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Solid Oxide Electrolyte Fuel Cell Review

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Abstract: Solid oxide fuel cells are a promising technology for electric power generation in the 21st century. The principles of SOFC operation, stack designs, materials, status of development and future challenges are discussed.

1 FUEL CELLS — GENERAL BACKGROUND

Fuel cells[1] convert gaseous fuels (hydrogen, natural gas, gasified coal) via an electrochemical process directly into electricity. Their efficiencies are not limited by the Carnot cycle of a heat engine, and pollutant output from fuel cells is magnitudes lower than from conventional technologies. A fuel cell operates like a battery, but does not need to be recharged, and continuously produces power, when supplied with fuel and oxidant.

Attempts to develop fuel cells as power sources have been made over many years. Initially they were developed mainly for space and defence applications. However, the recent drive for more efficient and less polluting electricity generation technologies resulted in substantial resources being directed into fuel cell development. Fuel cells, because of their high efficiencies (Fig. 1), low noise and pollutant output (Fig. 2), modular construction to suit load and excellent load following capability, promise to revolutionize the power generation industry with a shift from central power stations and long transmission lines to dispersed power generation at user sites. Several different types of fuel cells are currently under development:

(i) Low temperature fuel cells such as the Solid Polymer Electrolyte Fuel Cell (PEMFC) and the Alkaline Fuel Cell (AFC) are mainly considered for transport applications.
(ii) The Phosphoric Acid Fuel Cell (PAFC), a medium temperature fuel cell, classified as first generation, has been developed to the most advanced stage with PAFC power plants up to 11 MW currently operating.
(iii) The Molten Carbonate Fuel Cell (MCFC), a high temperature fuel cell operating around 650°C, is known as a second generation fuel cell. Prototypes of MCFC in the 100 kW range are under construction and evaluation.
(iv) The Solid Oxide Fuel Cell (SOFC), or third generation fuel cell, is attracting substantial interest[2] as it is regarded as the most efficient and versatile power generation system, in particular for dispersed power generation. The current operating temperature is around 1000°C but substantial efforts are under way to reduce the operating temperatures to 800–900°C.

2 SOFCs — ADVANTAGES, OPERATING PRINCIPLES

2.1 Special advantages of SOFC

Apart from the general advantages of fuel cells, such as environmentally friendly operation, SOFCs are fuel flexible and can operate on multiple fuels, including carbon-based fuels. This results in potentially higher overall fuel to electric efficiency of around 60% for single cycles and up to 85% efficiency for total systems. SOFCs deliver power densities of about 1 MW/m^3, and values as high as 3 MW/m^3 are possible for monolithic designs. The load following capability is excellent and electricity production can readily be tuned to the load requirements. Due to their high exhaust gas temperature they have the ability to cogenerate heat and electric power with the balance in favour of electric power.

2.2 Operating principle and thermodynamics of SOFC

A modern SOFC consists of an Y_2O_3-doped ZrO_2 electrolyte which is an oxygen ion conductor, sandwiched between a cathode (La–manganite) and an anode (Ni/ZrO_2–cermet).

At the cathode, oxygen from air is dissociated and converted to oxygen ions, which migrate through the electrolyte membrane and react with the fuel at the anode/electrolyte interface (Fig. 3). The open circuit (E_{ocv}) or reversible voltage (E_r) of

