Increasing the Capacity of a Flow Shop: Technical and Organizational Issues

by

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Submitted to the Department of Mechanical Engineering and the Sloan School of Management in partial fulfillment of the requirements for the degrees of

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Master of Science in Management

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Abstract

This thesis addresses the issue of increasing the capacity of a flow shop using existing assets. Options for increasing capacity are identified and discussed. A network queueing model is developed to analyze these options. Based on the model outputs, a change to the operation is suggested. This change would result in a 20% increase in capacity, an 84% reduction in process cycle time and an 81% reduction in work in process inventory.

The organizational issues of implementing the suggested change are investigated. A framework for classifying the type of organizational change is introduced. This framework is applied to the organization being studied to identify and analyze the challenges it faces. Strategies to overcome these challenges and the key learning points for the researcher are discussed.

Thesis Advisors:
Janice Klein, Senior Lecturer, Sloan School of Management
Stanley Gershwin, Senior Research Scientist, Department of Mechanical Engineering
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Chapter 1: Introduction

1.1 Thesis Objective

This thesis is the outcome of a joint research project between H. C. Starck Inc. and MIT, under the auspices of the Leaders for Manufacturing Program. The research for this thesis is conducted during a six-month period in 2000. The objective of this program is to improve customer service performance for metallurgical products by increasing the production capacity of the melt shop.

1.2 Problem Statement

The company is experiencing rapid increases in demand for their products made of tantalum. This demand is expected to continue for the foreseeable future. Decreased levels of customer service have indicated that one of the company's business units, metallurgical products, is unable to meet this growing demand.

The company needs to add capacity to the metallurgical business in order to be able to participate in the expansion and diversification in this market. Efforts are currently under way to expand via acquisition. This thesis will not focus on this set of activities, however. Instead, it will address what can be done to increase capacity with existing assets. Focusing on existing assets will enable the company to increase capacity in less time at low cost and little risk. Following this strategy will enable the company to meet the expanding short-term demands while long-term solutions, i.e. acquisitions and new facilities, are completed.

1.3 Thesis Overview

This thesis is intended to be an argument for the implementation of a strategy that uses the current assets of the melt shop more effectively. By using an unused asset, the plasma furnace, the company will be able to realize additional gross profits of $1.1
million annually and enjoy a one-time inventory reduction estimated at $1.3 million. This recommendation is intended to be complementary to the capacity expansion being planned. To this end, this thesis is composed of five chapters, the last four of which are described below.

Chapter two provides the context for the analysis. It will introduce the product, tantalum, and its uses. Next, it will discuss the company and the operational unit to be studied, the melt shop. Finally, it will illustrate the motivation for the project and frame the issue to be addressed.

Chapter three analyzes the melt shop with the intention of identifying a way to increase its capacity with the assets currently available. To accomplish this, the techniques to increase capacity are introduced and discussed. An analysis tool, a queueing network model, is presented. This tool is applied to the melt shop by developing three different scenarios and examining the resulting outputs.

Chapter four discusses the issues associated with implementing the change suggested by the analysis. An analytical framework for this discussion is introduced and then applied to this change effort. The barriers to changes are identified and discussed.

Chapter five presents the conclusions based upon the background of chapter two and the analysis of chapters three and four. The recommendations focus on actions that can be taken by the company to meet their objective of growing their metallurgical products business.
Chapter 2: Background

This chapter will provide the necessary background information for the subsequent analysis and recommendations. First, a description of the product, tantalum, and its uses is outlined. Next, a high-level view of the company, H. C. Starck, is provided. Third, a detailed description is given of the operation being studied, the melt shop. Finally, the motivation for this study and the problem statement are detailed.

2.1 Tantalum and Its Uses

Tantalum, chemical symbol Ta, is an element with atomic number 73. It is in the sixth period, with elements like tungsten and rhenium, and fifth family, with elements like vanadium and niobium. Tantalum exists as a metal. It is dense, specific gravity of 16.6. Its melting point is very high, 2,996°C, and is exceeded only by tungsten and rhenium. Tantalum is also highly corrosion resistant and ductile.

Tantalum is used by a wide variety of industries with a total worldwide annual consumption of about 550 tons. The computer and electronics industry uses tantalum capacitors on circuit boards. These electrolytic capacitors (and the vacuum furnace parts used to make them) account for about 60% of tantalum’s usage. In addition, the semiconductor industry uses tantalum for sputtering targets used to process their integrated circuits. In alloys where properties like high melting point, high strength, and good ductility are important tantalum is a good choice. Examples of these uses include chemical process equipment, nuclear reactors, and aircraft and missile parts. Also, because tantalum is not reactive, it is being used in medicine for surgical appliances. Finally, tantalum oxide is used to make glass with a high index of refraction for camera lenses.

Tantalum is not readily available. Ores are located in Australia, Brazil, Mozambique, Thailand, Portugal, Nigeria, Zaire and Canada. The refinement process from ore to pure
tantalum is complicated and requires several steps. As a result, tantalum is expensive, costing $100/lb for scrap. Compare this to several other metals. Aluminum costs $0.70/lb. Silver costs $64/lb. Gold costs $3,841/lb or $263/troy-oz. (WSJ 29-Mar-2001)

2.2 The Company

H.C. Starck Inc., the company, is a producer of tantalum and niobium products. It employs approximately 400 people at a 325,000 sq-ft complex. The company is part of H.C. Starck GmbH of Germany, an international company of 2,500 specializing in metals with high melting points such as tungsten, molybdenum, rhenium, tantalum and niobium as well as non-ferrous metals like cobalt and nickel. H.C. Starck GmbH is a member of the Bayer AG group, an international chemical and healthcare company that employs 145,100 people worldwide.

There are six different manufacturing operations within the company: powder, sinter, wire, melting, flat rolling and fabricating. These operations support four types of products: powder, wire, mill products and fabricated products. These products are made from one of three incoming materials. The first, $K_2TaF_7$, is an intermediate in the refinement of tantalum and represents the largest source of tantalum for the company. It is received from one of the other H.C. Starck GmbH companies located in Germany, Thailand or Japan. The second raw material is tantalum ingots. These are usually purchased at auction from the former Soviet Republics or the US government. The last type of raw material is scrap tantalum and there are two sources. Some is purchased from other companies, when they replace their vacuum furnaces, for example. The other source is the internal scrap flows of the company. See Figure 2 on page 16 for a schematic of the operations and the flows of material within H. C. Starck Inc.

Figure 1 below shows the revenue contribution of each business to H. C. Starck Inc. Powder is the largest at 42%. The second largest revenue source, specialty products, is made up of items that are imported from other groups within H. C. Starck for sale in the United States. The third largest business is metallurgical products at 19% (when milled
and fabricated parts are included). The fourth most important business by sales revenue is wire products at 12%.

![Revenue Contribution by Business](image)

**Figure 1: Revenue Contribution by Business**

### 2.3 Melt Shop

The melt shop and its tantalum processing operations are the focus of this study. This section will characterize the melt shop by describing its inputs, its products and the processes used to make these products.

