A Process Based Cost Model for Multi-Layer Ceramic Manufacturing of Solid Oxide Fuel Cells

By

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I would also like to thank Heather Benson-Woodward for her initial work to create the model structure and for her help with reference materials, periodic program updates and guidance throughout the project.

Lastly, I need to acknowledge and thank my family and friends who have always supported and sometimes nudged, or nagged, me through this odyssey.

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THESIS ORGANIZATION

A project to investigate high volume manufacturing scenarios for planar solid oxide fuel cells was started in part to understand the cost relationships in the absence of real world experience. This effort to build a cost model was initiated during a course at the Massachusetts Institute of Technology in 2001 and resulted in the development of two theses. One, Benson thesis, focused on the relationships of cell performance parameters, in terms of power density and operating temperature, to cost. The other, Koslowske thesis, focused on the evolution of the process based cost model to relate manufacturing issues (volume, yield, process choice) to cost. Figure A shows the diagram of the cost model and its three parts: a performance model, a process tolerance model and a process based cost model.

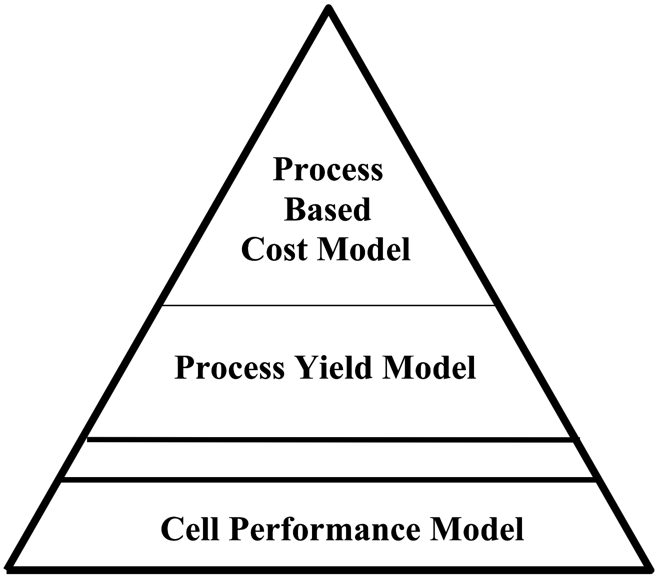


figure A.

In the first thesis, the cost model structure was created by Heather Benson-Woodward. The cell performance model calculates the electrolyte layer thickness and thickness tolerance based on cell performance targets of power density and operating temperature. A process tolerance model, incorporated into the process based cost model, determines materials losses based on layer thickness targets and tolerances compared to the capability of the layer forming method to achieve the required thicknesses. The results from this project were presented at the 2002 MRS meeting in Boston, MA. The corresponding paper, ‘A Performance Based, Multi-Process Cost Model for Solid Oxide Fuel Cells”, is presented as the second part of this thesis.

The first part of this thesis is a paper titled “A Process Based Cost Model for Multi-Layer Ceramic Manufacturing of Solid Oxide Fuel Cells” which presents a process based cost model to generate manufacturing cost data. Analysis of the cost data is framed by strategic manufacturing parameters. The development and evolution of this cost model into a robust analysis tool was the goal of this project. The content will be submitted to the Journal of Power Sources and to The Bulletin of the American Ceramic Society for publication.

A Process Based Cost Model for Multi-Layer Ceramic Manufacturing of Solid Oxide Fuel Cells

ABSTRACT

Planar Solid Oxide Fuel Cell (SOFC) manufacturing can be considered in the pilot plant stage with efforts driving towards large volume manufacturing. The science of the solid oxide fuel cell is advancing rapidly to expand the knowledge base and use of material combinations and layer forming methods for the unit cell. Few of the many processing methods, > 15, reported in literature for layer formation are used today in high volume manufacturing. For this reason it is difficult to establish future market demand and cost levels needed to plan a course of action. The need to select amongst different designs, materials and processes will require a robust tool to identify key trends in the various process combinations and manufacturing variables prior to making strategic investment decisions. The ability to accurately forecast investment requirements and manufacturing cost for a given high volume manufacturing (HVM) process based on expected volume is critical for strategic decisions, product placement and investor communications.

This paper describes the use of an updated process based cost model that permits the comparison of manufacturing cost data for various process combinations, production volumes, and electrolyte layer thickness values. The effects of process yield and

thickness tolerance are addressed. Processing methods discussed include tape casting, screen printing and sputtering.

INTRODUCTION

The success of solid oxide fuel cell (SOFC) technology depends on producing a cost competitive product within performance specifications that match or exceed those of other alternative energy sources. The application of a process based cost model to asses design and manufacturing variables will be an important tool for strategic decision making in the rapidly evolving effort to mass commercialize fuel cells as a competitive alternative energy source. Solid oxide fuel cells have been manufactured and successfully tested with two different cell configurations, tubular and planar. For this paper, only the planar solid oxide cell geometry will be addressed. Two planar cell architectures include anode and electrolyte supported unit cells. Based on patent applications and grants, the most established Anode-Electrolyte-Cathode (A-E-C) material combinations are yttria stabilized zirconia (YSZ) for the electrolyte, Nickel cermet (NiO-YSZ) for the anode and lanthanum strontium magnesium (LSM) for the cathode [1]. YSZ is the widely accepted standard electrolyte material, but research is being carried out to find replacement materials, such as gadolinium doped cerium oxide (GDC) and Scandia stabilized zirconia (SSZ), that offer the benefit of higher power output at lower temperatures [2]. The cell performance requirements of power density and operating temperature are directly linked to the electrolyte layer thickness, which in turn will affect the process cost.

High operating temperatures, resulting in increased costs to seal and operate the cell, have hampered planar SOFC commercialization [3]. At high cell operating temperatures the interconnect material is a ceramic, namely lanthanum chromate, which is expensive and difficult to manufacture. Operating temperatures in the first generation prototype SOFC generators were greater than 1000°C. The reduction of the cell operating temperature will allow use of less-costly materials for cell interconnect and system components [2,3,4]. One approach to lower operation temperature uses a reduced electrolyte layer thickness between 5-10 μm [5]. With the advances in lowering the cell operating temperature, the expensive ceramic lanthanum chromate interconnect is being replaced with Cr-alloys for cells that operate between 800 and 1000°C, and with ferritic steels for temperature ranges 600 and 750°C [3]. A tool that addresses the cost difference of the unit cell based on changing dimensional requirements is important to compare the various options and provide direction to meet future cost and performance criteria.

It is recognized that the interconnect and sealing materials and their corresponding process steps are a significant part of the full cell unit cell and stack costs. However, in this paper the interconnect and sealing costs are not addressed. One cost estimate indicates the possibility of an 85% reduction in material cost per kilowatt by replacing the ceramic interconnects with stainless steel [6]. For this analysis, it is assumed that the interconnect will be between 40 and 50% of the fuel cell stack cost [7].

The Solid State Energy Conversion Alliance (SECA) was formed under the Department of Energy to coordinate the development and commercialization of low cost solid oxide fuel cells for Defense, Transportation and Stationary Power applications.

Within this structure, the partners and their subcontractors are required to provide current cost estimates. Long-range performance and pricing targets within the SECA program call for the cost of a fuel cell generator of 3 to 10 kW to be at the $400/kW level by the year 2010. Table 1 shows the timeline and cost targets for the SECA program. [6] Ceramic cost, A-E-C, is calculated for a cell with ceramic interconnects using the assumption that a stack is approximately 30% of the total SOFC plant cost. The interconnects and balance of stack items are taken to be 60% of the stack cost in this analysis.

The question of standardization is addressed by the call for a uniform core SOFC stack module with size and power requirements. The modules will have dimensions of area (4 by 4 inches) and length (12 inches), and will be capable of delivering 5 kW of power [8]. When necessary, modules can be combined to fulfill higher power requirements.

