

SOLID OXIDE FUEL CELLS — THE NEXT STAGE

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Fuel cells are electrochemical systems that convert the chemical energy of the reactants directly into electrical energy. Over the last quarter of a century a number of fuel cell concepts have been developed up to and including commercial size devices. These are categorized according to the type of the electrolyte used in the cell (Fig. 1). All of the devices burn fuel at the anode or negative electrode, and consume an oxidant at the cathode or positive electrode.

The five main varieties of fuel cells, listed in increasing order of operating temperatures are:

- (a) Polymer electrolyte fuel cell (SPFC) approximately 80 °C.
- (b) Alkali fuel cell (AFC) approximately 100 °C.
- (c) Phosphoric acid fuel cell (PAFC) approximately 200 °C.
- (d) Molten carbonate fuel cell (MCFC) approximately 650 °C.
- (e) Solid oxide fuel cell (SOFC) approximately 1000 °C.

The technical status of one of these systems, namely the solid oxide fuel cell and its derivatives, is presented here with respect to the basic design concepts, the materials of construction and their fabrication processes.

The three main SOFC variations are:

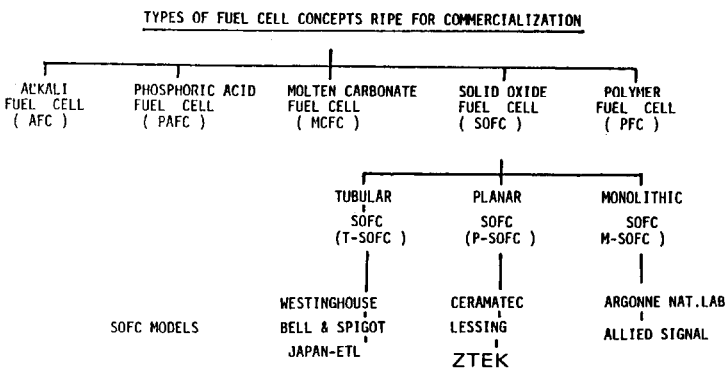


Fig. 1. An arbitrary selection of fuel cell concepts ripe for commercialization and of the various types of solid oxide fuel cell designs being vigorously investigated at this time.

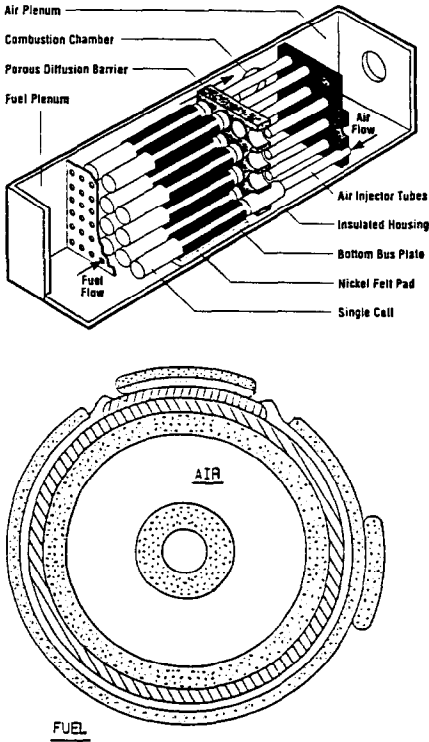


Fig. 2. Example of a solid oxide fuel cell tubular concept based upon the Westinghouse design.

- (a) Tubular design (Fig. 2).
- (b) Planar design (Fig. 3).
- (c) Monolithic design (Fig. 4).

The above three SOFC designs differ only in cell geometry construction. The 'cell' is the repetitive electrochemical building block, connected in series and parallel, which form the 'stack' or unit of fabrication. The basic SOFC 'cell' consists of the following common parts:

- (a) The anode.
- (b) The electrolyte.
- (c) The cathode.
- (d) The interconnect or bipolar plate.
- (e) The support tube (in the tubular design only).

A brief outline of the materials of construction of the above five components will highlight their commonality, for they are all based upon the same materials selection with minor dopant variations depending upon the fuel cell type and mode of fabrication. All are essentially ceramic materials,