#### 2.3.1 Inputs

The melt shop is a recycling operation. Figure 2 shows the flow of tantalum into and within the company and illustrates how the melt shop relates to the other operational units. There are three items of particular interest. First, the melt shop receives scrap tantalum from every operation within H. C. Starck. Second, scrap is also purchased from outside the company. The split between inside recycling and outside purchases is
approximately 50/50. Finally, and most importantly, the melt shop is the only supplier of inputs to metallurgical products, the mill shop and the fabrication shop.

![Diagram of H.C. Starck, Inc. and Its Flow of Tantalum, Carroll (2000)](image)

The scrap inputs come in a wide range of forms: powder, machine chips, wire, plate, sheet, foil, anodes and ingots. While the differing shapes of the input require a variety of processes, it is the issue of contamination that is most contentious.

### 2.3.2 Products

There are a limited number of products produced in the Melt Shop: a total of five alloys. They are denoted E, D, Q, S and W. These alloys are transferred to the other departments in the form of ingot, sheetbar or rod. The total number of products produced is eight given the shapes and alloys of the materials and is shown below in Table 1. These
products are used to make goods for the Ta-Metallurgical, Mill Products and Fabricated Products businesses. These products accounted for 19% of 2000 revenues for the company. See Figure 1 on page 15.

### Table 1: Products of the Melt Shop

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Ingot</th>
<th>Sheetbar</th>
<th>Rod</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Q</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>W</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

#### 2.3.3 Current Processes

The processes used by the melt shop transform scrap tantalum into sheetbars. The structure of the process is described best as a flow shop. There are a limited number of products with low volumes (compared to steel or aluminum manufacturing operations). There are twelve primary workstations that are separated by buffers. The cycle times for the processes are measured in hours. It is common for some process steps to take more than one 8-hour shift.
2.3.3.1 Typical Process Steps

Figure 3 shows the typical process steps in the melt shop. Scrap lots of tantalum arrive to the melt shop and are stored in drums. Different scrap lots are mixed together to make a blend of 2,250 pounds. Next, the blend is pressed into 50-pound bars to facilitate material handling. The bars are melted to form ingots. These ingots are cut in two so they be machined and are to easier handle. If the tantalum is being alloyed, half-ingots are used. Before being sent to mill shop, all half-ingots are pressed into sheetbars.

![Diagram of process steps]

Scrap Tantalum | Blend | Press Bars | Ingot | ½ Ingot | Sheetbar
---|---|---|---|---|---
2,250 lbs | 45 bars 50 lbs each | 2,000 lbs | -900 lbs | -750 lbs
2 jobs | 2 jobs | 2 jobs | 1 job | 1 job

Figure 3: Melt Shop Process Steps

2.3.3.2 Routings

There are twelve primary machines in the melt shop and three basic routes that use these machines. The final alloy and the type of raw material determine the route. The routes will be referred to as I, II and III. Below are detailed descriptions of each route that material can take from station to station in the melt shop.
2.3.3.2.1 Route I: Alloy E & D

Route I is unique because it is the only route that uses the electron beam furnace (7). The process to make alloy E and D is the same except additional steps are needed for alloy D. Both versions of route I will are discussed below and are denoted by Route Ia and Route Ib.

Route Ia takes the following path through the melt shop: 1-2-3-(4 or 5)-7-8-9-10-Out. A schematic of the route is given below in Figure 4.

![Figure 4: Route Ia](image)

The first operation is the mill (station 1). As new lots of material are received they are milled to break the scrap tantalum down into powder. After milling, the material is set aside until it is needed.

Next, various lots of previously milled powder are mixed together in the blender (station 2) to form a blend. The lots are chosen to yield an expected chemical composition that meets the specifications for the blend.

After the lots have been blended, they are pressed into bars (station 3). There are normally 45 bars weighing 50 pounds each.
Next, the bars are sintered (stations 4 or 5). There are four sintering ovens. The type of material determines which of the sintering ovens can be used. AA can be processed only in the ABAR furnace (station 4). AA blends make up 20% of the jobs processed. The ABAR furnace has a slower processing rate than the other three ovens and is also less reliable. MG and HY bars can be sintered in the other three ovens (station 5).

After sintering, the bars arrive to the queue for the electron beam (EB) furnace (station 7) where they will be melted into ingots. Each lot of bars must be melted twice in the EB furnace to make an ingot. The first melt is used to consolidate the bars into an ingot and remove impurities in the metal. The second melt is used to further refine the ingot and improve its surface quality. The first and second melts have very different processing times, 20 hours for first melts and 5 hours for second melts. The changeover times between the melts are long, 4 hours going from first to second and 8 hours going from second back to first. As a way to manage this process more efficiently, the company batches the jobs. A batch of jobs typically has 4 ingots.

After being melted in the EB furnace, the ingots are tested by quality control (station 8). This process takes seven days on average. 25% of the ingots do not pass testing on the first attempt. Ingots that fail testing are not reprocessed at first. They are retested. Retesting does not generally result in a different outcome. In most cases, the ingot that failed the test is downgraded and is used for lower purity ingots, i.e. alloys S and W. The low first-time pass rate is due primarily to the variability in quality of the incoming raw material. Remember, the melt shop recycles material and receives many different types of raw material from a variety of sources. The ingots that pass testing are considered "pure" tantalum at this point. The name for this alloy is "E."

Following quality control, the ingots are machined on a lathe (station 9) to remove the outer layer and the associated impurities that are concentrated there. Prior to being machined, the ingots are cut into two pieces so that they will fit onto the lathes.
After being machined, the smooth ingots are pressed \((\text{station } 10)\) from cylindrical ingots to 4" thick sheetbars and sent to the mill shop.

2.3.3.2.2  \textbf{Route Ib: Alloy D}

Route Ib takes is the same as Route Ia plus some additional steps. It follows the path: \(1-2-3-(4\ \text{or } 5)-7-8-9-10-11-12-9-10-\text{Out}\). A schematic of this route is given below in Figure 5.

![Figure 5: Route Ib](image)

Route Ib is the same as Route Ia up to station 10. If the ingot of alloy E at the Forge \((\text{station } 10)\) is to be alloyed to make D, it is pressed into a round bar and sent to the welding operation \((\text{station } 11)\). At the welding operation \((\text{station } 11)\) leaches of alloying metal are attached to the side of the bar of alloy E. This bar is then sent to the arc furnaces \((\text{station } 12)\) where it is melted to create alloy D. After melting at the arc furnaces, the ingots are sent back to the lathes \((\text{station } 9)\) where they are machined again to remove impurities and improve the surface finish of the ingot. Finally, the machined ingots of alloy D are pressed \((\text{station } 10)\) into sheetbars and sent to the mill shop \((\text{Out})\) for further processing.
2.3.3.2.3 Route II: Alloy Q, Alloy S & W (Light Scrap)

Route II takes the following path through the melt shop: 3-11-12-9-10-11-12-Out. Figure 6 shows a schematic of this route.