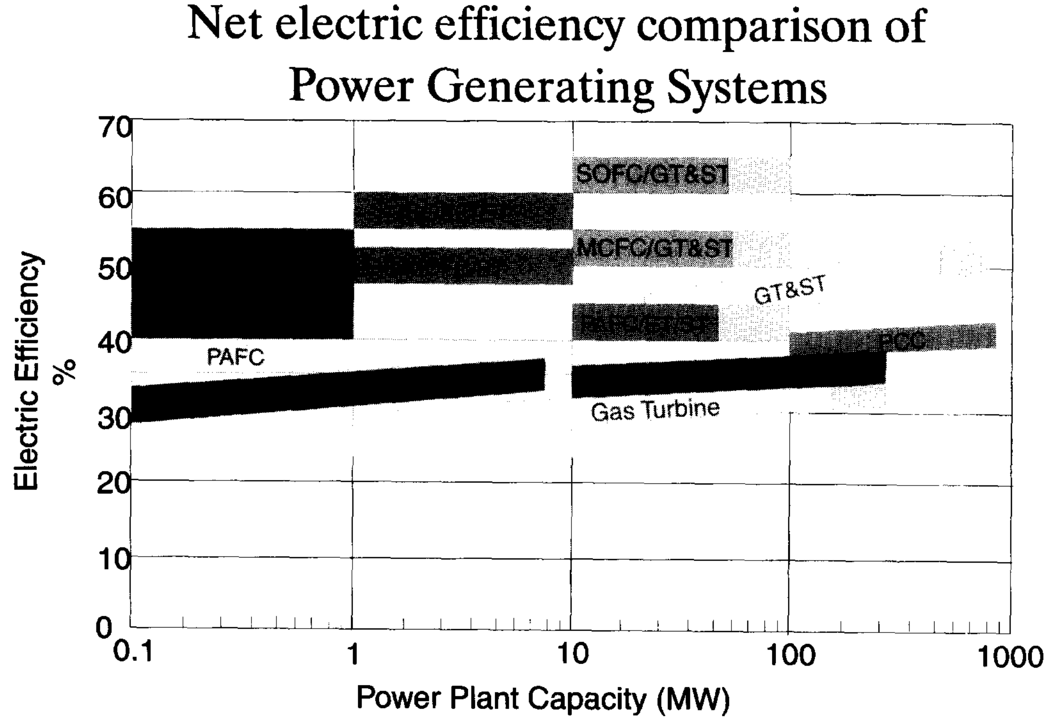

Fig. 1. Efficiencies: (FBCC, PCC advanced coal combustion technologies); Source: Siemens.

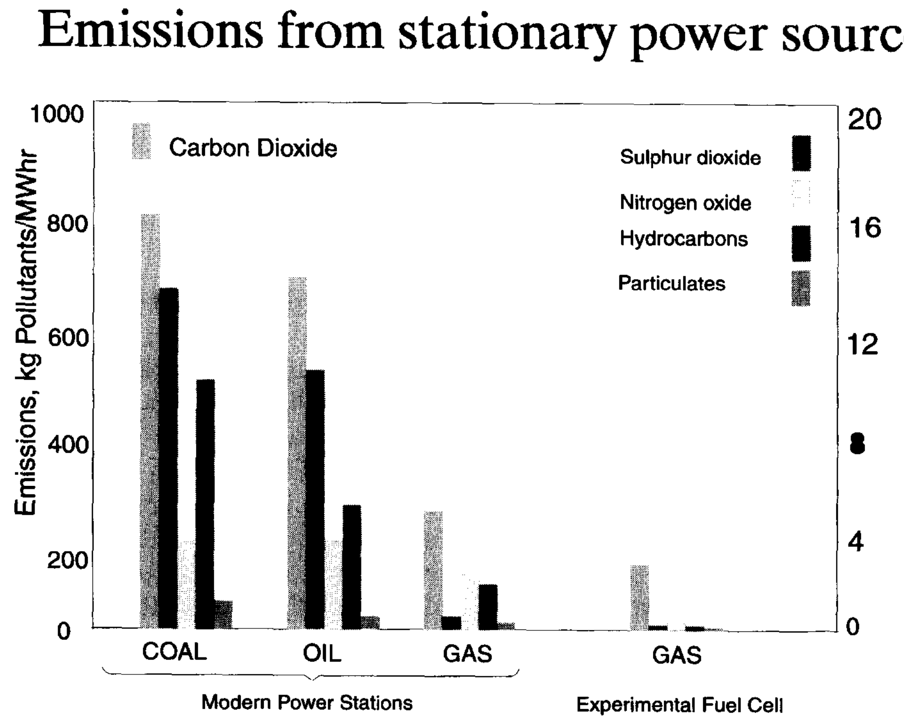

Fig. 2. Pollutant output from power generation technologies (Source: CEC).

