Project Number: IQP IB-1003 -42

Cost Modeling of Fuel Cells:

submitted to the Faculty

of the

WORCESTER POLYTECHNIC INSTITUTE

In partial fulfillment of the requirements for the

Degree of Bachelor of Science

by

Michael J. Hubacz

Ronnie P. Kupfer

Date: April 28, 2003

Approved:

Professor Isa Bar-On: Project Advisor

Acknowledgements

We would like to thank Professor Bar-On for advising this IQP. We would also like to thank Mark Koslowske for his assistance with this project.

Abstract

This Interactive Qualifying Project verified that a Process Based Cost Model could be effectively utilized to predict the cost of manufacturing fuel cells using available production data. The report shows that a one kilowatt fuel cell stack can be manufactured at a cost between $80 and $120. The report also shows that the cost model is sensitive to changes in material cost, production volume, and material thickness. Reduction in Fuel cell manufacturing costs will be dependent on reducing material costs.

Table of Contents

Table of Figures	Pgs. 2-3
Introduction	Pg. 4
Background	Pgs. 5-9
Methodology	Pgs. 10-11
Results	Pgs. 12-27
Initial Results	Pg. 12
Final Results	Pg. 12-27
Conclusions	Pg. 28
Appendices	Pg. 29
References	Pg. 30

Table of Figures

Figure 1. Fuel Cell Operation (A Polymer Electrolyte Membrane Fuel Cell) Pg. 7

Figure 2. A screen printing process. Pg. 9

Figure 3. A tape casting machine. Pg. 9

Figure 4. Total Cost Vs. Production Volume (Varying Layer Thicknesses) Pg. 12

Figure 5. 5 micron Thickness, 100k Production Volume Graph Pg. 14

Figure 6. 20 micron Thickness, 100k Production Volume Graph Pg. 14

Figure 7. 50 micron Thickness, 100k Production Volume Graph Pg. 14

Figure 8. 5 micron Thickness, 500k Production Volume Graph Pg. 15

Figure 9. 20 micron Thickness, 500k Production Volume Graph Pg. 15

Figure 10. 50 micron Thickness, 500k Production Volume Graph Pg. 15

Figure 11. 5 micron Thickness, 1% Material Loss Graph Pg.17

Figure 12. 5 micron Thickness, 5% Material Loss Graph Pg.18

Figure 13. 20 micron Thickness, 1% Material Loss Graph Pg. 18

Figure 14. 20 micron Thickness, 5% Material Loss Graph Pg. 19

Figure 15. 50 micron Thickness, 1% Material Loss Graph Pg. 19

Figure 16. 50 micron Thickness, 5% Material Loss Graph Pg. 20

Figure 17. Cost for 200,000 Unit Production Volume Graph Pg. 21

Figure 18. Cost Histogram, 5 micron Thickness Pg. 22

Figure 19. Cost Histogram, 10 micron Thickness Pg. 22

Figure 20. Cost Histogram, 20 micron Thickness Pg. 23

Figure 21. Cost Histogram, 50 micron Thickness Pg. 23

Figure 22. Cost Histogram, 5 micron Thickness Pg. 24

Figure 23. Cost Histogram, 10 micron Thickness Pg. 24

Figure 24. Cost Histogram, 20 micron Thickness Pg. 25

Figure 25. Cost Histogram, 50 micron Thickness Pg. 25

Figure 26. Yield Variation Vs. Part Thickness Pg. 27

Introduction

Process Based Cost Models

A Process Based Cost Model arranges data such as energy cost, labor cost, material cost, manufacturing cost, processes, and others. The model provides for these inputs to be altered to arrive at a final overall cost. (7) A Process Based Cost Model also allows the inspection of intermediate costs and the evaluation of alternatives. The ability to predict the manufacturing cost of a product before a single machine is bought or a laborer hired will help the entrepreneur assess the risk of entering a new technology field such as cost models.

Process Based Cost Models are effective tools for high production volume manufacturing because they can help predict the effects of changes in the product's market. Life Cycle Analysis costing encompasses costs from material acquisition to recycling and disposal. This can be useful for products with a long life span. It can show where costs can be made smaller and where costs can be recovered. (8) Engineering economics takes into account the broader aspects of manufacturing costs including taxes, depreciation, the time value of money, and others. (8)

Purpose

The purpose of this IQP was to prove the validity of a Microsoft Excel based cost model for Solid Oxide Fuel Cells. The cost model itself was designed as part of two master's degree theses. (2,6) This IQP evaluated the model to make sure that the cost results were sensitive to changes in materials and processing input variables. The model will also show that a one-kilowatt SOFC can be manufactured within a $500 to $1000 price range.

Background

Solid Oxide Fuel Cells are being considered for use in power generation. They produce electricity directly (without combustion) from a fuel source, which in turn creates a more efficient system. Because there is no combustion, no nitrous oxides are produced. When pure hydrogen is the fuel being used, only two byproducts result from the chemical reaction taking place within the fuel cell, heat and pure water.

Solid Oxide Fuel Cells have the potential to reach the public through the automobile industry, back up power supplies (i.e. UPS and home generators), and power generators for businesses. These Solid Oxide Fuel Cells would supply electricity to the motor of an electric car. The extra heat generated by the fuel cell would provide heat inside the car during winter months. As more fuel cell technology becomes available, whole power plants may use fuel cells to generate electricity for cities and towns.

Currently there is no significant commercial market for fuel cells. A major concern in manufacturing Solid Oxide Fuel Cells is the cost. Due to the lack of information and manufacture of fuel cells, predicting manufacturing costs is difficult. Where data was available for the manufacture of fuel cells, it was added to the cost model. Where data was not readily available from actual fuel cell production, expected costs from experience in other fields were added to the cost model. With this data in one model, attempts at predicting costs could be made.

Fuel cell operation consists of the following steps: (1) (See figure 1. below)

1. A hydrocarbon is fed to a reformer. (If pure hydrogen is used, no reformer is needed.)
2. The reformer produces H_2 +CO_2 + CO.*
3. The CO_2 is exhausted to the atmosphere.
4. The CO is mixed with H_2O and energy to form CO_2 + H_2.
5. The CO_2 is exhausted to the atmosphere.
6. All of the hydrogen produced is then used to produce electricity.
7. The H_2 is stripped of its electrons so the protons become separated from the electrons.
8. The protons pass through an electrolyte.
9. The electrons pass through an external circuit.
10. The hydrogen and electron are then recombined on the other side of the cell.
11. This hydrogen bonds with Oxygen to form water and heat, which are exhausted to the atmosphere.

* In SOFC fuel cells, which the cost model is designed for, Hydrogen and Oxygen are produced. The O- passes through the electrolyte layer and is then recombined with the Hydrogen at the other end of the circuit. The negatively charged Oxygen ion supplies the fuel cell with the electron.

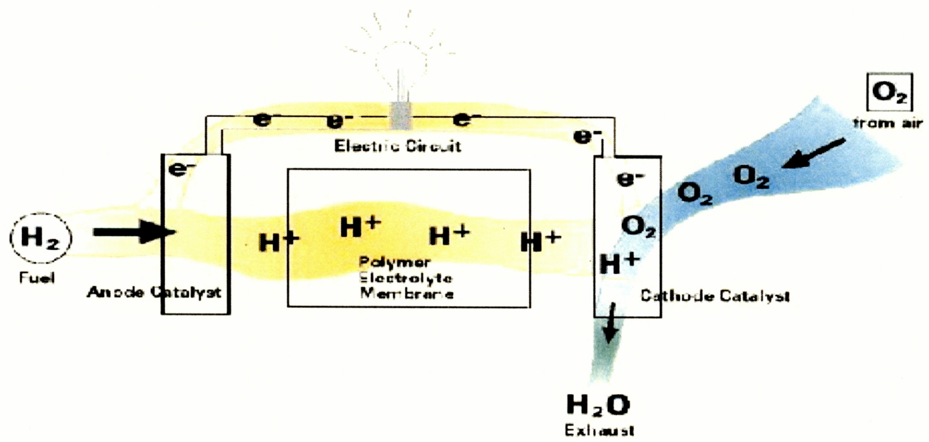


Figure 1. Fuel Cell Operation (A Polymer Electrolyte Membrane Fuel Cell) (5)

Six major types of fuel cells listed below. They differ mainly in the material that they use for the electrolyte.

1. Alkaline Fuel Cells contain potassium hydroxide as the electrolyte.
2. Polymer Electrolyte Membrane Fuel Cells use a proton exchange membrane as the electrolyte. (Figure 1.)
3. Direct Methanol Fuel Cells uses the Polymer Electrolyte Membrane technology but uses methanol directly without being reformed.
4. Phosphoric Acid Fuel Cells use phosphoric acid as the electrolyte layer.
5. Molten Carbonate Fuel Cells use a lithium-potassium compound in the carbonate as the electrolyte layer.
6. Solid Oxide Fuel Cells are unique because the internals of the fuel cell are completely solid. Yttria stabilized zirconia is used as the electrolyte.

The geometry of the Solid Oxide Fuel Cell can consist of two designs, a tubular design and a planar design. The cost model assumes a planar design. This geometry allows the cells to be stacked to achieve higher power. The interconnects of stacked fuel cells are not accounted for in the pricing of the fuel cells in this cost model. The overall size of one cell is a 10cm by 10cm square. The thickness of a cell is most heavily varied by the electrolyte layer. This IQP varied electrolyte layer thicknesses of 5, 10, 20, and 50 microns.

The power density of the fuel cells modeled is 1watt/cm^2. One fuel cell has an area of 100cm^2. Hence, one cell produces 100 watts. To obtain a one-kilowatt power output, 10 cells would need to be stacked together.

Each of these fuel cells operates in a different temperature range. The higher the operating temperature the more expensive the fuel cell will become due to the necessity to use more exotic materials in the fuel cell, and the more complex manufacturing processes employed to make the fuel cell. The operating temperature of Solid Oxide Fuel Cells is 800 to 1000 degrees Celsius. Lower temperatures of 500 to 600 degrees Celsius are desireable.

Two methods of manufacturing are programmed in the cost model. These two methods are Screen Printing and Tape Casting.

Screen-printing is a manufacturing method often used in putting designs on shirts and also in the electronics industry. It involves putting a pattern onto a material, which will not allow the slurry that is being laid down to pass through except for where the pattern is. The "stenciled" material is placed into a mechanism that holds it taut. The object that is going to have the pattern placed on it is laid underneath the "stencil". The "stencil" is closed on top of the blank material and the slurry is squeegeed over the pattern. This places a pattern of the slurry material on top of the blank material.

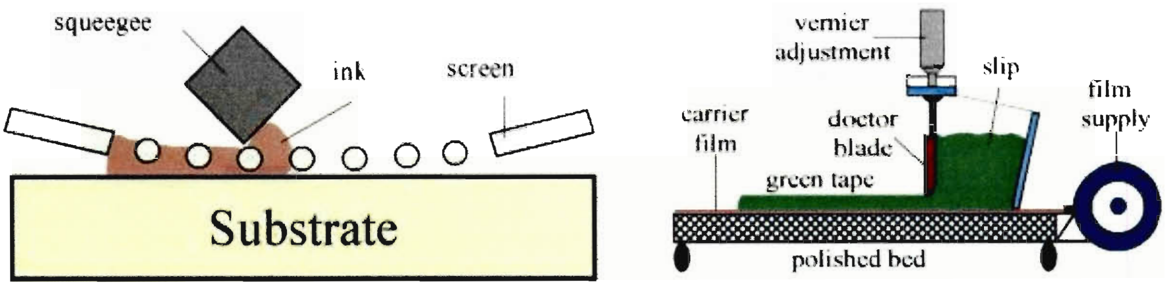


Figure 2. A screen printing process. (4)

In tape casting, binder, solvent, and ceramic material such as $ZrO_2(Y_2O_3)$ are put in a ball mill. The mixed slurry is passed into a hopper that drops a uniformly thick layer of the slurry onto a moving polymer based tape. As it is moving along, in a conveyer belt fashion, it is dried under heat. It is eventually passed along to an oven, which sinters it. In the tape casting process, keeping the thickness of slurry layer constant is key by maintaining proper blade distance from the tape. This gets particularly difficult when the layers get very thin.

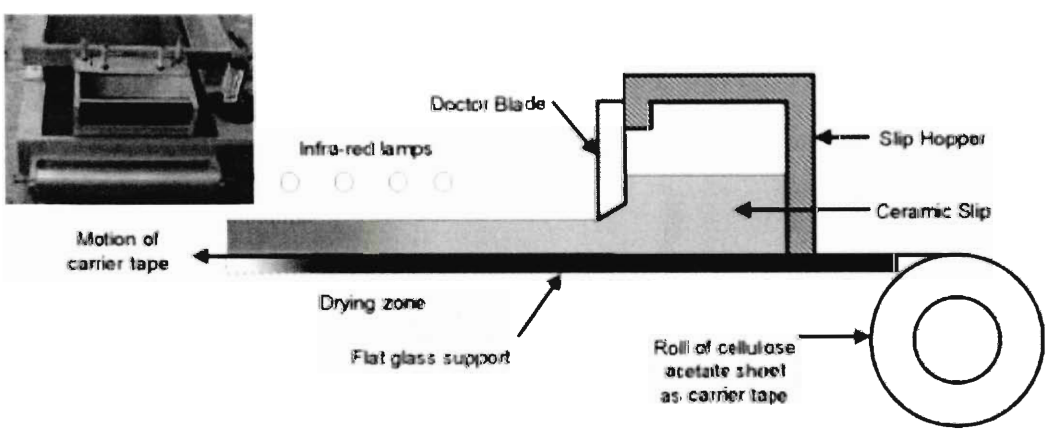


Figure 3. A tape casting machine. (3)

ENVIRONMENTAL COSTS:

The current cost model does not consider disposal costs. These costs would occur from wastes produced in the manufacturing process that could not be recycled.

