MANUFACTURING COSTS FOR PLANAR SOLID OXIDE FUEL CELLS

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ABSTRACT

In this paper we calculate how much one can afford to pay for a fuel cell, and set quantitative performance and cost targets that if met, will result in SOFC technology where the performance is high enough and the cost is low enough to generate commercial interest. To do this, we first calculate how much one can afford to pay for a fuel cell stack in two important applications: small scale cogeneration (200 kW_e) and large scale power generation (50 MW_e). We then compare the cost of the materials needed to fabricate the fuel cell with the allowable cost. Finally, we use a mathematical model of fuel cell performance to quantify some of the improvements that will be needed if planar fuel cells are to operate efficiently at 800°C or below.

INTRODUCTION

The materials, designs, and operating temperatures of solid oxide fuel cells (SOFCs) have evolved together over several decades of research. Because of the need to minimize ohmic losses through the yttria stabilized zirconia (YSZ) electrolyte as well as the need for high reaction rates at the electrodes (especially the air cathode), current SOFC designs are generally operated at approximately 1000°C.

However, the use of high operating temperatures creates a number of problems, including maintenance of gas tight seals, voltage degradation due to electrode sintering and interfacial reactions, mechanical stresses arising from differential shrinkage or thermal expansion, and difficulties in producing large stacks. Although these problems have been solved by appropriate selection of materials and fabrication techniques, the result is that the capital cost of current designs is too high for SOFCs to be commercially attractive.

In order to reduce fuel cell costs, the Gas Research Institute (GRI) program of
fundamental research on SOFCs is directed at two main areas, reduced temperature operation and the fabrication of planar cells. Reduced temperature operation facilitates the use of metal interconnects, which greatly reduces the cost of materials, while planar designs have lower ohmic losses, increased energy density (reducing both materials and fabrication costs per kW), and allows the use of lower cost fabrication methods. However, in order to achieve high power densities at low operating temperatures, research is needed to decrease voltage losses due to both electrolyte resistance and electrode overpotentials. In addition, planar cells will require the development of high temperature gas tight seals.

The objective of this paper is to determine how much one can afford to pay for a fuel cell, and to set quantitative performance and cost targets that if met, will result in SOFC technology where the performance is high enough and the cost is low enough to generate commercial interest. To do this, we first calculate how much one can afford to pay for a fuel cell stack in two important applications: small scale cogeneration (200 kWc) and large scale power generation (50 MWc). We then compare the cost of the materials needed to fabricate the fuel cell with the allowable cost. Finally, we use a mathematical model of the performance of a fuel cell to quantify some of the improvements that will be needed if planar fuel cells are to operate efficiently at 800°C or below.

ALLOWABLE SOFC STACK COSTS

We calculated the allowable cost for the SOFC stack in two applications, small scale cogeneration and large scale power generation. In order to determine the allowable cost, we assume that the cost of electricity produced by the fuel cell must be equal to or less than the cost produced by the most competitive current technology.

For the small scale cogeneration case, we assume that the application is a building or commercial site served by a 200 kW generating unit, and that the competitive technology is driven by a reciprocating engine. To make the comparison as clear as possible, we assume that the site can utilize all of the thermal energy produced by the generators, and that the cost of producing the heat as well as the value of the heat are equal in both cases (although both the cost of producing the heat and the quantity of heat produced will be slightly greater in the case of the less efficient engine driven system). We also assume that the fuel is natural gas at $4.00/MMBtu, that the overall electrical engine efficiency is 32%, and the overall electrical efficiency of the SOFC system is 40%. The analysis was carried out using the EPRI methodology (1) and a capital recovery factor of 20%. We analyzed two cases, one where the capital cost of the engine was $1344/kWc (typical of current systems) and an advanced case where the engine system cost was $640/kWc (an estimate of what can be achieved in the future with standardized construction and reduced installation costs) (2).
For the current technology co-generation case, the cost of power produced by the engine is the sum of the fuel costs (4.3¢/kwhr), the operating and maintenance costs (0.7¢/kwhr) and the levelized capital costs (3.2¢/kwhr), for a total of 8.2¢/kwhr. This must also be equal to the sum of the fuel costs, O&M costs, and levelized capital costs for the Balance of Plant (BOP) and stack for the SOFC. Because of the higher efficiency of the fuel cell system, the fuel costs are lower (3.4¢/kwhr). Additionally, the O&M costs are lower as well (0.5¢/kwhr). Taking the capital investment for the fuel cell BOP as $975/kW<sub>e</sub> (2.3¢/kwhr), we find (by subtraction) that we can afford 2.0¢/kwhr for the SOFC stack. This translates into an allowable capital cost of $820/kW<sub>e</sub>. This number is a strong function of the difference in efficiency between the fuel cell and the engine drops to $620/kW<sub>e</sub> for a SOFC efficiency of 35%. If we assume that the capital cost of the installed engine system is reduced to $640/kW<sub>e</sub> the competition is more difficult, and the allowable SOFC stack costs are much lower ($120/kW<sub>e</sub> for a 40% SOFC efficiency).

