Production System Design and Cycle Time Reduction in a Fuel Cell Manufacturing Operation
by
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Submitted to the Sloan School of Management and the MIT Department of Mechanical Engineering in Partial Fulfillment of the Requirements for the Degrees of Master of Science in Management and Master of Science in Mechanical Engineering

in conjunction with the Leaders for Manufacturing Program at the Massachusetts Institute of Technology June 1996

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Abstract

In a new manufacturing environment, there are many concerns that must be addressed for the successful manufacture of a product. When this environment carries the burden of excessive cost and schedule pressure, it is often difficult to know how and where to act. In this environment, it is important to have easy access to key information and then have a methodology for applying this information to accomplish the goals of the organization. This thesis presents (1) an operations tool for Fuel Cell manufacturing that provides vital information to manufacturing managers and (2) provides a case study for utilizing the model within the organization.

The first step in this thesis work was to develop a complete manufacturing model which includes both cost and operational inputs and produces as output the relevant operational and cost metrics for fuel cell manufacturing. Among the notable outputs are capacity utilization, yearly shifts required for production, and scrap cost. Output metrics for the model are added or deleted as appropriate. The second step utilizes the manufacturing model to identify the limiting process and then determines the best production planning system for this process. The output of this model is the optimal lot size plan given the current operating conditions.

Phase two of this work involves the analysis of the bottleneck operation and presents proposal(s) for improvements in the setup time, start-up time, and/or cycle time. Opportunities exist for the reduction of the limiting sub-process cycle time through heat transfer analysis of a critical process and duplication of some equipment. Setup and startup cost reduction possibilities exist which become important issues as the equipment reaches full utilization. Moving startup operations to non-production time and examining ways to reduce the setup time all contribute to increased production time. These initiatives result in increased capacity and cost avoidance in the face of demand growth as well as reduced production lead time. A proposal discusses the possible and recommended changes for this operation over time.
The results of this work are three-fold and all or part of this work has been implemented at the internship site. First, is a model that provides key information to the manufacturing organization and serves as a “what-if” tool for analysis. Second, an optimized operation of the bottleneck process results in cost savings. Finally, process improvement recommendations increase the capability of the bottleneck, thus postponing large capital investment.

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1. Introduction

1.1 Business Overview and Statement of the Problem

International Fuel Cells Corporation (IFC) is a division of United Technologies Corporation that reports through the Hamilton Standard Division. Over their 30 year history, they dedicated their efforts to the development of fuel cell technology for the space program (Apollo and Space Shuttle) and now produce and market a commercial product called the PC25™. This product competes in the electrical power co-generation as well as the premium power markets and is the only commercial fuel cell product offered today. The next chapter discusses, in detail, the manufacture and operation of a Fuel Cell.

Currently, the organization is in the middle of a transition from space and research work to full-scale commercial production. Coupled with this, the sales and marketing staff face the challenge of breaking into the co-generation market and securing sales for the newly developed manufacturing facility. The sales forecast for the next few years reflects this market development effort and shows a gradual growth in the volume produced. This increase in volume will help drive the cost of the PC25™ down to competitive levels. IFC must have cost reduction in order to actively compete in whatever market they choose to enter. Cost reduction and the optimization of the manufacturing facility at the projected volumes are the major problems facing them today. These problems must be solved for them to continue to grow in this market.
1.2 Thesis Objective and Deliverables

The objective of this thesis work is to develop a manufacturing model which will aid in the optimization of Fuel Cell stack manufacturing (the power generating portion of the powerplant). The proposal postulates that the optimization of this process will also result in cost reduction for the manufacturing operations. Figure 1-1 provides a graphical representation of this work and shows the outputs from its completion.

![Diagram showing process, method, and outputs]

**Figure 1-1**

This work begins by completely describing the manufacturing facility in a common spreadsheet model. The inputs for this are operations and cost based and the outputs show current equipment utilization, scrap cost, and the maximum possible production. The model’s purpose is to provide a “what if” tool for use in manufacturing projections.
for the future as well as to provide a method to identify the bottleneck operation and its input sensitivity.

The next step involves the actual optimization of the bottleneck process given fixed inputs. Since this is a batch operation, we utilize the Economic Order Quantity (EOQ) model to determine the optimal lot size to run at this operation given setup and part cost information. Output from this exercise is the optimal lot size and detailed cost information for the bottleneck process.

Finally, we present proposals for improving the bottleneck operation. Areas investigated include setup/changeover operation, cycle time reduction, and start-up operations as well as an analysis for future investment decisions. The outputs from this are recommendations for both short and long term improvements with equipment quotes and details as appropriate.

It is our intention that the first model be utilized in a real-time manner for future capacity projections as well as sensitivity analyses. The manufacturing model and engineering improvement efforts work together to show how a tool can be utilized to focus scarce engineering resources on the areas with the greatest chance for significant impact. Our further hope is that the identification of the bottleneck and the subsequent optimization of the process and its flow will be a case study example for other optimization efforts within the cell stack assembly (CSA) manufacturing arena.

1.3 Scope and Limitations

The scope of this work involves the Cell Stack Manufacturing area and includes all or a portion of this operation. For the development of the models and analysis, we omitted
all inputs from vendors (e.g. graphite substrate processing times and inventory) and thus assumed them to be in abundance. In general, a change from this assumption will not alter the results of the model.

The limitations of this work are important for the full understanding and use of the models. First, the model only includes the CSA manufacturing area and ignores the outside suppliers. This is a necessary assumption for the completion of the work in the required time. The downside is that this work does not provide as much insight as possible into the real lead-time associated with a cell stack.

Second, the work is presented in discrete time with many aggregate calculations. This treatment provides a very good estimate as to the capability and feasibility of the production strategy and equipment capability, but fails to confirm this in real time. A possible solution to this is to build a simulation model using the model inputs as inputs to the simulation and running it to obtain better resolution in terms of the effects of equipment reliability, machine capacity, and production strategy on equipment performance.

1.4 Thesis Structure

Section 1 of this work presents an introduction to the business, market, and shows the problems addressed by this thesis. Section 2 provides detailed background into Fuel Cell development and component parts. In addition, it presents a description of the manufacturing processes utilized to produce a cell stack assembly. Section 3 introduces and describes the manufacturing operations model (MOM) and presents key results from its output. A discussion of the equations and overall conceptual framework is included
for those interested. Section 4 presents the process optimization model and methodology and shows the potential results associated with implementation of the solution. Section 5 discusses the bottleneck improvement efforts and presents recommendations for future investment. Section 6 presents a summary of the work and provides conclusions regarding the overall benefit of the thesis work. The final section presents references used in creating this work.
2. Background

2.1 IFC's PC25\textsuperscript{TM} Phosphoric Acid Fuel Cell Powerplant

2.1.1 Fuel Cell Purpose and Description

A fuel cell is a power generation device which uses chemical inputs to create electricity. The chemical reaction combines hydrogen-rich gas with oxygen in the presence of a catalyst to generate electricity and steam (H\textsubscript{2}O). This is in stark contrast to the more traditional forms of power generation like diesel engines and gas turbines which involve combustion of a fuel to generate power. This chemical process produces greater fuel to electricity conversion efficiencies without the production of unwanted side products, which makes it an attractive option for the generation of power.

The fuel cell powerplant can best be understood by considering the example of a simple battery and a brief review of the electrolysis process. The fuel cell operates in a similar manner as a battery. While a battery utilizes reactants that are contained within its casing, the fuel cell uses fuel that is continuously supplied from external sources. Oxygen from the surrounding atmosphere and reformed hydrogen-rich fuel (such as natural gas) continuously pass through the fuel cell and are converted into power. An inverter transforms this power from direct current to alternating current for use in the given application.

Intuitively, the reaction can be best understood by thinking of the operation as a reverse electrolysis process. Electrolysis of water to produce hydrogen involves applying a voltage to a body of water. This causes two gases (oxygen and hydrogen) to be released
and allows the collection of the hydrogen gas (Figure 2-1). The fuel cell operates in the reverse of this process. The hydrogen (from the fuel) and oxygen (from the external environment) combine in the presence of an electrolyte (phosphoric acid) within the fuel cell to produce \( H_2O \) and release an electron. The electrolyte serves the dual purpose of allowing for the transfer of charged ions within the cell and insulating the electrodes. This electron attaches to the electrode creating a voltage differential between the two plates. Hundreds of cells stacked in series comprise the PC25™ Fuel Cell which generates 200 kW of power. Figure 2-2 provides a graphical representation of the reaction and shows the chemical equation which governs the reaction.

### 2.1.2 Advantages to Fuel Cell Power Generation

The advantages of utilizing fuel cells for power generation can be broken down into three distinct categories. The first is the efficiency and performance characteristics of the conversion process, the second is the modularity and transportability of the unit, and the third is the favorable environmental impact.

Any analysis of efficiencies in the power generation arena shows high efficiency yields for the conversion of fuel into power. The typical internal combustion engine is only 30% efficient. For the phosphoric acid fuel cell (such as the PC25™), this efficiency number ranges between 40% and 45%. Figure 2-3 shows a comparison between the fuel cell conversion efficiency and the other major processes currently in use for power generation. The fuel cell clearly has an efficiency advantage over every existing process both in total efficiency and in efficiency as a function of power output. The fuel cell is remarkably consistent in its efficiency, where other processes show a trend of poor
efficiency at low power output. In addition, utilization of waste heat in the form of steam from the fuel cell reaction increases the efficiency number to 80% to 85%.

The performance of the fuel cell is also a major selling point. The fact that power is generated through a chemical reaction means that the fuel cell has an excellent dynamic response to step loads (up to 1MW / second). In addition, the on-site location means that it provides a very clean power source (little distribution loss). These facts make it an ideal product for applications requiring clean power (IC manufacturers, hospitals, etc.) and for those who may experience step loads that require a fast response.

The second advantage is that the fuel cell’s modularity which makes it an ideal product for remote applications and the above described situations requiring clean power. The fuel cell powerplant requires only one input (a hydrogen source) which can be supplied from the local gas company or by using a containerized source. This makes it a relevant option for third world countries and remote parts of developed countries where the electrical infrastructure is not established.

Finally, the minimal environmental impact of the fuel cell makes it quite attractive in today’s environmentally conscious world. The only emissions from the fuel cell are trace amounts of carbon monoxide and carbon dioxide which is in stark contrast to the currently utilized power generation processes. In addition, the fuel cell operates without any moving parts and doesn’t require a combustion process which makes it very quiet. These attributes combine to make the fuel cell an environmentally friendly power generation device.
2.1.3 Fuel Cell Cost Competitiveness

Fuel cells have been in use in both test and space applications for the last 25 years. Their high power-to-weight ratio and the ability to drink the water output has made it the powerplant of choice for the US space program (starting with the Apollo program and continuing through today in the Space Shuttle program). Commercial acceptance of this product is impractical due to the high cost of purchasing raw materials and restrictive operating characteristics.

International Fuel Cells Corporation produces a powerplant for space applications and recently began production of a commercial powerplant. ONSI Corporation markets and sells the commercial powerplant using the trademark PC25. The unit produces 200 kW of power and low grade steam using natural gas as the fuel input. The powerplant has an operating life of 40,000 hours (about 5 years) and has an availability of over 95%. The majority of the downtime is scheduled maintenance.

Comparing the PC25™ powerplant with other proven power generation processes shows that its cost of electricity is significantly higher than general purchased power cost in the United States. Current PC25™ powerplants have a market niche in geographic locations with very high power cost and/or in applications where high power reliability and/or environmental regulations prohibit use of alternative equipment. Significant further cost reduction is required to reach a majority of the market. While actual cost reduction history and projections are proprietary to IFC, weight and volume are improving rapidly with a confirming downward trend and cost follows a similar pattern.
2.1.4 PC25™ Configuration

The PC25™ powerplant produces 200 kW of power at the voltage and frequency supplied normally by a standard electrical power grid. The inputs required are a natural gas source and oxygen supplied from the external environment. In addition, the fuel cell must be attached to a cooling tower for the removal of excess process heat. The physical footprint is 10 feet high, by 10 feet wide, by 18 feet long and it weighs 20 tons. Electrical connection from the fuel cell to the application is a simple, standard connection.