Methodology

The cost model was evaluated to make sure that the cost results were sensitive to changes in materials and processing input variables. To successfully verify the cost model a few different inputs were varied over a range of values. The outputs for cumulative process yield were graphed with their respective inputs. The inputs that were varied were electrolyte layer thickness, material loss, scrap rate, and production volume. Electrolyte layer thickness was changed to 5, 10, 20, and 50 microns. Material loss was changed to 1,2,3,4, and 5 percent. Scrap rate was changed in increments of 2 from 0 percent to 20 percent. Production volume was set at 50, 100, 200, and 500 thousand. Continuous sintering and batch sintering were varied to observe the change in cost.

The results of these iterations can be found in the results section. Upon examining this data it was found that sometimes, cumulative process yield came out to be zero. This showed that there must be a problem in the model. As it turned out there was a mistake in one of the formulas. This problem was fixed, and another set of iterations was completed and new data gathered. With the new data, the graphs below were made.

For the next set of data electrolyte thickness was set at 5, 20, and 50 microns. Material loss was changed to 1, 3, and 5 percent. Scrap rate was set at 0, 10, and 20 percent. This time the output for cumulative process yield, material cost, energy cost, labor cost, and total fabrication cost into a data table and graphed.

Using the previously created data tables, including the data that was created using the faulty equation, much of this data was graphed.

These graphs include:

1. Graphs of cost versus production volume
    i. 100,000, 500,000, 1,000,000-unit production volume
2. Holding thickness and production volume constant
    i. Graphing yield percentage versus sintering loss
3. Holding thickness and material loss constant
    i. Graphing yield percentage versus sintering scrap percentage
4. Holding production volume constant
    i. Cost as the number of shifts vary
5. Varying production volume
    i. Graphing the total cost made up of its constituent parts
    ii. Graphing the total cost made up of its constituent parts by percentage of the total cost
6. Varying part thickness
    i. Graphing yield as a result of part thickness
7. Varying production volume
    i. Graphing material cost as a function of the production volume
8. A comparison of cost between Continuous Sintering and Batch Sintering can be seen at the end of Appendix A.

Results

INITIAL RESULTS:

For the first set of data, which was run at a sintering scrap rate of 0 to 20 percent in intervals of 2 percent, with material loss of 1 through 5 percent, production volumes of 50k, 100k, 200k, and 500k, and various electrolyte layer thicknesses. It was found that when sintering scrap rate approached 18 percent and above for thin electrolyte layer thicknesses, the cost model predicted negative output values. This data can be seen in appendix A. As a result of this data flaw the equation in cell B84, on the intermediate output page, was altered. This produced data that was more consistent and accurate.

FINAL RESULTS:

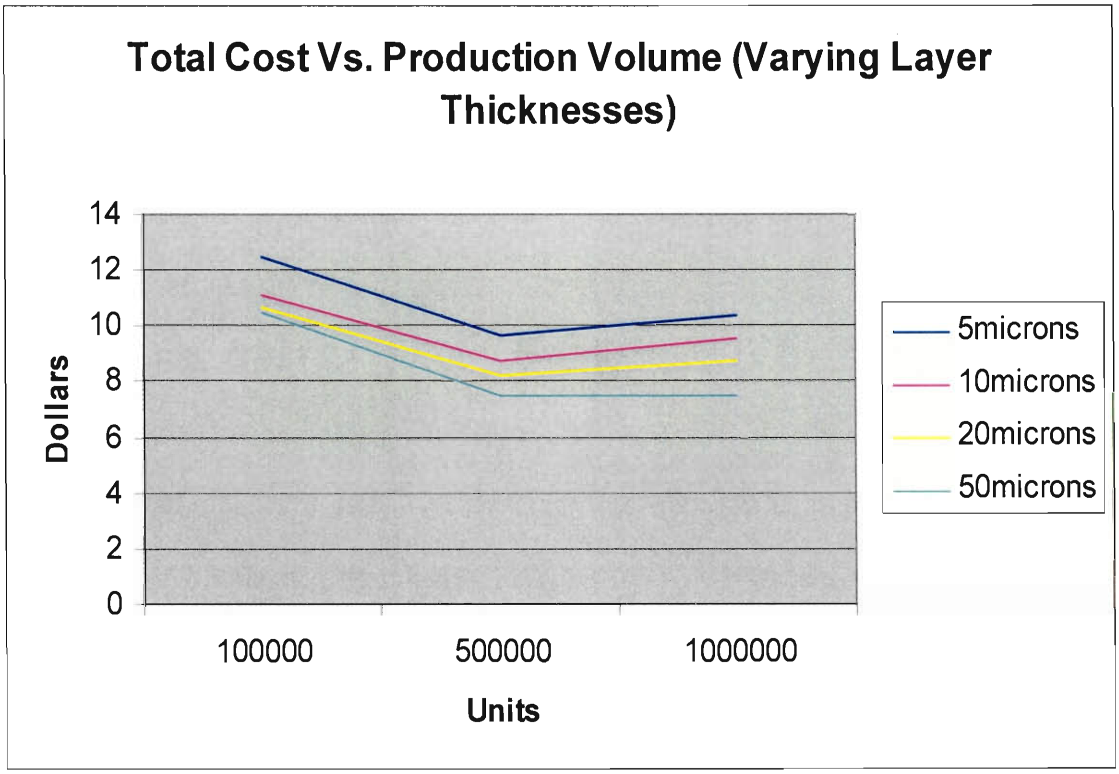


Figure 4. Total Cost Vs. Production Volume (Varying Layer Thicknesses) Graph

Figure 2 shows that as production volume increases, the overall cost will go down. However, as you approach 1 million units, costs go up slightly because more equipment needs to be purchased at that volume. As you produce more than 1 million units the costs will go down again due to better equipment utilization. The graph also shows that the overall production cost decreases for thicker electrolyte layers. This decrease in cost is limited. Eventually the material costs will take over and increase the overall cost as the thicknesses get large. The graph assumes each cell is a tape cast, 10cm by 10cm square that is fired using a continuously sintering kiln. The overall thickness of the cells is varied from 5, 10, 20, and 50 microns by changing the electrolyte layer thickness.

