highlights of the session on SOFC process design for natural gas were the papers 'Balance-of-Plant of SOFC Units for High Efficiency' by Kim Asberg-Petersen of Haldor Topsoe (Denmark) and 'Optimisation of SOFC Processes by Exergy Analysis' by Richard Gaggioli (USA). Both lectures revealed particularities of high temperature systems design but, while the first of the two stayed within the framework of first-law thermodynamics, the latter applied the second law of thermodynamics to the optimisation of SOFC processes. Gaggioli showed that good systems efficiencies can only be achieved if thermal losses at high temperatures are kept at a minimum.

In the second technical session of the first day the question of reforming of natural gas in SOFC systems was addressed by six speakers. Of all fuel cells the SOFC has the best potentials for achieving internal reforming or even in situ

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reforming within the anode chamber. The standard reforming catalyst nickel is present in the Ni-zirconia cermet anode. Also, the temperatures are sufficiently high to drive the reforming reactions. While steam reforming is adequate for larger systems, small SOFC converters will, as Vincenzo Antonucci (Italy) pointed out in his paper 'Natural Gas Reforming in Small SOFC Units', most likely use partial oxidation reactors for converting methane into carbon monoxide and hydrogen. Harald Landes of Siemens (Germany) addressed the interesting topic 'Fuel Quality and Suppression of Coking in a Methane-fuelled SOFC'.

The day ended with a reception by the municipality in the medieval town hall of Lucerne overlooking the famous wooden bridge which had just been rebuilt to its original beauty after its destruction by fire in August 1993.

The first morning session on Wednesday was devoted to modelling of SOFC cells and stacks. The superb survey lecture 'Cell and Stack Optimisation by Modelling' of Kemal Nisancioglu (Norway) was supported by five papers dealing with important aspects of SOFC operation such as performance, unsteady operation, optimisation of design parameters, reaction kinetics or reversed flow in SOFC monoliths. Once again, this session demonstrated the successful European approach to SOFCs. Mathematical modelling has been developed into an important tool for identifying problems and weaknesses of particular designs before laboratory or system hardware is built and tested.

The following session on modelling of SOFC systems proved equally valuable. Again, a survey lecture by Elmar Achenbach (Germany) 'Simulation of SOFC System Dynamics' set the stage for the following papers. Three-dimensional models of SOFC stack, gas flows in manifolds, distributions of temperature, potentials or species concentration, complete systems for combined heat and power applications and even SOFC-integrated power plants for natural gas were subjected to numerical analyses for the study of steady-state behaviour and/or dynamic response of yet to be built systems and hardware.

Wednesday afternoon was devoted to materials. In the first session ceramic materials for the SOFC were discussed. Brian H.C. Steele (UK) presented the 'State-of-the-Art SOFC Ceramic Materials'. For the first generation of SOFC systems (e.g. for the Westinghouse products) acceptable materials for electrolyte, anode, cathode and interconnect exist. There is no urgent need for the development of new substances now, but SOFC prototypes can be matured on the basis of 8 mol% yttria-stabilized zirconia (YSZ) for the electrolyte, Ni-YSZ cermet for the anode, strontium-doped lanthanum manganite (SLM) for the cathode and strontium-doped lanthanum chromite (SLC) for the interconnect. The five contributed papers and many posters addressed all four components of an SOFC element.

Then a session on fabrication processes for SOFC ceramics followed. In an excellent manner Ludwig J. Gauckler (Switzerland) presented the state-of-the-art of 'Processing of SOFC Ceramic Components' such as dry pressing, tape casting, tape calendering, screen printing, slurry coating, electrovapour deposition (EVD), physical-vapour deposition (PVD), thermal and plasma spraying or sintering with estimates of fabrication costs for typical ceramic SOFC components. Again, specific details like vacuum plasma spraying, tape calendering, powder making, fabrication supported electrolytes by thick film methods or of interconnects by wet-pressing techniques were discussed in the five following papers.

The banquet of that night was one of the highlights of the Forum. The science historian Peter Nolte (Germany) presented the first results of his study of the correspondence between the inventor of fuel cells, William R. Grove, and the Germany/Swiss scientist Christian Friedrich Schoenbein, Professor at Basle University between 1829 and 1868. Apparently, C.F. Schoenbein was not only a good friend of Faraday and Grove, but he laid the base for the discovery of the fuel cell effect and later offered an explanation of the phenomenon which for a number of years was rejected by Grove, but proved to be close to our understanding of the electrochemical process. To remember this important scientist (better known for his discoveries of ozone and gun cotton) the first Schoenbein Medal of Honour was bestowed upon Professor Brian C.H. Steele of Imperial College in London for his important contributions to the development of SOFC materials.

On Thursday the European SOFC Forum continued with a session on experimental optimisation of SOFC components. Again, the survey 'Cell and Stack Optimisation by Experiments' by Joep Huijsmans (The Netherlands) was followed by reports from five different laboratories in four countries including Japan. All presentations and some additional posters illustrate how rapidly the SOFC technology advances in the laboratory. While power densities of 200 mW/cm^2 were still admired some years ago, 550 or 980 mW/cm^2 were reported at Lucerne for operating temperatures of 800 or 940 °C, respectively. This astounding improvement is the result of two things: thinner electrolytes of only a few microns thickness and improved ceramic materials. With such power densities the SOFC can now easily compete with other fuel cells. Also, the operating temperatures can be reduced to enable designers to use ordinary stainless steels for metal interconnects rather than expensive nickel-base alloys or ceramics.