There are three major sections that make up the PC25™ powerplant (Figure 2-4). These are fuel processing, power generation (cell stack), and power conditioning. The fuel processing section is the equipment that converts the natural gas input into hydrogen. Hydrogen is the real input fuel to the cell stack. This process involves reacting the natural gas with steam (some of which is a by-product of the cell stack operation) to produce hydrogen and carbon dioxide. Power production occurs in the cell stack which makes it the heart of the fuel cell. The hydrogen reacts with oxygen from the air in the presence of a catalyst and an electrolyte. The catalyst enables the reaction to occur and the electrolyte, phosphoric acid in this application, acts as a conduit for the charged ions. Phosphoric acid can withstand the level of impurities found in natural gas which makes it ideal for this application. The final portion of the fuel cell is the power conditioner. This section converts the direct current produced by the cell stack into alternating current which makes the fuel cell customizable to specific country applications and requirements.
2.1.5 Cell Stack Composition and Part Description

Cell Definition

The cell stack, the power generating portion of the fuel cell, is a grouping of 256 individual cells within which the reactions described in the previous section take place. A single cell has the following components: an anode and cathode electrode, an anode and cathode electrode reservoir plate (ERP), a separator plate, and a cooler to regulate the cell temperature. Each electrode (anode and cathode) contains a catalyst layer which facilitates the chemical reaction of hydrogen and oxygen. An SiC matrix layer separates this electrode pair which prevents electrical shorting. The separator plate accomplishes this by preventing acid and gas to migrate between cells. In this function, it blocks the transfer of gas and acid but allows electrical and thermal conduction through the cell. A useful analogy for the cell stack is batteries in a flashlight. Stacking of cells, like batteries, increases the voltage and thus the power available from the cell stack since the current runs “vertically” through the cells. Figure 2-5 shows the composition of a substack within the PC25™ stack assembly.

Materials

Graphite makes up the majority of the composition of the cell stack. This is due to the fact that graphite is one of the only materials that conducts both electricity and heat, resists the acid environment, and acts as an acid reservoir due to adequate pore size. The process involved takes carbon composite sheets and heat treats them to different parameters to generate the customized porosity and conductivity levels required by the
fuel cell. The other materials utilized take the form of coatings applied to the different substrates. These coatings include a wetability treatment, the catalyst layer itself, and the matrix layer.

**Cell Components**

The electrode is where the reaction of the gases actually takes place and therefore is the most critical part of the cell stack and the fuel cell as a whole. The catalyst and matrix layers applied to the electrodes enable the reaction to take place. The goal with these parts is to make them as thin as possible to reduce the resistance and increase the electrical and thermal conductivity. The concern with making them too thin is that the electrodes might contact each other, causing a short in the stack. A short causes a local “hot spot” in the cell which can lead to the shut-down of the entire stack.

The electrode reservoir plates (ERP) are the parts which store the electrolyte and which facilitate the flow of the gases into the reaction zone. These gases flow perpendicularly to each other through grooves machined into the surface of the parts (flow fields). By creating a larger pore size in the flow fields than in the mated-pair electrode packages, the cells constantly fill with acid since it tends to wick to the region of smallest pore size. The reactant gases feed through the flow fields from opposite sides of the stack. Four manifolds, running the full stack length, contain and direct the gas flow.

In the manufacture of the cell stack, the anode and cathode reservoir plates mate with a separator plate between them to form an integral separator plate (ISP). This forming of
the ISP enables the parts to be made thinner and still retain their compressibility strength.

It also reduces the number of parts necessary to handle at final stack.

The final component is the cooler which regulates the temperature of each sub-stack.

The cooler composition is a serpentine stainless steel tube enclosed by a graphite shell.

This shell prevents the decomposition of the tube by the acid environment while enabling the thermal and electrical conductivity.

2.2 Cell Stack Manufacturing Operations

2.2.1 Introduction

The PC25™ cell stack manufacturing is in 60,000 square feet of production floorspace. Raw materials delivered to IFC (graphite substrates, coatings, phosphoric acid, and non-repeat parts) undergo a series of batch processes with the result being a completed cell stack assembly (CSA).

2.2.2 Process Description

There are five major parts that make up a complete CSA. These are the electrode mated-pair, the anode ERP, the molded cathode flow field (MCFF), the ISP, and the cooler. Each part requires specific processing steps which utilize a different sequence of the available equipment.

Electrode Mated-Pair

The electrode mated-pair is a combination of an anode electrode, a cathode electrode, a thin matrix layer, and phosphoric acid. Figure 2-6 shows the complete electrode
process flow. Substrates delivered from a vendor undergo a heat treat operation to create the necessary pore size and part uniformity. These parts move to the vulcan coating process which applies a layer to the parts to increase their wetability characteristics (a measure of how receptive the part is to accepting and retaining phosphoric acid). After application, the parts dry in a convection oven.

Upon completion, the parts move to the catalyst application process. Anode and cathode electrodes receive a different formulation of catalyst which is a direct result of their respective interfaces of fuel and air. The catalyst freezes in liquid nitrogen and then passes to a pulverizer. This grinder crushes the catalyst into a fine powder. This powder passes into the cloud chamber where a vacuum beneath the substrate draws the powder to the part surface. When the part exits this chamber, a stainless steel roller compacts the powder. A nitrogen atmosphere oven sinters the catalyst for a specific time at a tightly controlled temperature. After sintering, another roller compacts the catalyst. The final process is a visual inspection of the substrate.

The electrodes receive a fillerband printing which insures a uniform area for handling the load of the cell stack. A convection oven dries this fillerband after application. The parts then move to the edge seal operation where ink is impregnated into the parts to prevent the leakage of acid and gas to the edge of the stack. Again, the parts dry in a convection oven.

Matrix and mate is the final process that involves the joining of the anode and cathode electrodes. Both the anode and cathode electrode receives a silicon carbide (SiC) matrix layer and this layer dries in a convection oven. The parts feed by alternating type (anode / cathode) which is a departure from the standard batch operations philosophy. Upon exit
from the oven, the parts receive acid and equipment mates these two parts together. This mated-pair moves to the end of the line where a robot places it in the cell stack.

*Anode Electrode Reservoir Plate (A-ERP)*

The anode ERP is the part that allows the fuel to reach the electrode through the flow fields and also acts as the electrolyte reservoir for storing acid. Figure 2-7 shows the complete process flow. The anode ERP starts as a substrate that is heat treated to insure that it has the correct pore size and uniformity. The next step involves trimming the substrate to final size using a router mounted on an XY table. A sponge roller applies vulcan to the trimmed parts and then they are convection dried. Finally, a planer mill machines the parts to their final thickness and a robot unloads them to a buffer.

The parts move to the lamination cell where they combine with a separator plate and Teflon™. This sub-assembly moves to IR test to verify that the internal resistance is within specification. The next step in the process is the machining of the flow fields. A horizontal mill machines the flow fields into the surface of the ERP. The final step for the anode ERP’s is acid fill. It is interesting to note here that both anode ERP’s and MCFF’s must receive processing prior to stacking because the ISP’s also require the use of the same mills and acid fill equipment.

*Molded Cathode Flow Field (MCFF)*

The MCFF is the part that conducts the air to the electrode through the flow fields. Figure 2-8 shows the complete process flow for the MCFF. The molded cathode flow field begins as a green pre-form delivered from a vendor in quarter sizes. IFC loads the
pre-forms into a tool which contains them under pressure in a lamination cell. Upon exit from the cell, the parts undergo a check for internal resistance (IR). An IR that is too large will greatly affect performance of the entire stack due to the inability of the part to easily conduct both heat and electricity.

From the IR test stand, the parts move to the cathode mill where a horizontal mill with arbor and carbide cutters machines the flow fields. This is an identical setup to the anode ERP. Next, a robot sprays wetability coating on the flow field surface and an acid rake applies the requisite acid. Finally, the parts move to a buffer to await stacking.

**Integral Separator Plate (ISP)**

The ISP is a combination of an A-ERP, a MCFF, a separator plate (placed between them), and Teflon™ sheet that acts as the bonding "glue". The ISP conducts fuel and air to the electrodes and also separates one cell from another. The separator plate acts as an acid and gas barrier which prevents the shorting of the cells with one another while still permitting the conductance of heat and electricity. Figure 2-9 presents a complete process flow diagram for the ISP.

The A-ERP is the start of the process and its journey is exactly the same through the planing operation. The parts move to the lamination cell where the A-ERP, a separator plate, the MCFF pre-forms, and Teflon™ sheet combine to form an ISP pre-form. The lamination cell processes this pre-form for a specific time at temperature and pressure specification. When this is complete, the parts move to internal resistance testing and then to the machining area.
The mills previously described machine the ISP on the anode side (A-ERP) and then on the cathode side (MCFF). The next process fills the ISP with acid on the cathode side, flips it, and fills the ISP on the anode side. The completed part moves to the stacking area where a robot places it on the in-process stack.

*Cooler*

The cooler is the component that regulates the cell stack temperature by circulating water through the stack. Operating temperature is critical to stack performance which makes the cooler a very important component in the stack. Figure 2-10 shows a complete process flow for the cooler.

Much like the MCFF, the cooler begins as green pre-forms supplied by a vendor. These pre-forms load into a tool (4 quarters on the bottom) with a stainless steel, serpentine tube array and another 4 pre-forms. This cooler package loads into the lamination cell where it is held for a time at temperature and pressure specification.

When this cycle completes, the cooler undergoes internal resistance testing and then moves to the microgrinding operation. This process grinds both surfaces of the cooler to insure that they are flat and that the tube array remained in the center of the cooler. The flatness is important because of the thermal and electrical conductivity issues discussed previously. The centering of the tube array insures that the cooler provides uniform heat dissipation throughout the entire stack. Figure 2-5 shows how the cooler interacts with the sub-stacks. As can be seen, the cooler provides thermal regulation for the top half of one substack and the bottom half of another.
The final process for the coolers is the edge taping operation. This taping process is a guard against the threat of corrosion. High temperatures cause the phosphoric acid to be much more corrosive than at ambient temperature. The stainless steel tube would not last a fraction of the rated 40,000 hours if exposed to the acid. Upon completion of the taping, the coolers move to the stacking cell to await insertion.

2.2.3 Operations

The processing of these different parts requires the coordination of many different pieces of production equipment. The standard approach at IFC is batch processing of all the required parts. This is a direct result of the equipment and the volume constraints of the CSA manufacturing area.

The general production approach is divided into two parts. The first part of a CSA build is to produce the A-ERP’s, MCFF’s, and Coolers required for the full stack. These parts remain in a queue prior to the stacking robot until stack assembly. Pre-processing of ISP and electrode parts happens in parallel with the A-ERP, MCFF, and Cooler production. The second part of a CSA build is the actual stacking operation. The matrix and mate line and the machining / acid fill lines finish processing the electrodes and ISP’s respectively. The stacking robot places these onto the assembly fixture with the A-ERP, MCFF, and Cooler parts as required by the assembly specification. Assembly of manifolds, pressure plates, and insulation follows the stacking process. When this is complete, the test operation validates the stack and initializes it for operation. The completion of the cell stack is with its delivery to the powerplant assembly area. Figure 2-11 shows this assembly process in flow chart format.
CHEMICAL REACTIONS

CATHODE REACTION

Electrolysis

\[ 2H_2O \leftrightarrow 4H^+ + O_2 + 4e^- \]

Fuel Cell

\[ 4H^+ + O_2 + 4e^- \leftrightarrow 2H_2O \]

ANODE REACTION

Electrolysis

\[ 4H^+ + 4e^- \leftrightarrow 2H_2 \]

Fuel Cell

\[ 2H_2 \leftrightarrow 4H^+ + 4e^- \]

Figure 2-1
Fuel + Air → Power + Water + Heat + CO₂
+ NOx + SOx + CO + HC + Noise

Figure 2-2
Superior Economics through High Efficiency

Figure 2-3
FUEL CELL POWER SYSTEM

Figure 2-4
PC-25 STACK ASSEMBLY

Figure 2-5
ANODE ERP PROCESS FLOW

Figure 2-7
MCFF PROCESS FLOW

Green Preforms → Lamination → IR Test → Buffer

Flow Field Machining → Wetability Treat → High Velocity Dry → Edge Trim

Acid Fill → Stack → Buffer

Other Components
ISP PROCESS FLOW

- Raw Substrates
- XY - Vulcan - Planec Process
- Buffer
- Lamination
- IR Test
- Buffer
- Flow Field Machining
- Acid Fill
- Stack
- Buffer

Figure 2-9
3. Manufacturing Operations Model

3.1 Introduction

The manufacturing operations model (MOM) utilizes a common input sheet which links these values throughout the model. This creates a flexible structure to accommodate changes and what-if analyses. Each sheet within the Excel workbook represents a specific process and the standard calculations performed on this sheet are for that process only. The model produces a single output report that summarizes key information into a common format.

3.2 Model Inputs

MOM inputs fall into two general categories. The first is general information about the cell stack as well as information about the time available for manufacturing operations. The second is process specific data (both operations and cost) which varies based on the process considered.