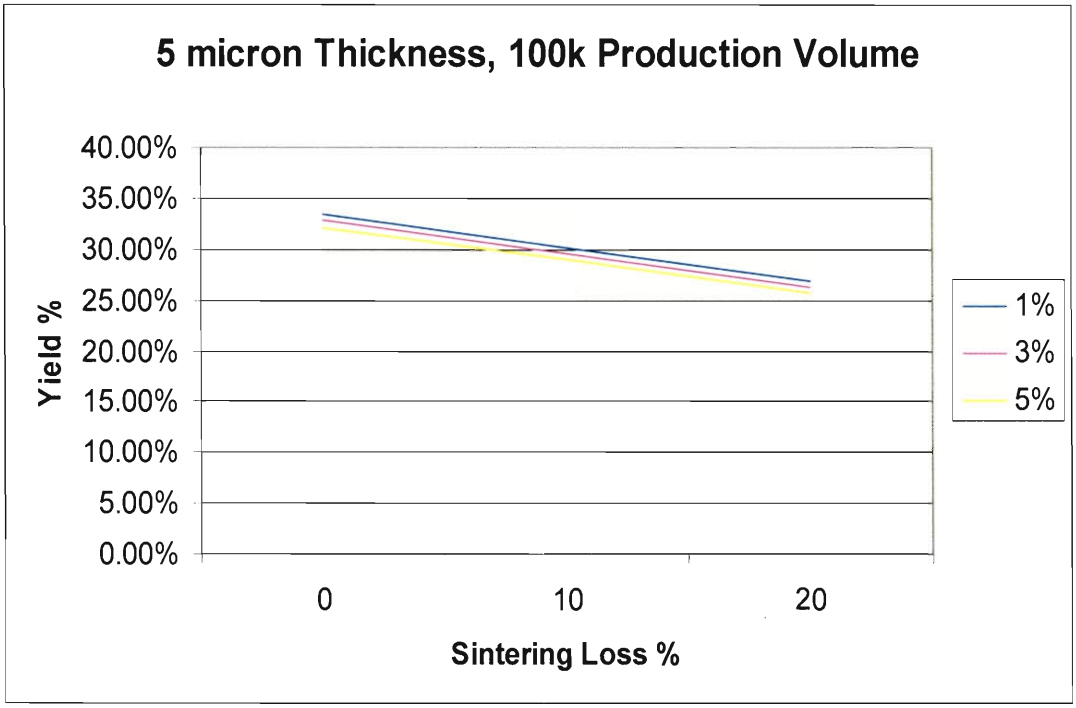


Figure 5. 5 micron Thickness, 100k Production Volume Graph

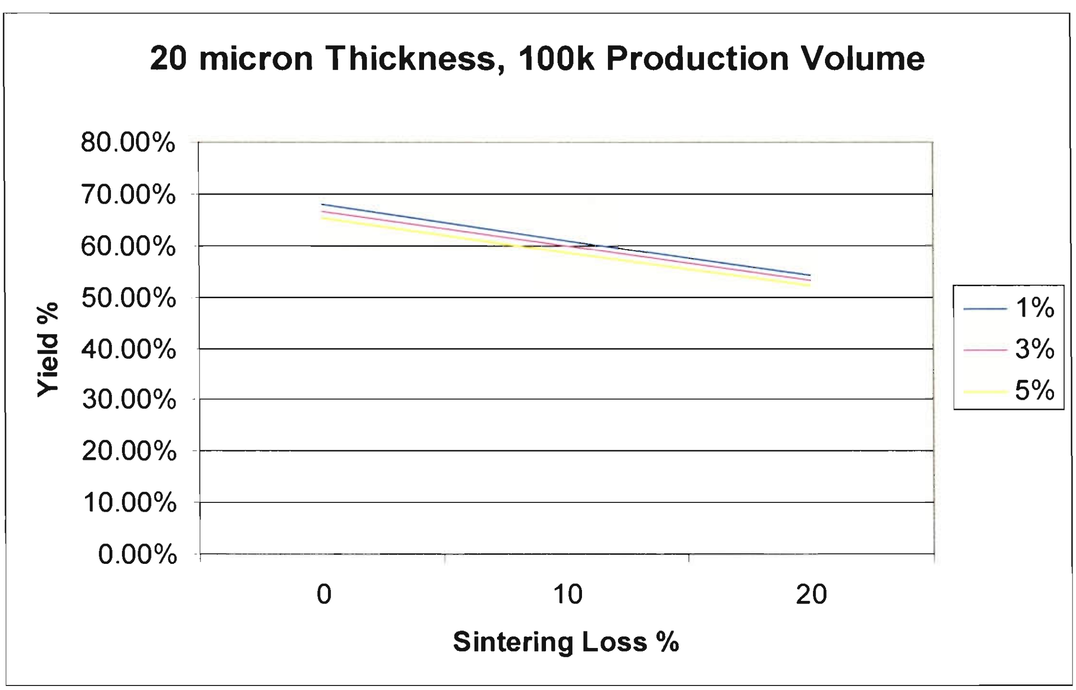


Figure 6. 20 micron Thickness, 100k Production Volume Graph

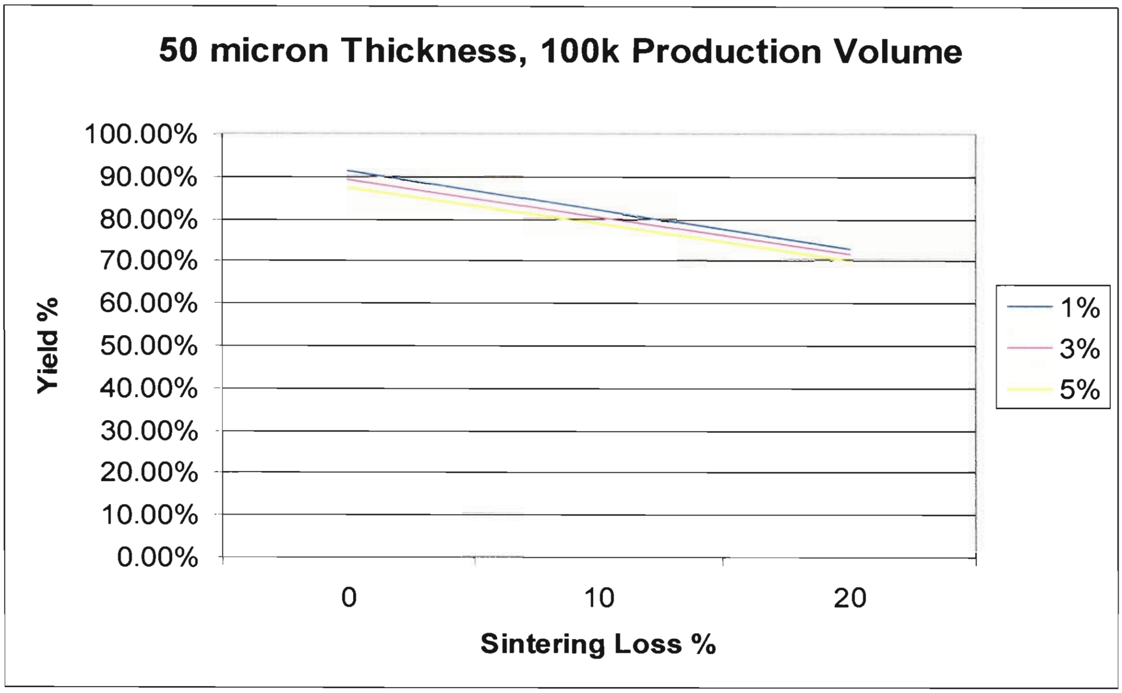


Figure 7. 50 micron Thickness, 100k Production Volume Graph

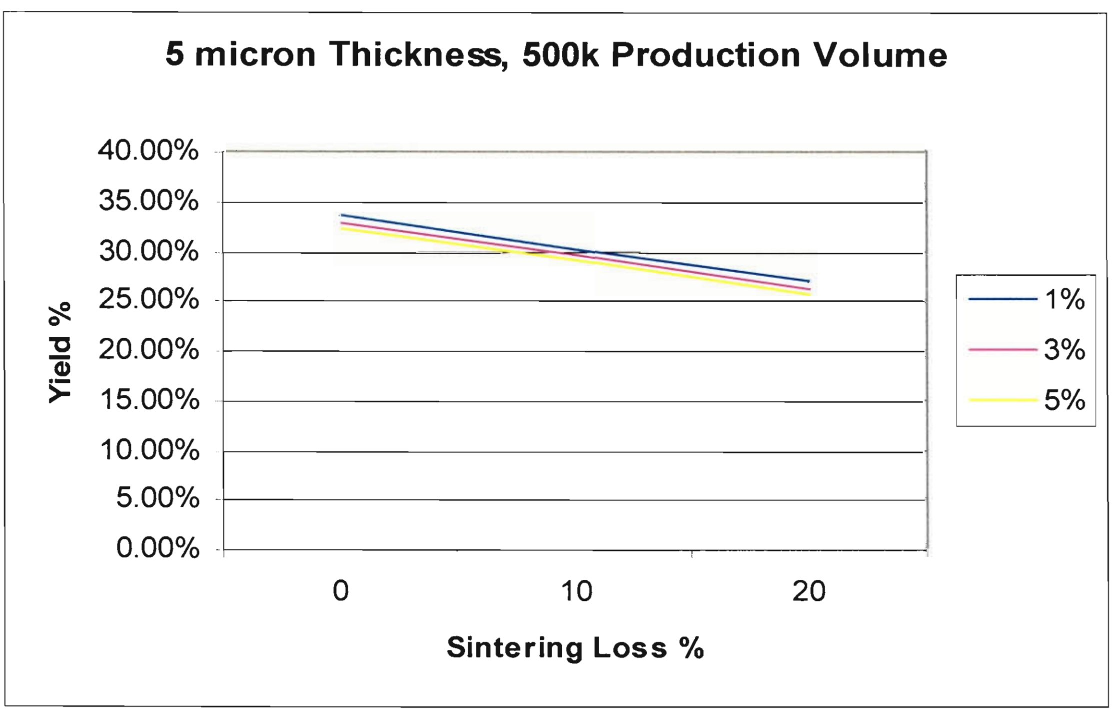


Figure 8. 5 micron Thickness, 500k Production Volume Graph

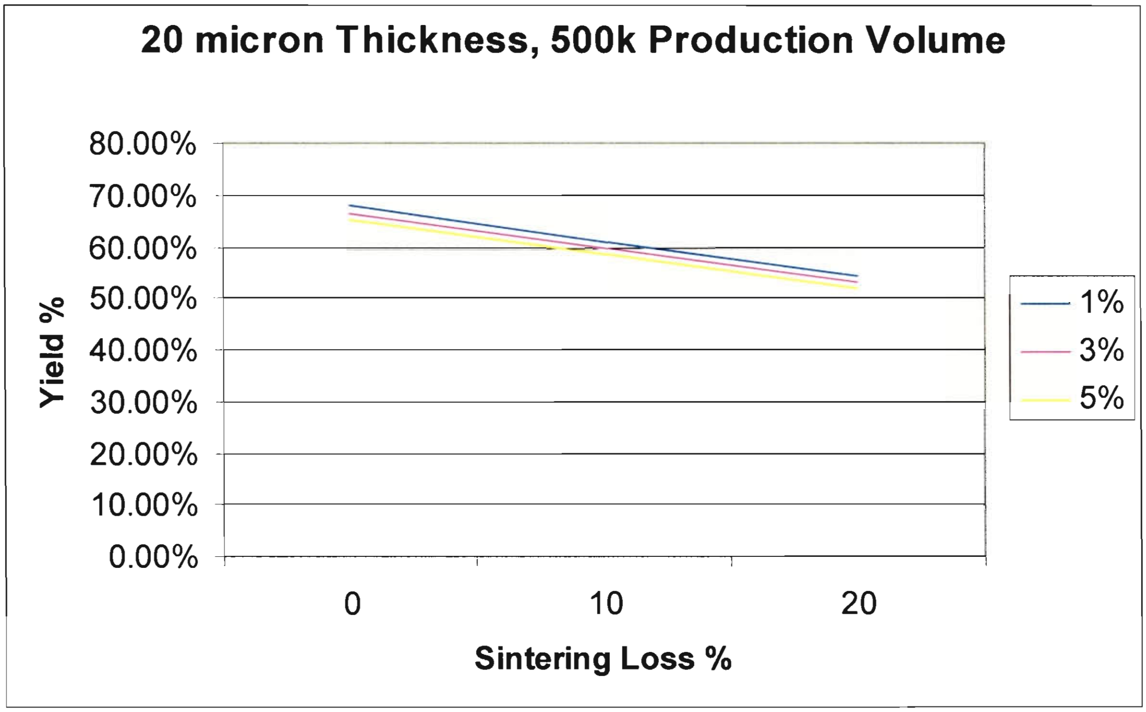


Figure 9. 20 micron Thickness, 500k Production Volume Graph

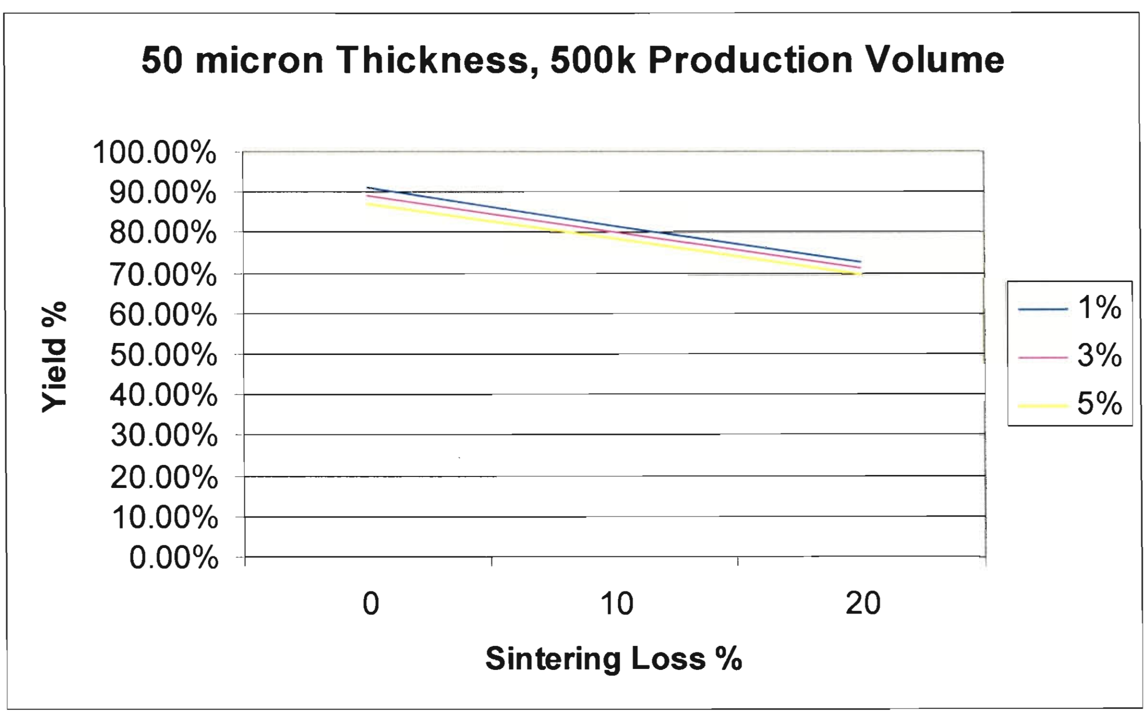


Figure 10. 50 micron Thickness, 500k Production Volume Graph

Figures five through ten show that yield decreases linearly as sintering loss and material loss increase. The graph assumes each cell is a tape cast, 10cm by 10cm square that is fired using a continuously sintering kiln. The overall thickness of the cells is varied from 5, 20, and 50 microns by changing the electrolyte layer thickness.