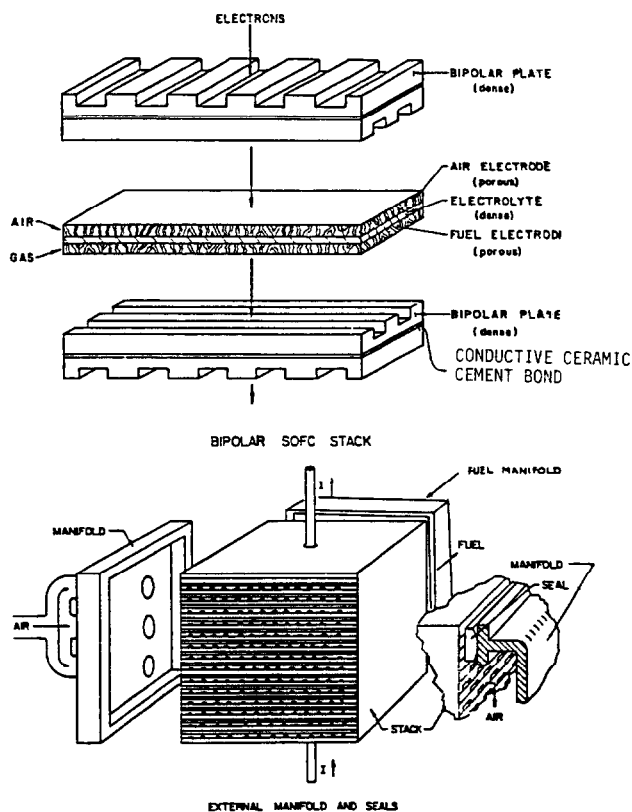


Fig. 3. Example of a solid oxide fuel cell planar concept based upon the Ceramatec and Lessing design.

synthesized and formed by conventional ceramic processes (Fig. 5). In each of the three SOFC types: the *anode* or fuel electrode is a porous cermet of nickel and an inert phase such as zirconia or yttria-stabilized zirconia; the anode is an electronic conductor with a projected current density in the range of 1 A cm^{-2} ; it is fabricated usually as a mixture of nickel oxide and stabilized zirconia which is converted to the conductive cermet *in situ* within the cell. The fabrication process, however, will differ with the respective designs:

(a) Tubular design: The anode is slurry dipped onto the electrolyte, dried and sintered, or flame or plasma sprayed directly onto the already sintered electrolyte.

(b) Planar design: The anode is flame or plasma sprayed onto the fired electrolyte or bipolar plate, or in the pseudo-hybrid design, the anode will be tape cast or calender rolled in the green state, followed by assembly prior to debinding and sintering.

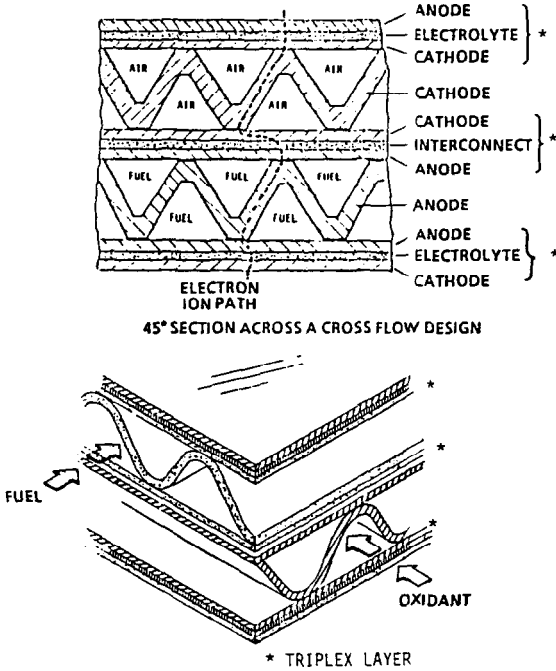


Fig. 4. Example of a monolithic solid oxide fuel cell concept based upon the Argonne National Laboratory design.

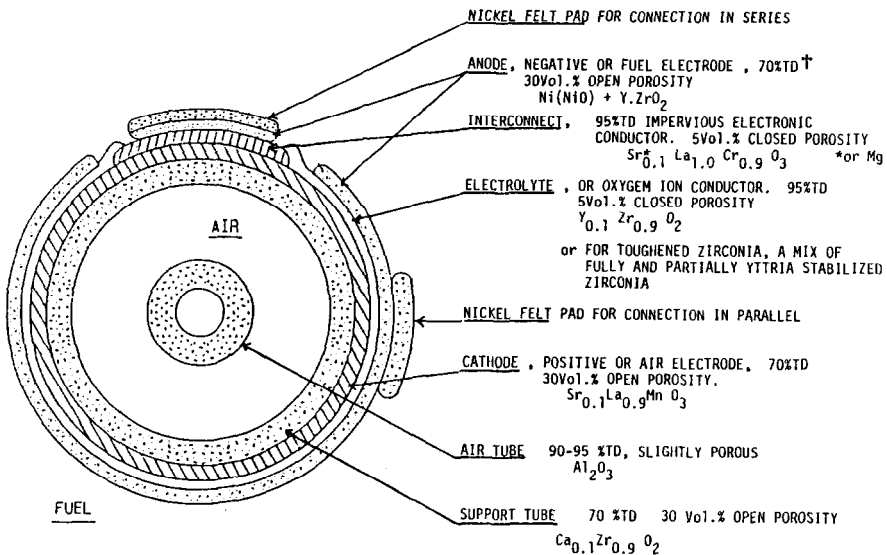


Fig. 5. List of solid oxide fuel cell components and their compositions using the Westinghouse concept as an example. Tube and layer thicknesses not to scale. †%TD = percent of theoretical density.