3.2.1 General Inputs

Table 3-1 shows a listing of the general inputs for the MOM. These inputs serve as the foundation for the model outputs and their alteration will affect the final model results. Since the variable names are self-explanatory and the cell stack part descriptions have been made in a previous section, no formal description will be presented regarding this information.
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<th>Description</th>
<th>Value</th>
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</thead>
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</tr>
<tr>
<td>Number of PC25™ Stacks Scheduled for Production</td>
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</tr>
<tr>
<td>Total Available Production Shifts</td>
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<tr>
<td>Number of Molded Cathode Flow Fields per Substack</td>
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</tr>
<tr>
<td>Number of Coolers per Substack</td>
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</tr>
<tr>
<td>Inventory Cost of Capital Percentage</td>
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<tr>
<td>Fully Burdened Hourly Labor Cost</td>
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</tr>
</tbody>
</table>

Table 3-1

3.2.2 Process Specific Inputs

Table 3-2 presents a listing of the process categories discussed in the model. Model inputs for each process category are the basis for internal calculations and final outputs. The remainder of this sub-section defines the input categories and provides some insight as to the purpose of each category.

<table>
<thead>
<tr>
<th>Cell Stack Assembly Manufacturing Process Listing</th>
<th>Electrode Vulcan</th>
</tr>
</thead>
<tbody>
<tr>
<td>ERP/ISP Vulcan&amp;Plane</td>
<td>Catalyst</td>
</tr>
<tr>
<td>Lamination</td>
<td>FillerBand</td>
</tr>
<tr>
<td>IR Test</td>
<td>BackSide Seal</td>
</tr>
<tr>
<td>Microgrind</td>
<td>Electrode Matrix&amp;Mate</td>
</tr>
<tr>
<td>Edge Tape</td>
<td>Stack Non-repeat Assembly</td>
</tr>
<tr>
<td>Cathode Mill</td>
<td>Stack Test</td>
</tr>
<tr>
<td>Anode Mill</td>
<td></td>
</tr>
<tr>
<td>ERP/ISP Acid Fill Line</td>
<td></td>
</tr>
</tbody>
</table>

Table 3-2

Scrap Percentage

This field accounts for the amount of parts lost to scrap during a standard production run. This loss includes out of specification parts, damaged parts, startup parts, etc. The numbers originate from a business planning document and serve as a starting point.
These values should be verified based on actual shop production to increase the accuracy of the model results.

**Equipment Uptime**

This field represents an effort to numerically account for the unexpected downtime associated with full-scale equipment operation. The initial numbers utilized in the model development are a function of local manufacturing management experience and operator input.

**Limiting Cycle Time (hours / piece)**

This is a process and part specific input that represents the amount of time in hours / piece that it takes for a part to be produced by the specific process. This time is a flow time that doesn't represent the amount of time for the first part to reach the end of the line but instead represents the steady state process time. This is a critical input for many of the calculations in the model.

**Incremental Part Cost by Process**

The part cost by process step is a critical field for the cost summary outputs desired from this model. For each part type and process combination, this sub-matrix lists the completed cost of the part. The data utilized in the model comes directly from a business cost model that accounts for all factors of production cost (direct and indirect).
**Required Heads**

This field represents the number of people required to run a specific process given the fact that you choose to run it. In other words, there is no consideration taken at this point as to how long you have to run the equipment. This field merely states that if the process is going to be run, it will require \( X \) people to run it.

**Shifts**

This input is a representation of the number of shifts that the specific operation runs during a given day. The purpose of this value is for the determination of the capacity utilization output. This is an important consideration because setup / startup activities are for a given production run each day. Therefore, the total number of hours that are available for production on each process must be known for an accurate determination of the outputs.

**Start-up / Setup (SS) Time**

This value is a supplement to the limiting cycle time field in that it captures the amount of time required for one complete changeover or startup on the specific piece of equipment. This time comes from actual operating data and current scheduling practices for the production of parts in the manufacturing area.

**First Run (FR) Time**

This column represents the “first run” time associated with a given process. This value captures the amount of time for the first part to travel through the entire process. The model uses this value only once per production start.
**Batch (Lot) Size**

This input accounts for the actual operational practices in the manufacturing arena. It is important for the determination of the number of setups required in a given time period. This input is a major focus of examination for optimizing the manufacturing operations and therefore also serves as a baseline for comparison.

**Total Number of Setups**

This is a calculated field within the input matrix. This calculation results in the number of setups required in the given time period.

\[ \text{Total Number of Setups} = \frac{\text{number of PC25™ units per time period}}{\text{batch size}} \]

**Total Startup / Setup (SS) Time**

This is another calculated field within the input matrix. This calculation determines the total time required for setup and startup activities. The model combines this result with production time figures to determine the equipment utilization and capacity of each piece of equipment.

\[ \text{Total Startup / Setup Time} = \text{[total number of setups]} \times \text{[ss_time]} \]

### 3.3 Process Sheet Description (generalized)

#### 3.3.1 Introduction

The following is a column by column description of the calculations, logic and assumptions utilized in the composition of this model. This description is made for a
specific process sheet but the reader should note that this is generalizable for all sheets (exceptions noted as indicated).

3.3.2 Column-by-Column Description

Total Parts per CSA

This is a straight calculation that uses the total number of substacks in one complete stack and multiplies this by the total number of parts that are in a substack. This value is the raw number of parts that are needed (a summation of anode and cathode) for production of a single cell stack and does not consider any scrap loss at this point in the model.

\[
\text{Total Parts per CSA} = [\text{number of substacks in 1 CSA}] \times [\text{number of electrode mated pairs in 1 substack}]
\]

Total Parts per Year (not required on all sheets)

This value is the number of individual parts per stack (described above) multiplied by the expected yearly volume of the cell stack manufacturing area. This value is the raw total number of parts required for production in the given planning period (assumed to be one year). There is no consideration of scrap or of demand variation at this point in the process. The total production number is merely the expected value of the demand for the coming year.

\[
\text{Total Parts per Year} = [\text{total parts per CSA}] \times [\text{number of PC25™ units for production}]
\]
Process Name

This column is self explanatory in that it defines the process name for the associated inputs and calculations.

Scrap %

This is the column that accounts for the loss associated with the expected scrap percentage of the process. This calculation is critical for the determination of numerous fields later in the worksheet. A lookup function draws this value from the input sheet.

Required Production

This field factors the loss from scrap into the model. The equation represents the number of parts that must be started at the process to insure that the correct number of good parts are available for the stacking operation.

\[
\text{Required Production} = \frac{\text{[total parts per year]}}{(1 - \text{[scrap percentage]})}
\]

Scrap Loss (year)

This field is the total number of parts that are lost to scrap during the period of production. This calculation simplifies the scrap cost calculation later in the model.

\[
\text{Scrap Loss} = \text{[scrap %]} \times \text{[required production]}
\]

Limiting Cycle Time

This is a lookup function that searches the input sheet matrix and matches the process and part type. The function returns the limiting cycle time in hours / piece.
Single Shift Production (pcs)

This calculated field utilizes the limiting cycle time information to determine the number of pieces possible in one 8-hour production shift. This value serves as a check to insure that the numbers in the model “make sense” as well as set the ground work for the establishment of labor standards for each part / process combination.

\[
\text{Single Shift Production} = \frac{([\text{total hours in 1 shift}] - [\text{first run time}])}{[\text{limiting cycle time}]}
\]

Shifts of Current Production

This column is a direct lookup from the input sheet. The value helps to determine the total capacity utilization and batch lead-time for the particular process and part.

Production Time (hours)

This field attempts to quantify the total amount of machine production time required to produce the number of pieces called out in the [required production] field. It should be noted that this field represents the pure production time and does not account for equipment downtime or the startup / setup cycles required to achieve a normal production rate.

\[
\text{Production Time} = [\text{limiting cycle time}] \cdot [\text{required production}]
\]

Start-up Time (hours)

This field is a supplement to the [production time] field. The start-up time calculation accounts for the initial production start-up time required to achieve full production rate. This value must be accounted for each day of production. This result captures the amount of production time utilized for the startup of equipment for production.
Start-up Time = [ft time] * [lead-time for batch (shifts)] * [total number of setups]

**Total Setup Time (hrs)**

This field is a supplement to the [production time] field. The total setup time field accounts for the set-up time associated with a specific process. The formula for this field is a lookup function to the [total ss_time] value for the specific process. The model copies this value directly from the input matrix.

**Total Time (hours)**

This calculation results in the total time required to produce a given volume of cell stacks at each specific process.

\[
\text{Total Time} = [\text{production time}] + [\text{start-up time}] + [\text{total setup time}]
\]

**Uptime**

This is a lookup function from the input sheet which represents the percentage of time that the machine produces parts when it is scheduled to run.

**Available Time (hrs)**

This is the total number of hours available in the time period specified in the input sheet.

\[
\text{Available Time} = [\text{number of days in planning period}] \times [\text{total available shifts}] \times [\text{number of hours in shift}] \times [\text{uptime}]
\]

**Shifts Required**

This field computes the number of shifts required to produce the specified number of PC25™ units. This provides an estimate as to the appropriate production plan for a given
volume and allows easy ‘what-if’ analyses to be performed with respect to production volume.

Shifts Required = [total time] / [available time for 1 shift]

**Headcount Required**

This field provides an estimate as to the amount of labor required to produce a given volume of PC25™ stacks.

Headcount Required = [shifts required] * [req'd heads] (from the input sheet)

**Capacity Utilization**

This is a key metric for any manufacturing operation because it represents the amount of work that is being passed through a given piece of equipment. This is important for knowing when the equipment is no longer capable of handling increases in volume.

Capacity Utilization = [total time] / [available time]

**Max Production (CSA)**

This field is another way to determine the maximum capacity of a given piece of equipment. It provides an estimate of the total amount of cell stacks that could be produced given the inputs for the [available time] field.

Max Production (CSA) = [available time (hrs)] / [average stack time (hrs)]

A description of the [average stack time] field comes later in this sub-section.

**Scrap Cost**

This is a representation of the amount of money that is associated with the given scrap percentage and production volume.
Scrap Cost = [scrap loss] * [piece cost] (from input sheet)

**Inventory Lot Size**

This is the standard batch size utilized for the given piece of equipment. This value is needed to determine the lead-time associated with production of the batch. This number also has impact on the average stack time field.

\[
\text{Inventory Lot Size} = \frac{\text{required production}}{\text{total number of setups}} \quad \text{(from the input sheet)}
\]

**Storage Space Required (boxes)**

Given the batch size run for this process, this field calculates the number of part containers required to hold the produced pieces.

\[
\text{Storage Space Required} = \frac{\text{inventory batch size}}{256 \text{ (electrodes) or 60 (all others)}}
\]

**Lead-time for Batch (days)**

This field computes the amount of time required to process a complete batch of parts and normalizes it to units of shifts for internal consistency. This field only accounts for the production time and does not include any startup or setup time computations. The numerator is the lead time calculation and the denominator converts the answer from hours to days.

\[
\text{Lead-time for Batch} = \frac{\text{inventory batch size} \times \text{limiting cycle time}}{\text{shifts of current production} \times \text{number of hours in shift}}
\]
Average Stack Time (hrs)

This field is the amount of time in hours required to process one CSA of parts and includes the processing time, the setup time and the first run time for the part/process combination. This field is critical to the calculation of the maximum production field.

\[
\text{Average Stack Time} = \frac{\{[\text{lead-time for batch (shifts)] * 8 \text{ hours/shift} +} \\
[\text{ss time (from input sheet)}] + \\
[\text{fr time (from input sheet)}] * ([\text{lead-time (shifts)] /} \\
[\text{number of shifts run}]) \} / \text{[batch size]}
\]

3.4 Output Sheet

3.4.1 Introduction

The Operations Summary sheet is the only planned output for the manufacturing operations model. The purpose of this sheet is to have a common report-like output that summarizes the relevant model results on a single sheet. It lists the output categories for each specific part/process combination as well as in a grouped format by part type.

3.4.2 Model Output

Table 3-3 shows a listing of the output categories in the manufacturing operations model that attempt to provide summary information for a given CSA production level.

<table>
<thead>
<tr>
<th>Production Volume (CSA/Year)</th>
<th>Process Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production Requirement (pcs)</td>
<td>Total Production Time (machine hours)</td>
</tr>
<tr>
<td>Shifts Required (annualized)</td>
<td>Raw Headcount Required (heads)</td>
</tr>
<tr>
<td>Capacity Utilization (%)</td>
<td>Maximum Production (CSA)</td>
</tr>
<tr>
<td>Production Shifts</td>
<td>Ideal Daily Production (pcs)</td>
</tr>
<tr>
<td>Scrap Cost ($ / year)</td>
<td>Headcount Cost ($ / year)</td>
</tr>
</tbody>
</table>

Table 3-3

A representative output sheet can be found in Figure 3-1.
3.5 Manufacturing Operations Model Results

The manufacturing operations model is the foundation of the production system design work performed for CSA manufacturing. The use of this model provides information needed for managing the entire manufacturing operations (capacity utilization, daily production, scrap cost, etc.) as well as targets the limiting flow for production system optimization.

3.5.1 Factory Utilization

One of the primary uses of the manufacturing operations model is to determine the current and future utilization of the factory equipment based on the current operating information. The model can also be used to determine the real operating capability associated with the current equipment configuration. The results of these analyses are presented below for the CSA manufacturing area.