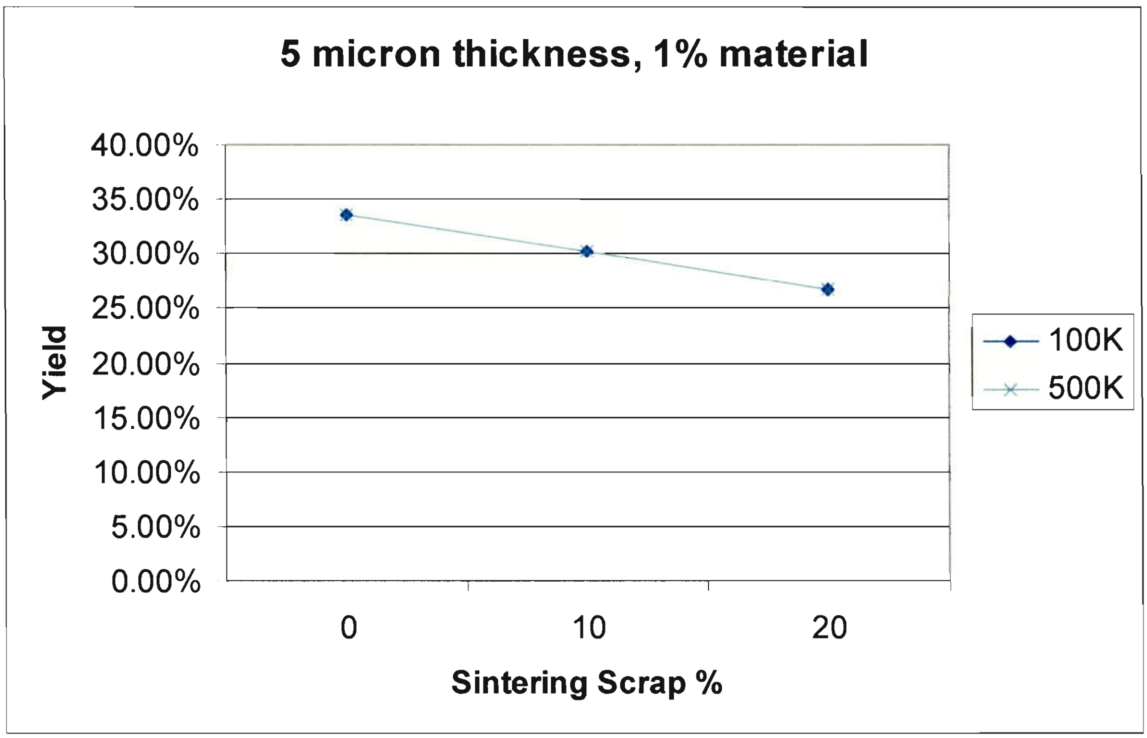


Figure 11. 5 micron Thickness, 1% Material Loss Graph

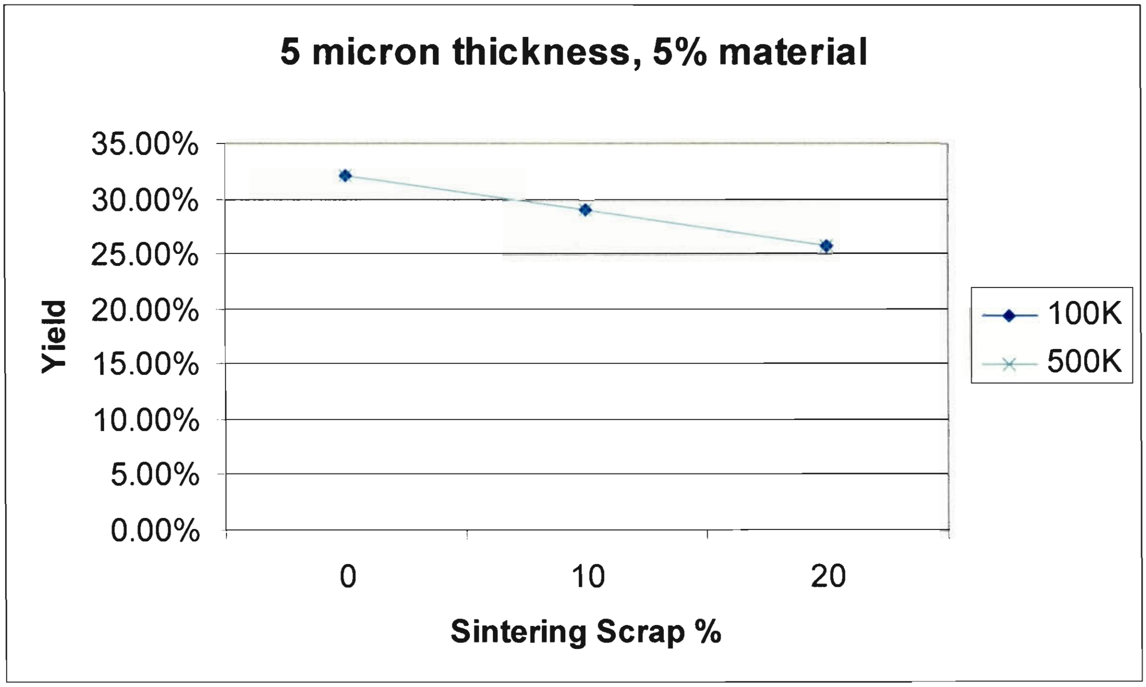


Figure 12. 5 micron Thickness, 5% Material Loss Graph

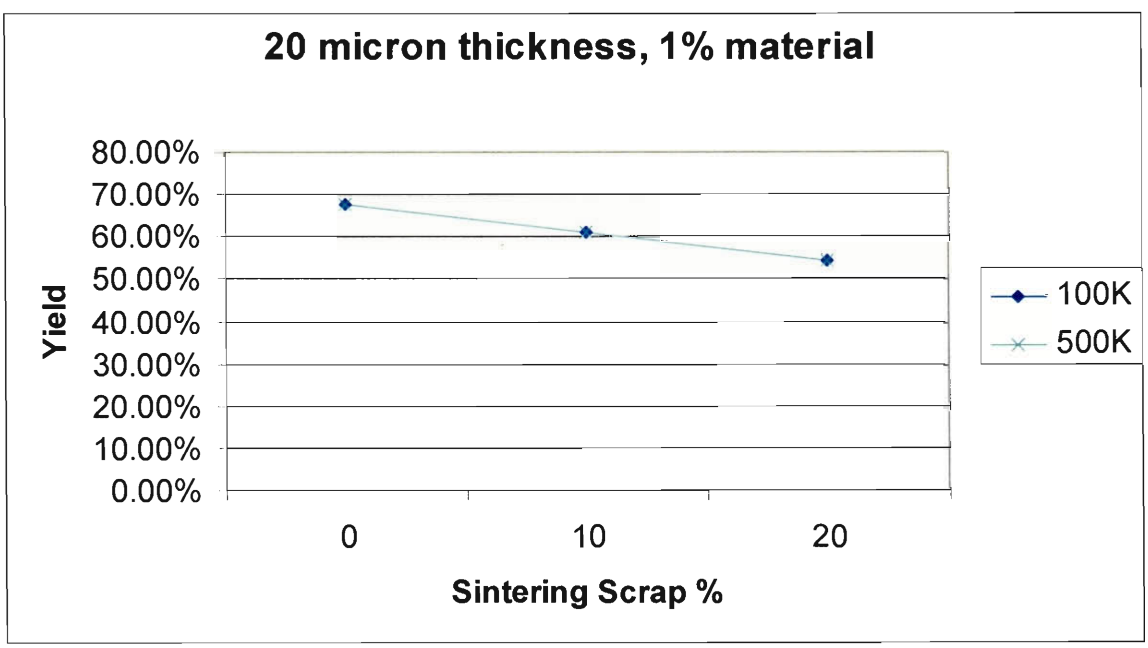


Figure 13. 20 micron Thickness, 1% Material Loss Graph

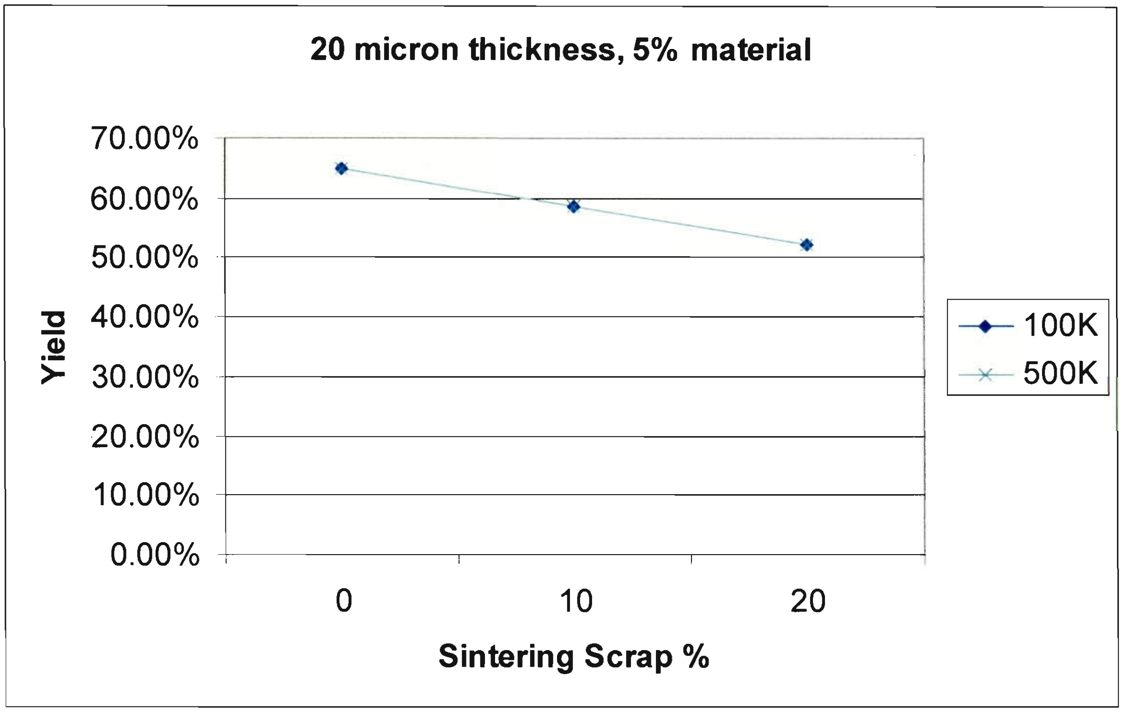


Figure 14. 20 micron Thickness, 5% Material Loss Graph

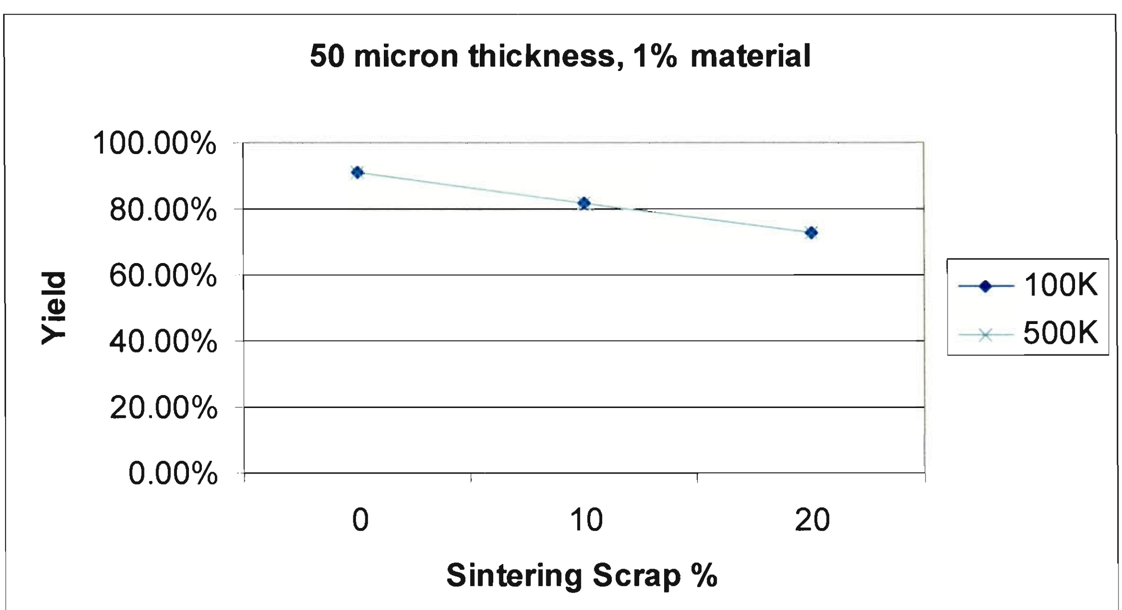


Figure 15. 50 micron Thickness, 1% Material Loss Graph

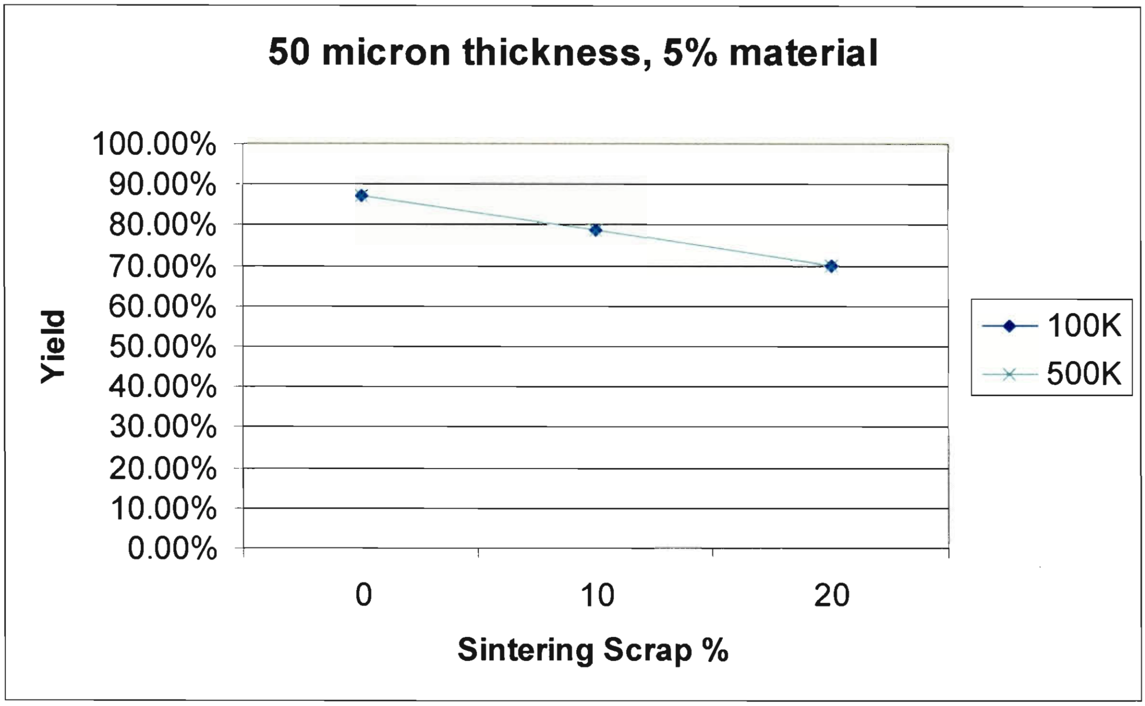


Figure 16. 50 micron Thickness, 5% Material Loss Graph

Figures eleven through sixteen show that yield stays the same regardless of the production volume. These graphs assumes each cell is a tape cast, 10cm by 10cm square that is fired using a continuously sintering kiln. The overall thickness of the cells is varied from 5, 20, and 50 microns by changing the electrolyte layer thickness.