Alloy Q in the form of a powder and Alloy S & W in the form of light scrap is received from other departments within H. C. Starck. It is pressed into bars (station 3). The pressed bars are welded together, end-to-end, to form three rods of equal length (station 11). These rods are melted together to form an ingot in the arc furnaces (station 12). This ingot is taken to the lathes (station 9) where it is machined to remove impurities and improve the surface finish. The ingot is then pressed to a smaller diameter rod (station 10). After having a hanger installed on its top (station 11) it is re-melted in the arc furnaces (station 12) before being sent to another department within H. C. Starck (Out) for further processing.

2.3.3.2.4 Route III: Alloys S and W (Heavy Scrap)

Route III takes the following path through the melt shop: 11-12-9-10-11-12-9-10-Out. A schematic of this route is given below in Figure 7.
Alloy S and W arrive in the form of thick pieces of scrap. This scrap metal is welded together (station 11) to form "rods" and a hanger is attached. These rods are melted together to form an ingot in the arc furnaces (station 12). This ingot is taken to the lathes (station 9) where it is machined to remove impurities and improve the surface finish. The ingot is then pressed to a smaller diameter rod (station 10). After having a hanger installed on its top (station 11) it is re-melted in the arc furnaces (station 12) before being sent back to the lathes (station 9) for machining. After machining, the ingot is forged (station 10) into a sheetbar and sent to the mill shop (Out) for further processing.

### 2.4 Evidence of a problem

The melting operation does not have enough capacity to support the demands being placed on it. There are three indications of this problem and they will be presented in this section. First, the on-time performance for metallurgical products is below the company target and is attributed to a lack of material from the melt shop. Second, there is under production in the melt shop versus current demand. Finally, and most importantly, demand for metallurgical products is expected to grow over the next three to five years and this will place additional demands on the melting operation. The majority of this growth is expected to be for alloy E while the other alloys stay relatively constant.
2.4.1 On-Time Performance

The company has a goal of 90% on-time performance. During 2000 the on-time performance of metallurgical products dragged the company average below the goal. While the other business units had performance above the 90% goal, the metallurgical products business is unable to meet the goal and had several months below 70% on time performance.

On time shipping performance is a customer service metric. At H. C. Starck Inc., this measure is reported monthly. It is calculated by identifying the number of orders that are sent to customers on or before the scheduled shipping date and dividing by the total number of orders scheduled to ship in the month.

An analysis showed that the primary reason for poor on-time performance is attributed to the lack of material from the melt shop. The Pareto chart showing this result is given below in Figure 8.

![Pareto Chart of the Reasons for Late Shipments](image)

Figure 8: Pareto Chart of the Reasons for Late Shipments
2.4.2 Underproduction for Current Demand

Delivery of products from the melt shop to the mill shop has not kept up with demand. The production planner of the mill shop submits requirements on a monthly basis. The amount request varies little from one month to the next. Ten months out of the eleven observed, the melt shop did not meet the ordered demand. The monthly demand and the deliveries are shown in Figure 9.

![Figure 9: Orders and Deliveries, Melt Shop](image)

* Data for August is not shown due to a plant-wide shutdown

The primary reason attributed to the poor delivery performance is low availability of the electron beam furnace (EB furnace). 76% of the total production of the melt shop passes through the EB furnace. The average uptime is 68% for the last half of the year. The low was 38% in June. The high was 75% in December.

The EB furnace is run on a 24/7 basis or 722 hours per month. 68% uptime gives 491 hours of available time. To meet demand, the EB furnace needs 448 hours for production (first and second melts for 16 ingots and 4 sets of changeovers). The average margin between the available time and the time needed is 43 hours. In months where the
availability is lower than average, the EB furnace can easily get behind and cause the poor delivery performance to the other departments that depend on its output.

2.4.3 Projected Growth in Demand

The final and most important indication is that demand for the products made by the metallurgical business unit is projected to grow over the next three to five years. Historically, this business unit has sold to the chemical processing industry. The markets in which it participates are changing and will affect the melt shop in two ways.

First, there will be an increase in the absolute level of demand. Sales of consumer electronics, such as computers, personal digital assistants (e.g. Palm Pilots) and cellular telephones, have been growing rapidly. The technology trend for these products is toward miniaturization, smaller devices with higher performance. Tantalum capacitors perform better than capacitors made of other materials, e.g. ceramics. This affects metallurgical products because they provide the tantalum parts needed for the vacuum furnaces used to make tantalum capacitors. The historical shipments and forecasted demand for mill products is shown below in Figure 10. The forecasted demand is taken from the sales and marketing group at the company and is assumed to be representative of the expected growth.
Shipments to the mill shop have been growing and are forecasted to continue.

Figure 10: Demand for Metallurgical Products, Historical and Forecasted

Second, the product mix for the metallurgical products business unit will change. There is projected to be a five-fold increase in the use of alloy E. This increase is due to expected sales in the computer and semiconductor industries for new products like sputtering targets. In addition, the purity of alloy E will need to be higher than the current process consistently can deliver.

The current and projected demand for each of the five alloys is shown in Figure 11. Notice that there is a significant increase in demand for alloy E. The amount of demanded of the other alloys is not expected to change. This increase in demand for alloy E will require that more tantalum be process than today and that they be of consistently high quality.
2.5 Response

Participating in these new markets will require additional melting capacity and processes that yield higher purity ingots. To accomplish this, the company has been active in expanding via acquisition. These new facilities will not be available for approximately two years, however. Given the forecasted growth in the tantalum market and the capacity constraints that now limit the company's production, their participation will be limited. This may result in lost sales and a loss of market share.

In order to avoid lost sales and a loss of market share, the company needs to develop a short to medium term response that will enable them to participate in the growing demand for alloy E until the capacity provided by the acquisition becomes available. Doing so will require using the assets currently available in a way that is more effective and investing in selected projects in order to increase the capacity of the melting operation.
Chapter 3: Analysis

This chapter will focus on the changes that can be made to the melt shop in an effort to increase its capacity within the next year. As indicated in the previous chapter, demand for Alloy E is expected to increase five-fold. For this reason, the analysis and subsequent proposals will focus on increasing the capacity associated with making this alloy.

This chapter will address the analysis in the following way. First, there will be a discussion of the methods for increasing the capacity of an existing operation. Second, the application of a queueing network model will be introduced. Third, the operations of the melt shop will be described in terms of a queueing model. This model will be used to study the options available to the melt shop. Different scenarios for operating the melt shop will be described and expressed in terms of the queueing model. Finally, the results of the models output will be discussed.

3.1 Increasing Capacity

This section will identify strategies to increase the capacity of an existing operation. Each one will be discussed and related to the melt shop operation. There is a significant body of work related to increasing capacity of an existing operation. The most famous is The Goal, Goldratt (1984). In it he outlines the Theory of Constraints. Graham (1998) combines his work with that of others in the field. Below are some of the steps that can be taken to increase the capacity or throughput of an operation. Each of these will be discussed below in relation to the melt shop.