Bottleneck Identification

Bottleneck identification can be performed in two ways with this model. We utilized the more straightforward method which is to consult the Max Production column to determine the maximum capacity for each process. We identified the bottleneck by comparing the max production values for all processes in the system. While trivial for the first process limiter, this model provides new information on the secondary bottleneck as well as a quantification of the actual capability of the current bottleneck.

For CSA manufacturing, the current system bottleneck is the catalyst deposition process. This process deposits catalyst on to the surface of a graphite substrate and must
make 600 parts (300 anode, 300 cathode) to produce 1 complete cell stack assembly. The current capability of this operation is 66 CSA per year. According to sales projections, this process will become a production constraint within the next 2 years if nothing is done to increase its production capability.

As previously mentioned, the identification of this process as the bottleneck is trivial because anyone familiar with the shop operation already knew this from experience. The value added is in terms of additional information. The CSA manufacturing group now has an accurate figure (66 CSA's) for maximum capacity of its current equipment configuration. The manufacturing operations model provides this information and the flexibility to determine the sensitivity of input changes for any process.

In addition to the bottleneck identification, the model also shows those processes which may also pose a problem assuming successful bottleneck process improvements (see Section 5). These processes are listed in order of increasing constraint: lamination process and acid fill lines. Under current operating conditions, the lamination cell can produce 94 CSA / year. A caveat associated with this is that this process is being run with 50% of the manpower and 33% of the tooling. Given full operating conditions, this process will be capable of producing over 150 CSA / year which brings it in line with the factory capacity. The electrode and "black" acid fill lines currently are capable of around 159 and 114 CSA / year respectively. A caveat associated with the "black" acid fill line is that this was studied during learning curve operations. It is believed that this process is capable of higher production (~125 CSA range) given normal production conditions.
CSA Manufacturing Capability

Throughout the start-up phase of PC25™ production, the question of production capacity and facility capability was always answered as 200 CSA / year. While this figure was the equipment design benchmark, everyone was well aware that this was not the true value. The problem was that no one really knew the correct value. The manufacturing operations model answers this question.

In examination of the model output, it is clear that except for the catalyst deposition equipment, the rest of the equipment can conservatively produce 125 CSA / year given the existing process time and uptime information. The production capability including catalyst deposition is approximately half of that value at 66 CSA / year. Thus, catalyst deposition should be the focus of the major improvement efforts for the production of cell stack assemblies. Improvement recommendations and production optimization associated with this thesis work focus on this process and its production flow.

3.5.2 Cost Reduction

The other major purpose of the manufacturing operations model is to identify key cost centers which can become target areas for improvement. The two key drivers considered in the model are the scrap cost and the direct labor cost for each process. Examination of the data for the CSA manufacturing area shows that at any given volume level, the headcount cost and the scrap cost are approximately equal. Each cost area amounts to 8% of the total cost.

The conclusion from this data is that there are processes where the amount of scrap cost far exceeds the labor associated with the process. This conclusion suggests two
important things. First, any effort to improve the scrap associated with the manufacture of a cell stack should be focused in the high scrap cost processes. These processes are the XY/Vulcan/Plane, the flow field milling operations (both anode and cathode), and the catalyst deposition. These three processes account for 55% of the total scrap cost associated with a completed CSA. Reduction in this area reduces the overall cost of the cell stack as well as frees up productive capacity (which is especially important for the catalyst deposition equipment). Second, there may be an opportunity with the processes mentioned (specifically the XY/Vulcan/Plane and Milling equipment) to add labor to reduce the scrap rate. A Pareto analysis of the causes for scrap at each of these processes would be required to determine if this was justified. Such an analysis is outside the scope of this thesis work but is mentioned as a potential starting point for scrap reduction efforts.
## OPERATIONS SUMMARY SHEET

<table>
<thead>
<tr>
<th>Production Volume (CSA / Year)</th>
<th>Production Requirement</th>
<th>Total Production Time (mach hrs)</th>
<th>Shifts Required (annualized)</th>
<th>Raw Headcount Required</th>
<th>Capacity Utilization *</th>
<th>Max Production (CSA)</th>
<th>Production Shifts</th>
<th>Max Daily Production (pcs)**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrode Vulkan</td>
<td>29,756.00</td>
<td>377.82</td>
<td>0.24</td>
<td>0.24</td>
<td>11.8%</td>
<td>43.7</td>
<td>1.00</td>
<td>722</td>
</tr>
<tr>
<td>Catalyst</td>
<td>29,010.00</td>
<td>318.87</td>
<td>1.52</td>
<td>3.81</td>
<td>76.2%</td>
<td>94.0</td>
<td>2.00</td>
<td>280</td>
</tr>
<tr>
<td>FillerBand</td>
<td>27,844.00</td>
<td>469.65</td>
<td>0.29</td>
<td>0.29</td>
<td>14.7%</td>
<td>44.0</td>
<td>2.00</td>
<td>614</td>
</tr>
<tr>
<td>BackSide Seal</td>
<td>27,652.00</td>
<td>425.34</td>
<td>0.27</td>
<td>0.27</td>
<td>13.3%</td>
<td>38.5</td>
<td>1.00</td>
<td>592</td>
</tr>
<tr>
<td>Electrode Matrix &amp; Mate</td>
<td>13,618.00</td>
<td>1,053.53</td>
<td>0.66</td>
<td>1.98</td>
<td>32.9%</td>
<td>152</td>
<td>1.00</td>
<td>127</td>
</tr>
<tr>
<td>Stack Test</td>
<td>50.00</td>
<td>2,000.00</td>
<td>2.00</td>
<td>2.00</td>
<td>50.0%</td>
<td>95</td>
<td>2.00</td>
<td>0.20</td>
</tr>
<tr>
<td>Stack Dress</td>
<td>50.00</td>
<td>1,200.00</td>
<td>1.20</td>
<td>1.20</td>
<td>30.0%</td>
<td>151</td>
<td>1.00</td>
<td>0.67</td>
</tr>
<tr>
<td>ISP Acid Fill</td>
<td>11,463.66</td>
<td>807.14</td>
<td>0.50</td>
<td>1.51</td>
<td>45.4%</td>
<td>110</td>
<td>1.00</td>
<td>158</td>
</tr>
<tr>
<td>Cathode ERP Acid Fill</td>
<td>1,637.67</td>
<td>322.45</td>
<td>0.20</td>
<td>0.60</td>
<td>10.5%</td>
<td>47.5</td>
<td>1.00</td>
<td>540</td>
</tr>
<tr>
<td>Anode ERP Acid Fill</td>
<td>1,637.67</td>
<td>322.45</td>
<td>0.20</td>
<td>0.60</td>
<td>10.5%</td>
<td>47.5</td>
<td>1.00</td>
<td>540</td>
</tr>
<tr>
<td>ISP Mill</td>
<td>12,207.02</td>
<td>249.04</td>
<td>0.16</td>
<td>0.08</td>
<td>29.9%</td>
<td>167</td>
<td>1.00</td>
<td>193</td>
</tr>
<tr>
<td>Cathode Mill</td>
<td>1,723.86</td>
<td>87.25</td>
<td>0.05</td>
<td>0.03</td>
<td>29.9%</td>
<td>167</td>
<td>1.00</td>
<td>193</td>
</tr>
<tr>
<td>Anode Mill</td>
<td>1,723.86</td>
<td>87.25</td>
<td>0.05</td>
<td>0.03</td>
<td>29.9%</td>
<td>167</td>
<td>1.00</td>
<td>193</td>
</tr>
<tr>
<td>Edge Tape</td>
<td>1,658.29</td>
<td>1,256.22</td>
<td>0.79</td>
<td>0.79</td>
<td>39.3%</td>
<td>124</td>
<td>1.00</td>
<td>11</td>
</tr>
<tr>
<td>Microgrid</td>
<td>1,675.04</td>
<td>138.75</td>
<td>0.10</td>
<td>0.20</td>
<td>5.0%</td>
<td>1,000</td>
<td>1.00</td>
<td>130</td>
</tr>
<tr>
<td>ISP IR Test</td>
<td>12,727.65</td>
<td>362.83</td>
<td>0.35</td>
<td>0.35</td>
<td>29.9%</td>
<td>167</td>
<td>1.00</td>
<td>193</td>
</tr>
<tr>
<td>MCFF IR Test</td>
<td>1,732.52</td>
<td>132.19</td>
<td>0.08</td>
<td>0.08</td>
<td>29.9%</td>
<td>167</td>
<td>1.00</td>
<td>193</td>
</tr>
<tr>
<td>Cooler IR Test</td>
<td>1,683.46</td>
<td>130.22</td>
<td>0.08</td>
<td>0.08</td>
<td>29.9%</td>
<td>167</td>
<td>1.00</td>
<td>193</td>
</tr>
<tr>
<td>Anode IR Test</td>
<td>1,732.52</td>
<td>132.19</td>
<td>0.08</td>
<td>0.08</td>
<td>29.9%</td>
<td>167</td>
<td>1.00</td>
<td>193</td>
</tr>
<tr>
<td>ISP Lamination</td>
<td>12,375.16</td>
<td>717.19</td>
<td>0.45</td>
<td>0.90</td>
<td>55.6%</td>
<td>97</td>
<td>2.00</td>
<td>305</td>
</tr>
<tr>
<td>MCFF Lamination</td>
<td>1,767.88</td>
<td>181.03</td>
<td>0.11</td>
<td>0.23</td>
<td>55.6%</td>
<td>97</td>
<td>2.00</td>
<td>305</td>
</tr>
<tr>
<td>Cooler Lamination</td>
<td>1,717.82</td>
<td>699.70</td>
<td>0.44</td>
<td>0.87</td>
<td>55.6%</td>
<td>97</td>
<td>2.00</td>
<td>305</td>
</tr>
<tr>
<td>Anode Lamination</td>
<td>1,767.88</td>
<td>181.03</td>
<td>0.11</td>
<td>0.23</td>
<td>55.6%</td>
<td>97</td>
<td>2.00</td>
<td>305</td>
</tr>
<tr>
<td>ISP XY/Vulkan/Plane</td>
<td>25,515.79</td>
<td>824.71</td>
<td>0.52</td>
<td>0.52</td>
<td>29.9%</td>
<td>167</td>
<td>1.00</td>
<td>286</td>
</tr>
<tr>
<td>Anode XY/Vulkan/Plane</td>
<td>1,822.56</td>
<td>194.62</td>
<td>0.12</td>
<td>0.12</td>
<td>31.9%</td>
<td>157</td>
<td>1.00</td>
<td>286</td>
</tr>
</tbody>
</table>

* Capacity utilization is based on 2 shifts of available time with machine downtime and shifts/breaks taken into account

** Daily Production is based on the number of shifts utilized per day. Thus, catalyst and lamination are based on 2 shifts and all others based on 1 shift

<table>
<thead>
<tr>
<th>Process Description</th>
<th>Total Production Time (mach hrs)</th>
<th>Shifts Required (annualized)</th>
<th>Raw Headcount Required</th>
<th>Capacity Utilization</th>
<th>Max Production (CSA)</th>
<th>Production Shifts</th>
<th>Max Daily Production (pcs)**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrode Subtotal</td>
<td>4,766.59</td>
<td>2.00</td>
<td>6.5</td>
<td>76.5%</td>
<td>66</td>
<td>2.00</td>
<td>129</td>
</tr>
<tr>
<td>Cooler Subtotal</td>
<td>2,244.89</td>
<td>2.00</td>
<td>1.9</td>
<td>56.5%</td>
<td>97</td>
<td>2.00</td>
<td>11</td>
</tr>
<tr>
<td>ISP Subtotal</td>
<td>3,160.92</td>
<td>2.00</td>
<td>3.4</td>
<td>56.5%</td>
<td>97</td>
<td>2.00</td>
<td>158</td>
</tr>
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<td>3,160.92</td>
<td>2.00</td>
<td>3.4</td>
<td>56.5%</td>
<td>97</td>
<td>2.00</td>
<td>158</td>
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<tr>
<td>Anode LERP Subtotal</td>
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<td>1.1</td>
<td>45.5%</td>
<td>97</td>
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<tr>
<td>Stack Operations</td>
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<td>50.0%</td>
<td>95</td>
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<td>56.4%</td>
<td>66</td>
<td>12.00</td>
<td>n.a</td>
</tr>
</tbody>
</table>

Figure 3-1

53
4. Production Strategy Model

4.1 Bottleneck Production Strategy

4.1.1 Introduction

The determination of the bottleneck operation from the operations model exposes a batch process with a long setup time. This raises the issue of whether the current lot size being used is optimal given the current process inputs. This lot size model analyzes the catalyst deposition process to determine the optimal operations policy for this cell.