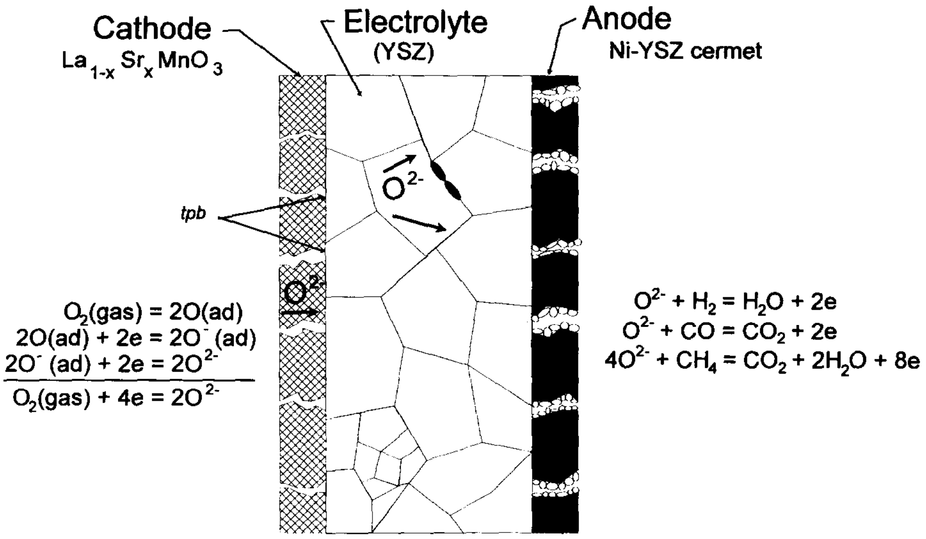

Fig. 3. Operating principle of SOFC.

the cell is given by the free energy (ΔG) of the fuel oxidation reaction, according to E_{ocv} (E_r) = $-\Delta G/nF$ (n = number of electrons transferred, F = Faraday constant). This voltage is typically 1.1–1.2 V for a single cell. Under load conditions the voltage of a single cell decreases to about 0.6–0.9 V and current densities up to 800 mA cm^{-2} can be achieved. The fuel/electric efficiency of a fuel cell is defined as the product of the electric and fuel efficiencies (ϕ_F, ϕ_E). The remaining chemical energy is available as high quality heat, allowing operation of combined cycles with expander, gas and/or steam turbines, thus further boosting fuel/electric efficiency.

The fuel efficiency (ϕ_F) is defined as the ratio of ΔG to ΔH of the fuel oxidation reaction. Fuel efficiencies for hydrogen, carbon monoxide and methane are 94%, 91% and 100% at ambient temperature and 69%, 61% and 100% at 980°C. Internal losses (resistive (IR) within the electrolyte and overpotential (η) at both electrode/electrolyte interfaces) lead to a further decline in the efficiency. The effective voltage, E, available from a fuel cell is given by $E = E_r - IR - \eta$ and the ratio E/E_r is defined as the electric efficiency (ϕ_E).

3 SOFCs — STACK DESIGNS

To achieve workable power outputs, single cells are combined to multi-cell units, the fuel cell stack. Numerous configurations have been reported,[3] differing in geometry, power density and method of sealing. Designs can be classified into (i) self-supporting ones, where the electrolyte (80–250μm in thickness) forms a structural element of the design and (ii) supported concepts, where the electrolyte is deposited as a thin layer (< 50μm) on porous support structures.

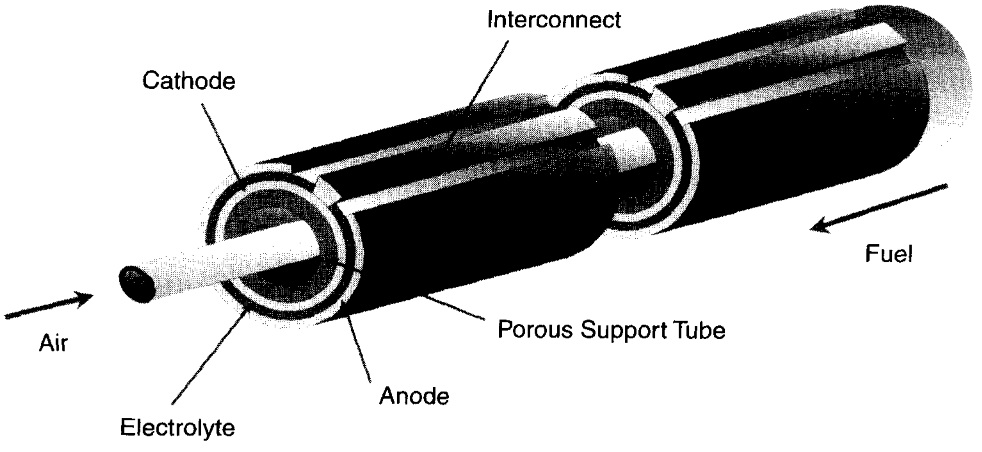

Fig. 4. Westinghouse tubular design SOFC.