The range of allowable stack costs is shown as a function of SOFC efficiency and the capital cost of the engine system in (Figure I).

We carried out a similar analysis for the case where the SOFC system would compete with an advanced aero-derivative gas turbine for large scale power production. In this case, we took the turbine efficiency and installed capital cost as 37% and $637. The capital recovery factor was 0.105 (lower than in the previous case to reflect utility financing). In this case, the allowable cost of the SOFC stack at an SOFC efficiency of 40% is $154/kW<sub>e</sub>. The allowable cost increases to essentially linearly with SOFC efficiency, reaching $392/kW<sub>e</sub> at an efficiency of 50%. In summary, we see that for the assumptions and applications evaluated, the allowable SOFC stack costs for future systems is on the order of $120 to $400/kW<sub>e</sub>.

**COST OF MATERIALS**

It is instructive to compare the allowable stack costs with the cost of the materials needed to make the cell (Table I). To carry out these calculations we assumed a power density of 3 kW/m² (400 mA/cm² at 0.75V), somewhat better than is now generally achieved by planar cells. The thickness of cell components was: cathode=70μm, electrolyte=200μm, anode 50μm, and interconnect=5,000 μm. The critical assumption is that we have a thick interconnect in order to provide low pressure drop passages for the flows of the air and fuel. This thick interconnect would be typical of that found in a large planar cell (0.25 to 1.0 m²) operating at 1.5 to 3.0 kW/m². Lower power densities and lower cell areas could use thinner interconnects. However, since interconnect thicknesses of 1,500μm are used even in today’s small 0.01m² planar cells that operate at low current densities (1.5kW/m²), the conclusions drawn below are robust.

We see that materials costs are dominated by the cost of the interconnect. This
Table I  Materials cost for the "base-case" cell. Operation at 1000°C, 4 kA/m², 3 kW/m²

| Element   | Thickness (µm) | Material | $/kg  | $/kw  | $/kw  |
|-----------|----------------|----------|-------|-------|-------|
| Cathode   | 70             | LSM      | $75.00| $6.50 | $6.50 |
| Electrolyte| 200            | YSZ     | $50.00| $17.50| $17.50|
| Anode     | 50             | Ni/YSZ  | $36.00| $2.70 | $2.70 |
| Interconnect | 5,000 (60% open)| LSC | $75.00| $293.50|       |
|           | 5,000 (90% open)| Ni      | $10.00|       | $14.80|
| Total     |                |          | $320.20| $41.50|       |

is not because the interconnect material costs that much more than other materials, but because more material is required to provide the area needed for the flow passages. While the interconnect cost could be somewhat reduced in small cells where only small flow paths are necessary, the conclusion is that if a ceramic material is used to provide the structural support and flow passages for the air and fuel, the cost of that component (cathode, anode, or interconnect) will dominate the cost of materials.

It is also instructive to compare the cost of materials with the allowable cost of the fuel cell stack (Figure II). We see if the SOFC must compete with gas turbines or future engine driven cogeneration systems, the cost of the stack using a ceramic interconnect is greater than the allowable cost except for very high power densities. Even if the thickness of the ceramic interconnect were reduced by two thirds, the materials cost alone (no fabrication costs included) would be greater than the allowable cost for power densities of up to 3 kW/m². Thus, it is obviously desirable to fabricate the interconnect from a metal (since the cost of high alloy metals is on the order of $10/kg, or 15% that of electronic ceramics).

RESEARCH NEEDS FOR REDUCED TEMPERATURE SOFCs

To quantitatively assess the improvements needed in electrolyte and cathode performance, we modeled the performance of an all-ceramic, planar SOFC. The model was a modified version of the PEN circuit analysis of Bossel (3). The model accounts for losses due to contact resistances, polarization, and ohmic losses in the Positive electrode (cathode), Electrolyte and Negative electrode (anode) (PEN) and interconnect. The model uses standard values for the resistivities of a LSM (La₀.₈₄Sr₀.₁₆MnO₃) cathode, YSZ (ZrO₂)₀.₉₂(Y₂O₃)₀.₀₈ electrolyte, nickel-zirconia cermet (Ni₀.₃₅/YSZ₀.₆₅) anode, and LSC (La₀.₈₄Sr₀.₁₆CrO₃) interconnect. Polarization resistance is 0.5 Ω cm² at 800°C, with an activation energy of 25 kcal/mole. The base case fuel cell analyzed was a cross flow design with a 70 µm thick cathode, 200 µm electrolyte, and a 50 µm anode. The
interconnect provides separate flow passages for both air and fuel, and is 5 mm thick with an open area of 60%. The rib to rib spacing on the interconnect is 5 mm and the ribs are 1 mm wide. This is a "typical" all ceramic planar SOFC design, but does not correspond exactly to the current design of any of the major fuel cell developers. The electrolyte provides the structural support for the trilayer, and has a thickness typical of that produced by tape casting techniques. The interconnect is perhaps somewhat thicker than necessary for current stacks in which the area of an individual cell is less than 500 cm², but typical of that which will be necessary if larger, more economical cells are to be fabricated. The polarization resistance is state of the art for a LSM/YSZ/Ni trilayer.