4.1.2 Literature Review

There is significant literature that deals with this issue in virtually every type of system application. Graves (1979) presents a detailed survey of the different conditions and system configurations that historically lead to the application of the Economic Order Quantity (EOQ) model and its hybrids. One relevant conclusion is that manual scheduling techniques are most effective and most often utilized in simple systems. Karmarkar (1987) examines the relationship between lot size, associated lead time and the equipment utilization. He concludes that there is a strong positive relationship between the lot size and the lead-time required to process the batch. As lot size increases, the lead time required to process the batch increases. In addition, he finds that equipment utilization is optimal at low setup times and small lot sizes. As the lot size approaches 1, however, setup time begins to dominate the production time which causes utilization to
spike. Therefore, there is clearly a limit as to the minimum lot size when faced with multiple products and non-zero setup times.

Karmarkar also develops an alternate lot size model which depends solely upon the demand, setup time and equipment processing time. This equation $2D\tau / (1 - D/P)$ where $D$ is the yearly demand, $\tau$ is the setup time associated with the equipment, and $P$ is the production rate of the machine in units/year. Groenevelt, et. al. (1992) examine lot sizing by expanding the simple EOQ model to incorporate equipment breakdowns. They conclude that the lot sizes increase when stochastic failures are included as part of the process. Finally, Corbey and Jansen (1993) discuss the EOQ model and stress the importance in considering relevant inputs when applying the model.

The author utilizes Nahmias’ (1993) treatment of these issues in their most classic sense, applying the EOQ model facing known demand with the inputs of fixed setup cost and inventory carrying cost. Due to the uncertainty in defining the actual values for setup cost, this model deals with a range of costs to determine the sensitivity of the process to these inputs. The output of this model is the optimal lot size for the catalyst deposition process considering a range of setup costs. This value generates a reference node to determine the cost and/or capacity implications of the current policy. A recommendation for action completes this analysis.
4.1.3 Economic Order Quantity Theory (EOQ)

Introduction

Nahmias (2nd ed.) Chapter 4, Section 5 and beyond describes the classic EOQ model in detail. This description serves as the foundation for this analysis. The critical value, $Q$, is the optimal production lot size given the current process parameters. The EOQ formula works to balance the setup and inventory carrying costs over a given period of time (year).

The formula for the optimal lot size is $Q = \sqrt{\frac{2K\lambda}{h}}$. The inputs to this equation are as follows:

- $K = \text{fixed setup cost per order in } \$\$
- $\lambda = \text{demand in units/year}$
- $h = I\cdot c = \text{holding cost in } \$ \text{ per unit per year}$
- $c = \text{cost of a single unit in } \$/\text{unit}$
- $I = \text{yearly inventory holding cost of capital in } \$/\$$

Components of Inventory

The policy described above includes two components of cost, lot size holding cost and setup cost. These components are vital to the determination of the real cost of any production policy and therefore must be considered to determine the optimal policy.

Batch Size Holding Cost

This is the cost associated with producing a batch of size $Q$ and its depletion over a time period $T = \frac{Q}{\lambda}$. Figure 4-1 (Nahmias Figure 4-4) shows this in graphical form.
This demonstrates that with the assumption of linear and known demand, the inventory on-hand over time is equivalent to the area of the triangle formed by the production lot size. Multiplying this on-hand inventory by the inventory cost of capital \( h \) generates the holding cost associated with this policy. The holding cost value provides a representation of the opportunity cost of producing a batch of size \( Q \).

**Setup Cost**

The setup cost associated with a particular operation is assumed in this model to be fixed and constant over time. Thus, it will always cost \( X \) dollars per setup for a particular operation. Traditionally, the setup cost for a manufacturing operation is the variable cost incurred when a piece of equipment must be changed-over to run a different part. In a non-production environment, this is the order cost and represents the cost to the organization for placing an order and having it delivered to the location. Setup cost components include labor, materials, and any maintenance associated with running a different part (cleaning, etc.). It is important to note that when the operation in question is the bottleneck for the process and at capacity, the setup cost is the value of the lost production time in addition to the above cost components. This is significant because the lost production time for a factory can be on the order of tens or hundreds of thousands of dollars per day where the variable setup cost is typically on the order of hundreds or thousands per day.
4.1.4 Model Development

Model Options

There are two main approaches for determining the optimal lot size for the catalyst deposition equipment. The first method involves using the EOQ model (or a hybrid) as described above to compute the optimal production lot size. This approach attempts to balance the costs or time associated with the setup and production of a given lot size of parts. The other method involves utilizing the known yearly demand to compute the total production time necessary to satisfy that demand. This total production time can then be subtracted from the total available time in a production year. The resulting time is divided by the average setup time to provide the number of setups in a year. Finally, the yearly production quantity is divided by the number of setups per year to give the lot size which effectively utilizes the entire available production time.

Relevant Factors

Earlier discussion in this section explained the composition of the basic EOQ model and the inputs that make up the model. Corbey and Jansen (1993) present a useful methodology for thinking about the inputs to the EOQ and determining those that are relevant to the analysis. The inventory holding cost is the easiest in that it is based on the rate of return that IFC uses for capital projects. This value is 20%. The setup cost is different in that there isn’t an easy way to determine its exact value. Therefore, we consider the lot size result over a relevant range of values to determine the sensitivity of the model to this input.
Sensitivity Analysis

The determination of the output sensitivity to the setup cost input requires setting up a model which considers the effect of changing the setup cost on the optimal lot size. We first define a relevant range of inputs such that the results consider a solution space that is possible in the operation in question. The analysis for the result sensitivity consists of varying the setup cost input over the defined range in increments that provide adequate resolution. For example, all inputs were held constant except for setup cost which ranged from $100 to $5,000. The standard plot has total cost on the vertical axis, the input in question on the horizontal axis, and standardized lot sizes as the legend.

Observing the output in this format provides information not only about the overall sensitivity of the system to a change in the input (which is characterized by the shape of an individual line) but also shows the impact of lot size (Q) on the total cost by the distance between lines for a given input. Thus, for each input, we are able to determine the overall system sensitivity to changes in the input value given a fixed lot size and can see the impact that changing the lot size can have given this range of inputs.

Based upon manufacturing interviews, the analysis considered lot sizes of 300, 600, and 900 pieces (where 600 pieces represented the current operating condition). The graph in Figure 4-2 shows that there is no real cost advantage to increasing lot size at low setup costs but as the setup cost increases, the advantage for increasing lot size also increases. The current operating region suggests that 600 pieces is a good starting position and there is an incremental gain (lowering of total cost) by moving to a 900 piece lot size. The other conclusion drawn from this analysis is that there is ample room
for error around the setup cost figure without significant impact on the final lot size recommendation.

4.1.5 Lot Size Analysis Results

The solution for the catalyst deposition line optimal lot size involves solving the classical EOQ equation.

\[
\text{EOQ} = \left[\frac{2 \times K \times \lambda}{h}\right]^{1/2}
\]

\[
\lambda = 15,000 \text{ pieces}
\]

\[
h = (20\%)(\$100) = \$20
\]

\[
K = \$1,000 \text{ (based upon hourly labor rate and material costs)}
\]

\[
Q_o = \left[\frac{(2)(\$1,000)(15,000)}{\$20}\right]^{1/2}
\]

\[
= 1,224 \text{ pieces}
\]

Thus, the application of the EOQ model resulted in an optimal solution of 1,224 electrodes for each setup performed on the machine. This solution suggests an increase in the lot size from 600 to 1,200 pieces. The alternate approach (determining the lowest possible lot size consistent with capacity) results in a lot size of 302 electrodes for each setup. This suggests a decrease in the lot size from 600 to 300 pieces.

The discrepancy between these approaches can be explained by the methodology employed to compute the results. The EOQ method provides a lot size that balances the cost associated with producing and storing in-process inventory and setting up / changing over the equipment. The alternate approach ignores the cost implications of producing a certain lot size and instead computes the time required to produce the yearly demand and uses the remaining time in the year for equipment setup.
To proceed in this analysis, it is necessary to choose a preferred methodology. We choose to apply and modify the EOQ approach because it more accurately aligns with the manufacturing objectives of IFC. The alternate approach assumes that operators are not mobile and only work on this single piece of equipment. In actuality, the operators that work at this process also work on subsequent processes that finish the electrode processing. Hence, the labor freed up by the larger lot sizes can be used productively elsewhere. With the EOQ approach, catalyst manufacturing is optimized to reduce the cost trade-offs associated with production. In addition, the negative implications of long setup times are emphasized which provides increased pressure for process improvements at this process (see Section 5).

When this data was presented to CSA management, there was understanding of the concept and the sensitivity graphs but the model did not present conclusions in the language of the current IFC systems. It was clear that total cost decreased if the catalyst deposition equipment ran larger lot sizes but the missing piece was the specific impact on CSA manufacturing. To solve this problem and verify the results of the theoretical model, we developed a supplemental model to the EOQ which presented the conclusions in a more meaningful format.

Together with the finance group, we developed a mini-overhead budget which closely represents the current financial metrics utilized in CSA manufacturing. This pool contained time variable costs, setup costs, and unit part costs. These costs formed the inputs for the supplemental lot size analysis. The analysis considered lot size values of 300, 600, 900, and 1,200 pieces. Figure 4-3 shows the graphical results of this
supplemental analysis. We present the data in graphical format with percentage cost values to protect the sensitive nature of IFC's manufacturing cost information.

As is evident from the results, there again is benefit to increasing the lot size and this benefit shows diminishing returns as the lot size grows. It is clear, thought, that a move to 900 pieces presents a significant savings while a move to higher values may not produce enough benefit to justify the switch. A move from 600 piece to 900 piece lots would reduce the per piece cost by 10%. An additional increase to 1,200 piece lots returns a percentage reduction of 14%.

4.2 Optimal Bottleneck Production Strategy

Based on these analyses, our recommendation is that the lot size for the catalyst deposition line be increased from 600 to 900 pieces. With the large setup time associated with this line, the increase presents benefits in both unit cost reduction and protection against unexpected downtime. This change represents a lead time increase of 2 days for the catalyst deposition process but the cost benefits obtained far exceed this penalty.
EOQ GRAPHICAL REPRESENTATION

Figure 4-1
Figure 4–2
LOT SIZE SUPPLEMENTAL ANALYSIS RESULTS

Figure 4-3
5. Bottleneck Process Improvement

5.1 Introduction

The bottleneck or limiting process for the CSA manufacturing operation is the catalyst deposition line which processes both anode and cathode electrodes for the cell stack. This process adds the greatest value for this process flow. It is also one of the more complicated operations associated with the manufacture of a cell stack. All of these factors makes this the ideal place to focus improvement efforts. This section presents a detailed process explanation and the various recommendations for change and improvement for the catalyst process.

5.2 System Description and Visual Representation

The catalyst deposition system involves numerous pieces of equipment arranged in a flow structure. The process is different for anode and cathode due to their differing composition. Therefore, there is a separate description and flow chart describing the two distinct parts.

5.2.1 Anode Electrode

The graphite substrates come into the catalyst room in lot sizes of approximately 200 pieces. One by one, the operator weighs the parts and places them on a shuttle table. The shuttle table indexes into the cloud tower which applies the finely ground catalyst onto the graphite substrate.
During the deposition process, the operator weighs out the next batch of catalyst and stages it prior to the grinding cabinet. Next, the operator prepares a charge of liquid nitrogen and manually deposits the catalyst nuggets into the canister. Then, the cooled nuggets are dumped into the micropulverizer and jetomizer.

While the process waits for the catalyst to freeze, the operator moves to the load scale and pre-weighs the next part. When the freeze process is complete, the substrate indexes into the catalyst deposition machine and the catalyst is released into the micropulverizer. The micropulverizer grinds the nuggets into a fine powder and feeds the catalyst dust to the cloud tower using the flow of pressurized nitrogen gas.

When the deposition is complete, the table returns to receive a new part and the completed part moves from the cloud tower through a compaction roller. After this, the operator takes a second weight measurement for the processed part. A computerized SPC program compares the two weight measurements to insure that the process applies the correct amount of catalyst to the part. The part then moves into a sinter oven where it bakes for a set time at temperature. Finally, the part passes through another compaction roller and an operator visually inspects and unloads the completed part to a buffer.

The process is very rhythmic for the operator. Figure 5-1 shows a representation of the operator's pattern and the associated process cycle time. Once the operation begins, the operator moves from filling the canister with \( \text{LN}_2 \) and catalyst to weighing the next batch of catalyst nuggets to loading a substrate to the cloud tower drawer. Next, the operator returns to weigh the next substrate and waits for the completion of the freeze process. Finally, the operator initiates the catalyst deposition process by indexing the cloud tower drawer and dumping the frozen catalyst to the grinder.
5.2.2 Cathode Electrode

The cathode process is quite similar except for the fact that it doesn’t involve the freezing of the catalyst. Cryogrind is not required because the Teflon™ content is lower in the cathode catalyst than it is in the anode. This small change, however, makes a significant difference to the operation and efficiency of the line.