The **tubular designs** belong to the class of supported concepts. In the Westinghouse design one tube represents a single cell (Fig. 4). This design is by far the most advanced SOFC concept (25 kW units). Stacks are constructed by bundling a number of tubes (6 × 3) together and connecting them with Ni felt pads. Support tubes of Ca-stabilized zirconia (or in the latest design the air electrode material, LSM, itself) sealed at one end form structural parts on to which active components of the fuel cell, air electrode LSM (1.4 mm thick), electrolyte (fully stabilized YSZ (thickness $\approx$ 40 μm)), fuel electrode (Ni/YSZ (thickness $\approx$ 100 μm)) and interconnector (thickness $\approx$ 35 μm) are deposited. Typical dimensions of the tubes are: 15–20 mm diameter, 1.5 mm wall thickness, 0.66–1 m in length (2 m long tubes are planned for MW system). The design does not require a seal, and the oxidant is injected through a co-axial ceramic injector tube near to the closed end of the cell and flows through the space between the cell and the injector tube to the open end of the cell. Fuel flows concurrent to the oxidant on the outside of the tube and the exhaust gas containing some unused fuel after passing through a diffuser plate combines with the partially oxygen-depleted air where it combusts. The tubular design developed by Mitsubishi Heavy Industries (MHI), differs from the Westinghouse design in so far that 15 small cell segments connected in series are deposited over an area of 41 cm in length (total tube dimensions: 21 mm diameter, 0.5 m length), and that fuel (not air) is injected through injection tubes into the inside of the tubular cells. MHI has constructed and extensively tested a 1 kW module consisting of 48 tubes. The major advantages of the tubular concepts are: no high temperature seals between cathode and anode compartments are required, and staged injection of feed and oxidant is possible. Disadvantages are lower power densities compared to other designs, and fabrication methods used to produce the thin adhering layers on the support tubes (CVD/EVD by Westinghouse, low pressure plasma spraying by Mitsubishi) are exotic and expensive. The cost targets necessary for SOFCs to become commercial are less likely to be achieved by the tubular concepts.[4]

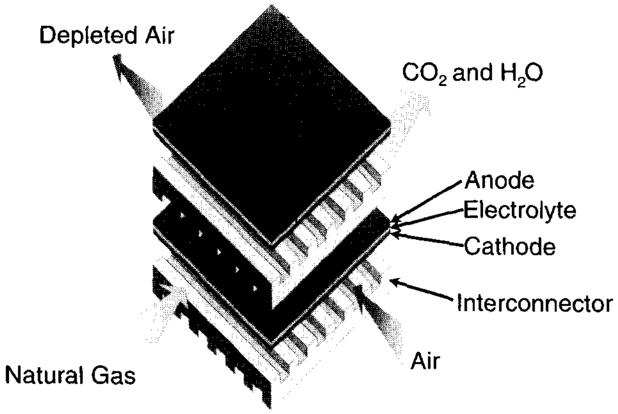

Fig. 5. Planar design SOFC.

Currently the most widely investigated concept is the **planar or flat plate design**, well known in other fuel cell types, which is viewed to have the potential of delivering the cheapest SOFC unit. In this concept, the components — electrolyte/electrode laminates produced by deposition of electrodes on to sintered electrolyte or laminated in the green state and co-fired, as well as interconnector plates with gas channels, made from ceramic materials or high temperature stable metal alloys — are fabricated individually and then stacked together and sealed with a high temperature sealing material to form either a fixed or sliding seal. External and internal co-flow, counter-flow and cross-flow manifolding options are possible. The simplest versions of this concept are the self-supported externally manifolded cross-flow planar stack (Fig. 5). The planar concept offers power densities of around 1 MW/m^3, cheaper fabrication methods (conventional ceramic green processing techniques) and simplified quality control as each component is fabricated separately and can be inspected before stack construction. The major challenges are the development of suitable seals and interconnect materials.