(c) Monolithic design: the anode is tape cast or calender rolled, and assembled into the monolith in the green state prior to sintering.

The anode thickness is usually 100 - 200 μm with a theoretical density of 70%, the porosity being of the open type. The precise formulation of the anode is invariably a propriety formula, but will fall between 10 to 30% of the volume of the inert phase. The nickel is added as the nickel oxide and is reduced to the metal as the cell is heated in the reducing fuel atmosphere.

The ionic conducting *electrolyte* in most of the SOFC designs has a typical composition of $\text{Y}_{0.1}\text{ZrO}_{0.9}\text{O}_2$ or as is sometimes written: $(\text{Y}_2\text{O}_3)_{0.1}(\text{ZrO}_2)_{0.9}$. Recent advances to toughen the zirconia, have introduced a two phase yttria-stabilized zirconia.

The trivalent Y^{3+} ion within the Zr^{4+} lattice produces anion vacancies and an oxygen ion conductor. The mobile ionic species within the electrolyte in the SOFC system are the O^{2-} ions as compared to protons (H^+) in the PAFC and SPFC and CO_3^{2-} ions in the MCFC (Fig. 6). The O^{2-} ion in the electrolyte travels from the cathode (air electrode) to the anode (fuel electrode) as does the carbonate ion in the MCFC. In contrast, the H^+ ion in the PAFC travels in the reverse direction from the anode to the cathode. All three current carrying species arrive at the appropriate electrolyte-electrode interface, or three phase boundary, and react with the gas phase within the porous electrode. The microstructural characteristic of this interfacial three-phase boundary is a critical parameter controlling the gas dynamics and the electrochemical efficiency of the fuel cell.

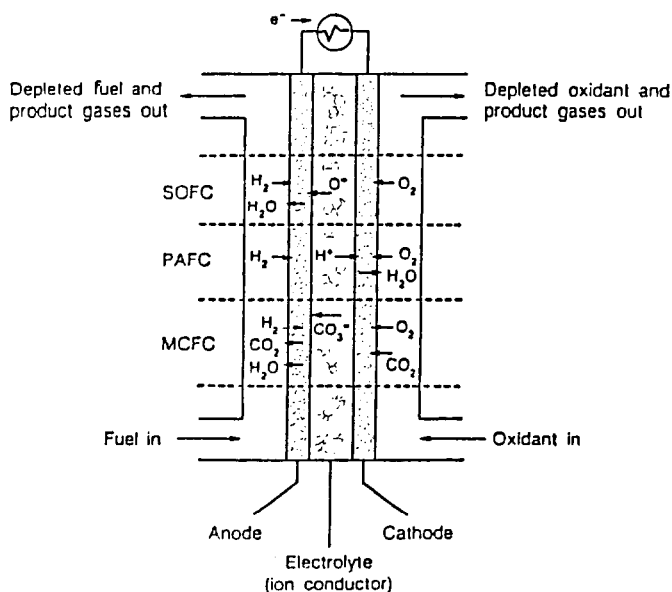


Fig. 6. Schematic illustration of various fuel cell ionic conductive species for the three main commercial designs.

A balance of properties and *in situ* performance within the two porous electrodes and the impervious electrolyte must be maintained if the cell is to function economically (lifetime up to 40 000 h) and at the appropriate temperature (1000 °C).

The method of fabrication of the electrolyte will differ depending on the design concept, namely:

(a) Tubular design: Electrochemical vapour deposition from the mixed chloride gas by steam reduction (see Fig. 2), or plasma spraying mixed oxide powders onto the cathode (see Fig. 7).

(b) Planar design: Electrochemical vapour deposition of the mixed chloride gases, or plasma spraying the mixed oxides onto the porous electrode, or for hybrid design, tape casting or calender rolling the green tape.

(c) Monolithic design: Tape casting or calender rolling tapes to form anode–electrolyte–cathode triplex layers.

The impervious electrolyte tape is usually in the order of 50 - 75 μm in thickness with a theoretical density of 95%. The remaining 5% of the volume is the closed type. Recent advances, however, in SOFC materials selection have included 'toughened' zirconia ceramics based upon a two phase fully and partially stabilized yttria–zirconia system.

The *cathode* or air electrode for all three types is based upon the lanthanum manganite perovskite structure doped with strontium, of the general formula $\text{Sr}_x\text{La}_{1-x}\text{MnO}_3$ where $x = 0.1$ to 0.2 . The cathode is a p-type electronic semiconductor and, similarly to the anode, is a 70% theoretical density porous structure that must permit rapid diffusion of the air or oxygen to the electrolyte three phase boundary and subsequently to flush out the inert nitrogen. The thickness of the cathode will again be dependent upon the design and fabrication process, namely:

(a) Tubular design: The air electrode is slurry-dipped as a 1 mm layer onto the support tube, dried and sintered. In the advanced design for a self supporting cathode the thickness may be increased above 1 mm and be fabricated by mandrel extrusion, high pressure slip casting into moulds and/or centrifugal casting.