Table 1. SECA cost targets for stationary power SOFC generators. [6]

Target year	2005	2008	2010
Power Rating (kW)	3 – 10	3 - 10	3 – 10
Cost / kW	$ 800.00	$ 600.00	$ 400.00
Ceramic cost / kW	$ 105.60	$ 79.20	$ 52.80

Previously published cost estimates have been provided by Arthur D. Little [7]. The results from the Monte Carlo analysis have been useful in comparing one or two process variables, but lack the power for strategic analysis and forecasting. Results are used in this paper as a comparison.

COST MODEL

A process-based cost model (PBCM) was created to compare mutli-layer ceramic manufacturing methods for a planar SOFC cell to costs associated with the fabrication. [9,10] The structure of this PBCM is designed to compare cost information between process combinations for a complete cell or individual layers. Materials and process information are used to build up the manufacturing cost for the specific SOFC cell design. Traditionally, cells have been processed by a combination of established 'wet' film techniques, such as tape casting or screen printing. Considerations of semiconductor processing, such as sputtering, are also investigated.

It is the goal of this work to use available research data to integrate multiple manufacturing process capabilities into a single cost model enabling accurate prediction of costs, both per piece and per kilowatt, as a function of cell characteristics, layer forming process and production volume prior to major equipment-based capital investment. It is expected that the model will evolve with the availability of further data and aggregate manufacturing experience.

Processing steps include, but are not limited to: slurry preparation, film deposition, sintering (batch or continuous), testing and waste disposal. The price of materials is dependent on the maturity of the market (demand) and capacity (supply) factors. The material price is shown in Table 2 and is kept constant. Process yield is dependent on layer thickness and process method and can greatly influence the final part cost. A process tolerance model was created to determine process capability as a function of layer thickness [9].

Input variables for each layer include: material, process, layer thickness and thickness tolerance. The total yearly output of the process, in number of finished cells, is the last required input.

The cost output is presented on a unit cell and yearly basis. The unit cell cost breakdown consists of both variable and fixed cost output. Variable costs include 1) material cost, including scrap, 2) direct process energy cost and 3) direct labor cost. Fixed costs are shown as 1) equipment cost, yearly payment, 2) maintenance cost, 3) building cost and 4) fixed overhead. The initial power density requirement is used to calculate a ceramic cost per kilowatt for the capacity of the process.

METHODOLOGY

The unit cell design for this paper will be an anode supported cell, including only the ceramic anode-electrolyte-cathode layers. The unit cell area is 10cm by 10cm (4 by 4 inches) in keeping with the SECA guidelines [6,8]. The default anode layer consists of a fixed 1 mm thick Ni-cermet layer formed by tape casting, unless stated differently. The electrolyte layer of YSZ is deposited onto the anode by any of the process options. The electrolyte thickness can vary from 5 to 80 μm. The LSM cathode layer is held constant at 50 microns thick, and uses the same process as the electrolyte layer. This paper mainly focuses on anode supported architectures, but a comparison to electrolyte supported cells is made.

The cost model was developed to provide comprehensive cost answers to strategic questions. Cost data in terms of unit cell or kilowatt output will be discussed for the following process variables:

1) Production volume from a low to high range of 20,000 to 700,00 units per year. This covers a range of between 300 and 12,000 fuel cell stacks assuming a 5 kW stack with a power density of 0.85 W/cm².
2) Electrolyte layer thickness, from 5 to 80 microns.
3) Process yield as function of layer thickness and forming method at the 5% and 10% levels.
4) Comparison to SECA 2010 cost target.
5) Cell support mechanisms, anode vs. electrolyte

VALIDATION:

Currently there is limited access to accurate cost data for high volume manufacturing of solid oxide fuel cells. During the initial validation phase for the process based cost model, outputs have been compared to published cost estimates [6,7] for solid oxide fuel cells. Accuracy of cost data is generally accepted to be +/- 50%, 30% and 10% for initial, proto-type and mature process cost estimates respectively [11].

A partial list of the assumptions used in this cost model and the Arthur D. Little [ADL] cost study are shown in Table 2. The co-sintered process was chosen for comparison in this case. The parameters in bold were run in the PBCM to compare effect of the operational assumptions. It is expected that the constants in red will increase cost and those in blue will decrease cost compared to this study.

Table 2. Parameters for cost model validation.

Parameter	**Cost Model**	**ADL[7]**
Ni Cermet (micron)	700	700
YSZ (micron)	10	10
LSM (micron)	50	50
Production volume (pcs / yr)	5,000,000	5,000,000
Power Density (W/cm²)	0.85	**0.5**
Fuel cell system output (kW)	25	25
Cumulative Process Yield	84%	**70%**
Working Days / yr.	240	**300**
Max. Number of shifts / day	2	**3**
Indirect : Direct Labor Ratio	0.5	**1**
Price, Building Space ($/m²)	1076	**580**
Kiln equipment, $	$ 700,000	**$ 500,000**
Kiln cycle time (hrs)	21	**12**
Kiln labor / machine	1	**0.2**
Tape casting equipment, $	$ 500,000	$300,000
Tape casting labor / machine	0.75	**0.2**

Cost data on a material, cell and kilowatt basis is presented in Table 3 for the cost model, ADL and cost model with ADL assumptions. The material cost as a percentage of total cost is very high, approximately 76%, for the ADL data compared with 22% for this study. The higher ADL material cost could be the result of contingency assumptions that can be as high as 50%. The total cell cost is roughly 70% higher for the process based cost model. Differences in total cost may be the effect of operational assumptions. The process based cost model places more attention on manufacturing considerations, such as equipment and fixed costs. The cost on a kilowatt basis is similar to the ADL value, mainly attributed to the higher power density per cell calculated by the cost model.

Table 3. Comparison cost model output, ADL [7] to PBCM

	ADL	PBCM	PBCM Using ADL assumptions
Mat'l \$ / cell	\$ 2.14	\$ **1.03**	\$ 1.13
Total \$ / cell	\$ **2.80**	\$ 4.74	\$ 4.11
\$ / kW	\$ **56.00**	\$ 60.77	\$ 82.22

The process based model's cost output, with the ADL assumptions listed in Table 2, is within 15% of the original cost model cost output. Material cost is higher due to the lower process yield. The total cost for a unit cell is lower, caused by direct labor allocation and equipment cost benefits due to a three shift operation. The kilowatt cost is higher mainly as the result of the lower power density assumption.

The process based cost output did not closely agree with previous cost estimates, however, the results show that it is important to understand all process and operation assumptions which can significantly influence the cost data.

A second material cost estimate was presented to be \$ 0.86 per cell for a Ni-cermet / YSZ / LSM combination with thickness values of 500, 10 and 50 microns respectively [6]. The process based cost model material cost for the same cell configuration is $ 0.80 per unit cell. This is within 10% and shows that the material cost portion of the model is accurate.

Cost data for a high volume manufactured part, an aluminum oxide plate, was chosen to provide another level of comparison. The comparison of cost output is shown in figure 1. The cost model shows good correlation at high production volumes for this product. At lower production volumes, the assumptions and equipment choices for the process based cost model are not sized correctly for a make to order plant with the low production volume, and therefore have excess capacity.

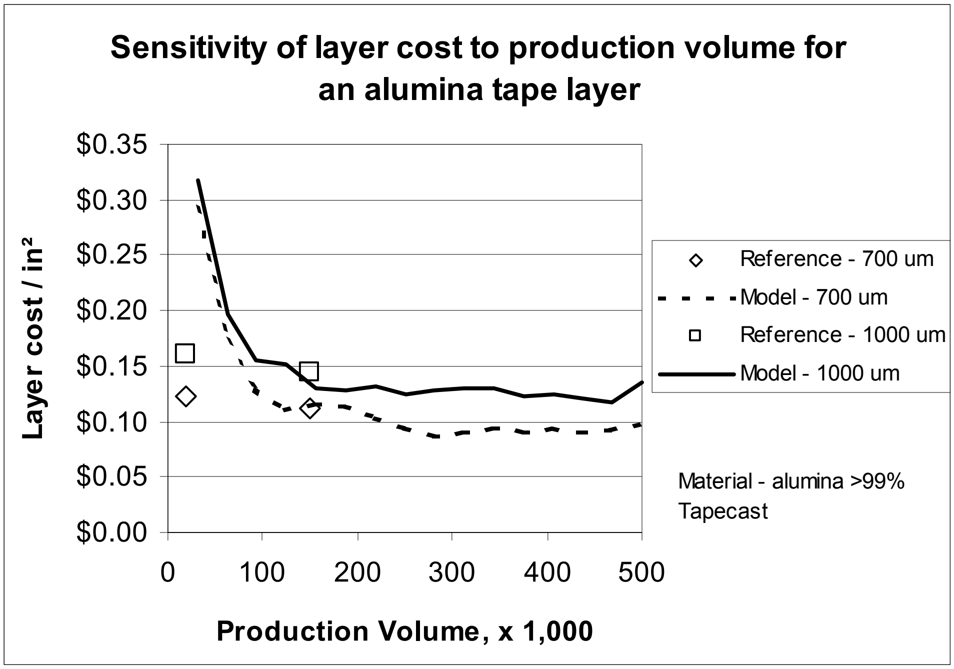


Figure 1. Comparison of cost model output to commercial product.