A **monolithic design** (original Argonne concept) is under development by Allied Signal Aerospace. Three types of monolithic stacks under consideration are: co-flow stacks (fuel and oxidant flow in the same direction), 180° counter-flow stacks and cross-flow stacks. In monolithic stacks laminated corrugated structures are fabricated, combined in the green state and co-sintered. The potential for very high power density makes the monolithic concept particularly attractive for aerospace and transport applications, but co-sintering proves to be very difficult. Mitsubishi Heavy Industries is developing a hybrid between monolithic and planar designs, the **MOLB (mono block layer built) concept**. A flat cathode/electrolyte/anode laminate is produced by screen-printing electrodes onto sintered electrolyte plates and co-firing at 1400°C. The interconnector is a flat sheet of La–Mg–chromite. Corrugated cathode and anode sheets form gas channels. The structure was sealed by either a fixed glass ceramic seal or a sliding seal using ceramic felt strips. Mitsubishi has constructed a 1.1 kW MOLB system consisting of three stacks of 40 cells, each 150 × 150 mm in dimension.

4 MATERIALS FOR SOFC

The high operating temperature of SOFC of around 1000°C is mainly dictated by slow oxygen transfer rates through the electrolyte at lower temperatures. This combined with the multi-component nature of the fuel cell and the required life expectancy of several years severely restricts the choice of materials for cell and manifold components. Each material used not only has to function optimally in its own right but has to be viewed in conjunction with the other cell components. Common requirements of all cell components are:

(i) chemical stability in fuel cell environments ($p(O_2) > 20$ kPa on the cathode side and $< 10^{-17}$ on the anode side) and compatibility with other cell components;
(ii) phase and microstructural stability;
(iii) minimum thermal expansion mismatch between various cell components (laminated structure);
(iv) for structural components, reasonable strength and toughness at the cell operating temperature, as well as reasonable thermal shock resistance;
(v) low vapour pressure to avoid loss of the material;
(vi) must allow cost competitive component fabrication.

Materials currently in use are discussed below.

4.1 Electrolyte

High efficiency fuel cells require electrolytes which, in addition to the general properties outlined above, must develop sufficient oxygen-ion conductivity (> 0.05 S cm^{-1}) at the operating temperature and remain ionic conductors in oxidising and reducing atmospheres. Doped zirconia-based materials offer the best possible choice at this stage. Dopants are selected from a large number of divalent and trivalent metal oxides (Y_2O_3, Yb_2O_3, Sc_2O_3, CaO, MgO, etc.), which stabilize the high temperature tetragonal or cubic phase to room temperature. In the ZrO_2–Y_2O_3 system, 2.5 mol% Y_2O_3 stabilizes the tetragonal (t) and 8.5 mol% Y_2O_3 the cubic (c) phase at 1000°C. The tetragonal phase is a small grain (0.5 μm) material with high mechanical strength, toughness and thermal shock resistance, and an ionic conductivity of 0.055 S cm^{-1} at 1000°C. In comparison, the large grained cubic phase has lower strength (at RT) but a conductivity of around 0.15 S cm^{-1} at 1000°C. CeO_2 doped with CaO, Y_2O_3, Sm_2O_3, Gd_2O_3 and a number of other rare earth oxides develops high oxygen-ion conductivity. However, the ionic conductivity regime is rather narrow, and in reducing environments, ceria based systems lose oxygen and develop electronic conductivity ($p(O_2)$ limit at 800°C of about 10^{-8}–10^{-10} kPa). If these materials are used in SOFCs they have to be protected on the anode side. The best oxygen ion conducting electrolyte is doped bismuth oxide with about an order of magnitude higher conductivity at 700–800°C than zirconia, but with the disadvantages of easy reduction, high reactivity and very low strength and toughness.

4.2 Cathode

The most common cathode material used in SOFC systems is doped La–manganite (LSM), a p-type semiconductor. Doping $LaMnO_3$ with lower valent cations enhances the electronic conductivity by increasing the Mn^{4+} content in the material. Sr doped La–manganite (LSM) is the currently preferred cathode material. The extent of Sr doping dictates the electronic conductivity and the thermal expansion coefficient. A change of the morphology of the cathode layer with time (decreasing three phase contact area and limiting gas diffusion) and interfacial reaction between cathode and electrolyte during operation limit the life of SOFCs and need to be minimized. A number of other materials have been considered, such as La–Sr–cobaltite, a material with much higher electronic conductivity, and in addition high ionic conductivity, but with the disadvantages (compared to LSM) of a high thermal expansion coefficient and lower stability due to interface reactions with the electrolyte.