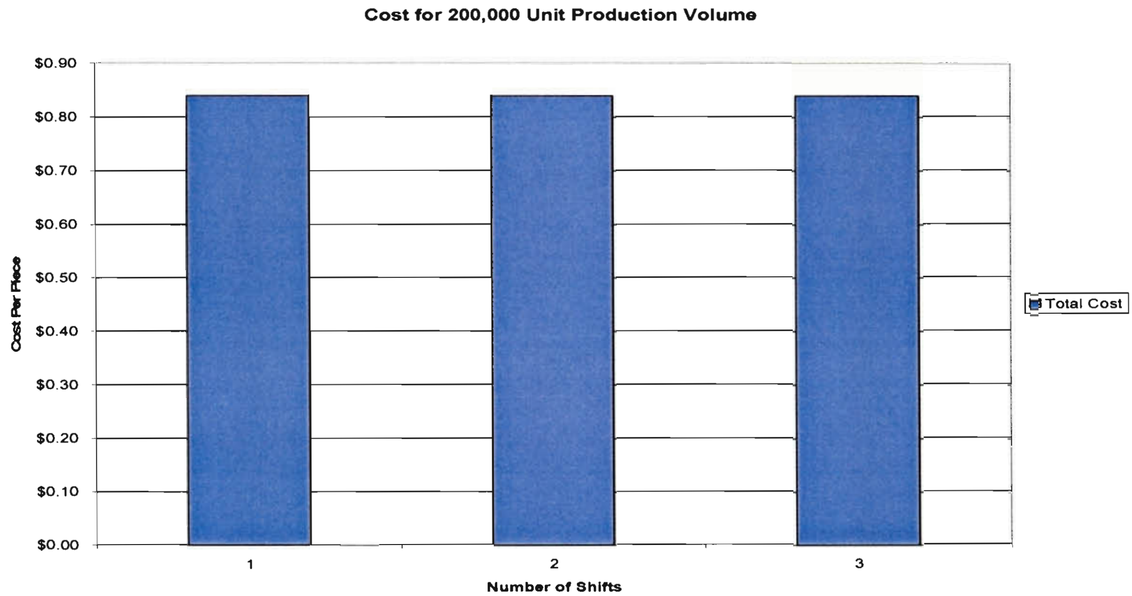


Figure 17. Cost for 200,000 Unit Production Volume Graph

Figure fifteen shows that the cost per piece does not decrease as the number of shifts increases. This is a result of the cost model. It is unclear whether or not this should be the expected result. Data for 100, 000 and 500,000 unit production show the same result. The graph assumes each cell is a tape cast, 10cm by 10cm square that is fired using a continuously sintering kiln. The overall thickness of the cells is held constant at 20 microns.