- Identify the system's capacity constrained operation (bottleneck)
- Increase the bottleneck's availability
- Offload work from the capacity constrained operation to other stations
- Decrease variability
- Schedule production based on the capacity constrained resource (Drum)
- Buffer the bottleneck operation against starvation (Buffer)
- Tie the release of new jobs to the status of the constraint's buffer (Rope)
3.1.1 Identify the "Bottleneck"

The bottleneck operation is also known as the capacity constrained resource. It is defined as the station with the highest utilization. Utilization, \( u \), is defined as the ratio of arrival rate to the processing rate, \( r_a / r_p \). The arrival rate, \( r_a \), is the number of jobs arriving to a workstation per unit time. The processing rate, \( r_p \), is the number of jobs completed by the workstation per unit time. Alternatively, it is the inverse of the time needed to process a job at the workstation, \( r_p = 1/t_p \). The operation with the highest utilization is often the one with the longest queue. Cycle time increases rapidly as the utilization of stations approach 100%. This fact is captured in the relation below which is plotted in Figure 12 (Hopp & Spearman, 2000).

\[
CT \propto \frac{1}{(1-u)}
\]
In the case of the melt shop, the EB furnace is the bottleneck. Its utilization is the highest among any station in the melt shop as indicated by several observations. First, there is often large queue of material in front of it. Second, it is run 24 hours a day, seven days a week in order to meet the production demands. It is the only operation, with the exception of the ABAR furnaces, that did so. Third, calculations made in Appendix B confirm that its utilization is above those of the other station in the melt shop. Finally, most of the people involved in running the melt shop operation recognized the EB furnace as the constraint they needed to manage most carefully.

3.1.2 Increase Availability

One of the first steps in increasing the capacity of an operation is to increase the constraint's availability. Availability is the percent of time that a station is able to process jobs. The availability can be defined as the ratio of mean-time-to-fail (MTTF) to the total available time. Total time available is the MTTF plus the mean-time-to-repair (MTTR). This relationship can be stated as follows (Hopp & Spearman, 2000).

\[
\text{Availability} = \frac{\text{MTTF}}{\text{MTTF} + \text{MTTR}}
\]

There are two ways to increase a station's availability. First, decrease the MTTR. To do this one must focus on diagnosing and fixing problems with the machine as quickly as possible. Second, increase the MTTF. Doing this requires making the station's process more robust and less likely to fail.

The management and operators of the melt shop suffered a big blow to the availability of the EB furnace in the year 2000. They made a change to the electron beam guns and its associated control systems. This change had a major negative effect on the EB furnaces availability. The MTTR increased because the maintenance people and operators are not skilled in diagnosing and repairing failures of the new electron beam guns. The MTTF
decreased because the new gun system, as installed, is not robust and would fail frequently. The result is a decrease in this key machine's availability.

The management and operators of the melt shop together with the maintenance group and electron beam gun vendor are addressing the issue of availability on the EB furnace. The company uses a measure of availability they call "uptime." It is the number of hours in a day that a machine is able to produce (but not necessarily producing) divided by the total number of hours in a day. They have been successful in increasing the average uptime from a low of 38% in June to 75% in December. This is accomplished by increasing the MTTF through improved gun maintenance and design changes to the EB guns. MTTR has been decreased by having the vendor develop and teach repair procedures and by having a better system for ensuring spare parts availability. Further increases to the availability will enable increases in the capacity of the operation.

3.1.3 Offload Work

Offloading work from the bottleneck operation means giving work to other machines that are capable of performing the same task but have lower levels of utilization.

At the outset, there appears to be no other piece of equipment that can do the work of the EB furnace. It is a highly specialized machine that consolidates sintered bars into ingots and purifies the tantalum scrap of contaminates. The EB furnace does this in two steps. The first melt, which takes 18 hours, is used to consolidate the blends from bars into ingots and remove some contaminates. The second melt, which takes 6 hours, is used to further purify the ingot and improve the surface quality of the ingot.

There is, however, another machine, the plasma furnace, that might be used to do some of the work of the EB furnace. There are three reasons why this is appealing. First, it is especially efficient at removing oxygen, one of the contaminates that cause the first-melt in the EB furnace to be lengthy. Second, the plasma furnace is not being used. Finally,
the plasma furnace is capable of taking un-sintered bars and melting them into an ingot. If the plasma furnace could be utilized to eliminate sintering completely and perform the first melts now being done by the EB furnace, this would represent an increase in capacity. The queueing model will explore the implications of this process change in later sections.

The plasma furnace is purchased eleven years ago and has not been used very much since. Several years ago it was configured to produce copper-niobium, an alloy needed for the super-conducting super-collider project to study sub-atomic particles. That project did not receive the needed funding and this business evaporated. Since that time, management has invested to make the changes needed to melt tantalum. There has, however, been little urgency associated with making the plasma furnace operational and integrating it into the tantalum refining processes.

### 3.1.4 Decrease Variability

Increases in variability, like utilization, lead to increases in cycle time. The effect is not as dramatic as utilization but is still important. The cycle time, $CT$, is an increasing function of the variability of the arrivals to a station and the variability of the station’s process. A convenient way of characterizing variability is to use the squared coefficient of variation (scv), $c^2$. The scv is defined as the variance divided by the mean squared: $c^2 = \sigma^2 / \mu^2$. In the case of arrival processes, $c_a^2$ would be composed of the variance and squared mean of the inter arrival times. For workstation processes, $c_p^2$ is the determined by the variance and the squared mean of the time needed to complete a job. Using these, the effect on $CT$ can be expressed using the following relationship (Hopp & Spearman, 2000).

$$CT \propto \frac{c_a^2 + c_p^2}{2}$$
In the context of the melt shop, the EB furnace represents a highly variable process. It processes work in batches of four ingots. As a result, the next downstream operation, quality control, receives four ingots (8 jobs) over two days. This is followed by a span of five days during which the EB furnaces processes its next batch of four ingots. This has two implications. First, this leads to long queues at the EB furnace given that it is also the bottleneck operation. Second, the quality control group may be over-utilized during the days it receives the four ingots and under utilized at other times. This adds time to the total process and increases the number of jobs that are waiting to be processed by quality control. Both of these contribute to lengthening the total manufacturing cycle time and decreasing the system throughput.

Smoothing this part of the production process would help in decreasing the manufacturing cycle time and increasing the throughput of the melt shop. Reducing variability of the inter-arrival times is addressed in two ways: decreasing the processing times and decreasing the change over times. The ideal would be a batch size of one that requires only one short processing step.

Given that the refinement process currently takes two melts to complete, it seems unlikely that the melt shop would be able to eliminate one of those melts without somehow adding another furnace. Remember, however, there is another furnace that is not being used, the plasma furnace. If a process could be developed to do all first melts on the plasma furnace and all second melts on the EB furnace, the goal of doing one melt with no change over could be achieved.

3.1.5 Drum-Buffer-Rope

The drum-buffer-rope method of managing a manufacturing operation, described by Goldratt (1984), has elements that are applicable to the melt shop. Due to the focus on increasing the melt shop's capacity, the concept of buffering the capacity constrained resource against starvation is most applicable. If the bottleneck operation is starved for
work, it is a lost opportunity. No more production will flow from a process than what is produced by the bottleneck operation.