4.3 Anode

On the anode side the atmosphere is reducing and metals are being used as electrodes (Ni, Co, Ru, Pt). Ni is the preferred choice due to its low cost and acceptable performance, but has low resistance to grain growth and sintering. Ru has better performance and stability but is expensive and very toxic. For maintenance of the porous structure of the anode layer and to reduce TEC mismatch with the electrolyte, the anode is used as a cermet of metal and stabilized zirconia. Ni/yttria–zirconia is the best anode material at this stage. For direct conversion of methane in the fuel cell, reasonable performance has been obtained with mixed conductors, such as doped ceria based systems.[5] However,. the large volume change on reduction of the oxide and phase transformations cause anode layers to spall off the electrolyte.

4.4 *Interconnect*

In the tubular concept, interconnections within the cell are made with $La_{1-x}(Sr, Mg)_xCrO_3$ layers and cells are connected with nickel felt pads. Ceramic interconnect layers ($La_{1-x}(Sr, Mg)_xCrO_3$) are also used in monolithic stacks. In the planar design concept, three interconnect options — ceramic, metallic (high temperature alloys) and cermet — are possible. Metals have the advantages of high electric and thermal conductivities which minimize temperature gradients in stacks and easier fabrication, but require corrosion resistant layers and thermal expansion mismatch is generally large. Siemens, in conjunction with Plansee AG, has developed a Cr-based alloy which matches the thermal expansion of yttria–zirconia over a wide temperature range. However, a substantial amount of work is still required to establish the suitability of this alloy for interconnects in SOFC.

4.5 *Manifold and seal*

Manifolds are fabricated from ceramics or refractories. In monolithic designs only stack to manifold seals are necessary, as individual cells are sintered together. In the planar concept seals between cells and between the manifold and stack are essential. Melt type and gasket type seal options have been explored, and the most common seal materials used to date are glass or glass-ceramics.

5 FABRICATION OF CELLS

Fabrication methods need to be selected according to:

(i) cell design (self-supporting or supported designs);
(ii) desired properties;
(iii) cost (fabrication is one of the most important cost factors); and
(iv) suitability for mass production.

The seal-less, tubular Westinghouse design is a supported cell design, where thin layers of cell components are deposited on porous tubes (Ca–ZrO_2 or LSM), fabricated by extrusion methods. Air (LSM) and fuel (Ni) electrodes are deposited by slurry coating and sintering. The electrolyte (9-YSZ) and the interconnect ($La_{1-x}Mg_xCrO_3$) are deposited by electrochemical vapour deposition (EVD), a technique developed and optimized by Westinghouse. The deposition is carried out above 1200°C with metal halides in an H_2/CO_2 atmosphere. The fabrication technique results in thin layers with excellent properties, but is very costly.

Self-supporting designs, such as monolithic and flat plate cells, are produced by well established green ceramic processing methods followed by high temperature sintering. Tapecasting and calender rolling are the most common fabrication routes for 100–300μm thick electrolyte sheets. Single cell structures are produced by deposition of electrodes on to sintered electrolyte plates by screen-printing or slurry coating, followed by firing, or by co-sintering, green laminates of air electrode (LSM)/electrolyte (YSZ)/fuel electrode (Ni–YSZ). The green laminates are produced by tapecasting or calender rolling individual layers, followed by laminating.

Supported flat plate structures, gaining new importance for thin film intermediate temperature SOFCs, often use a combination of green and sintered processing techniques. Porous support structures of electrodes are fabricated by tapecasting, calender rolling or extrusion, on to which thin films of electrolyte are deposited by either spray techniques (flame, plasma and laser spraying), vapour depositions or sputtering techniques. Electrolyte films in the micron range with good properties have been produced by magnetron sputtering,[6] electrophoretic deposition[7] and calender rolling.[8] Magnetron sputtering and calender rolling have the potential to be cost effective and are suitable for mass production.

6 STATUS OF SOFC TECHNOLOGY

The most recent intense effort in SOFC development started in 1985 in the USA and in Japan, in 1989 in Europe, and in 1991 in Australia. R and D programs on SOFC development are supported by governments and private companies, and worldwide many R and D organisations carry out SOFC development programs.

6.1 *USA*

In the USA the SOFC development work is progressing on tubular, monolithic and planar designs. Programs are funded by DOE, GRI, EPRI and private interests. R and D on SOFC is carried out by Westinghouse, Allied, Ceramatec, Z-Tek, Babcock and Wilcox, Corning, Caterpillar, by government laboratories (Argonne) and several universities.