RESULTS AND DISCUSSION

Single Layer Process Comparison

Process based cost model results for individual layers of electrolyte material (YSZ) for the various process methods have been investigated to identify manufacturing cost trends. Single layer cost sensitivity to production volume and cost breakdown as a function of process are shown in figure 2a,b. As expected, the layer cost decreases with increasing production volume for the tape casting and screen printing processes. The analysis shows that for tape casting and screen printing, the cost advantage is realized quickly with volume increases to around the 200,000 piece per year production level. After this level, small cost gains are made at increasing volumes. The sputtering layer cost does not show a significant cost change, mainly due to the influence of the high equipment cost.

The manufacturing cost breakdown comparison for a 50,000 piece production volume is presented in figure 2b. The direct labor component is the highest percentage of the unit cost for tape casting and screen printing while for sputtering, the equipment cost dominates. The high cost associated with sputtering a thick ceramic layer rules out this process for all but the thinnest layers. Based on this comparison between the processes, one can rank them as tape casting is low cost/high volume, screen printing is low cost/low volume and sputtering is high cost/low volume, but provides a high quality layer.

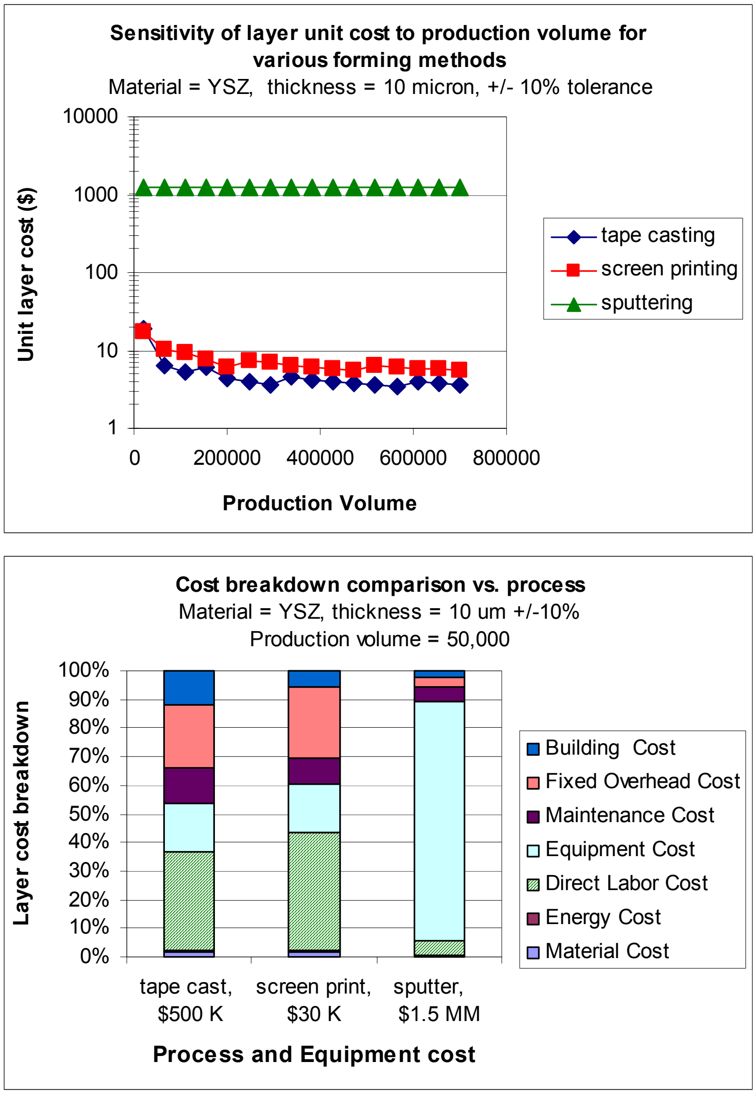
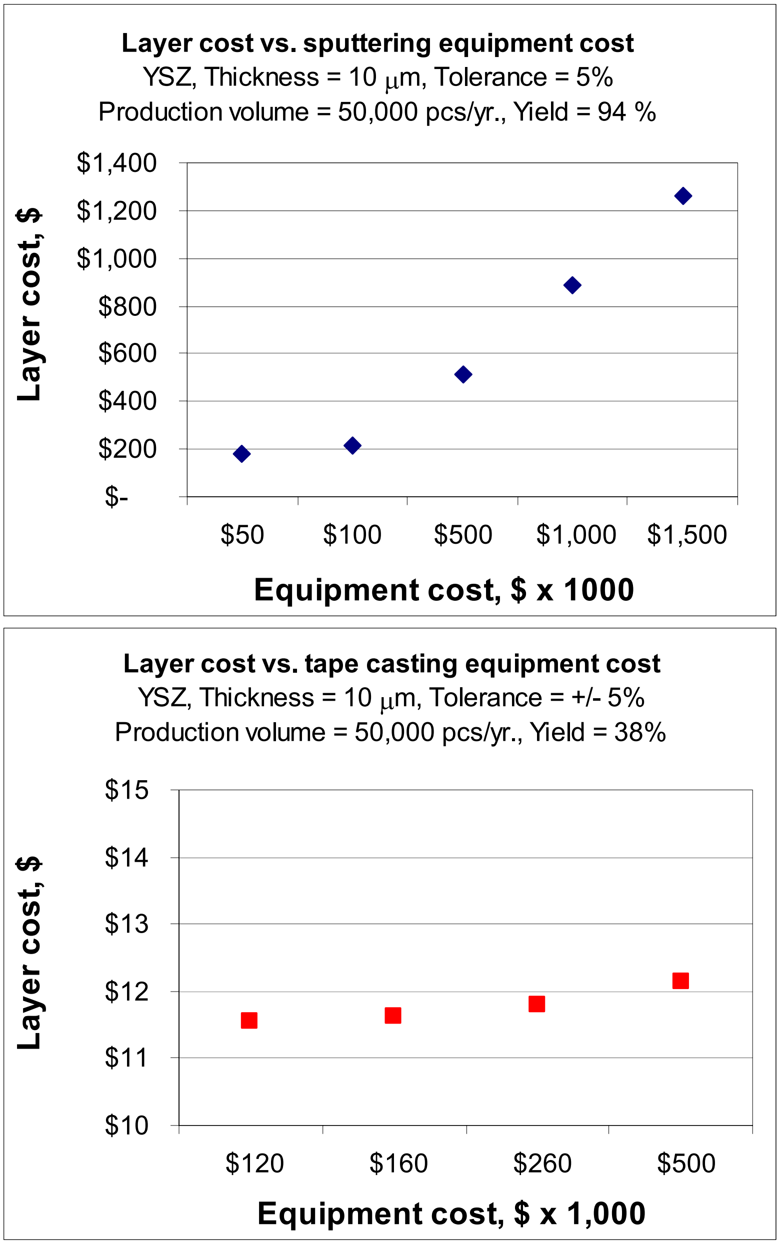


Figure 2a, b: Comparison of single layer cost as function of production volume and process.