(b) Planar design: The air electrode thickness will be limited to the control and ability to retain the open porosity by a plasma or flame spraying process, *i.e.* 500 - 1000 μm . Hybrid design: tape cast or calender roll within a triplex layer. Co-extrude followed by sintering, could be an alternative to the spraying and will enable a better control of the porosity by the addition of organic pore formers.

(c) Monolithic design: Tape casting or calender rolling the cathode followed by co-rolling the triplex layers prior to corrugation, stacking and sintering. The thickness of the cathode is of the order of 40 to 50 μm .

The SrLaMnO_3 cathode tends to sinter at a lower temperature than the three sister layers in the monolith. The above mentioned methods for the fabrication of the cathode, *i.e.* slurry dipping, tape casting, calender rolling, slurry spraying and extrusion have included an organic pore former to control and retain the open porosity within the tape while in fabrication and in operation.

The *interconnect* or *bipolar plate* composition is based upon the electronically conducting lanthanum chromite perovskite structure doped with either strontium or magnesium. The following general formula applies to most designs $\text{Sr}_x\text{La}_1\text{Cr}_{1-x}\text{O}_3$ where $x = 0.1$ to 0.2 . In a similar fashion to the electrolyte, the interconnect is impervious to the fuel and oxidant gas and experiences (during operation at 1000°C) both an oxidizing and a reducing environment. It should be appreciated how few candidates are available for the interconnect under these conditions where stability of both the crystal phase and the stoichiometry are essential. The interconnect thickness and mode of fabrication are again related to the SOFC design, namely:

(a) Tubular design: By electrochemical vapour deposition of the mixed chloride gases of Sr or Mg, La and Cr by steam reduction at a temperature between $1300 - 1600^\circ\text{C}$ onto selected masked areas of the electrolyte (Fig. 5). The thickness is about $60\ \mu\text{m}$.

(b) Planar design (the bipolar plate is synonymous with the interconnect): The bipolar plate in the planar design is the support member of the SOFC cell housing the gas channels and acting as an impervious barrier. The process of fabrication is either by thick tape casting, calender rolling, injection molding or by classical wet or dry pressing. The 3 to 4 mm thickness will open up numerous fabrication techniques which are not applicable in thin film processing. The green or unfired plaque is either hard-fired followed by coating with the other electrodes or for the hybrid design bisque-fired then coated. The closing of the porosity in the bipolar plate will occur within the final shrinkage stage of co-sintering.

(c) Monolithic design: Tape casting or calender rolling. It has proved difficult to incorporate the interconnect into the 'one process' MSOFC procedure mainly due to the higher required sintering temperature to achieve the desired impervious state. It requires at least 1600°C to sinter the interconnect to 95% theoretical density and at this temperature the anode and cathode overdensify, closing off almost all their open porosity.

The *support tube* appears only in the Westinghouse and in the early bell and spigot design on which the Japanese ETL hybrid is based (Fig. 7). The support tube is the structural member of the tubular-SOFC system and also acts as the oxidant gas conduit (Fig. 2). The early composition was calcia-stabilized zirconia of the general formula: $\text{Ca}_x\text{Zr}_{1-x}\text{O}_2$ where $x = 0.1$ to 0.2 . The wall thickness of the T-SOFC support tube is about 1.5 to 2 mm and is highly porous to the oxidant gas. The initial porosity may be as high as 40% of the volume which within the further fabrication stages and in operation may close down to 25 - 30% of the volume. The support tube for the ETL bell and spigot design is made of porous alumina, which acts as the mandrel onto which the other SOFC components are plasma or flame sprayed using suitable masking devices.

With the Westinghouse design the support tube enters the T-SOFC fabrication line as a closed-ended bisque tube onto which the cathode, interconnect, electrolyte and the anode are sequentially deposited. The support tube experiences cumulatively five or six temperature (1200 to 1600°C)