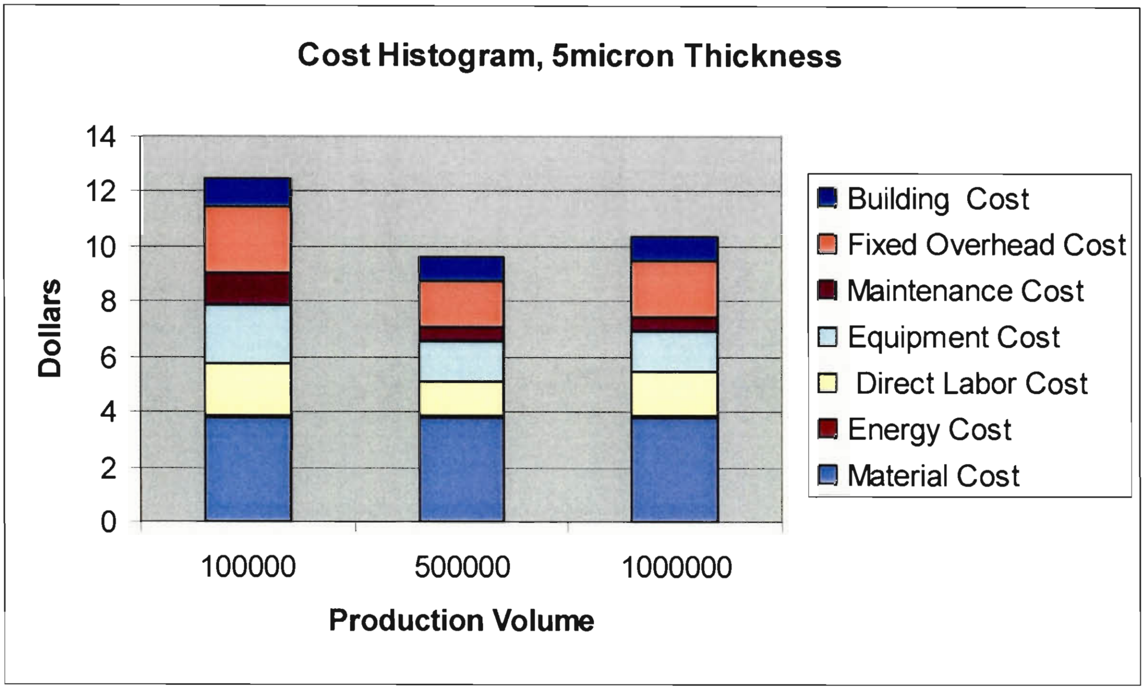


Figure 18. Cost Histogram, 5 micron Thickness

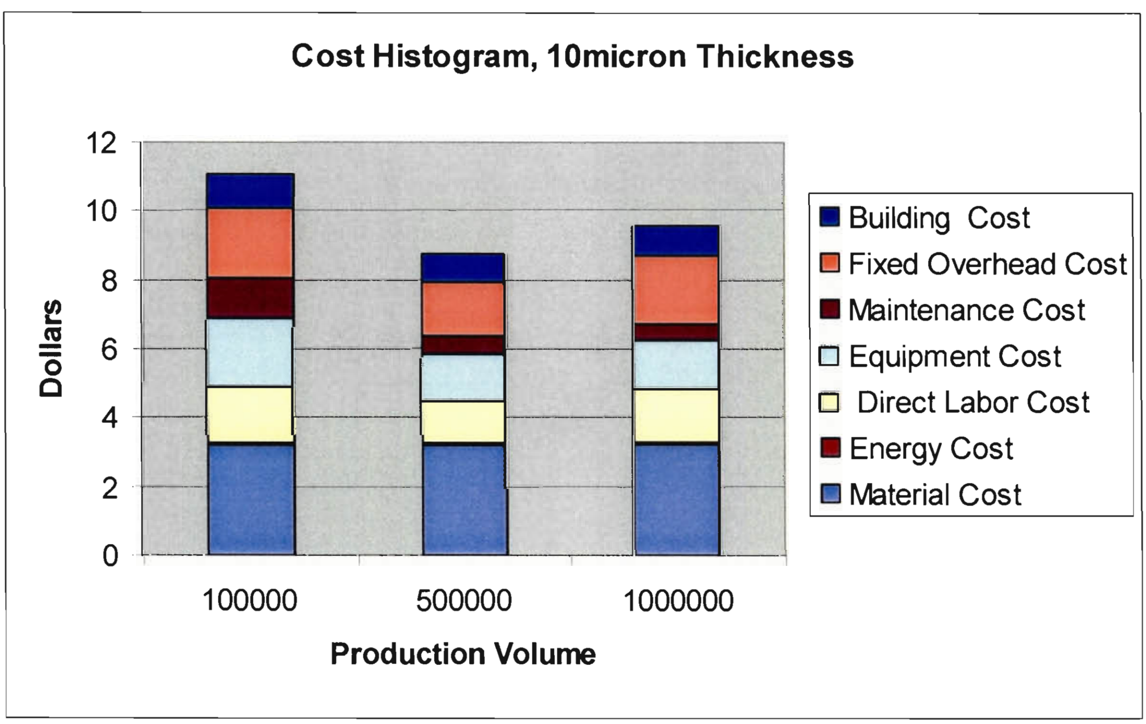


Figure 19. Cost Histogram, 10 micron Thickness

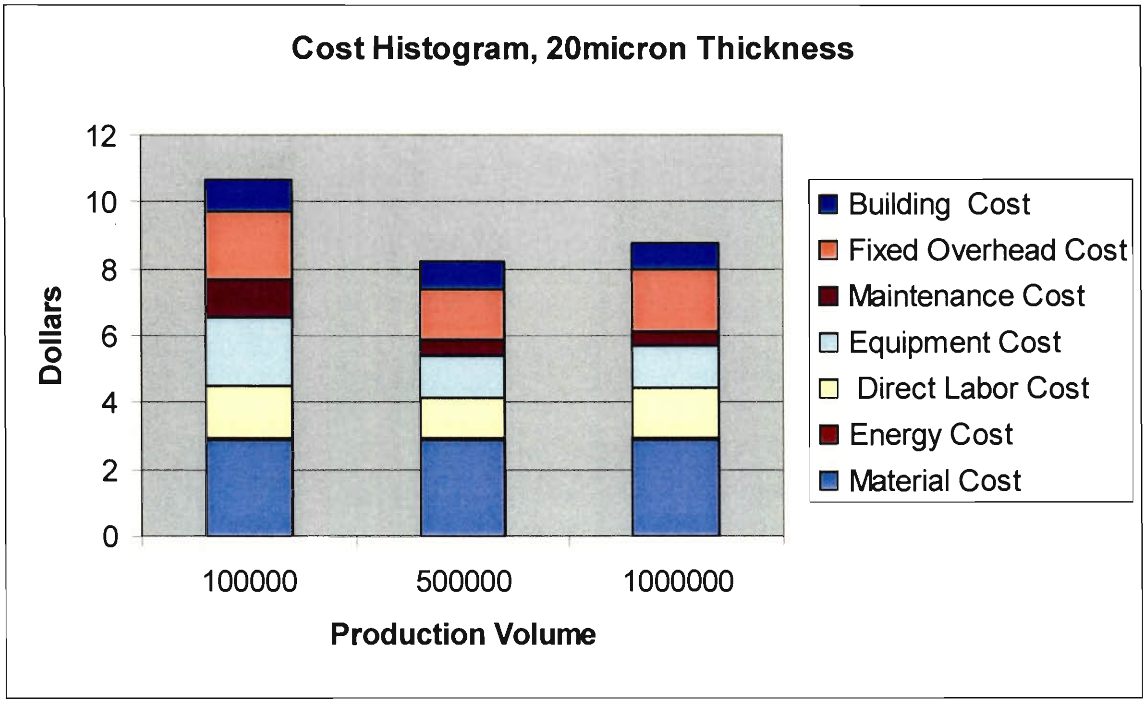


Figure 20. Cost Histogram, 20 micron Thickness

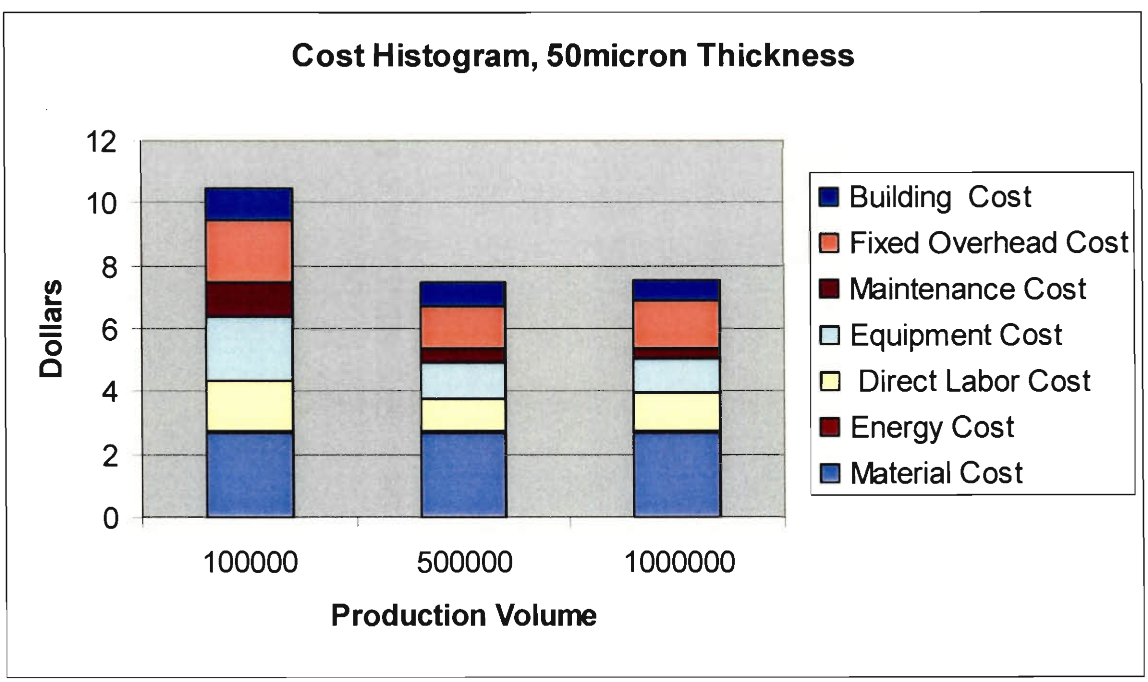


Figure 21. Cost Histogram, 50 micron Thickness

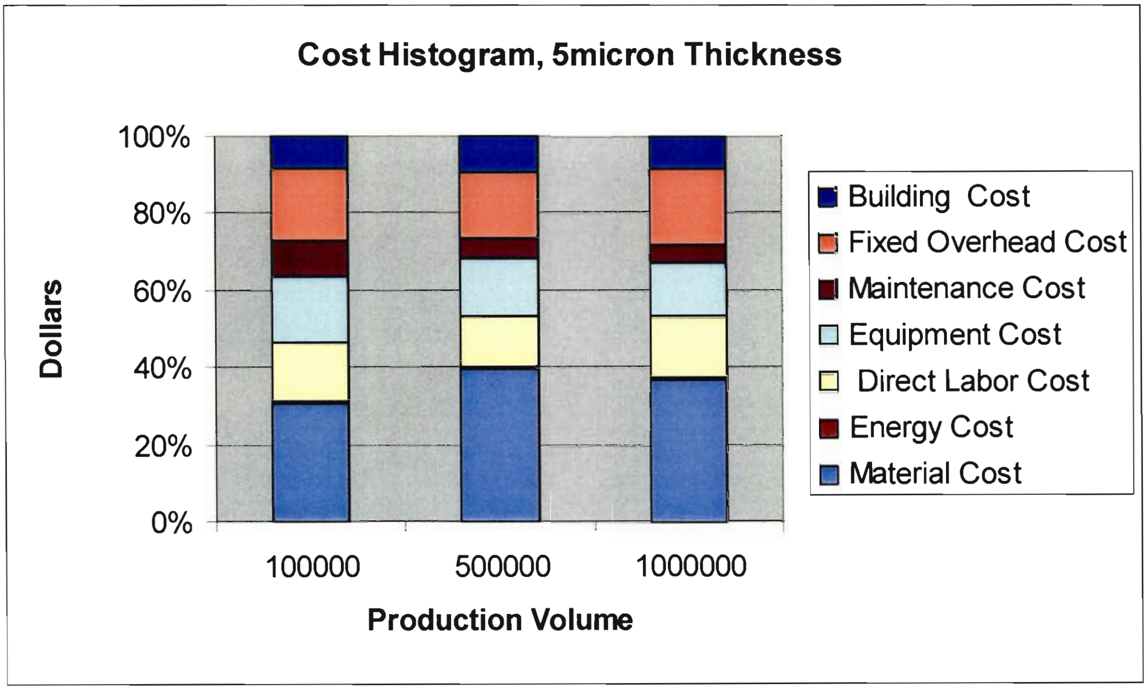


Figure 22. Cost Histogram, 5 micron Thickness

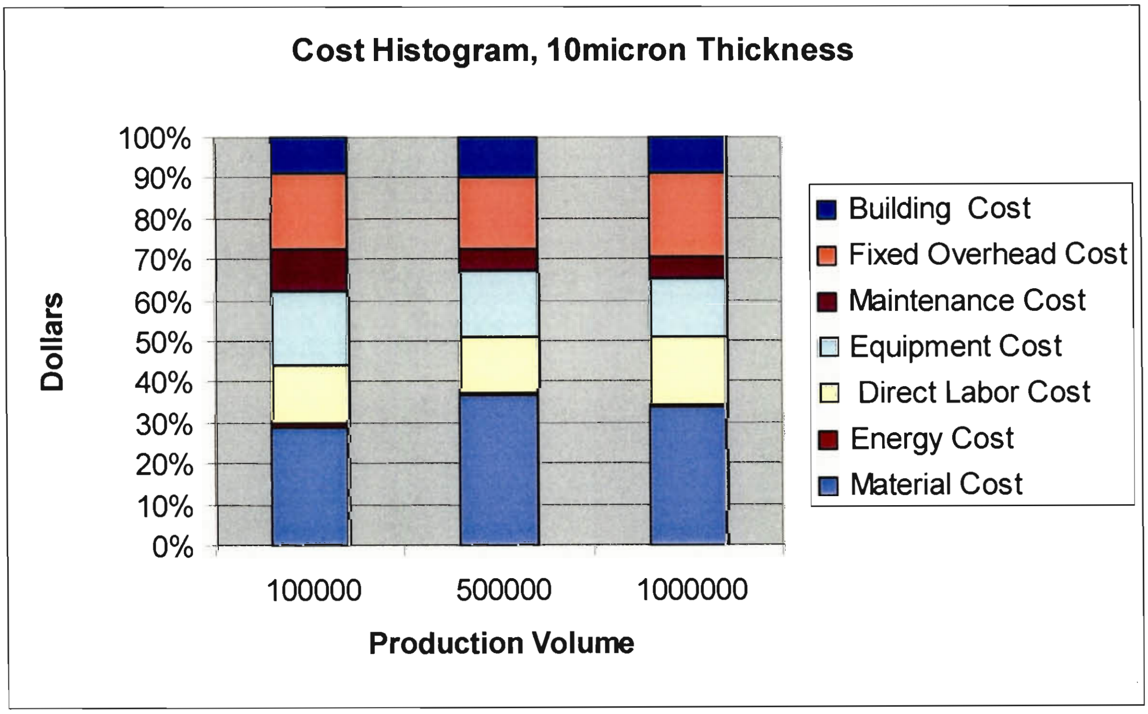


Figure 23. Cost Histogram, 10 micron Thickness

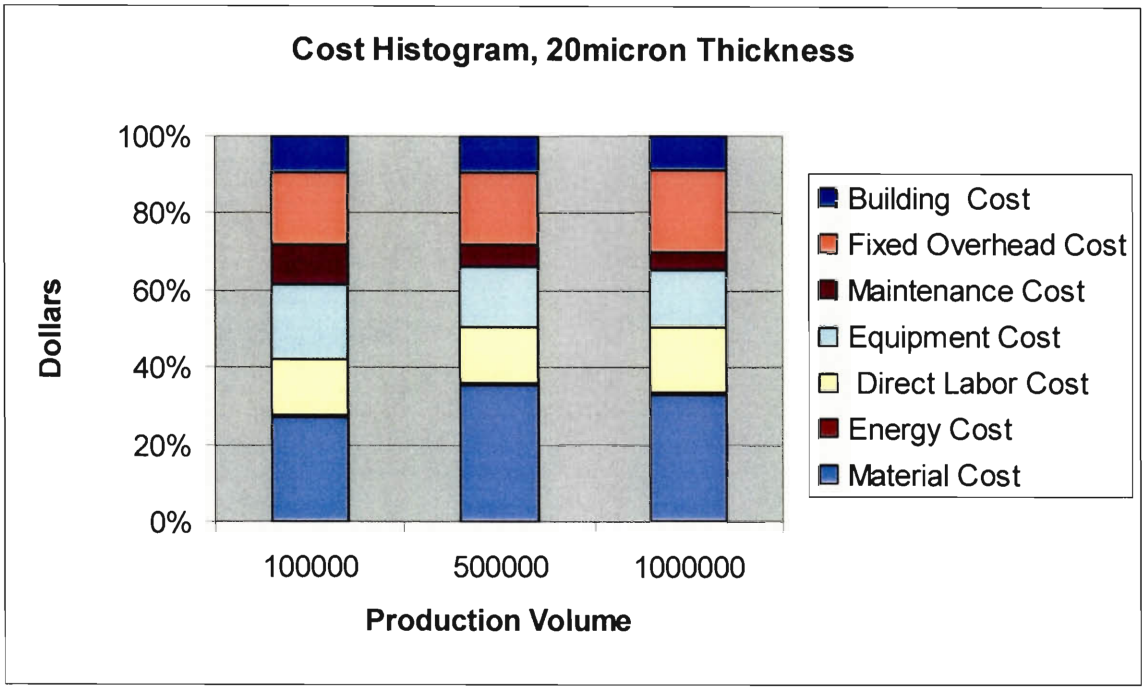


Figure 24. Cost Histogram, 20 micron Thickness

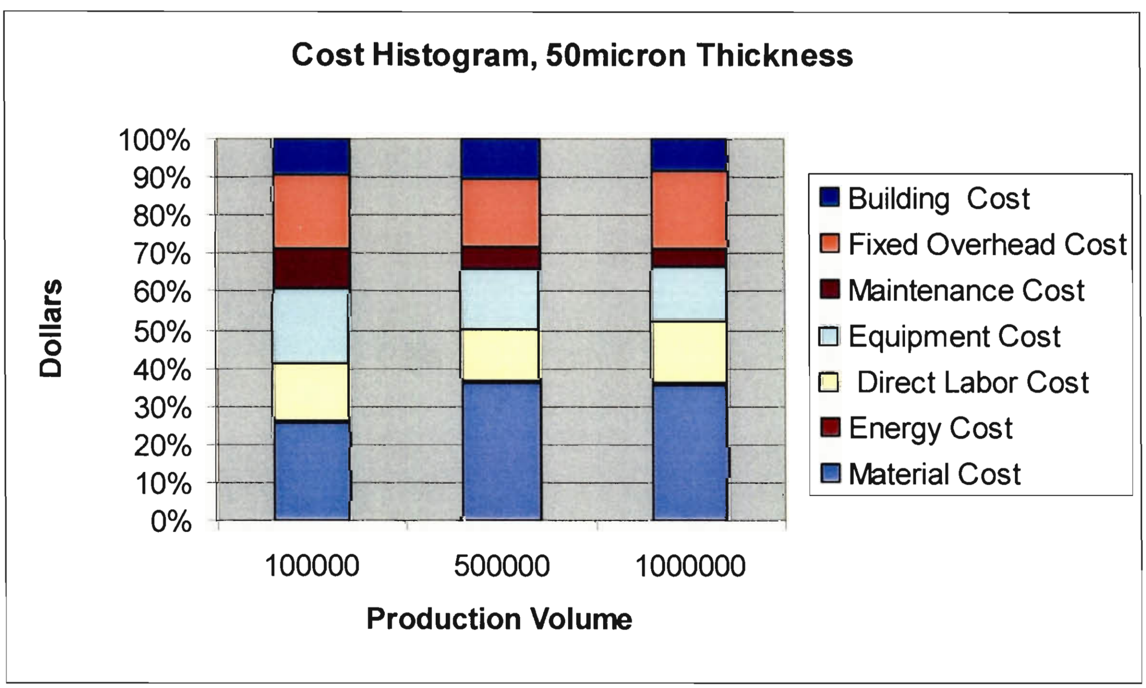


Figure 25. Cost Histogram, 50 micron Thickness

Figures eighteen through twenty-five show the total cost and how the cost is broken up into its constituent parts. Figures eighteen through twenty-one show the value the constituent parts make of the total, in dollars. Figures twenty-two through twenty-five show the percentage the constituent parts make of the total. These graphs show that material costs make up the largest percentage of the total cost for all production volumes and thicknesses. However, as production volume increases, the material cost makes up a larger portion of the total cost. After a production volume of 500k, more equipment needs to be purchased and overhead cost increases. These graphs assumes each cell is a tape cast, 10cm by 10cm square that is fired using a continuously sintering kiln. The overall thickness of the cells is varied from 5, 10, 20, and 50 microns by changing the electrolyte layer thickness.

The percentage histograms give a quick reference to how large of a percentage each part of the cost is, compared to the total cost, which is 100 percent. Where as a value based histogram only gives the amount of money spent on each constituent part, stacked to add up to the total amount. Hence, it is clearer to see with the percentage histogram how the constituent parts change individually when comparing different production volumes.

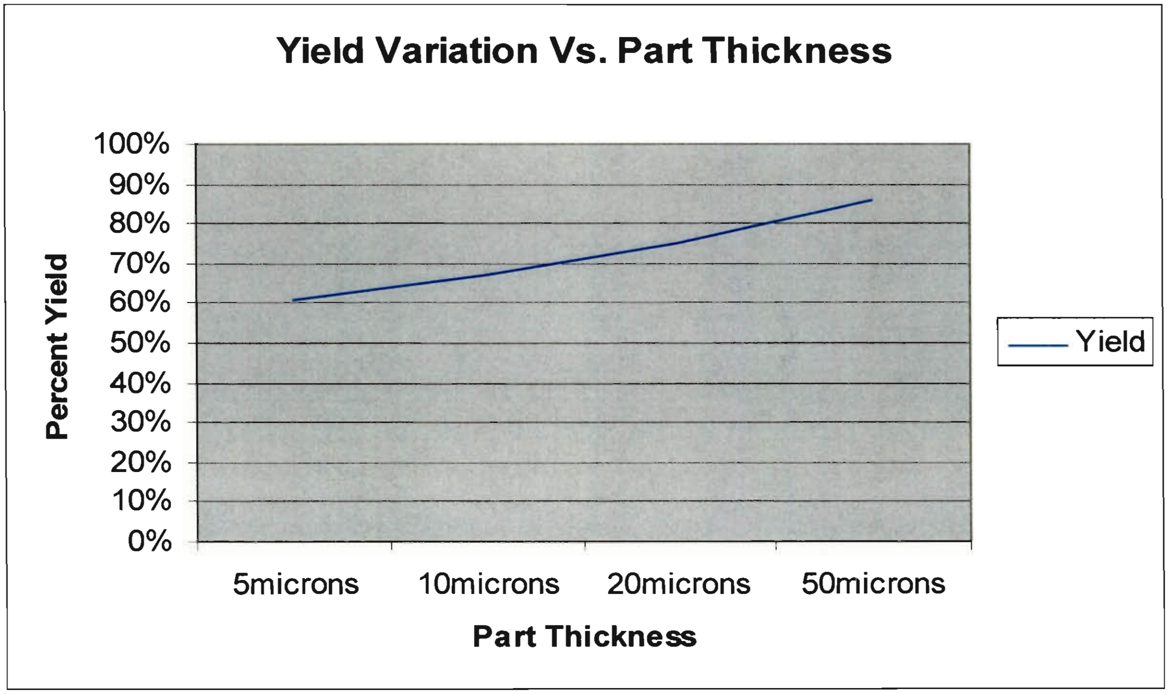


Figure 26. Yield Variation Vs. Part Thickness

As seen in Figure twenty-six, yield percentage increases as part thicknesses increases. The graph assumes each cell is a tape cast, 10cm by 10cm square that is fired using a continuously sintering kiln. The overall thickness of the cells is varied from 5, 10, 20, and 50 microns by changing the electrolyte layer thickness.

Conclusions

The results appear to be consistent with the data that was obtained for the cost model design. Due to the highly proprietary nature of the manufacturing costs of the fuel cells, reliability of the results cannot be 100 percent corroborated.