The major impact of this difference is that the elimination of cryogrind freezing enables the full automation of the catalyst weigh process. The operator fills a hopper with a large batch of cathode catalyst nuggets which feeds the catalyst to a trough and into the dump canister. When the canister is empty, the system automatically measures out the correct amount of catalyst and only needs attention from the operator to refill the hopper and to clear out the bottom of the hopper when catalyst gets jammed (an infrequent occurrence).

This automation simplifies the process for the operator which allows for the use of only one operator in the room (anode electrode processing requires two operators). The operator now starts by loading a substrate to the cloud tower drawer and indexes the part into the tower. This signal also dumps the automatically dispensed catalyst to the vibra-trough and into the micropulverizer.

After loading and indexing the part, the operator weighs out the next substrate. Finally, the operator moves to the cloud tower unload and takes the second weight measurement to verify that the cloud tower deposited the correct amount of catalyst on the substrate. This part moves into the sinter oven and on to final compaction and
inspection. The operator now returns to load the next part. The flow chart in Figure 5-2 shows the cathode operation for comparison to the anode.

It is clear from contrasting the two flow charts and descriptions that the cryogrind operation adds complexity and cost to this process. It is the reduction of this complexity that is the goal of the process improvement work proposed in this section.

5.2.3 Process Change-Over

The change-over process associated with the catalyst deposition equipment is the combination of a number of steps which range from changing physical equipment to extensive cleaning. Figure 5-3 shows a detailed flow chart which illustrates the parallel paths followed and the specific steps associated with the change-over process.

The process begins with the cleaning of the cloud tower. One operator removes the piping that connects the tower to the grinding equipment and scrubs the tower side walls to remove all of the catalyst powder that accumulated over time. Next, the operator vacuums the base of the tower to prevent the powder from spreading into the room. In parallel with this cleaning operation, another operator cleans the weigh and grind equipment using the vacuum to remove any powder or catalyst nuggets spilled during normal operation. The weigh and grind equipment cleaning requires the complete disassembly of the equipment to insure thorough cleaning of all surfaces that have potential contact with the catalyst nuggets or powder.

After completing the cloud tower cleaning, the next step requires the changing of the transition mask (the "tool" that determines the deposition flow and geometry of the catalyst on the substrate). There is a different distribution pattern for anode and cathode
which requires a different final mask footprint. This mask ensures that the electrode receives the correct amount and outline of catalyst. The changing of the transition mask involves major disassembly of the cloud tower equipment. Upon removal from the cloud tower, the operators manually lift the mask off of the input table and place it on a transport cart. They next load the new mask to the table and reverse the disassembly process to complete this section of the change-over. It should be noted that the seal between the mask and the processed part must be changed every 2-3 uses of the mask which adds time and complexity to the process.

Finally, the input table must be re-taped according to a template to accommodate the different sized footprint of the catalyst layer. The cloud tower draws the power catalyst to the electrode using vacuum drawn through the table. Therefore, since the application outline differs for anode and cathode electrodes, the amount of open pores in the table itself must match. In parallel with this taping operation, an operator changes the compaction roller paper.

In total, the change-over operation studied required 3 operators and one production shift (8 hours) to complete. Based upon observation and discussion with operators and operations management, we believe that there is room for improvement which could reduce the time in half given certain process improvements. The following sub-section discusses these options in more detail.
5.3 Short-Term Improvement Proposals

5.3.1 Cycle Time Reduction Opportunities

**Cryogrinding Analysis**

The need for the addition of cryogrind has come about due to the high Teflon™ content in the anode catalyst formulation. Grinding the catalyst into a fine power causes the anode catalyst to heat up and stretch out. This tendency to "fibrilate" has a negative impact on the performance of the electrode. To combat this problem, IFC engineering applied cryogenic grinding to change the material properties of the anode catalyst which made it easier to grind. Since the cathode catalyst has a lower Teflon™ content, it wasn’t necessary to adopt this process for both formulations.

**Time Lost to Cryogrind Process**

Through watching the process and performing time studies on the machine and operator interaction, we determined the time loss associated with the cryogrind process addition. Figure 5-4 shows the breakdown of the times associated with the anode electrode process. As is evident, the cryogrind process causes a wait time of 76 seconds per substrate for the cloud tower. Independent of the additional time caused by cryogrind, the cloud tower is the limiting process. Therefore, this additional time directly affects the capacity of the CSA manufacturing area and if left unchanged, will cause the pre-mature purchase of new equipment to accommodate forecasted volumes for PC25™ sales.
Catalyst Freeze Time Analysis

The first place examined for cycle time reduction was with the actual time that the catalyst is held in the LN$_2$ environment. The current time is 2 minutes and we proposed investigating this time to determine whether it was too long, too short or just right.

The first step was to measure a catalyst nugget and determine its composition. The nuggets are cylindrical in shape with an average height of 8 mm and an average diameter of 4 mm. For the heat transfer analysis, we assume a situation of pure conduction and a 95% cooling threshold. In addition, we conservatively utilize the properties for Teflon$^\text{TM}$ as representative for the whole catalyst nugget.

The next step requires verification of the pure conduction assumption. To do this, we calculated the Biot (Bi) number to determine its relationship to 1. A Bi value small compared to 1 signifies negligible internal conduction resistance which invalidates our assumption. Conversely, a Bi value large compared to 1 signifies negligible surface convection resistance which validates our assumption. The following equation is the basis for this calculation.

\[
\text{Bi} = \frac{h \cdot s}{k}
\]

where

- \(\text{Bi} = \) Biot number (dimensionless)
- \(h = \) convection heat transfer coefficient (W/m$^2 \cdot$ K)
- \(s = \) characteristic dimension (radius, m)
- \(k = \) thermal conductivity (W/m$ \cdot$ K)
The values utilized for this analysis appear below and represent the relevant range of values that could be expected for this situation. As stated previously, all values are for Teflon™.

\[
\begin{align*}
h_{\text{max}} &= 10,000 \quad \text{W/m}^2 \text{ K} \\
h_{\text{min}} &= 2,200 \quad \text{W/m}^2 \text{ K} \\
h_{\text{ave}} &= 6,100 \quad \text{W/m}^2 \text{ K} \\
\text{radius} &= 0.004 \quad \text{m} \\
k_{\text{max}} &= 1.00 \quad \text{W/m K} \\
k_{\text{min}} &= 0.35 \quad \text{W/m K}
\end{align*}
\]

Given these inputs, there were three values calculated for the Bi number. These three were the largest possible number, the smallest possible number, and the conservative value. The conservative value uses the average convection coefficient with the maximum thermal conductivity number available. The results of these calculations are as follows.

\[
\begin{align*}
\text{Largest Value} &= 114.29 \\
\text{Smallest Value} &= 8.80 \\
\text{Conservative Value} &= 24.40
\end{align*}
\]

As is evident from inspection, all of the Bi numbers calculated are large compared to 1 which serves to validate our initial assumption. This allows us to utilize a pure conduction model to determine the time necessary to freeze the catalyst to 95% of absolute LN\textsubscript{2} temperature (77 K).

The heat transfer model for pure conduction treats the catalyst nugget as an infinite cylinder. This is possible due to the length to radius (l/r) ratio of 3:1. This is convenient
since it allows the use of heat transfer tables to determine the freeze time. The actual model utilized is as follows.

Conditions: \[ \frac{[T(r=0,t) - T_i]}{[T_0 - T_i]} \]

Equation: \( \frac{(T - T_0)}{(T_i - T_0)} = 0.95 \) (for 95% cooling condition)

@ \( F_0 = \frac{(\alpha \cdot t)}{r_0^2} \) = 0.60 (from tables of conduction for an infinite cylinder)

Time: \( F_0 \cdot \frac{r_0^2}{\alpha} \), where \( \alpha = \text{thermal diffusivity of Teflon}^\text{TM} = 1.50E-07 \text{ m}^2/\text{sec} \)

Time = \( 64.0 \text{ seconds} \)

An alternate model that provides similar results is expanded upon below. This model assumes that the \( F_0 \) number is > 0.20 which corresponds to a “long time, \( t \)” condition.

We verify this condition at the end of the calculation to confirm the assumption.

For \( F_0 = \frac{(\alpha \cdot t)}{r_0^2} > 0.20 \) (“long times”)

\( \theta_i = \frac{(T(r=0,t) - T_i)}{(T(t=0) - T_i)} = Ae^{-2.562 \cdot 10^{-4} \cdot r^2} \)

for an infinite cylinder with \( Bi \sim 10 \)

\[ A = 1.568 \]

\[ \lambda^2 = 4.750 \]

For \( \theta_i = 0.05 \) (95% cooling -- \( T(r=0) = 88K \))

Time = \( -\ln (0.05/1.568) \cdot (1/4.750) \cdot ((0.04)^2 / 1.5E-07) \)

Time = \( 77.4 \text{ seconds} \)

Is assumption of \( F_0 > 0.20 \) valid?

\[ F_0 = \frac{(\alpha \cdot t)}{r_0^2} = (1.5E-07) \cdot 77.4 / 0.004^2 \]

\[ F_0 = 0.73 > 0.20 \]

Therefore, as can be seen from the above formulations, the current time of 120 seconds for freezing of the anode catalyst appears to be too long. The average of the calculations above gives a nominal value for freezing time of approximately 70 seconds.
This amounts to a 50 second potential time reduction which results in a direct increase in the overall throughput and production capability of the factory.

*Catalyst Heat-up Analysis*

In observing the catalyst deposition process and specifically the cryogrind portion of the process, there was the realization that the catalyst, after being dumped from the cryogrind canister, sits in the grind delivery trough an average of 45 seconds before processing begins. The specific time range is from 20 seconds for the first part to enter the grinding equipment to 70 seconds for the last part.

This time range that the parts sit prior to grinding is a time when the parts have the opportunity to heat back up toward room temperature. This heat-up could work against the whole philosophy of using cryogrind in the operation. Thus, we perform an analysis to determine the effects of this wait time on the temperature of the catalyst nuggets. A comparison of the pre-grind and target temperatures will determine if this wait time presents a problem to the function of the process.

The heat transfer analysis for this problem must include convection to the air and conduction to the stainless steel trough to thoroughly investigate the effects of the waiting time. A reasonable assumption is that convection governs the warming process. We validate this assumption by calculating the Biot number (as done for the cooling analysis) and comparing it to 1.00. Using the radius and thermal conductivities from the earlier calculation and the convection heat transfer coefficient below, we calculate the Biot number to be in the range 0.04 to 0.11. The fact that this is very small compared to 1.00
validates our assumption that convection governs the warming process and enables us to use this condition to determine the temperature of the catalyst prior to grind.

Assuming convection to the air \( (T_{\text{air}} = 300 \text{ K}) \), we can utilize a lumped capacity equation as follows:

\[
\begin{align*}
\text{Time} & \quad \text{Catalyst in Trough} \\
T_{\text{air}} & = 300 \text{ K} \\
T_o (95\% \text{ cooling}) & = 88 \text{ K} \\
h (\text{heat transfer coefficient}) & = 10 \text{ W/ m}^2 \text{ K (range 1-30)} \\
\text{radius} & = 0.004 \text{ m} \\
T & = \frac{\rho \cdot c \cdot \text{volume}}{h \cdot \text{area}} \\
& = 1500 \text{ seconds} \\
T_f & = T_o + (T_{\text{air}} - T_o) \cdot (1 - \exp(t/T)) \\
T_f (t=20 \text{ s}) & = 91 \text{ K} / -182 \text{ C} / -296 \text{ F} \\
T_f (t=45 \text{ s}) & = 94 \text{ K} / -179 \text{ C} / -290 \text{ F} \\
T_f (t=70 \text{ s}) & = 98 \text{ K} / -175 \text{ C} / -284 \text{ F}
\end{align*}
\]

Given the results of this model, the average and maximum time conditions have no significant effect on the warming of the catalyst. This suggests that the warming of the catalyst is negligible and can safely be ignored.

\textit{Double Canister Proposal}

Another option considered for the elimination of the 76 second cryogrind wait time is the addition of a second catalyst weigh and dispense system. The general idea is to keep the deposition cycle time constant at 120 seconds and to add additional equipment to eliminate the wait time associated with the freezing of the anode catalyst. In theory, it is
possible to eliminate over 90 seconds from the process cycle time through this addition. This value assumes perfect operator movement and no interruptions to the work rhythm. The proposal would reduce the cycle time associated with the production of electrodes. The elimination of this time translates into cost savings by the elimination of the variable costs associated with running this equipment (labor, electricity, etc.).

A more realistic (and conservative) value for the savings is to consider a 60 second cycle time reduction. This provides a benchmark value for financial analysis and represents a "real world" attainable value. Thus, if this path is chosen, the project should achieve or exceed its return on investment and payback projections. A reverse economic analysis determined the maximum amount of capital that could be spent given the 60 second per anode substrate savings. Table 5-1 below presents the details of this analysis. Figure 5-5 shows a proposed drawing of the new cabinet configuration.