There is a range of sputtering equipment prices and capabilities from small manual units to large fully automated semiconductor processing cells. The choice of equipment will depend on layer quality, cell layer thickness and production needs. The effect of equipment cost for sputtering and tape casting is shown in figure 3a,b. As the equipment cost for sputtering is reduced, the layer cost drops significantly. At the 10 micron thickness, a sputtered layer is still significantly higher in cost than the wet



Layer cost vs. sputtering equipment cost
YSZ, Thickness = 10 μm, Tolerance = 5%
Production volume = 50,000 pcs/yr., Yield = 94 %

Layer cost vs. tape casting equipment cost
YSZ, Thickness = 10 μm, Tolerance = +/- 5%
Production volume = 50,000 pcs/yr., Yield = 38%

Figure 3a,b: Layer cost sensitivity to sputtering and tape casting equipment cost.

forming methods, approximately $200 vs. $12. Although it is not shown in this paper, the sputtering process becomes interesting at layer thicknesses of 1-5 microns, where yield and layer quality are paramount.

Process Yield:

As the film thickness for the electrolyte layer decreases, the effect of process yield plays an increasing role. Defects such as pin holes, inclusions and micro-cracks become a serious threat to forming gas tight layers. Operating design requirements, namely power output and temperature tolerances are directly related to the thickness of the electrolyte layer. As layer thickness is reduced, the tolerance band required for performance reasons becomes a hurdle to production. Figure 4 shows the process yield as a function of layer thickness for the processing methods addressed in this paper. There has been no consideration to process maturity or process/equipment adjustments, particularly in the wet forming techniques, which would increase the process yield. The wet forming techniques show a good yield at 80 micron and higher layer thickness. The screen printing process shows better yield due to trim scrap assumptions for the tape cast process. At the layer thickness of interest in the literature, 10 microns, the process yield is very low for the wet techniques. Conversely, the sputtering process is very uniform and consistently shows a high yield. As the tolerance level is increased, both tape casting and screen printing reach an 80% process yield at the 20 micron layer thickness. Figure 5 shows that low yield for thin layers increases the unit cost.

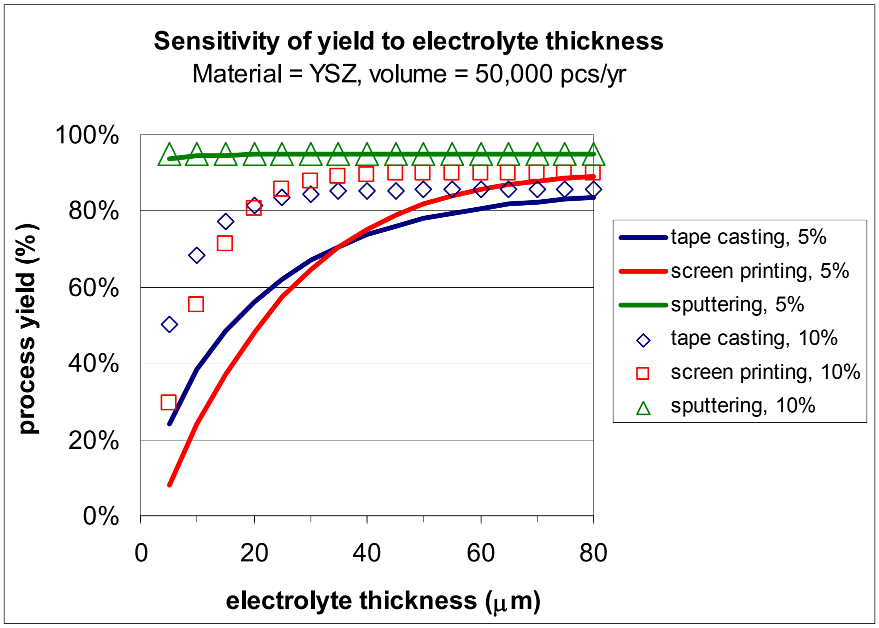


Figure 4. Process yield for various layer forming methods, thickness values, and tolerance levels.

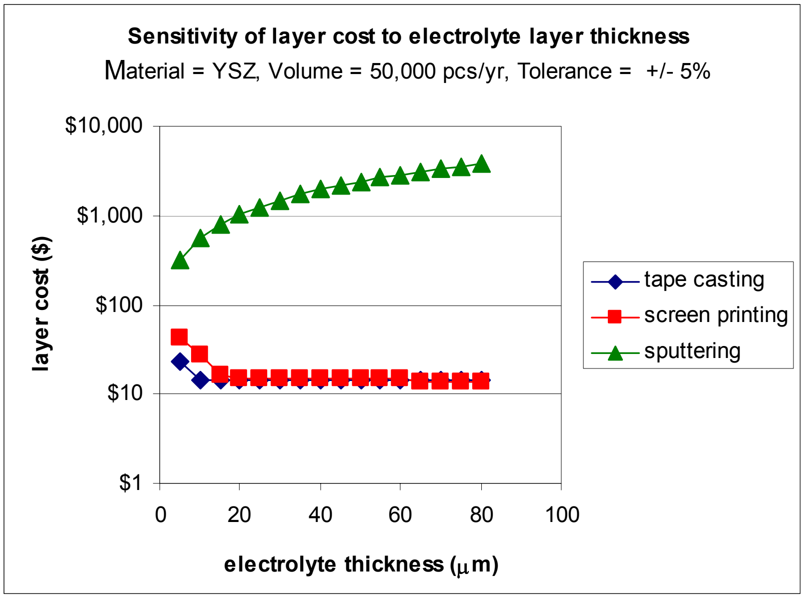


Figure 5. Influence of layer thickness and process on cost.

Multi-layer cell cost comparison

Production volume effects were shown to lower cost for the single layer process. The cost breakdown comparison for low and high production volumes for a multilayer cell are given in figure 6. Increasing production volume reduces the unit cell cost by 50%. Equipment cost and direct labor efficiencies are the two main reasons for the cost reduction.

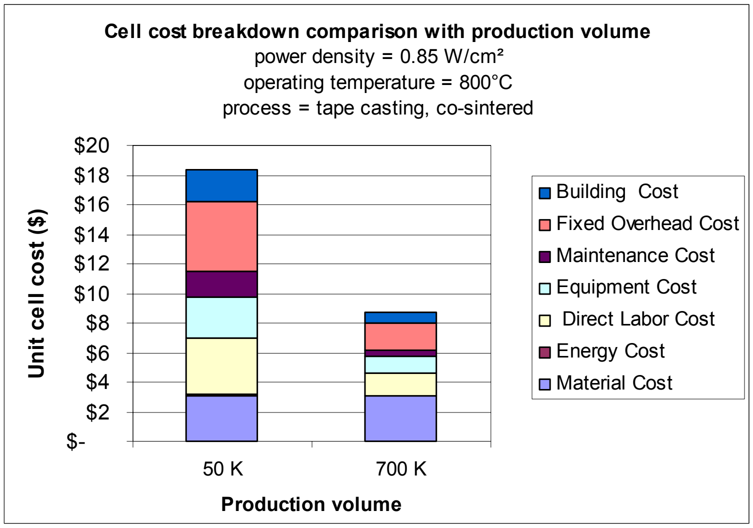


Figure 6. Cost component comparison versus production volume.

The choice of process combination for cell layer formation is an important decision in terms of initial capital outlay determined by equipment capacity reasons. Cost data for several process combinations are presented in figure 7. The tape cast/co-sintered results in the lowest unit cell cost, slightly lower than the tape cast/screen print multi-sintered combination. The sputtering of electrolyte and cathode on a tape cast anode results in the highest cost. It is interesting that the tape cast/sputtering/screen print combination is roughly an order of magnitude higher than the lowest options. This indicates that sputtering is higher in cost, but the material quality requirements may dictate that this process is used. Also, very thin electrolytes, less than 5 microns, make the sputtering option more viable.