Material costs appear to be the largest hindrance in lowering the price of fuel cells. One method to bring down the cost of fuel cells would be to reduce the electrolyte layer thickness. However, the simple processes examined currently, tape casting and screen-printing, produce large scrap rates with thin electrolyte layers, hence increasing the cost.

According to the data and graphs, the manufacturing cost of one fuel cell ranges from $8 to $12, on average. Because only ten fuel cells are needed to produce one kilowatt, the price of such a fuel cell stack, neglecting the interconnect costs, would range from $80 to $120.

Appendix

Data For Yield Percentage Graphs (Pgs. 14-20)

Cost Per	Part	Production	Volume		2 Shifts		YSZ	
		of	100000	Per Day			Electrolyte	
Thickness	Mat'l Loss	Sintering Loss		Material	Energy	Labor	Total	Yield
microns	%	%		Cost	Cost	Cost	$	%
5	1	0		0.1461	0.0428	0.635	2.709689	33.51%
5	1	10		0.1582	0.0428	0.635	2.721977	30.15%
5	1	20		0.1732	0.0428	0.635	2.737277	26.80%
5	3	0		0.1484	0.0428	0.635	2.711973	32.83%
5	3	10		0.1607	0.0428	0.635	2.724504	29.55%
5	3	20		0.176	0.0428	0.635	2.74011	26.26%
5	5	0		0.1507	0.0428	0.635	2.714351	32.15%
5	5	10		0.1633	0.0428	0.635	2.727137	28.94%
5	5	20		0.179	0.0428	0.635	2.743062	25.72%
20	1	0		0.2519	0.0428	0.635	2.823538	67.86%
20	1	10		0.2757	0.0428	0.635	2.849966	61.07%
20	1	20		0.3054	0.0428	0.635	2.880554	54.29%
20	3	0		0.2563	0.0428	0.635	2.828124	66.49%
20	3	10		0.2806	0.0428	0.635	2.855026	59.84%
20	3	20		0.3109	0.0428	0.635	2.88621	53.19%
20	5	0		0.2609	0.0428	0.635	2.832896	65.12%
20	5	10		0.2857	0.0428	0.635	2.860292	58.60%
20	5	20		0.3167	0.0428	0.635	2.892098	52.09%
50	1	0		0.4372	0.0428	0.635	3.028462	90.94%
50	1	10		0.4816	0.0428	0.635	3.076744	81.85%
50	1	20		0.5371	0.0428	0.635	3.136126	72.75%
50	3	0		0.4455	0.0428	0.635	3.037124	89.11%
50	3	10		0.4908	0.0428	0.635	3.086279	80.20%
50	3	20		0.5474	0.0428	0.635	3.146762	71.28%
50	5	0		0.4541	0.0428	0.635	3.046133	87.27%
50	5	10		0.5003	0.0428	0.635	3.0962	78.54%
50	5	20		0.5582	0.0429	0.635	3.159623	69.82%
Cost Per	Part	Production	Volume		2 Shifts			
		of	500000	Per Day				
Thickness	Mat'l Loss	Sintering Loss		Material	Energy	Labor	Total	Yield
microns	%	%		Cost	Cost	Cost	$	%
5	1	0		0.1461	0.0427	0.254	1.619665	33.51%
5	1	10		0.1582	0.0427	0.254	1.632311	30.15%

5	1	20		0.1732	0.0427	0.254	1.647611	26.80%
5	3	0		0.1484	0.0427	0.254	1.621949	32.83%
5	3	10		0.1607	0.0427	0.254	1.634839	29.55%
5	3	20		0.176	0.0427	0.254	1.650445	26.26%
5	5	0		0.1507	0.0427	0.254	1.624328	32.15%
5	5	10		0.1633	0.0427	0.254	1.637471	28.94%
5	5	20		0.179	0.0427	0.254	1.653754	25.72%
20	1	0		0.2519	0.0428	0.254	1.734589	67.86%
20	1	10		0.2757	0.0428	0.254	1.760301	61.07%
20	1	20		0.3054	0.0428	0.254	1.791963	54.29%
20	3	0		0.2563	0.0428	0.254	1.739533	66.49%
20	3	10		0.2806	0.0428	0.254	1.76536	59.84%
20	3	20		0.3109	0.0428	0.254	1.797619	53.19%
20	5	0		0.2609	0.0428	0.254	1.744305	65.12%
20	5	10		0.2857	0.0428	0.254	1.770985	58.60%
20	5	20		0.3167	0.0428	0.254	1.803507	52.09%
50	1	0		0.4372	0.0428	0.254	1.938438	90.94%
50	1	10		0.4816	0.0428	0.254	1.987079	81.85%
50	1	20		0.5371	0.0428	0.254	2.047176	72.75%
50	3	0		0.4455	0.0428	0.254	1.947458	89.11%
50	3	10		0.4908	0.0428	0.254	1.996972	80.20%
50	3	20		0.5474	0.0428	0.254	2.058171	71.28%
50	5	0		0.4541	0.0428	0.254	1.956825	87.27%
50	5	10		0.5003	0.0428	0.254	2.007608	78.54%
50	5	20		0.5582	0.0428	0.254	2.0696	69.82%

Effect of Shifts Data, Graph (Pg. 21)

				Yield			
				Production	Volume		
Thickness	Mat'l Loss	Sintering Loss		50000	100000	200000	500000
microns	%	%					
5	1	0		32.84%	32.84%	32.84%	32.84%
5	1	2		29.52%	29.52%	29.52%	29.52%
5	1	4		26.20%	26.20%	26.20%	26.20%
5	1	6		22.87%	22.87%	22.87%	22.87%
5	1	8		19.55%	19.55%	19.55%	19.55%
5	1	10		16.23%	16.23%	16.23%	16.23%
5	1	12		12.90%	12.90%	12.90%	12.90%
5	1	14		9.58%	9.58%	9.58%	9.58%
5	1	16		6.26%	6.26%	6.26%	6.26%
5	1	18		2.94%	2.94%	2.94%	2.94%
5	1	20		0.00%	0.00%	0.00%	0.00%
5	2	0		31.84%	31.84%	31.84%	31.84%
5	2	2		28.52%	28.52%	28.52%	28.52%
5	2	4		25.20%	25.20%	25.20%	25.20%
5	2	6		21.87%	21.87%	21.87%	21.87%
5	2	8		18.55%	18.55%	18.55%	18.55%
5	2	10		15.23%	15.23%	15.23%	15.23%
5	2	12		11.90%	11.90%	11.90%	11.90%
5	2	14		8.58%	8.58%	8.58%	8.58%
5	2	16		5.26%	5.26%	5.26%	5.26%
5	2	18		1.94%	1.94%	1.94%	1.94%
5	2	20		0.00%	0.00%	0.00%	0.00%
5	3	0		30.84%	30.84%	30.84%	30.84%
5	3	2		27.52%	27.52%	27.52%	27.52%
5	3	4		24.20%	24.20%	24.20%	24.20%
5	3	6		20.87%	20.87%	20.87%	20.87%
5	3	8		17.55%	17.55%	17.55%	17.55%
5	3	10		14.23%	14.23%	14.23%	14.23%
5	3	12		10.90%	10.90%	10.90%	10.90%
5	3	14		7.58%	7.58%	7.58%	7.58%
5	3	16		4.26%	4.26%	4.26%	4.26%
5	3	18		0.94%	0.94%	0.94%	0.94%
5	3	20		0.00%	0.00%	0.00%	0.00%
5	4	0		29.84%	29.84%	29.84%	29.84%

5	4	2		26.52%	26.52%	26.52%	26.52%
5	4	4		23.20%	23.20%	23.20%	23.20%
5	4	6		19.87%	19.87%	19.87%	19.87%
5	4	8		16.55%	16.55%	16.55%	16.55%
5	4	10		13.23%	13.23%	13.23%	13.23%
5	4	12		9.90%	9.90%	9.90%	9.90%
5	4	14		6.58%	6.58%	6.58%	6.58%
5	4	16		3.26%	3.26%	3.26%	3.26%
5	4	18		0.00%	0.00%	0.00%	0.00%
5		20		0.00%	0.00%	0.00%	0.00%
5	5	0		28.84%	28.84%	28.84%	28.84%
5	5	2		25.52%	25.52%	25.52%	25.52%
5	5	4		22.20%	22.20%	22.20%	22.20%
5	5	6		18.87%	18.87%	18.87%	18.87%
5	5	8		15.55%	15.55%	15.55%	15.55%
5	5	10		12.23%	12.23%	12.23%	12.23%
5	5	12		8.90%	8.90%	8.90%	8.90%
5	5	14		5.58%	5.58%	5.58%	5.58%
5	5	16		2.26%	2.26%	2.26%	2.26%
5	5	18		0.00%	0.00%	0.00%	0.00%
5	5	20		0.00%	0.00%	0.00%	0.00%
20	1	0		67.54%	67.54%	67.54%	67.54%
20	1	2		64.91%	64.91%	64.91%	64.91%
20	1	4		62.29%	62.29%	62.29%	62.29%
20	1	6		59.66%	59.66%	59.66%	59.66%
20	1	8		57.03%	57.03%	57.03%	57.03%
20	1	10		54.40%	54.40%	54.40%	54.40%
20	1	12		51.77%	51.77%	51.77%	51.77%
20	1	14		49.14%	49.14%	49.14%	49.14%
20	1	16		46.51%	46.51%	46.51%	46.51%
20	1	18		43.88%	43.88%	43.88%	43.88%
20	1	20		41.25%	41.25%	41.25%	41.25%
20	2	0		66.54%	66.54%	66.54%	66.54%
20	2	2		63.91%	63.91%	63.91%	63.91%
20	2	4		61.29%	61.29%	61.29%	61.29%
20	2	6		58.66%	58.66%	58.66%	58.66%
20	2	8		56.03%	56.03%	56.03%	56.03%
20	2	10		53.40%	53.40%	53.40%	53.40%
20	2	12		50.77%	50.77%	50.77%	50.77%
20	2	14		48.14%	48.14%	48.14%	48.14%

20	2	16		45.51%	45.51%	45.51%	45.51%
20	2	18		42.88%	42.88%	42.88%	42.88%
20	2	20		42.25%	42.25%	42.25%	42.25%
20	3	0		65.54%	65.54%	65.54%	65.54%
20	3	2		62.91%	62.91%	62.91%	62.91%
20	3	4		60.29%	60.29%	60.29%	60.29%
20	3	6		57.66%	57.66%	57.66%	57.66%
20	3	8		55.03%	55.03%	55.03%	55.03%
20	3	10		52.40%	52.40%	52.40%	52.40%
20	3	12		49.77%	49.77%	49.77%	49.77%
20	3	14		47.14%	47.14%	47.14%	47.14%
20	3	16		44.51%	44.51%	44.51%	44.51%
20	3	18		41.88%	41.88%	41.88%	41.88%
20	3	20		41.25%	41.25%	41.25%	41.25%
20	4	0		64.54%	64.54%	64.54%	64.54%
20	4	2		61.91%	61.91%	61.91%	61.91%
20	4	4		59.29%	59.29%	59.29%	59.29%
20	4	6		56.66%	56.66%	56.66%	56.66%
20	4	8		54.03%	54.03%	54.03%	54.03%
20	4	10		51.40%	51.40%	51.40%	51.40%
20	4	12		48.77%	48.77%	48.77%	48.77%
20	4	14		46.14%	46.14%	46.14%	46.14%
20	4	16		43.51%	43.51%	43.51%	43.51%
20	4	18		40.88%	40.88%	40.88%	40.88%
20		20		40.25%	40.25%	40.25%	40.25%
20	5	0		63.54%	63.54%	63.54%	63.54%
20	5	2		60.91%	60.91%	60.91%	60.91%
20	5	4		58.29%	58.29%	58.29%	58.29%
20	5	6		55.66%	55.66%	55.66%	55.66%
20	5	8		53.03%	53.03%	53.03%	53.03%
20	5	10		50.40%	50.40%	50.40%	50.40%
20	5	12		47.77%	47.77%	47.77%	47.77%
20	5	14		45.14%	45.14%	45.14%	45.14%
20	5	16		42.51%	42.51%	42.51%	42.51%
20	5	18		39.88%	39.88%	39.88%	39.88%
20	5	20		39.25%	39.25%	39.25%	39.25%
50	1	0		90.86%	90.86%	90.86%	90.86%
50	1	2		88.70%	88.70%	88.70%	88.70%
50	1	4		86.54%	86.54%	86.54%	86.54%