Westinghouse is generally regarded as the world leader in SOFC development. The company chose the tubular concept and has developed it to an advanced state. A 3 kW generator was tested for about 6000 h and a 20 kW unit for 1700 h, both fuelled by natural gas. The largest SOFC system to date has been a 25 kW prototype system, which consists of 2 units of 20 kW, each constructed from 4 modules (5 kW in size) of 8 stacks (18 cells per stack). One system was configured for maximum electricity output and produced 36 kW at 85% fuel utilisation and 44 kW peak output. The second one, designed for combined heat and electricity generation, produced 33 kW AC power and 27 kW of steam. The output from a single cell (50 cm active area length) in these generators was 52 W (0.25 W/cm^2). For a 100 kW unit, currently under construction, 1 m long single cells are planned (output 100 W/cell) and air electrode support tubes will replace Ca-stabilized zirconia supports. For MW generators, 2 m long single cells are being considered.

Allied originally developed the Argonne monolithic SOFC design, which promised the highest power density, and has constructed 2, 4 and 12 cell stacks with limited success, as co-sintering of the laminate structure proved extremely difficult. Allied is now developing a supported flat plate concept, which consists of a 100–200μm thick Ni–YSZ anode (up to a size of 215 × 240 mm) fabricated by calender rolling, on to which a 1–10μm thick electrolyte film is rolled. The resulting bilayer is co-sintered and the cathode is deposited by slurry painting. From a single cell Allied achieved a maximum power density of about 300 mW cm^{-2} at 800°C.

Other players, including **Ceramatec** and **Z-tek**, are developing planar stacks with either metallic or ceramic interconnects and have constructed units up to 1 kW. Ceramatec is also collaborating with other SOFC development teams, such as Sulzer and Elkem, and supplying SOFC components to these and other groups.

6.2 Europe

Only planar type designs are being developed in Europe, by organisations such as Siemens and Dornier in Germany, Sulzer in Switzerland, ECN in the Netherlands and Statoil and Norcell consortia in Norway.

Siemens is the leading team in Europe. Siemens has designed a multi-cell arrangement which is internally manifolded and which consists of arrays of cells (up to 16 cells per layer) which are welded or diffusion bonded onto a metallic window foil. Cell sizes of 50 × 50 mm^2 are being used currently (electrolyte thickness 70–150μm), but 100 × 100 mm^2 single cells and small arrays are under development for multi-kW units. Single cell performance is excellent with power densities of 300–400 mW/cm^2 at 930°C, the maximum temperature tolerated by the metal interconnect. The electrolyte sheets are tapecast and sintered, and the electrodes screen-printed and co-fired. The multi-cell sandwich layers are stacked in between metallic interconnect plates which incorporate the gas channels. A high temperature Cr-based alloy matches thermal expansion of the electrolyte but requires protective coatings. Siemens has built stacks in the hundred watt range and achieved power densities around 175 mW/cm^2, and is currently working on a kW size stack.

Statoil, the Norwegian oil company, started its SOFC development effort early in 1991. The company is developing planar cell technology with La(Ca)CrO$_3$ interconnects. Statoil sources electrolyte plates (70 × 70 mm^2, 100–200μm thick) from various manufacturers. Anode (40μm thick, 60% Ni and 40% 8-YSZ) and cathode (La$_{0.5}$Sr$_{0.5}$MnO$_3$, 25μm thick) layers are deposited by screen-printing followed by firing. Ceramic interconnects are fabricated in-house by cold uniaxial pressing and sintering. Statoil has constructed and operated a number of smaller stacks, and aims to test a 10 kW unit by the end of 1995.

Sulzer in Switzerland is developing an interesting design, HEXIS (heat exchanger integrated stack). The concept has less severe sealing requirements and uses an LSC interconnect and a metallic current collector. At 920°C, a 70 mm diameter (31.4 cm^2 active area) two cell stack produced 1.7 V OCV, and 1.0 V at 150 mA/cm^2 at 35% fuel utilisation. Sulzer aims to build multi-kW prototype units by 1996.

6.3 Japan

In Japan all three basic designs (tubular, monolithic and planar) are being developed. The NEDO sponsored Moonlight project on SOFC technology is in its second six year phase, which will finish in 1997, with targets of 1–3 kW modules and power densities of 180 mW/cm^2 by the end of 1995, and 10–30 kW modules using external reforming for natural gas with power densities of 200 mW/cm^2 by the end of 1997. The tasks are divided among various players with development of planar-type modules being carried out by Fuji Electric and Sanyo Electric Co., development of materials and fabrication technology by a number of companies with ceramics expertise, and engineering and systems being developed by CRIEPI, Mitsubishi Heavy Industries (MHI) and Electric Power Development Co.