The managers of the melt shop seemed to grasp the importance of buffering the constraint. There is always a queue of material in front of the EB furnace. This ensured that when it is operational, there is work available.

The concepts of "drum," scheduling work based on the constraint and "rope," releasing new jobs to a route based on the status of the bottleneck's buffer, might be helpful to consider but are not discussed here further.

### 3.2 Queueing Network Model

As a way to explore changes to the melt shop processes and their effect on the throughput of the operation, a queueing network model of the melt shop is developed. Doing so enabled a comparison of several possible process scenarios for the melt shop. This section will provide the information needed to understand the development of the model by describing its background, assumptions, inputs and outputs.

#### 3.2.1 Model Background

This model provides a steady state approximation of the throughput and flow time that is accurate enough to evaluate the changes proposed here. The approach used is summarized in the paper of Suri, et. al. (1993). Others, whose work is referenced, include Suri & DeTreville (1991), Whitt (1993), Buzacott & Shanthikumar (1993) and Hopp & Spearman (2001).

The model uses node decomposition of an open queueing network made up of GI/G/m queues. This network consists of a twelve separate processing stations and a single class of material. Arrivals to the network are characterized by the mean and variance of the inter-arrival times of customers, which are assumed to be generally distributed. The
station service times are also assumed to have general distributions characterized by the mean and variance. Jobs travel from station to station based on transition probabilities. These probabilities form a set of traffic equations that link the GI/G/m queueing processes together. Jobs are serviced on a first-come-first-served basis. Service times at each station are i.i.d (assumed to be independent of one another).

### 3.2.2 Model Assumptions

The melt shop does not satisfy two of the assumptions identified above. First, there is not one class of material in the melt shop. There are a variety of raw materials that are used to make five different alloys. Second, jobs are not always completed on a first-come-first-served basis. Queues are often rearranged so that similar jobs can be processed together.

The model itself is not changed to take these violations into account but they are addressed. In the first case, the input data are calculated in a way that captures the effect of the differing materials in the mean and variance of the station's processing times. In addition, only two of the three alloys pass through the EB furnace, alloys E and D. Demand for alloy D is assumed to be constant over the time period considered. Regarding the second violation, the queueing discipline of first-come-first-served is assumed to be "good enough" given the added complexity required of the model for a marginal improvement in accuracy.

Interested readers are referred to the Appendix A for a more detailed discussion of the queueing network model.

### 3.2.3 Model Inputs

Using this model, each station $j$ can be characterized by the 5-tuple, $\{ c_{0j}^2, c_{pj}^2, r_{0j}, r_{pj}, m_j \}$. $c_{0j}^2$ is the squared coefficient of variation (scv) of the inter-arrival times to the network.
from the outside. \( c^2_{pj} \) is the scv of the processing time of station \( j \). \( r_{pj} \) is the inter-arrival rate of jobs to the network from outside. \( r_{pj} \) is the processing rate of station \( j \). Finally, \( m_j \) is the number of servers/machines at station \( j \).

In addition to the characteristics of each station, \( j \), the routings between stations need to be identified. This is done using transition probabilities. For example, if all jobs at station one go to station two, the probability would be 1.0. Conversely, if no jobs go from station one to two, the probability would be 0.0. See Appendix B for a detailed description of the model inputs used here.

### 3.2.4 Model Outputs

The output of the model are the inter-arrival rates and the scv of the inter-arrival times to each station, \( j \), \( r_{pj} \) and \( c^2_{pj} \) respectively. These are used to calculate the system's performance characteristics, throughput, \( TH \), cycle time, \( CT \), and work-in-process, \( WIP \). Each of the metrics is discussed below.

The throughput of the system, \( TH \), is found by adding together the arrival rates of the three raw material stream. Because of conservation of material, what goes in must equal what comes out for process in steady state. The arrival rates for the current scenario are calculated based on available data and are shown in Appendix B.1. For the other scenarios, the arrival rate of the raw material for alloy E is adjusted to the point where the workstation with the highest utilization reaches 85%. This level of utilization was chosen because it is the utilization of the EB furnace, the bottleneck operation, in the current scenario.
The manufacturing cycle time, $CT$, is found in two steps. In step one, the time in queue, $CT_{qj}$, is calculated using the Kingman equation. (Hopp & Spearman, 2000)

$$CT_{qj} = \left( \frac{c^2_{qj} + c^2_{pj}}{2} \right) \left\{ \frac{u_j}{1-u_j} \left[ \frac{1}{r_{pj}} \right] \right\}$$

This equation is also known as the VUT equation because the time in queue at a station is dependent on the variability ($V$), utilization ($U$) and average processing time ($T$) of the station. The variability term is calculated using the squared coefficient of variation (scv) of the inter-arrival times, $c^2_{qj}$, and the processing time at the station, $c^2_{pj}$. The utilization term is $u_j = r_{qj} / r_{pj}$. The average processing time is the inverse of the processing rate or $1/r_{pj}$. In step two, the total manufacturing cycle time, $CT$, is the sum of all of the queue times, $CT_{qj}$, and all of the processing times at each station, $1/r_{pj}$.

Finally, the total number of jobs in the system, $WIP$, is calculated using Little's Law.

$$WIP = (TH)(CT)$$

### 3.3 Scenarios

Three scenarios are built using a queueing network model. These are called "current," "50% to plasma." and "100% to plasma."

- The "current" scenario attempts to model the performance of the operation as it exists presently, i.e. it does not include the plasma furnace in its processes.

- The "50% to plasma" scenario modifies the "current" scenario by eliminating the use of the ABAR sintering furnace and routing $\frac{1}{2}$ of the pressed bars through the plasma furnace. The other $\frac{1}{2}$ are sent through the GCA/AC sintering furnaces.

- The "100% to plasma" scenario modifies the "current" scenario further to eliminate sintering completely and routes all un-sintered pressed bars through the plasma furnace. The sections that follow will describe in greater detail the assumptions, inputs and outputs of the scenarios identified above.
3.3.1 Scenario Assumptions

In addition to the assumptions articulated in Section 3.2.2, Model Assumptions, this section will identify several additional assumptions that are specific to this analysis. These assumptions are made to enable a comparison of the scenarios that is direct and focused on the suggested changes. First, the model is a steady state model. Second, there are three raw material inputs. They are assumed to have different routes through the melt shop that ultimately lead to different products. Thirdly, there is one class of material and the transition probabilities between stations is kept the same between scenarios unless the stations are directly involved in the change from one scenario to another. The routing matrix that is formed by these probabilities is designed to capture all three of the raw material inputs and their associated routes through the melt shop. Fourth, the development of the scenarios focus on the route used to make alloy E. It is the product with the largest projected growth and the alloy for which the melt shop needs to increase capacity. Fifth, the processing rate of the quality control department is adjusted in each scenario to maintain a total time (queue and process) for quality to be at least 4 days. This is done because quality control is a pipeline delay. The variability is assumed to be approximately half as much as EB furnace. Finally, the arrival rates govern the throughput of the system. What goes into the process will come out, given that this is a steady state model. In the current scenario, the EB furnace has a utilization of 85%. The arrival rate of the alloy E raw material is adjusted in the 50% and 100% Plasma Scenarios so that no major piece of equipment exceeds 85% utilization.