The ROI calculations state that the 60 second reduction in cycle time would support up to a $45,000 investment. This would give a 1.6 year payback and a 20% ROI. Investigation into the cost of purchasing and implementing such a plan (shown below) indicates that that the total cost would be about $25,000. This lower investment figure makes the financial numbers even more attractive.

<table>
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<th>Duplicate Equipment</th>
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<tr>
<td>New Cabinet and Materials</td>
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</tr>
<tr>
<td>Labor and Installation</td>
<td>$ 5,000</td>
</tr>
<tr>
<td>Total Investment</td>
<td>$ 25,000</td>
</tr>
</tbody>
</table>
If implemented, the cycle time reduction can be increased to 75 seconds (15 additional seconds) based on operator learning and experience using the system. This would completely eliminate the effects of the cryogrinding process, returning the operation capacity to its original value.

Return on Investment Analysis
Catalyst Deposition Line Productivity Improvement

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<td>DCRR</td>
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<td>Payback Period (yrs)</td>
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<td></td>
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<table>
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<th>Capital</th>
<th>Depreciation</th>
<th>Cash Flow</th>
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<td>$(48,510)</td>
<td>$(46,510)</td>
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<td>3</td>
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<td>-</td>
<td>-</td>
<td></td>
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<td>-</td>
<td>$15,587</td>
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</tbody>
</table>

Table 5-1

Other Cycle Time Reduction Opportunities

Cloud Tower Process

Given the elimination of the cryogrind cycle time (76 seconds), the next within-process limiter is the cloud tower / catalyst deposition. The sub-process begins with the loading of a substrate to the drawer and pushing a button which shuttles the drawer into the tower and releases the catalyst to the grinding equipment. The drawer shuttles into the tower and then raises up to press against the catalyst mask (the conduit through which the catalyst moves). The grinder and cloud tower work together to deposit catalyst on to the part at a rate of approximately 1 gram / second. Finally, the drawer lowers, and the completed part moves out to the compaction roll and on to the rest of the process. This
process takes 124 seconds to complete which is the longest of any of the operations associated with catalyst deposition. Figure 5-6 shows a graphical representation of this process and presents the cycle time data for each section of the sub-process.

**Shuttle Drawer Cycle**

Examination of the cycle time data presented in Figure 5-6 reveals that the shuttle table indexing into and out of the cloud tower accounts for 30 seconds of the 124 seconds required for this part of the process (24%). This presents an opportunity for cycle time reduction. The recommended course of action is to speed up the drawer indexing for both the input and output from the cloud tower.

Specifically, the recommendation is to start with speeding up the output from the cloud tower to its maximum possible speed. This will reduce cycle time without any impact on the electrode. The next step is to speed up the input travel of the drawer as much as possible without putting the part at risk of lifting off the drawer. An estimate of the total time savings is roughly 10 seconds. It is important to note that any time saved is additional capacity for the catalyst deposition machine.

**Catalyst Delivery**

Another observation which comes from study of the equipment is that the cloud tower waits 18 seconds on average (14.5% of total time) for the catalyst to enter the grinding equipment. This wait time is pure waste and should be eliminated. The solution to this problem is to adjust the controls to activate the vibra-trough right after the canister dumps
the catalyst. This will lead to an increase in daily throughput and overall capacity for the catalyst deposition equipment with little to no capital investment required.

**Weighing Process**

Upon exit from the cloud tower, the electrode parts (both anode and cathode) pass through a compaction roller and then undergo a second weight count. This weight count verifies that the equipment deposited the correct amount of catalyst on to the substrate. This weighing operation requires an operator to push a button to send the value to a computer which keeps track of the part and determines whether to accept or reject the electrode.

This proposal suggests the automation of that second weighing to eliminate the need for operator effort after feeding the part to the compaction roller. There are currently systems on the market which will position the part in place, make the measurement, and send the value to a computer or similar tracking device. Elimination of this responsibility provides the operator more time to focus on the cloud tower process and may, in combination with the previous recommendation, lead to the elimination of the extra operator for anode electrodes.

**5.3.2 Setup Time Reduction**

As mentioned in the setup/change-over description section above, there is potential for improvement in the change-over time for the catalyst deposition process. The recommended improvements fall into two categories which are (1) minor hardware changes and preparation, and (2) safety issues. Any long-term equipment changes (new
purchases) will consider the change-over and safety issues as part of the specification for the equipment.

**Minor Hardware Changes and Preparation**

The place to start the improvement process is with little items that when combined can add up to a significant improvement in both time and worker attitude regarding the job at hand. As mentioned above, the process begins with the removal of piping from the cloud tower. This connection involves using 8 bolts with nuts and washers. The operator must loosen each bolt with a box-end wrench which involves much twisting and takes longer than necessary. This recommendation involves changing these bolts to quick-connect fasteners which has the potential to save 5-10 minutes from this process.

The second area for short term change is in the input table taping process. This process requires the use of a guidance mask and numerous strips of tape which must be scraped clean and re-applied at each change-over. This process can take anywhere from 30 to 60 minutes to complete which makes it a prime target for improvement. We propose production of a thin template (purchased or made in-house based on cost and manpower availability) for both anode and cathode dimensions which could be set in place and anchored down by adhesive on the side which contacts the table. This recommendation has the potential to reduce the time required from 45-60 minutes to 10-15 minutes.

The final area for improvement in the short term is with the seal that must be applied to the transition mask. Currently, the seal is pre-cut to rough size and applied to the mask. Then, an operator trims the seal to final size as necessary. This final trim is an
unnecessary step that could be eliminated given an improved tool to make the seal. This seal is currently made in-house and IFC might consider purchasing this from an external vendor who is familiar with cutting the material. The estimated savings is again on the order of 10-15 minutes.

**Safety Issues**

The study of the change-over process revealed that there were two safety issues that should be a part of any improvement effort. The first involves the use of razor blades to trim and scrape away excess material. Implementation of the taping and seal recommendations in the previous sub-section will effectively eliminate these concerns. The second issue involves the ergonomics associated with the change-over. The lifting and bending involved with the removal and installation of the transition mask is unacceptable from an ergonomics standpoint. It involves excessive lifting with the back and unnatural bending positions for removal and reattachment. At this point in the development, there is not much that can be done except for managerial controls and perhaps the implementation of different procedures for moving the mask. In the future, any new equipment should be designed to take this into account such that the easy way to do the job is also the ergonomically correct way.

**5.4 Decision Criteria**

In examining the numerous options that are available for short-term process improvement, it becomes difficult to determine which proposals to accept. Given this difficulty, we propose decision criteria and utilize these criteria as a framework for the
process improvement effort. The first criteria is capital cost which is a common consideration throughout most companies operating today. The second is the impact that each improvement area has on total capacity of the bottleneck. Taking into account the large difference between the bottleneck capability and the next limiting process (see Manufacturing Operations Model results in Section 3 for review), this becomes a large determinant for how to proceed. Finally, the ease of implementation must be considered to determine whether the increase in production capability is in fact worth the effort of implementation.

In reviewing the short-term process improvement ideas, it is evident that the proposals are already grouped in terms of capital investment required for the project. This grouping reflects a common theme throughout the internship project and this thesis work of reduction / avoidance of capital expenditures. The current manufacturing infrastructure reflects IFC’s belief that future volumes will justify their decision to invest in automation and extra capacity. Hayes and Wheelwright’s product-process matrix (Figure 5-7) is a useful tool to show IFC’s current and desired positions. At low volumes, their current alignment creates an expensive product due to the excessive overhead allocation across a relatively small volume. In terms of the matrix, this places them in the left-most circle. Their desired location is to move to the right which would reflect a growing market and increased production volumes. These increased volumes across a constant capital infrastructure would result in the reduction of product cost due to economies of scale in the production process. In the current state, it is clear that capital expense should be minimized whenever possible without undermining the ability to manufacture a quality product.
The second criterion utilized in the decision making process is the change in capacity provided by the proposed process improvement. The different categories investigated for process improvement were cloud tower cycle time, setup time, startup time, and cryo-grind cycle time. All proposals for improvement generate some capacity increase but the real question is which improvement projects give the largest increase for the smallest change in time. To determine this, the proposed time savings generated in the previous sub-section were entered into the manufacturing operations model to determine their impact on the production capacity of the catalyst deposition process. Figure 5-8 presents the results of this analysis. As can be seen from the graph, this criterion suggests that the base cycle time improvements should be first followed by setup time reduction, cryo-grind cycle time reduction and finally startup time reduction.

Finally, the ease of implementation must be considered along with the other two criteria to determine a plan of attack for improving the catalyst deposition process. This is often thought of as a cost item but we wish to separate it from the decision regarding capital investment. This area represents the time and effort required to engineer and implement the project. It is utilized as a final verification after the first two criteria are met to determine whether a project is worth doing or not. It could be possible to have a project that requires little capital investment and provides a large increase in production capacity but is so difficult to implement that its benefits would never be realized. This criterion did not impact our final recommendation but should be considered as a part of the decision process.
5.5 Long-Term Equipment Plan

In examining the future growth projections for fuel cell production, there is going to be the need to invest significant capital in the catalyst deposition process equipment to enable the attainment of future production requirements. The above improvement suggestions can and should be employed in the short term to extend the capacity of the CSA manufacturing arena but it is also necessary to plan for the inevitable need to purchase new equipment.

A conservative projection suggests that the impact of the above suggestions can increase the catalyst deposition manufacturing capacity from its current value of 66 CSA / year to approximately 90 CSA / year. This projection assumes no decrease in machine uptime. According to the projected volumes for PC25™ sales (Figure 3-2), this should be adequate capacity for the next 3-5 years. After this time, there will be the need to replace this equipment to accommodate the expected sales growth 5 years and beyond.

Based on the time spent studying the line and the above suggestions, we developed a machine specification to serve as a foundation for future efforts to build the new catalyst deposition equipment. This specification focuses attention on minimizing equipment change-over times (less than 4 hours) and reducing the cycle time associated with the cloud tower to more closely match the oven speed (~ 1 part / minute). A design that meets these criteria will bring this equipment in line with the current capacity of the other equipment in the CSA manufacturing area (about 150 CSA / Year). Volume expansion beyond this value will require duplication of the current CSA manufacturing facility or the continuous use of overtime to meet production.
5.6 Recommendations

Based on the work presented in this section, we present a plan of attack for the improvement of the catalyst deposition process. Sensitivity analysis results obtained through the use of the manufacturing operations model (Figure 5-8) confirmed the optimal path for increasing the output capability of the bottleneck process. This is an interpretation of that path for action in the coming years.

The first area to concentrate efforts is in places that do not require investment of any capital dollars. In essence, success in these areas equates to free capacity. The two critical changes that fall into this category are the cryo-freeze time associated with the anode catalyst and the change-over time from anode to cathode. The heat transfer analysis previously presented shows that a minimum of 30 seconds can be reduced from the anode cycle time and we believe that this can easily be increased to 50 seconds without any effect on the grinding performance of the catalyst. This amounts to a policy and process change but doesn’t require any investment to implement. The decrease in cycle time can result in an increase of 4-8 CSA/year depending on the actual cycle time reduction.

The second “free” change is with respect to the catalyst deposition change-over time. Analysis shows that an 8 hour reduction in time (i.e. moving the maintenance to 3rd shift) would result in an increase of 13 CSA/year in production capacity. Again, this is a policy and personnel change that doesn’t require any capital investment. The combined effect of these two changes with no decrease in machine uptime would result in an theoretical increase of 17-21 CSA/year. This would enable the CSA manufacturing area
to produce 87 CSA / year (on average) with minimal or no cost. It should be clear that these two steps are the first places to invest time and engineering effort.

The third “zero cost” area for investigation is with the timing of the cloud tower mechanicals. Specifically, there is time that can be reduced from the table indexing and catalyst delivery system. With some effort and possible controls modifications, there is the opportunity to save at least 10 seconds per part from the overall base cycle time of the cloud tower which limits the catalyst deposition production. The conservative combination of the three improvements would increase the theoretical production capacity by 25 CSA / year for an overall new capacity of 91 CSA / year.

The next phase of improvement is that which requires the investment of minimal capital dollars. This part of the recommendation serves as a backup to the above “zero cost” options. For example, the proposal to eliminate the cryogrind cycle time penalty by adding another weight count scale can serve as a fall-back position if reasons surface that prohibit the reduction of the freeze time for the anode catalyst.

The other “small investment” recommendations involve efforts to reduce the amount of time the operator must spend on the process. The goal here is to eliminate the need for the second operator when running anode electrodes. This investment would be in a computerized weighing and tracking system for the electrode substrates and a new system for cryogrind. One or both of these ideas would free up enough time to allow only 1 operator to run the catalyst lines which may become an attractive option as volumes increase. This “eliminated” operator would be available for relief or additional quality checks somewhere else in the system.
Finally, there is an equipment specification that is ready for quotation for the purchase of new equipment. It is clear that this equipment will need to be replaced within the next 5 years due to either volume, deterioration, or a combination of both. Therefore, the specification serves as a foundation for this future purchase. We present this specification as a starting point which should be amended as the parts and process technology change. The key factors which should not be sacrificed in the new system are reducing the cloud tower cycle time and change-over time. If volumes warrant, having dual lines to replace the single line may be the best alternative.