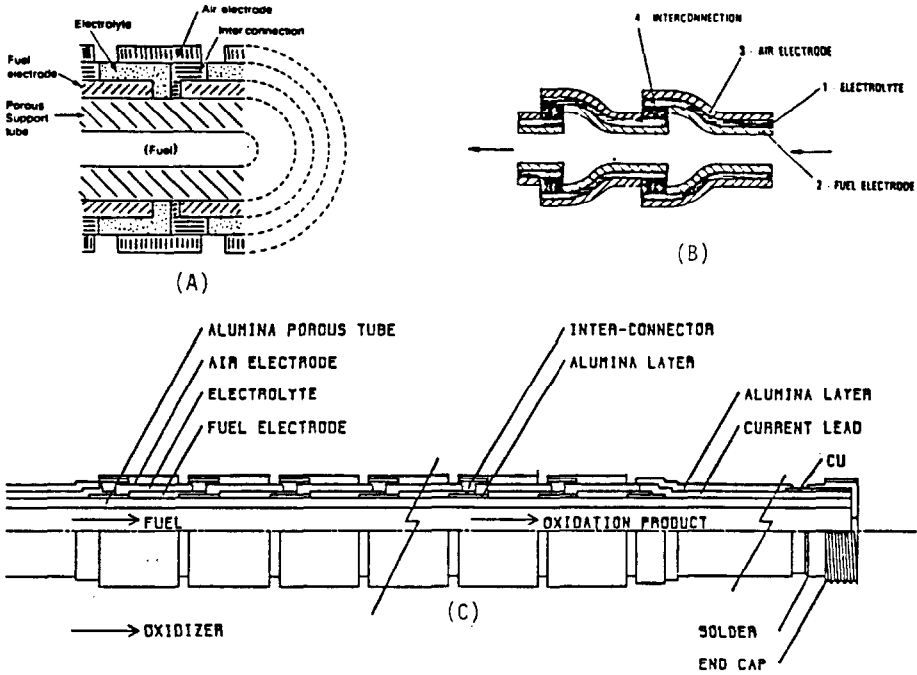


Fig. 7. Three examples of the solid oxide fuel cell ‘bell & spigot’ tubular concept based upon (A) Wade *et al.* [1]; (B) early Westinghouse design [2]; (C) Japan-ETL design.

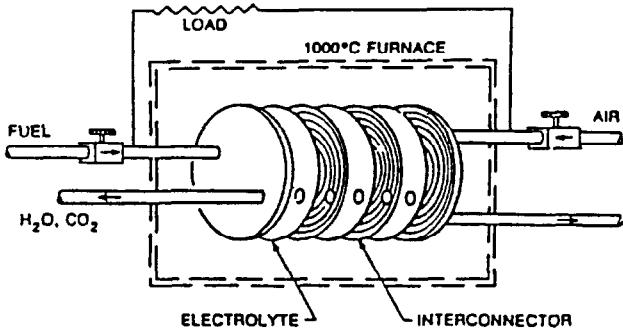


Fig. 8. Example of a solid oxide fuel cell planar model based upon the Ztek [3] design sponsored by EPRI in a 10 cell/1000 h test.

cycles within its fabrication life. Unfortunately the support tube in the original T-SOFC design accounted for 70% of the weight of the cell, which contributed to the lower energy density of the design relative to the monolith. The replacement of the calcia-stabilized support tube by a self supporting cathode will improve the energy density.

Although there are other SOFC designs (Fig. 8) the materials of construction are essentially those outlined above. Each of the various SOFC

design concepts, now vigorously being developed in many countries for ultimate commercialization, exhibit their own characteristic problems in fabrication. The tubular concept, well advanced in field testing, uses expensive and very sophisticated electrochemical vapour deposition, masking and demasking, dip or spray coating to sequentially build up the various layers necessary for the electrochemical cell. The planar device relies on achieving controlled porosity in the plasma process and a high level of flatness for the building units to ensure edge seal integrity, minimum internal leakage crossover and most importantly to minimize interfacial resistance. The monolithic design will require all the skills and ingenuity of the ceramicist to match each of the mating layers through the stages of debinding and sintering, cooldown from the final thermal process, and throughout the thermal-ratchetting of cell operation. The debinding and sintering shrinkage of the four components and their thermal expansion coefficients must not differ by more than 5%. The converse of this will lead to delamination, cracking and reduction in cell performance.

The most adverse changes in SOFC performance are due to an increase in the internal resistance (IR), or IR drop across each cell. Due to the relatively low ionic and electronic conductivity of the oxide ceramic materials of choice, to reduce the IR drop, SOFCs are essentially thin film devices. The fabrication of thin layers in many thousand square meters in area has now become a specialized technology. Some of the specific processes of fabrication being:

- (a) Slurry spraying.
- (b) Slurry dipping.
- (c) Tape casting.
- (d) Calender rolling.
- (e) Thin lamellar extrusion.
- (f) Flame spraying.
- (g) Plasma spraying.
- (h) Electro and chemical vapour deposition.
- (i) Plasma assisted CVD.
- (j) Laser assisted CVC.

The first five process methods prepare a thin layer in the green state which will require further processing prior to the final sintering stage. The remaining five process techniques produce a high density layer, not necessarily requiring further treatment. However many of the sophisticated techniques used in the semiconductor device industry are being used in the development of the SOFC. Examples are screen printing, continuous sheet casting onto a moving substrate, masked CVD and laser assisted CVD. Likewise it is envisaged that over the next decade, parallel researches into superconductivity will contribute to the search for new or improved conductive SOFC materials.