50	1	6		84.37%	84.37%	84.37%	84.37%
50	1	8		82.21%	82.21%	82.21%	82.21%
50	1	10		80.05%	80.05%	80.05%	80.05%
50	1	12		77.89%	77.89%	77.89%	77.89%
50	1	14		75.72%	75.72%	75.72%	75.72%
50	1	16		73.56%	73.56%	73.56%	73.56%
50	1	18		71.40%	71.40%	71.40%	71.40%
50	1	20		69.23%	69.23%	69.23%	69.23%
50	2	0		89.86%	89.86%	89.86%	89.86%
50	2	2		87.70%	87.70%	87.70%	87.70%
50	2	4		85.54%	85.54%	85.54%	85.54%
50	2	6		83.37%	83.37%	83.37%	83.37%
50	2	8		81.21%	81.21%	81.21%	81.21%
50	2	10		79.05%	79.05%	79.05%	79.05%
50	2	12		76.89%	76.89%	76.89%	76.89%
50	2	14		74.72%	74.72%	74.72%	74.72%
50	2	16		72.56%	72.56%	72.56%	72.56%
50	2	18		70.40%	70.40%	70.40%	70.40%
50	2	20		68.23%	68.23%	68.23%	68.23%
50	3	0		88.86%	88.86%	88.86%	88.86%
50	3	2		86.70%	86.70%	86.70%	86.70%
50	3	4		84.54%	84.54%	84.54%	84.54%
50	3	6		82.37%	82.37%	82.37%	82.37%
50	3	8		80.21%	80.21%	80.21%	80.21%
50	3	10		78.05%	78.05%	78.05%	78.05%
50	3	12		75.89%	75.89%	75.89%	75.89%
50	3	14		73.72%	73.72%	73.72%	73.72%
50	3	16		71.56%	71.56%	71.56%	71.56%
50	3	18		69.40%	69.40%	69.40%	69.40%
50	3	20		67.23%	67.23%	67.23%	67.23%
50	4	0		87.86%	87.86%	87.86%	87.86%
50	4	2		85.70%	85.70%	85.70%	85.70%
50	4	4		83.54%	83.54%	83.54%	83.54%
50	4	6		81.37%	81.37%	81.37%	81.37%
50	4	8		79.21%	79.21%	79.21%	79.21%
50	4	10		77.05%	77.05%	77.05%	77.05%
50	4	12		74.89%	74.89%	74.89%	74.89%
50	4	14		72.72%	72.72%	72.72%	72.72%
50	4	16		70.56%	70.56%	70.56%	70.56%
50	4	18		68.40%	68.40%	68.40%	68.40%

50		20		66.23%	66.23%	66.23%	66.23%
50	5	0		86.86%	86.86%	86.86%	86.86%
50	5	2		84.70%	84.70%	84.70%	84.70%
50	5	4		82.54%	82.54%	82.54%	82.54%
50	5	6		80.37%	80.37%	80.37%	80.37%
50	5	8		78.21%	78.21%	78.21%	78.21%
50	5	10		76.05%	76.05%	76.05%	76.05%
50	5	12		73.89%	73.89%	73.89%	73.89%
50	5	14		71.72%	71.72%	71.72%	71.72%
50	5	16		69.56%	69.56%	69.56%	69.56%
50	5	18		67.40%	67.40%	67.40%	67.40%
50	5	20		65.23%	65.23%	65.23%	65.23%

Histogram Data (Pgs. 22-25) Also Graph on Pg. 12

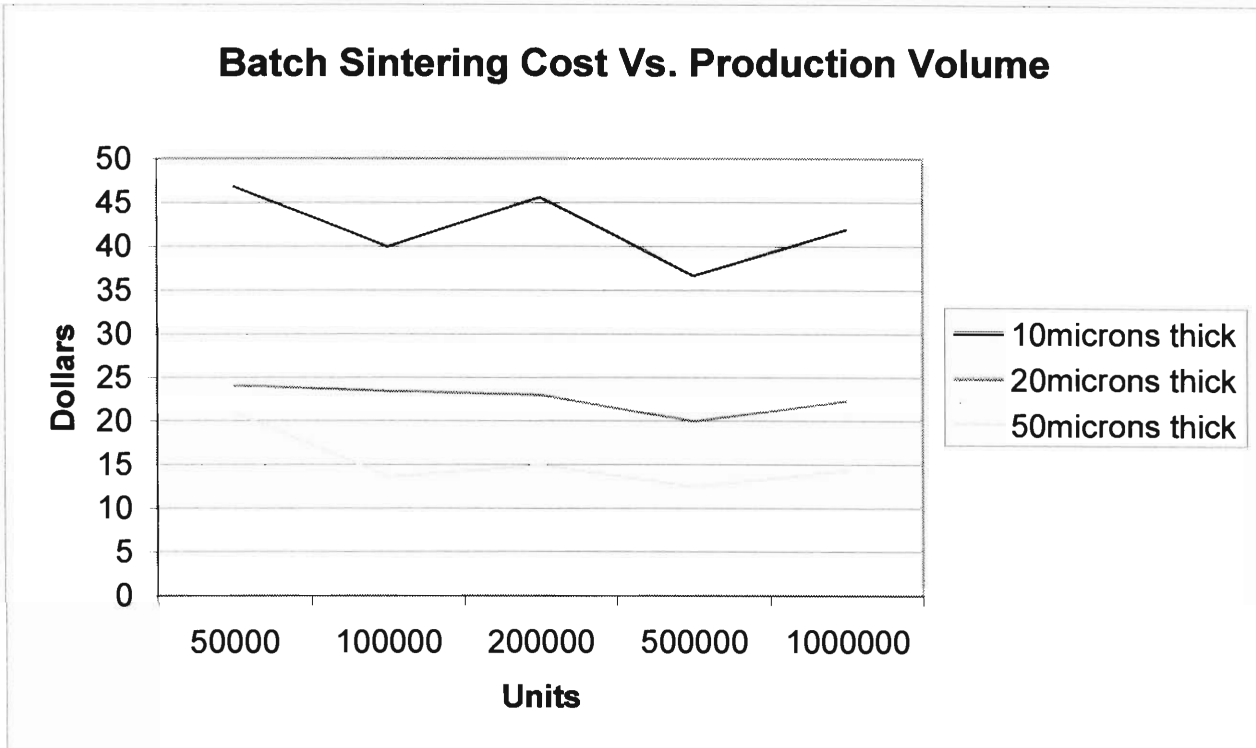
Thickness		Production Volume		
	100000	500000	1000000	
	3.815532	3.815532	3.815532	Material Cost
5microns	0.064641	0.046095	0.045698	Energy Cost
	1.90512	1.27008	1.619352	Direct Labor Cost
	2.096384	1.45336	1.460486	Equipment Cost
	1.175377	0.517377	0.505377	Maintenance Cost
	2.38289	1.645815	2.022107	Fixed Overhead Cost
	1.004642	0.904917	0.876161	Building Cost
	12.44459	9.653176	10.34471	Total Fabrication Cost
10microns	3.228164	3.228164	3.228164	Material Cost
	0.06116	0.042884	0.04252	Energy Cost
	1.5876	1.206576	1.5876	Direct Labor Cost
	2.018001	1.374977	1.374977	Equipment Cost
	1.148209	0.490209	0.478209	Maintenance Cost
	2.029144	1.55776	1.97625	Fixed Overhead Cost
	1.000437	0.843199	0.843199	Building Cost
	11.07271	8.743768	9.530919	Total Fabrication Cost
20microns	2.884186	2.884186	2.884186	Material Cost
	0.057339	0.03939	0.036513	Energy Cost
	1.5876	1.206576	1.492344	Direct Labor Cost
	2.018001	1.279136	1.279208	Equipment Cost
	1.118746	0.460746	0.448746	Maintenance Cost
	2.025067	1.539391	1.852894	Fixed Overhead Cost
	0.995878	0.781126	0.781126	Building Cost
	10.68682	8.190552	8.775017	Total Fabrication Cost
50microns	2.69793	2.69793	2.69793	Material Cost
	0.052939	0.030484	0.032794	Energy Cost
	1.5876	1.016064	1.206576	Direct Labor Cost
	2.018001	1.183438	1.073987	Equipment Cost
	1.087186	0.429186	0.369686	Maintenance Cost
	2.020619	1.325101	1.501566	Fixed Overhead Cost
	0.990994	0.776242	0.64802	Building Cost
	10.45527	7.458446	7.53056	Total Fabrication Cost

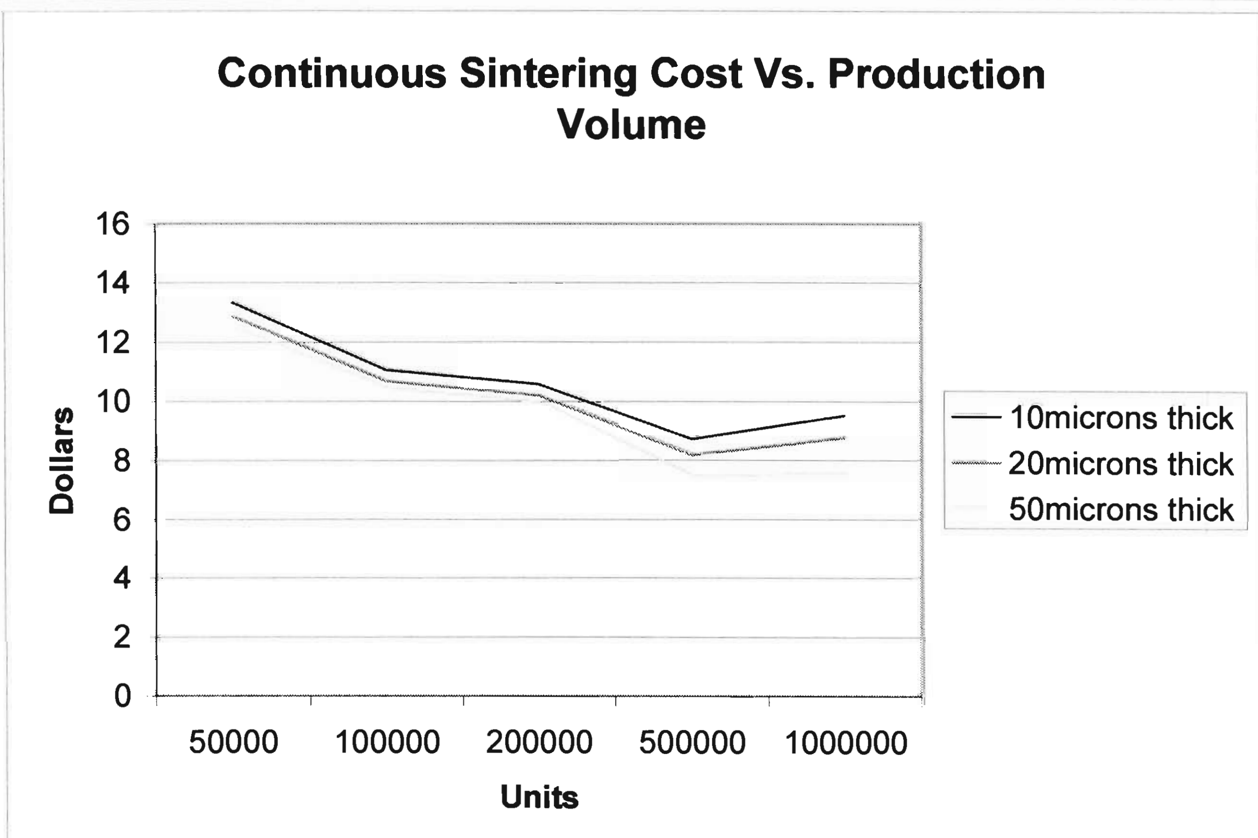
Data for Yield Variation Graph Pg. 27

Thickness	Production Volume				
	50000	100000	200000	500000	1000000
	Yield				
5microns	61%	61%	61%	61%	61%
10microns	67%	67%	67%	67%	67%
20microns	75%	75%	75%	75%	75%
50microns	86%	86%	86%	86%	86%

Comparison of Cost Between Continuous Sintering and Batch Sintering

	Continuous Sintering		Production Volume		
	50000	100000	200000	500000	1000000
	Total cost per piece				
10microns	13.33874	11.07271	10.59424	8.743768	9.530919
20microns	12.86318	10.68682	10.2086	8.190552	8.775017
50microns	12.53088	10.45527	9.977549	7.458446	7.53056
	Batch Sintering		Production Volume		
	50000	100000	200000	500000	1000000
	Total cost per piece				
10microns	46.8388	39.95928	45.61076	36.69177	41.89737
20microns	24.04494	23.41904	22.98342	19.96877	22.33348
50microns	20.89236	13.57038	14.92579	12.43774	14.35879


Batch Sintering Cost Vs. Production Volume
50
45
40
35
30
25
20
15
10
5
0
Dollars
50000
100000
200000
500000
1000000
Units
10microns thick
20microns thick
50microns thick


Continuous Sintering Cost Vs. Production Volume
16
14
12
10
8
6
4
2
0
Dollars
50000
100000
200000
500000
1000000
Units
10microns thick
20microns thick
50microns thick

References

1. Carrette, Friedrich, Stimming: *Fuel Cells-Fundamentals and Applications,* Pgs. 13-18.
2. H. Woodward: A Performance Based, Multi-Process Cost Model for Solid Oxide Fuel Cells, MS Thesis WPI, May 2003.
3. http://www.cranfield.ac.uk/sims/materials/processing/tcintro.htm
4. http://www.cyf-kr.edu.pl/academic/OBRMHiR/ imaps/data/txt/txt11.htm
5. http://www.fuelcells.org/whatis.htm
6. M. Koslowske: A Performance Based, Multi-Process Cost Model for Solid Oxide Fuel Cells, MS Thesis WPI, May 2003.
7. http://msl1.mit.edu/356_1998/rk_1/RK_15.htm
8. http://www.glue.umd.edu/~sandborn/courses/lcecon.html