In summary, this is a three phase improvement plan that involves short-term, zero and low cost alternatives and a long-term, high cost replacement plan. We believe that this is in line with IFC’s desire to reduce cost and presents a viable plan for extending the production capability of the catalyst deposition line, while looking to the future for a more permanent solution.
CATALYST DEPOSITION LINE -- OPERATOR/MACHINE CHART

1. Weigh Substrate and Stage Part Prior to Drawer
   - Load Substrate to Drawer when Available
     - Wait for Catalyst Freeze to Complete
       - Dump Canister, Grind Catalyst and Shoot to Substrate
         - Weigh, Compact Sinter, Compact, and Inspect

2. Operator Movement
   - 1. Fill Canister with LN₂ and Load Catalyst
     - 2. Weigh 30.5g of Catalyst

3. (50.4) Freeze Catalyst

Legend:
Dashed Arrow -- Operator Sequence
Solid Arrow -- Part Sequence
(Time) is in Seconds

Figure 5-1
CATALYST DEPOSITION LINE -- CATHODE ELECTRODE

1. Load Substrate (x+1) to Drawer and Release Catalyst to Grinder
   (25.6)

2. Operator Movement
   Weigh Substrate (x+2) and Stage Part Prior to Drawer

3. Unload Substrate (x) from Cloud Tower, Weigh and Feed to Sinter Oven
   (60)

4. Automatically Weigh 42.3 g of Catalyst for Substrate (x+1)
   (40)

Grind Catalyst and Shoot to Substrate (x+1)
   (124.0)

Legend
Dashed Arrow -- Oper Sequence
Solid Arrow -- Part Sequence
(Time) is in Seconds

Figure 5–2
Catalyst Deposition Line -- Change-Over Process

Cloud Tower

- Disconnect piping from tower flange and scrape with wire brush
- Vacuum out cloud tower base; in and around mask

Transition Mask

- Index table and raise to meet mask; vacuum off unload tarp
- Loosen and disconnect mask-to-frame attachment and input-side cross beam
- Unbuckle 12 connectors

Weigh and Grind

- Vacuum catalyst from all cabinet and grind surfaces
- Relocate hopper-to-canister trough and lock into place
- Vacuum out canister-to-grinder trough
- Thaw and clean canister(s)
- Detach grinder from cabinet
- Detach pipe from grinder to cloud tower
- Disassemble grinding equipment; vacuum and brush internal and external surfaces

Figure 5-3-1
CATALYST DEPOSITION LINE -- CHANGE-OVER PROCESS

Transition Mask

- Lower table and index to load position
- Vacuum mask
- Lift and rotate mask onto portable cart
- Vacuum mask
- Scrub remaining powder from fixed tower transition
- Vacuum unload tarp and lower tower
- Unload new mask from storage rack

Weigh and Grind

- Re-assemble all equipment and install new micropulverizer gasket to housing
- Re-attach grinder to cabinet

Compaction Roller

- Remove roll cover and tape
- Clean roll surface
- Raise roli for new paper application
- Apply fresh paper and tape
- Lower roll back into position

Figure 5-3-2
CATALYST DEPOSITION LINE -- CHANGE-OVER PROCESS

**Transition Mask**
- Load "removed" mask to rack
- Remove mask-to-part rubber seal and clean edge
- Apply 2-sided tape to seal surface and new rubber seal using template; trim to size
- Load new mask to input table
- Index table into tower and raise
- Buckle latches to mask and lower and attach input-side bracket
- Run system "dry" to flush out remaining power

**Input Table Taping**
- Remove tape from vacuum input table using razor blades
- Install template on to table
- Re-apply fresh tape according to template

Figure 5-3-3
## CATALYST DEPOSITION LINE -- TIME STUDY ANALYSIS

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<th>Anode Processing (seconds)</th>
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<th>Sample 2</th>
<th>Sample 3</th>
<th>Sample 4</th>
<th>Sample 5</th>
<th>Average</th>
<th>Std. Dev.</th>
<th>Man or Machine</th>
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<td>9.39</td>
<td>8.17</td>
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<td>120.00</td>
<td>120.00</td>
<td>120.00</td>
<td>120.00</td>
<td>120.00</td>
<td>-</td>
<td>Machine</td>
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<td>Sum</td>
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<td>36.00</td>
<td>30.75</td>
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<td>26.91</td>
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<td>25.61</td>
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<table>
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<th>Sample 3</th>
<th>Sample 4</th>
<th>Sample 5</th>
<th>Average</th>
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<td>26.91</td>
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<td>25.61</td>
<td>3.54</td>
<td>Operator</td>
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<table>
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<th>Sample 3</th>
<th>Sample 4</th>
<th>Sample 5</th>
<th>Average</th>
<th>Std. Dev.</th>
<th>Man or Machine</th>
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<td>14.89</td>
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<td>15.10</td>
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<td>76.01</td>
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<td>75.85</td>
<td>3.29</td>
<td>Machine</td>
</tr>
<tr>
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<td>15.63</td>
<td>14.28</td>
<td>13.98</td>
<td>14.02</td>
<td>14.61</td>
<td>0.74</td>
<td>Machine</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
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<th>Min</th>
<th>Max</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20.00</td>
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<td>45.00</td>
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</tbody>
</table>

**Figure 5-4**
PROPOSED DOUBLE CANISTER CABINET DESIGN

Weigh and Grind Cabinet with 2 Canisters

Figure 5-5
CATALYST DEPOSITION LINE -- CLOUD TOWER PROCESS

(25.6) Load Substrate to Drawer when Available

(15.2) Index Table to Cloud Tower

(18.3) Wait for Catalyst to Reach Grinder

(75.9) Catalyst Deposition

(14.6) Index Table to Load Position

simultaneous

Freeze Catalyst

Dump Catalyst

Grind Catalyst

Figure 5-6
## PRODUCT – PROCESS MATRIX

<table>
<thead>
<tr>
<th>Product Structure</th>
<th>Process life cycle stage</th>
<th>Process Structure</th>
<th>Process life cycle stage</th>
</tr>
</thead>
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<td>I</td>
<td>Low Volume -- low standardization, one of a kind</td>
<td>I</td>
<td>Low Volume -- low standardization, one of a kind</td>
</tr>
<tr>
<td>II</td>
<td>Multiple products low volume</td>
<td>II</td>
<td>Multiple products low volume</td>
</tr>
<tr>
<td>III</td>
<td>Few major products higher volume</td>
<td>III</td>
<td>Few major products higher volume</td>
</tr>
<tr>
<td>IV</td>
<td>High volume -- high standardization, commodity products</td>
<td>IV</td>
<td>High volume -- high standardization, commodity products</td>
</tr>
</tbody>
</table>

- **I** Jumbled Flow (job shop)
- **II** Disconnected line flow (batch)
- **III** Connected line flow (assembly line)
- **IV** Continuous flow

**Figure 5–7**
Figure 5–8
6. Summary and Conclusions

6.1 Introduction

The goal of this thesis work was to develop and implement a manufacturing operations tool that could be utilized to help understand and improve the current and future fuel cell manufacturing operations. The previous sections outlined three distinct phases which supported this goal and showed the implementation of each phase of the work. Each section has value as a specific example of either developing or using simple models to improve manufacturing operations. In addition, the progression of work from model development to improvement recommendations presents a case study for future adaptations of this structure.

This work and the process utilized to accomplish it has been validated by IFC through the use and implementation of the recommendations presented. First, IFC is using the Manufacturing Operations Model to better understand their manufacturing operations. Second, the lot size recommendation has been implemented on the bottleneck process since January 1, 1996. Finally, the cryo-freeze time reduction has been tested and the parts are being produced with a shorter freeze time. The results of this change are a capacity and quality increase. In addition, IFC is currently investigating the implementation of the dual-scale proposal to further reduce the cycle time associated with the bottleneck.
6.2 Manufacturing Operations Model

The idea behind the development of the manufacturing operations model was to provide a simple-to-use tool for determining the current state of the cell stack manufacturing operations and provide the operations management with "what-if scenario" capability. In addition to providing these tangible benefits, the model is very flexible to accommodate future changes in the process and is written in Microsoft Excel™ to allow for the widest acceptability and usability.

The first critical result from the model is the collection of current operating data for all of the processes utilized to manufacture a cell stack. These values for cycle time, scrap percentage, equipment uptime, etc. were previously estimated but never verified through detailed study. Now, IFC has the current data and a model to utilize the data to determine critical operational metrics. The model will hopefully provide adequate motivation to keep the previously mentioned values current.

The second and third results from the model deal with its outputs. The model provides insight into the hierarchy of constraining processes required for cell stack manufacture. In addition to identifying the bottleneck operation (catalyst deposition), the hierarchy provides insight into the next limiting process to allow for better decision making with regard to equipment upgrade and capacity expansion. The other key output provides a relationship between scrap percentage and total cost for a given production volume. This relationship provides data that can be utilized to focus process improvement efforts on the equipment that contributes most to the cost of the operation.
These outputs work together to help focus efforts on improving process capacity and reducing cost.

6.3 Production Strategy Model

The production strategy model is the next step in the process once the bottleneck has been identified. In essence, this step assumed that all bottleneck inputs were fixed and attempted to determine whether the process was being run optimally. By application of the EOQ model and sensitivity analysis for the inputs, the conclusion is that the process is not currently being run in an optimal way. In order to translate this result into IFC systems metrics, another model was utilized based on a mini-overhead budget developed specifically for the bottleneck process. This model confirmed the EOQ result and proposed that the production lot size be increased to achieve lowest operating cost for the bottleneck process.

Therefore, a lot size of 900 pieces was recommended which reduces piece cost by 10% and minimizes the lead-time penalty associated with the lot size increase. Karmarkar (1987) presents the relationship between lead-time and lot size and shows that as lot size increases, the lead-time for processing the lot also increases. Thus, there is a trade-off. Larger lot sizes increase the lead time for processing the lot, but decrease the utilization. He also shows that the lead-time is significantly affected by capacity utilization (as utilization increases toward 100%, lead-time increases) which enhances the support for bottleneck analysis in a manufacturing system. This lot size increase is recommended as a short-term fix to optimize the current operating parameters and balance the system-wide effects of making a change. Lowest cost would suggest a larger
lot size but the lead-time penalty becomes significant as lot sizes are increased beyond 900 pieces.

6.4 Bottleneck Process Improvement

The final part of this thesis recognizes that the inputs to the bottleneck process are not fixed and various improvement ideas are proposed to increase the production capacity of this process. We suggest a two-phased strategy for process improvement which includes a short-term ("zero" cost) phase and a long-term phase. In the short-term, we propose plans to reduce the cycle-time and change-over time that require no capital expenditure to implement. Together, these improvements amount to a capacity increase of 38% utilizing conservative estimates for cycle-time improvements. This increase allows IFC to avoid a large capital expenditure to satisfy demand over the next 5 years.

The second phase of the improvement strategy is the recommendation to purchase a new piece of equipment. The existing equipment is old and isn’t going to last forever. It also wasn’t designed to facilitate quick change-over or with ergonomic concerns in mind. Therefore, a preliminary specification was written and given to the process equipment group outlining the key concerns and design requirements for this process. The critical parameters were to have a change-over time of less than 2 hours and an overall cycle time that matched the current convection dryer capability (1 part / minute).

6.5 Conclusions

The work performed and presented in this thesis provides a framework for approaching a new manufacturing situation and shows how common and simple tools can
be utilized to achieve important results. This conclusion echoes one made by Hetzel (1993) which showed the effectiveness of using a simple model to elevate the importance of and quantify critical process drivers and to provide concrete, implementation-oriented outputs. Our model uses data collected from the individual operations and summarizes it into a format useful to IFC manufacturing management. The outputs from this model aid management decision making as well as provide data for further analysis.

The improvement activity around the bottleneck operation shows two important insights. First, that simple bottleneck analysis is a powerful tool that can produce significant results with minimum effort. Second, that a staged approach to bottleneck improvement can often produce the best results. These insights support some of Blossom’s (1995) conclusions in implementing a lot size model in a manufacturing organization. Primarily, our work presents further evidence that small, well-focused efforts can produce significant results. In this case, the results took the form of “zero cost” process improvements and future investment avoidance.

In general, the structure of the framework presented suggests that operations changes (like production lot sizing) should be attempted first to determine whether an immediate savings can be realized. Next, both short and long-term process improvements should be analyzed and the most promising chosen for implementation. Our work at IFC suggests that low (or zero) capital cost opportunities are often an available and effective route when considering potential process improvement projects.
7. Bibliography