3.3.2 Scenario Inputs

The inputs to the queueing network model for each scenario will be detailed here. The three scenarios are called "Current Process," "50% to Plasma" and "100% to Plasma". Remember from Section 3.2.3 each station $j$ can be characterized by the 5-tuple, 
$$\{ c_{0j}^2, c_{pj}^2, r_{0j}, r_{pj}, m_j \}.$$ Table 2, shown below, displays these characteristics of the twelve stations for each of the three scenarios.
There are several items of particular interest. In the current process, the plasma furnace is not used at all. Second, "50% to plasma" scenario adds the use of the plasma furnace and eliminates the use of the ABAR furnace for sintering. 50% of the jobs from raw material type I are assumed to be sent to the plasma furnace while the other 50% are assumed to be sent to the GCA/AC sintering furnaces before going to the EB furnace for melting. Finally, the "100% to Plasma" scenario assumes that the sintering furnaces are not used at all. Instead, all jobs of raw material type I are sent to the plasma furnace for first melts before going to the EB furnace for second melts. Note the increase in processing capacity of the EB furnace that results from only doing one melt.

Table 2: Workstation Inputs for All Three Scenarios

<table>
<thead>
<tr>
<th>$j$</th>
<th>Station</th>
<th>$m_j$</th>
<th>$r_{pj}$ [jobs/day]</th>
<th>$c_{pj}^2$ [-]</th>
<th>$r_{pj}$ [jobs/day]</th>
<th>$c_{pj}^2$ [-]</th>
<th>$r_{pj}$ [jobs/day]</th>
<th>$c_{pj}^2$ [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mill</td>
<td>1</td>
<td>2.14</td>
<td>0.50</td>
<td>2.14</td>
<td>0.50</td>
<td>2.14</td>
<td>0.50</td>
</tr>
<tr>
<td>2</td>
<td>Blend</td>
<td>1</td>
<td>2.46</td>
<td>0.50</td>
<td>2.46</td>
<td>0.50</td>
<td>2.46</td>
<td>0.50</td>
</tr>
<tr>
<td>3</td>
<td>1500T</td>
<td>1</td>
<td>4.00</td>
<td>0.50</td>
<td>4.00</td>
<td>0.50</td>
<td>4.00</td>
<td>0.50</td>
</tr>
<tr>
<td>4</td>
<td>ABAR</td>
<td>1</td>
<td>0.29</td>
<td>7.00</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>5</td>
<td>GCA/AC</td>
<td>3</td>
<td>0.69</td>
<td>0.50</td>
<td>0.69</td>
<td>0.50</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>6</td>
<td>Plasma</td>
<td>1</td>
<td>--</td>
<td>--</td>
<td>2.77</td>
<td>0.50</td>
<td>2.77</td>
<td>0.50</td>
</tr>
<tr>
<td>7</td>
<td>EBF</td>
<td>1</td>
<td>1.14</td>
<td>2.92</td>
<td>1.14</td>
<td>2.92</td>
<td>1.14</td>
<td>2.92</td>
</tr>
<tr>
<td>8</td>
<td>QC</td>
<td>1</td>
<td>1.14*</td>
<td>0.50</td>
<td>1.15*</td>
<td>0.50</td>
<td>1.80*</td>
<td>0.50</td>
</tr>
<tr>
<td>9</td>
<td>Lathe</td>
<td>2,3**</td>
<td>1.50</td>
<td>0.50</td>
<td>1.50</td>
<td>0.50</td>
<td>1.50</td>
<td>0.50</td>
</tr>
<tr>
<td>10</td>
<td>2000T</td>
<td>1</td>
<td>3.81</td>
<td>0.65</td>
<td>3.81</td>
<td>0.65</td>
<td>3.81</td>
<td>0.65</td>
</tr>
<tr>
<td>11</td>
<td>Weld</td>
<td>1</td>
<td>4.00</td>
<td>0.50</td>
<td>4.00</td>
<td>0.50</td>
<td>4.00</td>
<td>0.50</td>
</tr>
<tr>
<td>12</td>
<td>Arc</td>
<td>1</td>
<td>2.44</td>
<td>0.40</td>
<td>2.44</td>
<td>0.40</td>
<td>2.44</td>
<td>0.40</td>
</tr>
</tbody>
</table>

* QC behaves like a pipeline delay. The processing rate is adjusted to keep it total station cycle time (queue + process) at least four days.

** 2 lathes are used for the Current and 50% Plasma Scenarios. 3 lathes are used in the 100% Plasma Scenario. Lathes are not considered a major piece of equipment so one was added to keep them from becoming the capacity constrained resource.
Each of the parameters were evaluated to determine the sensitivity of the output to changes in these inputs. The number of machines, $m_j$, for a station affects the utilization of any workstation. The system output is only changed if it occurs on the bottleneck operation or another near constraint. The number of machines is known with certainty and therefore not subject to errors. Both the arrival rates to the system, $r_0j$, and the processing rates for each station, $r_{pj}$, play a large role in the performance of the system. The arrival rates to the system are variables that determine the throughput of the system. Changes to the processing rates of the bottleneck and near-constraint operations result in significant changes to the throughput. The model is not sensitive to the squared coefficient of variation (scv) for the arrival rates, $c_{0j}^2$, nor the processing rates, $c_{pj}^2$, unless the values are very large, i.e. greater than 2. To address these features of the model, the parameters for processing rates were chosen carefully. When it was possible, SAP data from the company was used. Data from direct observation was used when information from SAP was unavailable. The scv of highly variable processes like the EB furnace and Quality were found using observational data. The values for the scv of the other processes were assumed to be 1.0. See Appendix A for a discussion of each of the parameters for each workstation.

The capacity for each work station is shown below in Figure 13. It is derived from the input data displayed in Table 2.
The routings of jobs is different for each of the scenarios. The differences are illustrated in the figures below. Notice two things. First, the "50% to plasma" scenario (Figure 15) adds the use of the plasma furnace but does not alter the batch management of the EB furnace. Second, in the case of the "100% to plasma" scenario (Figure 16) the plasma furnace replaces both the sintering processes and the first melt in the EB furnace. For interested readers, the routing matrix for each of the scenarios and the calculations used to determine the probabilities can be found in the Appendix B Section B.2.
Figure 14: Current Process

Figure 15: 50% to Plasma Process

Figure 16: 100% to Plasma Process
3.3.3 Scenario Outputs

The output for the three scenarios, based on the queueing network model, is presented in this section. The results will be summarized in the tables and figures that follow.