MHI is considered to be the leading SOFC developer in Japan. It pursues three different designs. A 1 kW stack based on a multi-cell tubular concept (15 cells/tube) produced by plasma spraying has been developed and tested. 1 kW modules have been constructed of a monolithic type stack concept (MOLB), which has been tested for over 1000 h, but substantial improvements are required for acceptable stack life. For a 40 cell stack (15 × 15 cm^2 area/cell), a power output of 538 W was obtained at a cell voltage of 0.7 V/cell for air/hydrogen (50% fuel utilisation). Three stacks connected in series produced a combined power output of 1328 W at a cell voltage of 0.65 V and 1205 W at 0.7 V. MHI is also interested in planar type stacks. Cells with an area of 100 cm^2 with ceramic interconnects have been constructed. The planar technology is the least developed within MHI with only a few 100 W stacks having been built.

Fuji Electric is developing a disk shaped substrate type planar stack with centre manifolding. The substrate (3 mm thick and 50, 100 or 200 mm in diameter) is Ni–8YSZ cermet, which is prepared by cold pressing. A 200–300μm thick 8YSZ electrolyte layer is deposited by DC/RF sputtering onto the substrate and the cathode $(La_{0.85}Sr_{0.15})MnO_3$, 50$\mu$m) is slurry coated. The bi-layer ceramic separator plate consists of a 3 mm thick substrate of cathode material (prepared by cold pressing) with a dense 200μm thick layer of La–Ca–chromite deposited by plasma spraying. A 10 cell stack produced an E_{ocv} of 9.15 V and a power output of 410 W (5.2 V and 80 A) at 1000°C in air/3–5% H_2O–H_2. Tests for 2000 h at 200 mA/cm^2 resulted in an average degradation rate of 35μV/h. Degradation problems were related to poor heat distribution in the stack (local overheating) and Fuji is experimenting with a metallic interconnect. The company is fairly advanced in systems design and modelling.

Sanyo Electric is developing an internally manifolded planar design with metallic interconnect. An 11 cell stack with 125 cm^2 active area per cell at 982°C gave an E_{ocv} of 11.68 V and a maximum power output of 263 W. The stack started deteriorating after about 700 h of stack operation with increases in both ohmic and interfacial resistances. The 20 cell stack produced 415 W maximum power output.

6.4 Australia

A project on SOFC development started in CSIRO (Australia's major R and D organisation) in 1991 (a project on SOFC related technologies existed in CSIRO since the mid 1980s). In 1992 a consortium of CSIRO, major utilities, BHP (Australia's largest company) and government R and D bodies established **Ceramic Fuel Cells Ltd** (CFCL), with the aim to provide a commercial focus for a national SOFC development effort. The company is developing planar stack technology, focusing in particular on cost effective fabrication technology. Several different interconnect options are being explored. CFCL has tested single cells up to 2500 h with good performance. Small stacks with power densities above 300 mW/cm^2 have been operated.

7 FUTURE DIRECTION

Solid oxide fuel cells have the potential to revolutionize electric power generation in the next century, and developments to date look promising. Areas which need innovative solutions involve:

(i) improved interconnect materials and seals,
(ii) cost competitive fabrication, and
(iii) long term stability.

The high operating temperature is a major cause for accelerated degradation due to sintering of electrodes and interfacial reactions. Similarly, the choice of materials and fabrication methods are limited, adding to the cost of SOFCs. Lowering the temperature to 800–850°C will lead to higher thermodynamic efficiency, lower degradation of cell components, wider choice of materials for stack components and lower costs. In the planar design a metallic interconnect with marked advantages over ceramic interconnects can be used, sealing is easier and gas manifolding and auxiliary equipment (heat exchangers) can be made of conventional high temperature materials.

Oxygen ion conduction through the YSZ electrolyte membrane is a highly activated process, thus resulting in high voltage losses across the layer at lower temperatures. This limitation can be overcome by:

(i) developing electrolytes with low resistance at intermediate temperatures (novel electrolyte materials or improvement of known electrolytes); and
(ii) increasing conductance of electrolytes by using thin film concepts, which require development of substrate technology and thin film deposition methods.

In addition, other cell components such as electrodes and seals have to be modified for optimal operation in the intermediate temperature range.

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