New to SOFC conferences was the session on mechanical testing of SOFC components. The determination of failure criteria for ceramic parts remains one of the key issues of mass fabrication of SOFCs. Various methods for testing SOFC ceramics were discussed in this session. At Lucerne, the results of a very important IEA activity were finally presented to an international scientific audience.

The second morning session was closed by the survey 'Metals and Alloys for High Temperature SOFC Applications' by the Dutchman Willem J. Oudakkers presently working in Germany. As the operating temperatures are reduced metals are rapidly intruding SOFC stacks as interconnects, current collectors, separating plates or gas distributors. This

will open many options for the cost reduction and for new applications of the technology. This important change may eventually reduce the SOFC stack cost to less than US$ 100/kW.

In the afternoon the commercialisation of SOFC technologies was discussed. Two papers dealt with projects to install Westinghouse 100 kW units in Europe. Then Peter B. Bos presented his 'Low-Risk Commercialisation Program for Market-Driven Residential Fuel Cell Systems' which was highly appreciated by the audience. In essence, the author showed that fuel cells may never be raised over the commercial threshold with a limited number of technology-driven demonstrations of MW fuel cell systems, but that free-market mechanisms must be activated for the commercialisation of large numbers of small mass-produced kW units. By its very nature, so Peter Bos, the SOFC has the best market chance as a small natural gas cogenerator for domestic applications.

The rest of the afternoon was spent on the Lake of Lucerne on flag ship 'Stadt Luzern' (built in 1929) of the fleet of nostalgic paddle wheel steamers. It was a memorable afternoon with Swiss folk music, drinks and a superb candlelight dinner.

On Friday the European SOFC Forum continued with two technical sessions on SOFC for natural gas applications. The morning began with 'A Study for a 200 kWe System for Power and Heat' by Mark R. Taylor of British Gas (UK). Then speakers of Statoil (Norway), the Electrotechnical Laboratory (Japan), SOFCo (USA), Fuji Electric (Japan), Dornier (Germany), Sulzer (Switzerland), Tokyo Gas (Japan), SINTEF (Norway), the Institute of High-Temperature Electrochemistry (Russian Federation) and Medicoat (Switzerland) presented their latest system developments. Most of these groups have reached the kW-level of power output. Because of the high modularity of SOFCs most authors see no urge to increase the size of their laboratory units. Most of them claim that by adding stacks to their system the power output could be multiplied without difficulties. Also, some stacks or systems have logged over 40 000 hours of operations with acceptable loss of performance. Sulzer intends to commercialise a 5 kW SOFC cogenerator as early as 1997.

The 'Evaluation of the Westinghouse SOFC Technology for Electric Utility Applications in Japan' by Masatsune Harada of NEDO (Japan) was a highlight of the second morning session. Harada's study of three power plants incorporating a large number of Westinghouse tubular SOFC bundles reveals that the lowest cost of electricity can be expected for a 300 MW SOFC-integrated steam power plant operated on liquid natural gas. The 300 MW plant involving coal gasification and a LNG 20 MW SOFC-integrated steam power unit deliver electricity at higher prices.

SOFC for liquid fuel applications and the Westinghouse programme were discussed on Friday afternoon. Kevin M. Myles of Argonne National Laboratory (USA) started with 'Liquid-Fuelled SOFC Power Sources for Transportation', a critical survey which indicated that the SOFC has a good chance to be used in transportation systems (cars, trucks, trains, boats), be it as on-board power supply or as power source for propulsion. For liquid hydrocarbons the elevated operating temperatures pose no serious disadvantages when comparing an internally reforming SOFC with other fuel cells, which start delivering power only after the reformer has been brought to operating temperature.

An SOFC developer of Germany presented the 'Development of a 1 kW SOFC 12 Volt d.c. Power Generator operated on Liquid Gas' for remote applications where conventional car batteries are now in practice. A model of the portable apparatus was even shown in the concurrent product exhibit.

Then Raymond J. Bratton of Westinghouse (USA) updated the audience on the well-known SOFC programme which remains to be the most advanced in the world.

The First European SOFC Forum was closed with an exquisite talk by Walter Giersberger (Switzerland) of the Swiss Gas and Water Industry Association. His presentation 'Technical Perspectives, Market Potentials and Business Opportunities for Natural Gas-Related SOFC Technologies' not only summarised the four exciting days of technical discourse, but provided an outlook into the future. For the natural gas industry the SOFC technology is one of the most promising developments of today.

Without doubts, the First European SOFC Forum did not only accomplish its goals of advancing SOFC engineering, but it also proved to be a highly successful event for establishing personal links and friendships. The atmosphere provided by the organisers, a blend of scientific conferences and workshop, the choice of a charming location, the quality of management and the discipline of the speakers have all contributed to the outcome of this event. Also, the Proceedings containing 94 papers and posters on 1050 pages in two volumes were handed out to all participants at the time of registration. Copies can still be ordered for CHF 200 from the editor and publisher: Ulf Bossel, Morgenacherstrasse 2F, CH-5452 Oberrohrdorf, Switzerland, Fax: +41-56-4964412.

Based on the success of the First European SOFC Forum the Programme Committee decided to have follow-up meetings every even year modelled after the first one at Lucerne. During the closing ceremony the Second European Solid Oxide Fuel Cell Forum was announced for 6 to 10 May, 1996 in Oslo, Norway. Bernt Thorstensen will be the chairman. Information can be obtained from the following address: Second European SOFC Forum Secretariat, c/o SINTEF Forum, PO Box 124, Blindern, N-0314 Oslo, Norway, Tel: +47-2206-7300, Fax: +47-2206-7350.