Table 3 shows the key metrics of the queueing model output together with the actual metrics of the current process. There are differences between the current actual and the current model scenario. The average cycle time (CT) for the model is 3% higher. The work-in-process (WIP) is 6% higher. Throughput (TH) is 3% higher. The differences between the model results and the actual figures for the current scenario are an absolute indication of inaccuracy. They point out the effect of the simplifying assumptions mentioned earlier. When comparing the model outputs of the different scenarios, the inaccuracy is assumed to be trivial. The assumptions of the model are the same from one scenario to the other. Only the parameters needed to represent the different scenarios are changed.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>CT</th>
<th>WIP</th>
<th>TH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual, Current</td>
<td>70</td>
<td>101</td>
<td>1.44</td>
</tr>
<tr>
<td>Model, Current</td>
<td>72</td>
<td>107</td>
<td>1.49</td>
</tr>
<tr>
<td>50% to Plasma</td>
<td>51</td>
<td>75</td>
<td>1.49</td>
</tr>
<tr>
<td>100% to Plasma</td>
<td>11</td>
<td>20</td>
<td>1.79</td>
</tr>
</tbody>
</table>
3.3.3.1 Throughput

Figure 17 shows the throughput for each of the three model scenarios together with the current actual output. In this plot, higher throughput is best. The model output of the current processes is 1.49 jobs/day. The actual output is 1.44 jobs/day, a difference of 3%. Adding the plasma furnace and sending 50% of the press bars through it does not cause an increase in throughput. The lack of change results from the fact that the EB furnace, the bottleneck operation, does not have an increase in capacity. The same amount of material goes through it and two melts are still required of each lot of press bars. Going to a single melt at the EB would improve throughput. This is what happens in the 100% to Plasma scenario. The plasma furnace does the first melts consolidating the press bars to ingots and doing some purification. The EB furnace does second melts, refining the tantalum further. This enables the EB furnace to now do only one melt per lot. No batching is required. The "100% to Plasma" scenario has a throughput of 1.79 jobs/day, an increase of 20% over the current scenario.

![Throughput Improvement](image)

Figure 17: Throughput for Each Scenario
### Cycle Time

Figure 18 shows the total process cycle time for each of the three model scenarios together with the current actual cycle time. In this plot, lower cycle time is best. The model output of the current processes is 72 days. The actual time is 70 days, a difference of 3%. The 50% to plasma scenario replaces the ABAR sintering furnace with the plasma furnace. Doing this reduces cycle time from 72 days to 51 days or 30%. The 100% to plasma process is even faster at 11 days of cycle time. The improvement over the current process is 84%. This scenario benefits from the elimination of the ABAR furnace as well. The queue time at the EB furnace is nearly eliminated. Batching is no longer required. Also, there is a reduction in variability that translates into shorter queues at stations downstream from the EB furnace.

![Cycle Time Improvement Graph]

**Figure 18: Average Cycle Time for Each Scenario**
### 3.3.3.3 Work-In-Process Inventory

Figure 19 shows the work in process (WIP) inventory for each of the three model scenarios together with the current actual WIP inventory. In this plot, lower WIP is best. The model output of the current processes is 107 jobs. The actual WIP is 101 jobs, a difference of 6%. The 50% to plasma scenario replaces the ABAR sintering furnace with the plasma furnace. Doing this reduces WIP from 107 jobs to 75 jobs or 30%. The 100% to plasma process has an even lower level of WIP at 20 jobs, an improvement of 81% over the current process. The cycle time savings mentioned in the previous section enable the melt shop to operate with a lower level of WIP and still maintain a higher throughput.

![Figure 19: Work In Process Inventory for Each Scenario](image)
3.3.3.4 Utilization

Figure 20 shows the utilization of the twelve stations in the melt shop for each of the three scenarios considered. There are several items of interest in this figure. First, the bottleneck process can be identified for each scenario. For the "current" and "50% plasma" scenario it is the EB furnace. The Quality Control operation becomes the bottleneck in the case of the "100% to plasma" scenario. Additional capacity increases would needed to be directed at this resource in order to further improve throughput. Second, the maximum utilization is 85% by design. It is the maximum utilization allowed for the scenarios considered because it is the maximum utilization found in the current situation. Note, a third lathe was added for the "100% to plasma" scenario to keep the utilization below 85%. Third, higher levels of throughput require higher utilizations. This is illustrated by comparing the "100% to plasma" with either the "current" or the "50% to plasma" scenario. Finally, because the throughput is identical, between the "current" and the "50% to plasma" scenarios many of the workstations have identical utilizations. The only differences in utilization come in the stations directly affected by the process changes: sintering, melting and quality.

![Utilization for Each Melt Shop Station](image)

**Figure 20: Utilization for Each Station in Melt Shop**
3.4 Discussion of Results

The results of the model indicate that using the plasma furnace to perform all first melts can increase the production rate while lowering both the cycle time and work-in-process inventory of the melt shop. This is not surprising. Adding capacity (plasma furnace) to the EB furnace (the bottleneck operation), eliminating the need to do two melts, increases the production rate for melting. Increasing the capacity of melting resulted in a 20% increase in throughput of the whole process. In addition, the process cycle time and work in process inventory are reduced by 84% and 81% respectively. This is accomplished by eliminating the sintering process and the batching at the EB furnace.

Processing all of the pressed bars through the plasma furnace is important critical to achieving these results. Simply using the plasma furnace for some of the materials will not result in the benefits mentioned above. There are two primary reasons for this. First, the EB furnace would be required do two melts on the sintered lots that do not go through the plasma furnace. This would prevent the increase in capacity. Second, continuing to do both melts on the EB furnace will require batching. These batches lead to long queue times and extra inventory.

Based on these observations the recommendation would be to implement the "100% to Plasma" scenario. This change would affect alloys E and D directly and would require the following changes:

- Do all first melts in the plasma furnace.
- Do all second melt in the EB furnace.
- Eliminate sintering. Do not sinter the pressed bars before melting them.

Making these changes will increase operational effectiveness of the melt shop. These are discussed below. There are several issues associated with this change. These are process
verification and raw material availability. These barriers to implementation will also be discussed in this section.

### 3.4.1 Increased Operational Efficiency

While this proposal does not substitute for the new manufacturing facility planned by the company management, it does provide a short to medium term solution to the issue of under capacity of the melt shop. It is capacity that limits the growth of the metallurgical business.

The suggested change will improve the key operational metrics. Throughput will increase. Manufacturing cycle time will be reduced. Both of these will be improved with lower levels of work in process inventory. Furthermore, there will be a decrease in the inter-arrival variability associated with the sintering and EB furnace operations. This will enable a smoother flow of work to their downstream operations, like quality control.

Quality may also be improved by sharing the task of purification between the plasma and EB furnaces. The plasma furnace can be used to upgrade the scrap to a more consistent but intermediate purity by removing oxygen. The EB furnace can focus on second melts. As a result, it may be possible to optimize its process parameters and furnace configuration to produce high purity ingots of alloy E on a more consistent basis.