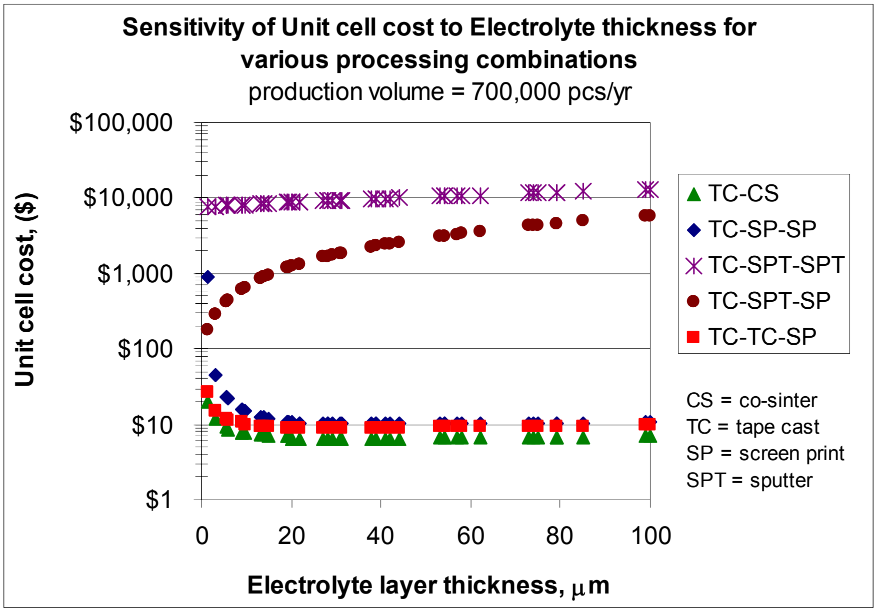
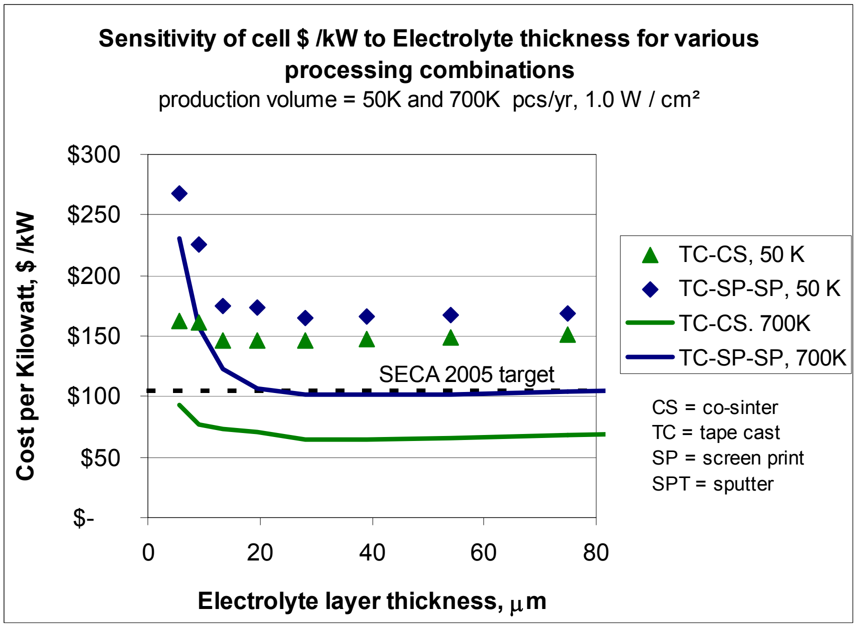


Figure 7. Unit cell cost comparison between various process combinations.

<u>Cost Comparison to SECA target:</u>

Cost per kilowatt data compared to the 2005 SECA target is presented in figure 8 for a tape cast, co-sintered and tape cast-screen print-screen print process combinations.



Two production volumes, 50,000 and 700,000 pieces per year, are also compared. The low production volume cannot meet the SECA cost target. High production volume will reduce cost substantially to meet the cost target for cell designs with electrolyte layers of twenty microns and above.

Figure 8 Sensitivity analysis, cost / kW, versus electrolyte thickness for two production volumes and process combinations.

Power Density

Higher power densities, usually correspond to lower electrolyte thickness and lower material cost. Figure 9 shows that the lower unit cell cost correlates to lower material costs as cell power density increases. The trend holds for the kilowatt cost as function of power density as presented in figure 10.

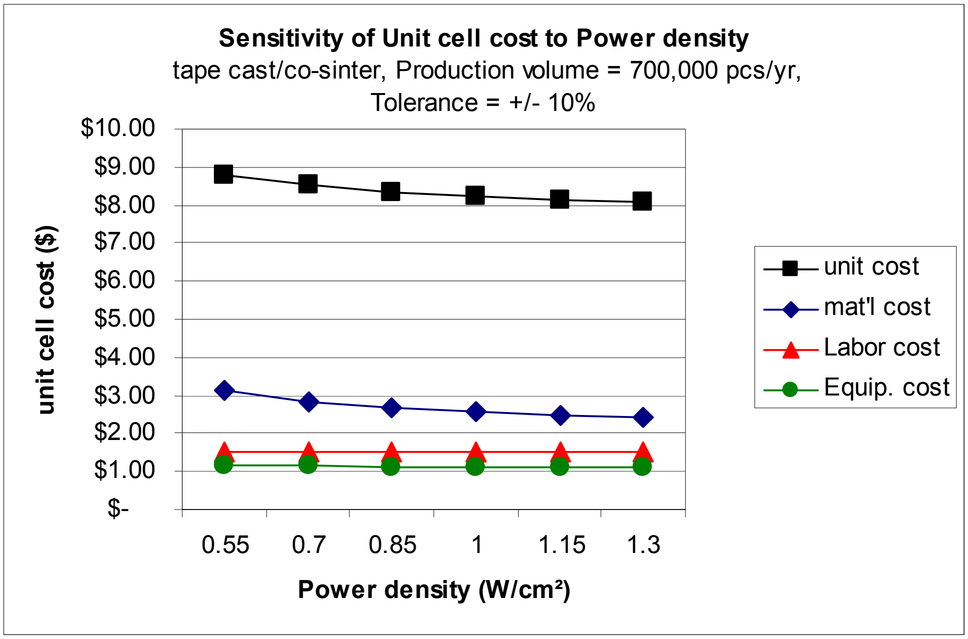


Figure 9.	Sensitivity analysis, cost / kW, versus electrolyte thickness for two production volumes and process combinations.

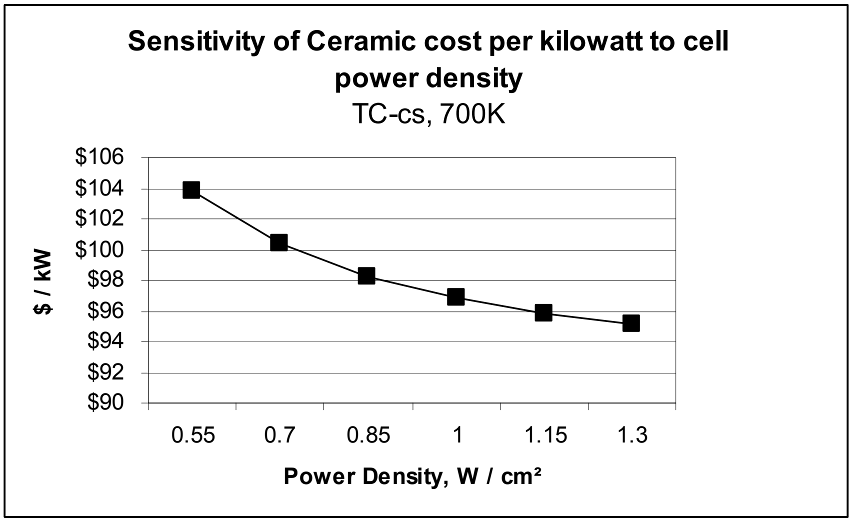


Figure 10. Kilowatt cost per cell power density output.