In order for a technology to be evaluated against a background of a long term energy programme, based partially on fuel cells, it is prudent to know the economics of the alternative concepts, to thoroughly understand

and quantify the materials and processes of production, and to evaluate the ultimate need and size of the SOFC module required by the customer. These requirements will reflect the variability of performance under the customer's field conditions, and for the manufacturer, the degree of sophistication and availability of the materials of construction. For the manufacturer an under estimation of the materials availability or reproducible quantities of a chosen process can have profound repercussions to the price of electricity and the cost per kilowatt installed.

The 'degree of reproducibility' of a fabrication process precis the technical and developmental requirements necessary for the SOFC manufacturer to address over the next five years. Unfortunately, unlike fossil and nuclear power plants, fuel cell plants based on solid oxide technology are built up from a large number of small fuel cell stacks. It is impossible to make a large fuel cell from green ceramic components — the manufacturing building unit. Therefore can one million of a component, identical in all respects, be made from knowledge and experience of making only a thousand?

The manufacturing building unit is the fabricated component which travels through the processing line from raw materials to the final product and which is capable of being quality assured as an acceptable entity. For each of the three SOFC concepts reviewed, the manufacturing unit is:

(a) Tubular design: The single power generating tube of about 200 - 300 W capacity.

(b) Planar design: The single plate cell prior to stacking of 300 - 500 W capacity.

(c) Monolithic design: The stack, built from 50 - 200 cells in the green state. The capacity of the stack in the sintered state will be 25 - 50 kW.

The manufactured unit fabricated for shipping, *i.e.* the assembled SOFC with bus bars, conduits, manifolding, insulation etc., envisaged for the three fuel cell types is:

(a) Tubular design 10 - 15 kW module.

(b) Planar design 20 - 25 kW module.

(c) Monolithic design 0.5 - 1.0 MW module.

These units will be assembled into larger commercial size plants on site.

For the cell fabricator, it is important to know the relationship between the size of the shipping unit and the components which are capable of being quality assured prior to release. This will then reflect the cost of the unit. Present numbers reflect an arbitrary target of \$1500/kW SOFC stack installed which is related to a SOFC fabrication cost of \$350 - \$450 for the fabrication of the ceramic fuel cell stack prior to connecting to the manifolding and gas conduits. Both these cost figures will restrict the raw materials of manufacture to about \$50 to \$70 per kW. The above numbers are target costs for the 90s and should be used as 'drivers' for the fuel cell technologists to create a mind-set in scale-up procedures from the laboratory scale to the industrial commercial plant.

To achieve a hypothetical fuel cell production of six-sigma, the statistician's term to define virtually error free performance, both process

and product must be rigorously quality controlled/quality assured. The axiom — “the product is a natural extension of a process, and in many cases they are inseparable” — will be amply applicable to the ceramic fuel cell fabrication. Extending this axiom further, not only is the product an extension, but both the process and product are likewise an extension of the raw materials and their process and source of supply. The manufacturer of the future may be faced with a multitude of series and parallel material flow system networks each of which must be quality controlled/quality assured prior to the acceptance of a component.

Advanced materials have drawn researchers around the world to evaluate new and sophisticated ways of making materials that ordinarily would not be economical or capable of large-scale production. For example, the conventional method of making the mixed perovskite for conductive electrodes was by mechanically mixing the oxides or carbonates of the cations. To break up the bisque after reaction calcining, percussion ball milling was invariably required. Although the early electrode materials were made by this procedure, the method is not applicable to fuel cell electrode fabrication, unless stringently quality controlled. The solid state method invariably leads to poor sinterability, hard strongly bonded agglomerates, inhomogeneity, mixed oxide phases, abnormal and bimodal grain size, poor reproducibility and shrinkage control, imprecise cation stoichiometric ratios and unstable mechanical and electrical properties within the cell. Regrettably this solid state method seems to be the only process available to date with batch and lot yields in the thousands of kilograms per day capacity.

At this time small 1 to 10 kg batches of the mixed cation electrode and interconnect materials have been successfully prepared using the Pechini technique based on the co-precipitation from the mixed cation polymeric precursor. The Pechini method uses citric acid and cation salts with ethylene glycol. This produces a resin like solid which after charring at about 400 - 800 °C, results in a fine mixed perovskite powder. Unfortunately this process does not lend itself to 1000 kg/day batches due to the high cost of ethylene glycol and to an excessive off gasing exothermic stage. However derivatives of this excellent synthesis technique may be capable of scale-up. SOFC ceramic components will possibly require the following parametric definitions to accurately and precisely define the requirements of a specification of the ‘starting’ materials:

(a) The starting powder stoichiometry which, within the fabrication process and under the cell operating conditions, will achieve the desired product stoichiometry.

(b) The starting powder morphology. The standard sub-set of this being (i) particle size and distribution; (ii) surface area.

(c) The chemistry of the starting powder.