The voltage losses of the model cell are shown as a function of temperature in Figure III. We see that the voltage losses due to the interconnect, contact resistance and in-plane IR drop are small (approximately 0.1 V total) and independent of temperature. However, the voltage losses due to cross plane resistance (which is dominated by the IR drop through the YSZ electrolyte) and polarization increase rapidly as the temperature is lowered. At 800°C the maximum power density of this cell is quite low (1.64 kW/m²).

Obviously, if we wish to operate a planar SOFC at temperatures on the order of 850°C or lower, we must lower the resistance of the electrolyte. This can be accomplished either by decreasing the thickness of the electrolyte or substituting an electrolyte with lower resistivity. A factor of 10 reduction in either the thickness or resistivity from those assumed in the base-case design is enough to reduce electrolyte IR losses to negligible amounts at all temperatures above 700°C (Figure IV). Since there is little impact on performance once the electrolyte is thinner than 20 μm, the choice of thin film fabrication techniques can be based on cost and performance instead of the ability to fabricate even thinner films. Likewise, the conductivities of alternative electrolytes such as stabilized bismuth oxide (Bi₂O₃) and doped ceria (CeO₂) are sufficient to reduce the electrolyte resistance to negligible amounts at temperatures above 700°C (4).

GRI is currently funding research on both thin film electrolyte fabrication methods and alternative electrolytes. Allied-Signal is using a tape calendering process to produce YSZ 1-10 μm layers of YSZ on a Ni/YSZ cermet anode. Northwestern University is using reactive magnetron sputtering to prepare 12 μm layers of YSZ and the University of Missouri-Rolla is preparing thin electrolyte layers from polymer precursors. Higher conductivity electrolyte systems are being developed by Ceramatec/U. Utah and SRI International. Ceramatec/U. Utah is developing YSZ clad ceria as a thick but highly conductive electrolyte, and a proprietary electrolyte is being developed at SRI.

If the resistance of the electrolyte is sufficiently reduced, electrode polarization (primarily due to oxygen reduction at the cathode) becomes limiting. If we wish to operate a cell with high current density (3 kW/m²) at 800°C, a factor of 4 reduction in
the interfacial resistance is required. If the goal is to operate at temperatures below 800°C, at least a factor of 10 reduction in interfacial resistance is needed.

The University of Missouri-Rolla has developed techniques for preparing thin film La-Sr-Co-Fe cathodes on YSZ and ceria. These electrode materials have interfacial resistances 1 to 2 orders of magnitude lower than LSM/YSZ. The University of Pennsylvania is using mixed conducting titanium doped YSZ as the anode and terbium doped YSZ as the cathode of an all zirconia fuel cell. The use of mixed conducting phases as electrodes increases the area available for the electrochemical reactions, while the use of zirconia based ceramics for all of the components of the trilayer reduce the problems of materials compatibility and differential thermal expansion. Northwestern University is investigating the sputter deposition of sub micron catalytic layers at the electrode-electrolyte interface to reduce polarization losses. All of these methods have been shown to significantly reduce the interfacial resistance and overpotential.

The overall cell performance as a function of current density at 800°C and 1000°C is shown in Figure V for the cell with improved electrode and electrolyte performance. We see that at 800°C the maximum power density is 5.8 kW/m², three and a half times that of the base case design.

This study illustrates that order of magnitude improvements in performance can potentially be achieved by reducing electrolyte and overpotential losses. For constant fabrication costs (in $/m²), the improvement in power density translates directly into reduced capital costs. However, the uncertainties in the analysis must be kept in mind. As the resistances that are dominant in the base-case are reduced, processes that are neglected in the model such as mass transfer and reforming kinetics (if internal reforming is used) become relatively more important. Additionally, although polarization losses occur at both the cathode and anode, work in progress addresses primarily improvements in the cathode. As cathode losses are reduced, anode kinetics may become rate limiting. Thus, as in any parametric modeling exercise, the model becomes less accurate as the design departs from the base case for which the model was developed. However, the magnitude of the effects modeled and the conclusions drawn are relatively insensitive to the limitations of the model.

The modeling effort shows that research underway has the potential to significantly improve the power density (and hence cost) of intermediate temperature planar SOFCs. Therefore, as these features are incorporated into cells and cell stacks, the major issue will become achieving stack performance that is proportional to single cell performance (stack design and fabrication).
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Figure I  Allowable stack cost as a function of SOFC efficiency for various competing engines.
Figure II  Costs as a function of power density. The horizontal lines correspond to material costs, the sloped lines correspond to allowable total costs for the three competing engines.

Figure III  Performance of the model planar ceramic SOFC as a function of temperature at a current density of 4 kA/m².
Figure IV  Performance of the model planar SOFC as a function of temperature with the electrolyte thickness reduced to 20 μm. (230 μm anode, 50 μm anode, current density = 4 kA/m²)

Figure V  Improved cell performance as a function of current density (electrolyte IR losses decreased by a factor of ten and electrode interfacial resistances decreased by a factor of 4) over base case.