Anode versus Electrolyte Supported Cells

The first planar SOFC architecture was an electrolyte supported cell in which a thick YSZ layer was used to support the two electrode layers. The question of whether electrolyte supported cells can be cost competitive is investigated. Anode supported cells are currently being developed for cell performance and stack sealing benefits. Figure 11 shows the target thickness for given power densities as function of operation temperature. Lower electrolyte thickness results in lower cell operating temperatures and higher power density values. The shift in performance requirements and the physical material limits of mechanical integrity and microstructure combine to provide a crossover between electrolyte and anode supported geometries. For this study this limit is close to 150 microns. The performance differences between an electrolyte supported and an

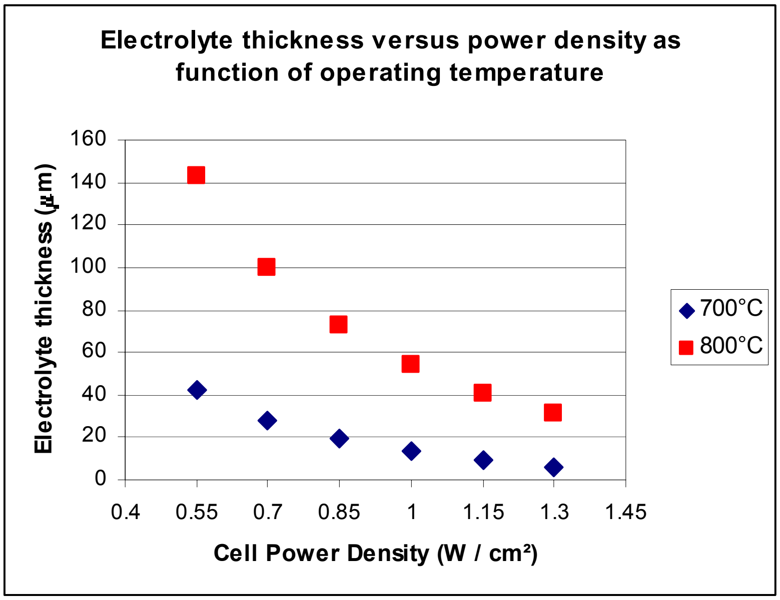


Figure 11. Electrolyte thickness requirement as function of target power density and operating temperature.

anode supported SOFC cell are sufficiently different that one cannot compare the cell geometries directly.

Cell dimensions and cost output for anode and electrolyte supported cells are compared in Table 4. The electrolyte supported cell has a lower unit cell cost as a result of the higher process yield compared to the anode supported cell process. The high yield lowers the direct labor and equipment cost components as shown in figure 12. The material cost per cell is lower for the anode supported cell due to the YSZ layer thickness. This reduced electrolyte thickness results in a higher power density and lower overall cost per kilowatt for the stack, making the anode supported cell design most attractive when considering the entire SOFC plant.

Table 4. Comparison data between anode and electrolyte supported cells.

	Anode supported		Electrolyte supported	
	Process	Thickness (μm)	Process	Thickness (μm)
Anode - Ni Cermet	tape casting	700	screen printing	40
Electrolyte - YSZ	screen printing	10	tape casting	150
Cathode - LSM	screen printing	50	screen printing	20
Unit cell cost	$10.15		**$8.97**	
$/ kW	**$119.83**		$179.49	
Power density (W / cm²)	0.85		0.55	
Operating temp (°C)	650		800	

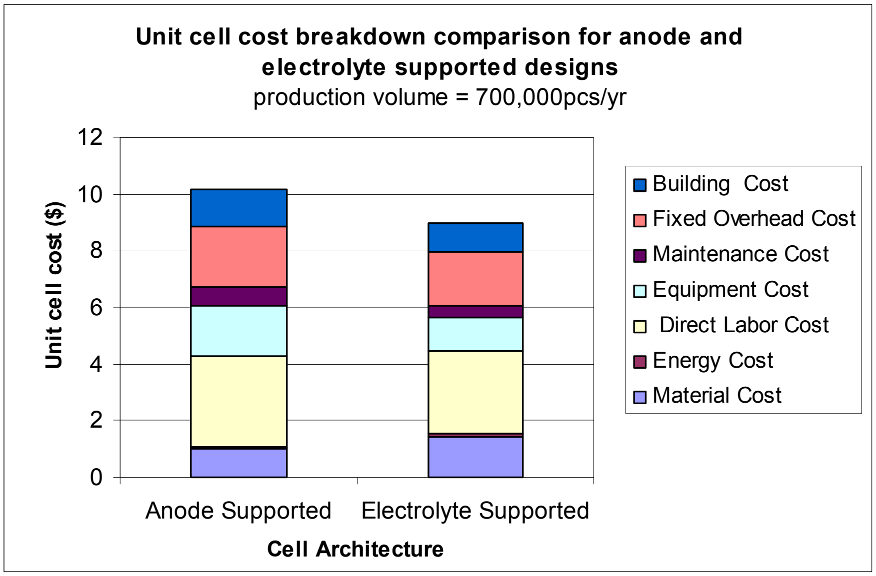


Figure 12. Cost structure comparison between anode and electrolyte supported cell geometries.

SUMMARY

A wide range of cost data from the process based cost model for multi-layer ceramic processing of solid oxide fuel cells has been presented. The results show good correlation with independent sources for the material cost, but process assumptions differences lead to a large discrepancy between the overall cost estimates per unit cell and per kilowatt. Higher unit cell costs in this model were related to thickness tolerance assumptions, associated with the thinner electrolyte layer, equipment capacity and equipment labor assignments.

The unit cell cost data shows that there are several viable process routes to produce a multi-layer ceramic and meet current, and future, cost targets. SECA cost targets can be obtained with sustained high volume manufacturing levels.

The model provides a tool to identify key cost factors that are important in strategic capital funding decisions. Process yield, production volume and equipment choices can dramatically affect the unit cost values.

- Production volumes increasing between 10,000 and 200,000 cells per year will show the most dramatic cost reductions.
- Process yield directly influences the unit cell and stack cost, and is dependent on the specific process and layer tolerance.
- Lower equipment cost shows significant cost reductions for sputtering, but small effects for tape casting.
- The anode supported cell is the most attractive option when considering total cost / kilowatt of a fuel cell system.

Multiple factors can be responsible for driving cost down for this product. Once the market reaches a sustaining level, cost advantages may be realized in maximizing the process by using three shifts per day. Bulk material pricing reductions will provide a large part of the cost reduction, provided material supply can be scaled accordingly. Experience and engineering advances will increase process yield and process throughput.

As the demand for electrolyte thickness reduction increases, the capability to evaluate process choices to maximize productivity and layer quality is needed.

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A Performance Based, Multi-Process Cost Model for Solid Oxide Fuel Cells

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ABSTRACT

Cost effective high volume manufacture (HVM) of solid oxide fuel cells (SOFCs) is a major challenge for commercial success of these devices. More than fifteen processing methods have been reported in the literature many of which could be used in various combinations to create the desired product characteristics. For some of these processes, high volume manufacturing experience is very limited or non-existent making traditional costing approaches inappropriate. Therefore, modeling tools are needed to aid in the selection of the appropriate process combination prior to making expensive investment decisions.

This project describes the development of a multi-process cost model that permits the comparison of manufacturing cost for different processing combinations and various materials considering production volume, process tolerance and process yield. Two processing methods are discussed, tape casting and screen printing.

The results are compared with data and experience from the fuel cell and electronic packaging industries. Initial comparisons show good agreement with this experience base. Sensitivity of manufacturing costs to SOFC performance requirements such as maximum power density and operation temperature is investigated.

INTRODUCTION

The success of SOFC technology depends on producing a cost competitive product within performance specifications that match or exceed those of other alternative energy sources.

Information detailing SOFC materials characterization, device performance and processing alternatives is available in abundance through the literature [1,2]. However, the state of manufacturing can still be considered in the development or pilot plant stage. The need to select amongst different designs, materials and processes will require a tool to aid in these decisions. The ability to accurately forecast investment requirements and manufacturing cost for a given high volume manufacturing (HVM) process based on expected volume is critical for strategic decisions, product placement and investor communications.

It is the goal of this work to use available research data to integrate cell performance requirements and manufacturing process capabilities into a single cost model. This cost model will be a powerful tool enabling accurate prediction of per piece stack costs as a function of cell performance and process variation prior to major equipment-based capital investment. During process maturity, these models can be used to highlight areas for process and performance optimization resulting in the greatest cost savings. This paper reports only a preliminary effort in this direction. It is expected that the model will be refined with the availability of further data.