In previous years the above three parameters were enough to ‘index’ the starting powders and for the industrial ceramicist to tailor the variables of the process to fit the properties of the raw materials. Today however

these are not enough. SEM, EDEX, powder shape, emission spectroscopy, X-ray diffraction of the powders and possibly others are needed to 'fingerprint' the raw materials or to detect the degree of differences and similarities between prior and subsequent lots. Most raw powder specifications are relative rather than absolute, being compared and related to powder lots in the experimental trials which 'work'. The theoretical specification for the pure powder is not a practical proposition in the commercial field. However the hypothetical requirements of the SOFC ceramicist to achieve the six sigma process will inevitably lead scientists to search for the 'perfect powder'.

For the SOFC requirements this possibly consists of a nanophase sub-micron, mono-distribution of particles whose mean deviation from the norm is no greater than -5% relative. The 'perfect powder' compositional stoichiometry likewise should not differ from the required mean by, at least, the cumulative limits of error of all the evaluations determined on the individual constituents.

In the search for flaw-free ceramic layers in the SOFC fabrication, the properties of the starting materials are of paramount importance in the control of the layer integrity through the debinding and sintering stages. In parallel, similar careful research must be directed to process control throughout all the stages of fabrication, especially in the sometimes forgotten debinding of the green state.

Thin layer fabricators are now using multi-component organic systems in the ceramic preparations to achieve the desired match with other layers. As many as six to eight organics may be used in the slip or 'leather' stage. These organics will all be required to crack or volatilize between room temperature and $500\text{ }^{\circ}\text{C}$ without leaving any carbonaceous residue to alter the stoichiometry by a carbothermic reaction. The gas phase evolution in such a mixture is many hundreds of volume percent. The fuel cell ceramic infrastructure must be capable of accommodating this gas evolution without distortion or delamination. The following will be the tools of the quality assurance analyst in the monitoring of the fabrication process.

(a) The recording differential dilatometer: To measure the shrinkage throughout the debinding and sintering stages.

(b) The differential scanning calorimeter: To assess any phase changes in the constituents which could cause delamination on thermal cycling.

(c) Thermogravimetric analysis: To measure the weight loss in the debinding and sintering stages.

(d) Thermovapouremetric analysis: To assess the gaseous evolution species on burnout of the organics.

(e) The X-ray diffractometer: To assess the crystallographic phases present in the starting materials and in the final product.

(f) X-ray CAT* scan or MRI**: To assess the layer or structural integrity of the assembled stack.

*Computerized Axial Tomography. ** Magnetic Resonance Imaging.

However it must be realized that the sintering process of a ceramic 'starts' at one degree above room temperature. Above this all the individual constituents begin the intricate process of decomposition, rearrangement and finally the mechanism of compaction. Of the many new procedures open to the ceramicist to supplement these, the following are worthy of interest:

(a) The supply of ultra fine powders in the Ångstrom range (nanophase materials).

(b) The use of microwave processing of ceramics.

In previous years the researcher had thought little of the sources of the materials of his research if and when his endeavors reach the commercial production scale. The premise that a materials market source will always develop in sympathy with the demand may not necessarily be true in the 90s. As an example, for a SOFC 200 MW/year manufacturing capacity the following will be required:

(a) Tubular design: 4 million SOFC generator tubes.

(b) Planar design: 2 million SOFC generator plates.

(c) Monolithic design: 750 000 SOFC plates.

The active surface area for a 200 MW plant will be in the order of 50 - 80 000 m² and this will represent in bulk raw materials weight for the tubular design:

(a) CaZrO₂ ~ 500 000 kg.

(b) Y and Zr chlorides ~ 50 000 kg.

(c) NiO ~ 50 000 kg.

(d) SrLaMnO₃ ~ 200 000 kg.

(e) SrLaCrO₃ ~ 100 000 kg.

For the monolithic design the weights of the raw materials will be somewhat lower, namely:

(a) Y.ZrO₂ ~ 170 000 kg.

(b) SrLaMnO₃ ~ 100 000 kg.

(c) SrLaCrO₃ ~ 50 000 kg.

(d) NiO ~ 50 000 kg.

(e) Organics ~ 100 000 kg.

These material requirements are three orders of magnitude greater than the present day capacity 'prepared' on the 1 - 10 kg scale, to fit the SOFC fabricators specifications. The consistency and reproducibility from lot to lot, and batch to batch is well below the standards required for large-scale production. This is forcing the developmental technologist to change the process to fit the raw materials. This is a dangerous situation of a 'moving' target-moving platform which for the production quality assurance manager is a veritable nightmare. The next stage in the development of the SOFC technology will possibly be in the direction of requiring the SOFC fabricator to perform critical path analysis on each of the components, their fabrication process and their raw materials. This is to detect, prior to the decision point of commercialization, weak areas in the system, the process, or stages within the process which when viewed against a backcloth of present day technology are incapable of scale-up.