BACKGROUND

Two planar SOFC architectures are currently investigated: anode supported and electrolyte supported stack geometries. In the anode supported architecture the 0.5 to 1 mm thick anode is tape-cast from a Nickel Cermet material. The electrolyte layer made of Yttria Stabilized Zirconia (YSZ) is either tape-cast or screen printed onto the anode. The electrolyte thickness can vary from 10 to 150 µm. The cathode consists of an approximately 50 µm thick Lanthanum Strontium Magnesium (LSM) oxide layer. For the electrolyte supported architecture the electrolyte is more than 150 µm thick and the anode is correspondingly thinner. This paper focuses on anode supported architectures.

Recently, interest has focused on optimization of SOFC cell performance at reduced (<800 ^{o}C) operation temperature. This will allow use of less-costly materials for cell interconnect and system components [3,4]. One approach to accomplish this lower temperature operation uses reduced electrolyte layer thicknesses of 5-10 µm [5].

Of the more than 15 different processes suggested for HVM of SOFC's [6], tape casting, screen printing, electrochemical vapor deposition (EVD), thermal spraying and RF sputtering are the most widely employed but in small scale settings. In the absence of HVM expertise the challenge becomes predicting economic viability of a process in a cost challenged high volume manufacturing condition for decisions amongst design and process alternatives

METHODOLOGY

The unit cell modeled within this cost model consists of a 1 mm thick tape-cast anode. The electrolyte thickness is varied according to the performance requirements and can be either tape cast or screen printed. The 50 µm thick cathode uses the same process as the corresponding electrolyte layer. The cells are co-fired in a batch process. The area of such a cell is assumed to be 10 cm by 10 cm .

The modeling effort consists of three steps: 1) the use of a device performance model to calculate the required film thickness for a given operating temperature, maximum power density and performance tolerances for each of these parameters, 2) the calculation of the process yield at each layer for a given process at the required film thicknesses tolerances and 3) the overall cost to produce a cell stack using data provided by step 1) and 2).

Device Performance Model

The dependence of the film thickness on operating temperature is derived from a general polarization model of the cell voltage as a function of the current density. This model includes corrections for ohmic losses as well as anode activation and concentration losses [7]. Each of these corrections is discussed separately in the literature [7-9] and is integrated here into the expression for the cell voltage. Cathode effects are neglected due to cell geometry in anode and electrolyte supported devices as supported by refs [7-9]. This results in an equation for power density with respect to current density and temperature as shown in equation 1 below. This performance model is compared to experimentally determined maximum power density results from the literature for YSZ in Figure 1 [7-13]. Correlation to the literature results is very good throughout the range of power densities.

$$P(i) = i * V(i) = i * [E_o - iR_i - a - b\ln(i) + \frac{RT}{2F}\ln(1 - \frac{i}{i_{as}}) - \frac{RT}{2F}\ln(1 + \frac{p_{H2}^{0} i}{p_{H2O}^{0} i_{as}})] \qquad (1)$$

where P = *power density (W/cm*^{2}*),* i= *current density (A/cm*^{2}*),*
i_o= *effective exchange current density(A/cm*^{2}*),* V= *Voltage (Volts),*
E_o= *open circuit voltage (Volts),* R= *gas constant (J/mol deg),*
T=*Temperature (K),* F= *Faraday constant (C/mol),*
$a = -RT/4\alpha F * \ln i_o$ $b = -RT/4\alpha F$
p^o_{H2} = *partial pressure of hydrogen at the anode/electrolyte interface(atm)*
p^o_{H2O} = *partial pressure of water vapor in the fuel(atm)*
p^o_{O2} = *partial pressure of oxygen in the oxidant (atm)*

R_i = *area specific resistance of the electrolyte (Ohm cm^2)*

$$= R_i = \mathrm{R}_{e\,l} + R_{ct}^{eff} = \frac{l_e}{\sigma_e} + R_{ct}^{eff} \quad where \quad R_{ct}^{eff} = \sqrt{\frac{BR_{ct}}{\sigma_e(1 - V_v)}}$$

i_{as}=*anode limiting current density (A/cm*^{2}*)* $= \frac{2Fp^o_{H2}D_{eff,a}}{RTl_a}$

$D_{eff,a}$ = *effective diffusion coefficient on the anode side cm*^{2}*/s*

l_a = *anode thickness, cm* l_e = *electrolyte thickness, µm*
R_{ct} = *intrinsic (area specific) charge transfer resistance, (Ohm cm*^{2}*)*
σ_e = *ionic conductivity of the electrolyte (S/cm)* V_v=*layer porosity*
B=*microstructural dimension (grain size of material) (um)*

Device operation temperature, power density and a nominal anode thickness are entered into the performance model. Layer thickness tolerances are calculated using this model. The process yield is then calculated for each layer based on this variation using the process tolerance models as outlined in the next section.

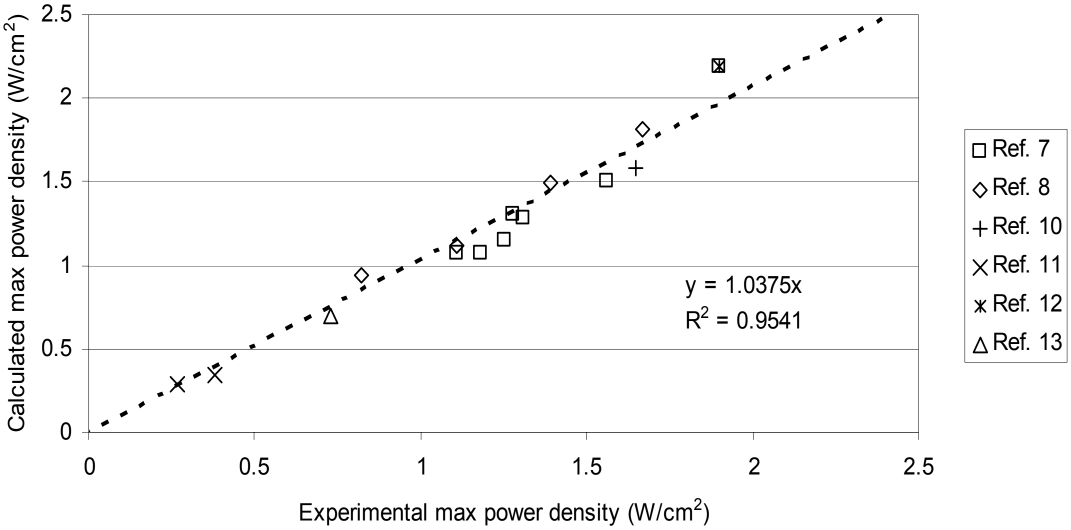

Figure 1. Comparison of calculated maximum power density to published experimental power density results.

Process Tolerance Models

For a given film deposition process, the film deposition rate will vary across the deposition surface. This variation results in thickness variation which can be measured by external measurement of film thickness across the surface. From these measurements, a standard deviation, or film thickness tolerance, at the target film thickness can be determined.

The cell performance models use nominal, minimum and maximum layer thicknesses to determine process yield for each layer. The standard deviation is calculated at the nominal thickness assuming a normal distribution. The probabilities for the minimum and maximum film thicknesses are calculated based on the nominal thickness and process standard deviation values. These probabilities are converted to a percentage upper and lower yield loss for each layer.

Process Based Cost Model

A process-based cost model (PBCM) maps a process and its operating conditions to cost [14]. Materials and process information are used to build up the manufacturing cost for anode supported SOFC's processed by either tape-casting for all three layers or tape-casting of the anode and screen printing of the other two layers. The parameters of the model are based on information from the literature augmented by the experience of the authors and specific data obtained from suppliers.

The model considers slurry preparation, film deposition, and co-firing in a batch process. The material choices are kept constant, as is the price of the materials. The expected variation of yield is estimated based on the process described above and adjusted to values based on experience with tape-casting of conventional materials. Materials cost and yield will greatly affect the final cost and further refinement is needed in this area. At this initial stage disposal costs have been ignored. This should be incorporated in the future.