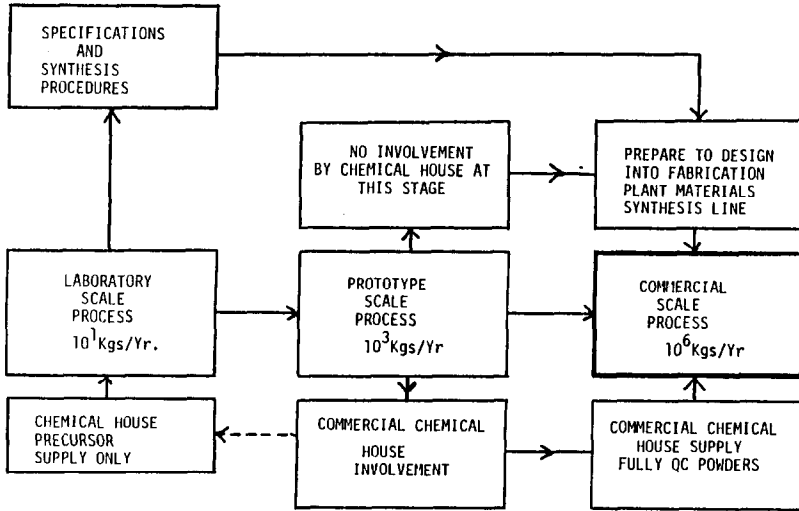


Fig. 9. Schematic illustration of the development of a solid oxide fuel cell commercial source supply of raw materials based upon a quality control dominated fabrication process.

Possible solutions to the variable source starting materials will lie in achieving a good working relationship with a commercial chemical house at the earliest possible time in the experimental programme (Fig. 9). In the development of a preparative or fabrication process, large temperature/time/pressure coefficients of reaction should be avoided, *i.e.* do not base a technology on a process with a control of ± 2 at 500°C for 15+ min. These values will invariably create either a very expensive product or a variable supply. It is essential to develop a fabrication procedure with built in fail-safe quality assurance staging points which will prevent a "bad" component progressing up a fabrication line undetected. The cumulative worth of a SOFC component as it progresses through the process increases exponentially. The worth of a monolithic SOFC 50 kW stack changes from less than \$1000 worth of raw materials to about \$20 000 after sintering. One single layer within the stack can fail the entire stack.

A detailed evaluation of the manufacturing flow charts should include a lookout for a 'material virus' — a component, part, source or design which when 'injected' into a system can cause profound damage at a later and invariably a critical point. The virus can be subtle in that it will not affect the component in which it is in, but will fail or cause deterioration in another. An example of a potential material virus would be the poor control of the manganese stoichiometry in the air electrode mix. Through the fabrication and operation of a fuel cell, the cathode may perform well, yet the excess manganese could migrate to the electrolyte and cause an internal electronic short.

For the future SOFC ceramicist the following are areas of possible interest within the preparation and synthesis of SOFC materials, which over the next decade are worth paying attention to for their influence on scale-up:

- (a) Mixed oxide powders by new polymeric precursors.
- (b) Mixed cation sol-gel synthesis.
- (c) EVD and CVD plasma and laser assisted processing.
- (d) Microwave processing of the precursor and raw materials.
- (e) Microwave processing throughout the entire ceramic stages.
- (f) Ultra-fine colloidal particle research and the colloidal mill nanophase material.
- (g) High intensity ultrasonics in preparative processes.
- (h) High intensity and high speed water jets.
- (i) Fluidized bed-microwave processing of microspheres.
- (j) Explosive or supercritical drying or precipitation processes.
- (k) Emulsion ion-exchange co-precipitation of mixed cations.
- (l) Controlled precipitation from organic and mixed solvents.
- (m) Compositional and stoichiometric inhomogeneity control.
- (n) Advances in tape casting and calender rolling of thin films.

Of these, the microwave treatment of ceramics will probably have the most profound and significant impact on the entire ceramic research and development technology and the ceramic industry in general from the refinement of the raw materials to the end product. This is an area to be carefully watched over the next decade.

The ceramicist-developer-fabricator has now, and into the 90s, an impressive number of analytical and preparative tools of the trade which can be applied to monitor the entire materials processing and the analysis of the process. Many of the tools are 'real time' quality control systems which provide instant feedback to the plant operator of the conditions and in some devices potential problems within the process. The next stage in the SOFC for the fabricator will be to assess the process analytics available to the process and to apply these in a prudent fashion and frequency to achieve that six sigma state within the SOFC development.

SOFC have a tremendous future in their ability to generate clean and efficient power and their capability of adaption for large-scale power generation by modular design and by microgeneration using down sized modules. At this time the SOFC electrochemistry is reasonably well understood; the materials of choice are in the process of final screening for the next jump; the next stage in the material science of the SOFC will be to increase the volume of these materials to the prototype and then to the commercial level.

For the SOFC corporate organizations however, fuel cell technology may follow in the same path of two sister technologies, namely those of semiconductors and superconductors, with respect to the hi-tech maxim: 'They who control the materials control the technology'.