RESULTS AND DISCUSSION

The cost model was tested against the results obtained previously by ADL [15]. Using the assumptions published in ADL reports the results agree well with those reported previously as shown in Figure 2.

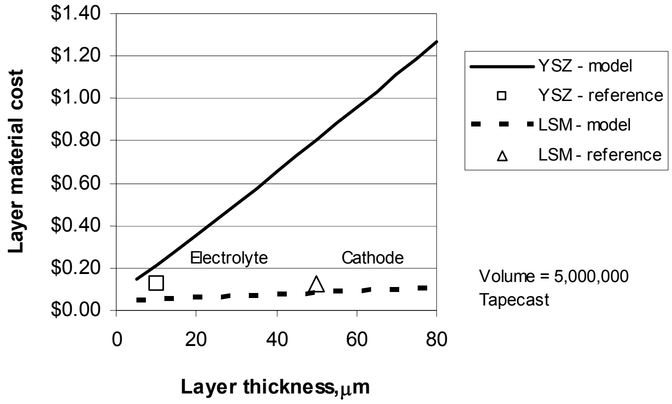

Figure 2. Comparison of model results with data from the literature [15].

The cost model was employed to evaluate the sensitivity of the two processes to the production volume and to the performance parameters of the cell. For these studies the assumptions were changed from those employed by ADL. The number of shifts was reduced from 21 to 10 per week.

Sensitivity to production volume is shown in Fig. 3. Both graphs show a rapid decrease in cost as the production volume increases from 50,000 to 150,000 units per year. The slight increase in cost at about 180,000 units/year is due to additional equipment. Materials cost dominates the total cost for high production volumes. It is expected that this cost will decrease as high volume materials pricing takes effect.

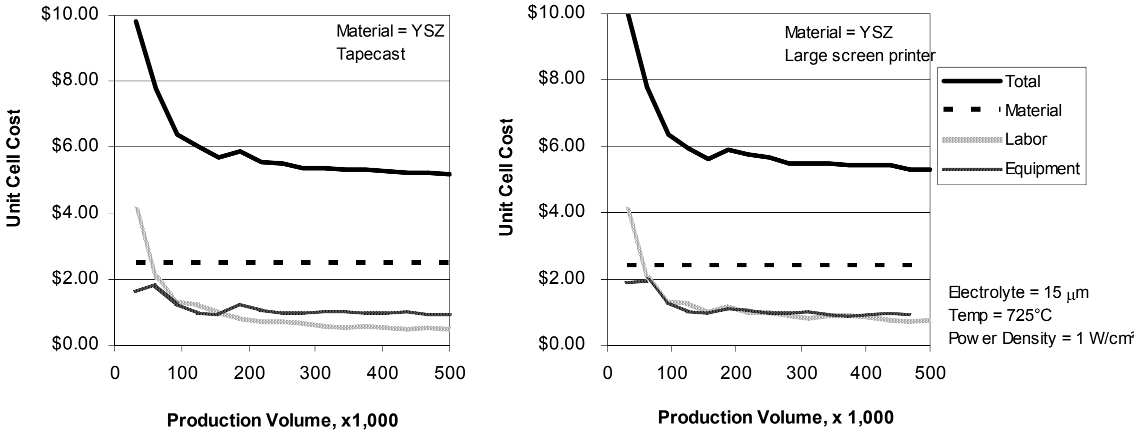

Fig. 3. Total cost and cost elements versus production volume for tape-casting or screen printing of electrolyte/cathode layers

Fig. 4 shows total cost and cost elements for the electrolyte layer as a function of thickness of the layer. The added material dominates the cost increase. Higher costs for thin layers are due to reduced yields. Labor cost for screen printing is significantly larger, but the equipment cost is less.

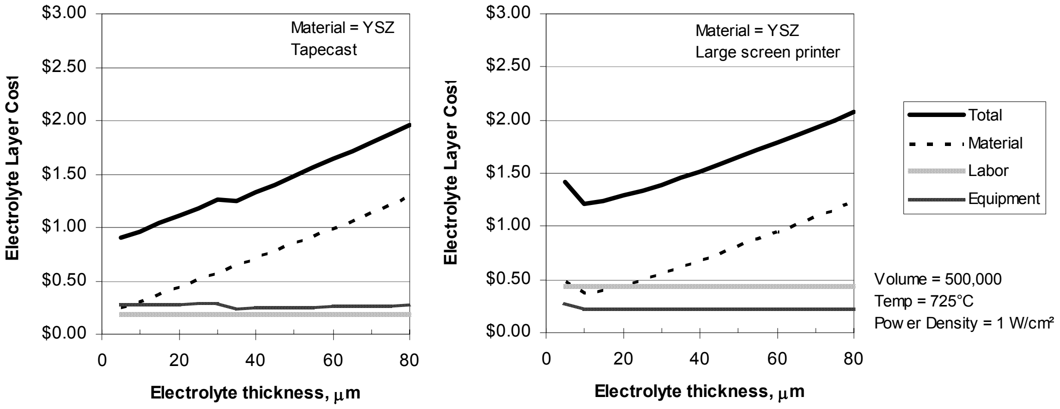

Figure 4. Total cost and cost elements for electrolyte layers of varying thickness.

Figure 5 shows constant cost contours per unit cell as a function of operating temperature and power density. A decrease in operating temperature requires a decrease in electrolyte thickness in order to maintain the same power density. This decrease in thickness results in a decrease in unit cell cost as shown in these figures.

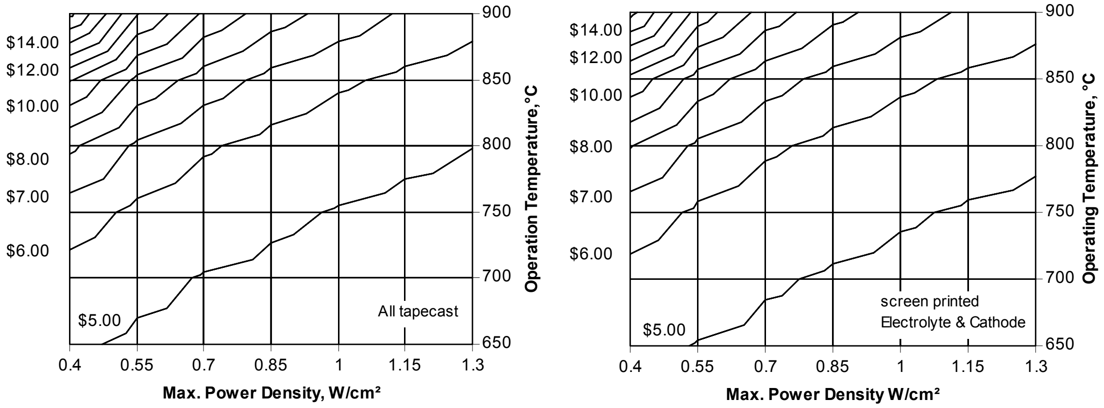

Figure 5. Contour maps of constant unit cell cost as a function of power density and operating temperature for tape-cast and screen-printed electrolyte/cathode layers, respectively.

CONCLUSIONS

A modeling tool is presented that relates manufacturing cost of SOFCs to power density for a range of temperatures. The results for tape-casting and screen-printing show similar total costs with differences in cost break down

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SUMMARY

The combination of the two thesis projects, culminating in the two journal articles, presents a powerful tool to analyze solid oxide fuel cell costs based on performance, process and tolerance interactions. Three models are combined to create the cost model. A process tolerance model is incorporated into the process based cost model to determine manufacturing costs. The cell performance tolerance model can be used to separately to identify unit cell geometry based on cell performance targets.

The cost model is used to generate cost data to address specific strategic questions in terms of the stack and plant output levels. Cost output can be presented and compared on the material, cell, stack and power output levels. The effect of strategic choices can be shown as trends within a single cost parameter, or as comparisons between the cost output parameters. However, the choice of comparison parameter will change the view of the cost landscape. The use of cost maps integrates performance, production and comparison parameters to provide a comprehensive view of the cost landscape. Therefore, the demand for higher power density and lower operating temperature requirements can be balanced by design trade-offs to attain the lowest cost product.