Given the assumption that the market for tantalum is growing and that every additional pound of output from the melt shop can be sold, sales will be increased for the company if more tantalum can be refined. The assets used to create those sales are nearly constant. Investments in process development, the purchase of another lathe and possible more testing capacity are what will be needed. Taken together, this provides an increase in the return on assets (ROA). The expected annual increase in gross profit from increased capacity is $1.1M. The one-time savings from inventory reduction are $1.3M.
Annual Increase in Gross Profit

\[
(1.79 \text{ jobs/day} - 1.44 \text{ job/day}) \left( \frac{240 \text{ days}}{\text{year}} \right) \left( \frac{750 \text{ lbs}}{\text{job}} \right) \left( \frac{\$20}{\text{lb}} \right) = \$1.1M
\]

One-Time Inventory Reduction

\[
(101 \text{ jobs} - 20 \text{ jobs}) \left( \frac{750 \text{ lbs}}{\text{job}} \right) \left( \frac{\$20}{\text{lb}} \right) = \$1.3M
\]

The above calculation is based on the production rates generated by the queueing network model and a conservative estimate of the gross margin for each pound of tantalum produced.

### 3.4.2 Potential Issues

Two technical issues have been cited as reasons for not implementing a change of this type. The first is process verification. The second is raw material availability. Each of these will be addressed in turn.

#### 3.4.2.1 Process Verification

Making the proposed change represents a significant alteration to the current production process. The issues of feasibility, yield and quality remain unanswered. At this time there is simply not enough data to make an informed decision.

Currently, there is an engineering study underway to determine the capabilities of the plasma furnace in processing tantalum. Three observations are possible at this point. First, the testing does not appear to have been a consistent, focused effort. It has been underway for nearly a year without reaching a conclusion. Second, early indications from the testing are that the plasma can be used in the way described. Finally, in the
absence of test data and the need to meet today's demand, management has kept the production process as is.

Given the results described above, it is important to complete process testing as soon as possible. An informed decision about whether or not to implement this change cannot be made without the test data. Not having the data results from a choice about how to allocate limited resources. Testing will not be completed in a timely manner unless the value of using the plasma as described is seen as important. The potential benefits warrant serious consideration and a commitment to completing the testing.

3.4.2.2 Raw Material Availability

Raw material availability is a concern shared by many within the company. Tantalum is a thinly traded commodity. The demand for tantalum grew much faster than supply last year, leading to a large increase in the prices of tantalum scrap. Historically, a stockpile of tantalum has been accumulated to protect against these features of the market.

Processing tantalum scrap at a faster rate could be seen as a threat to this approach. Faster processing might lead to a reduction in the stockpile of tantalum that protects the company from the vagaries of the market. Doing this would subject them to more fluctuation in their primary raw material inputs.

Assuming that the melt shop had more capacity, the response to these concerns would be to choose to operate below the maximum capacity. Doing so would represent a strategic decision on the part of the company. In the current situation, the decision of how much to produce is being made for them. Production is limited. If the market demand increases for metallurgical products, as it did this last year, the company is limited in its ability to participate.
Stated another way, the expanded capacity enables the company to be more competitive. It will be able to win new customers and buy raw material away from its competitors. New customers could be won due to the increased capacity that allows the company to supply their needs. Critical raw materials can be bought using the increased revenues that result from the expanded capacity, making it more difficult for competitors to find the inputs they need.
Chapter 4: Implementing Change

Recommending solutions is easy. Implementing changes, however, is much more difficult. Furthermore, a solution that goes unimplemented is no solution at all. Up to this point, the discussion has focused on developing a technical solution to the problem of under-capacity in the melt shop. The focus will shift now to look at the work needed to implement a change such as the one proposed.

This discussion of change will be done in three parts. First, the concept of technical and adaptive work will be described. Next, this framework will be applied to the melt shop. Third, the observed barriers to change and adaptive work will be identified and discussed.

4.1 Technical Work versus Adaptive Work

A common model of how change happens is characterized by being top-down, radical, discontinuous and planned. The thinking is that once the right solution is identified, all the pieces will fall into place. While this is a common view of change, it is not very helpful.

Heifetz (1994) proposes a different mental model that is more appropriate. He describes two kinds of work related to making change: technical work and adaptive work. Given these two kinds of work, he identifies three types of situations that generally arise. These are shown in Table 4 below and illustrated in the subsequent sections using the same example originally used by Heifetz: the doctor-patient relationship.
Table 4: Situation Types, Heifetz (1994)

<table>
<thead>
<tr>
<th>Situation</th>
<th>Problem definition</th>
<th>Solution &amp; implementation</th>
<th>Primary responsibility for the work</th>
<th>Kind of work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I</td>
<td>Clear</td>
<td>Clear</td>
<td>Physician</td>
<td>Technical</td>
</tr>
<tr>
<td>Type II</td>
<td>Clear</td>
<td>Requires learning</td>
<td>Physician &amp; patient</td>
<td>Technical &amp; adaptive</td>
</tr>
<tr>
<td>Type III</td>
<td>Requires learning</td>
<td>Requires learning</td>
<td>Patient &gt; physician</td>
<td>Adaptive</td>
</tr>
</tbody>
</table>

4.1.1 Type I Situation

In the first situation, Type I, the problem definition and the solution are clear and unambiguous. This leadership situation requires an expert to identify the problem and propose a solution. The implementation is easy, requiring little change to the way people behave. This is referred to as technical work. The physician-patient analog is one where the patient has an infection. The patient comes to the doctor for diagnosis and treatment. The doctor diagnosis the disease after some testing and gives the patient a prescription. The patient fills the prescription, takes the medicine and is "cured" with little alteration to their lifestyle.

4.1.2 Type II Situation

A Type II situation is more complex. In this case, the problem definition is clearly identified (technical work) but the solution and implementation of that solution require that work be done on the part of the affected people (adaptive work). In the doctor-patient scenario this might equate to a patient with heart disease. The diagnosis is clear. The solution is also clear, e.g. eat different foods, get more exercise, stop smoking, etc. The implementation of the solution, however, requires active participation on the part of
the patient (adaptive work). The patient needs to make different life choices in order to
treat the heart disease.

4.1.3 Type III Situation

Situations of Type III are the most complex. All three aspects require learning and change: problem definition, solution and implementation. Everyone involved must change his or her current approach in order to effectively deal with this situation. Returning to the doctor-patient example, this might equate to a patient with terminal cancer. There may be two possible problem definitions. One problem definition might be to focus on the cancer. This will lead to actions relating to treatment. Given that nothing can be done to stop the disease from ending the patient’s life, this may not be appropriate. A second approach might be to help the patient prepare for the end of life. Following this problem statement recognizes what is occurring and the actions taken are aimed at preparing the patient and their loved-ones. In this example there are multiple problem definitions. Each might lead to different solutions. The patient plays the largest role in deciding which is most appropriate for them. The doctor plays a facilitating role. No expert opinion will resolve the diagnosis of terminal cancer.

4.1.4 Summary

The situation types described above and summarized in Table 4 provide a framework for thinking about organizational change and leadership. Type I scenarios require technical work. Type II situations require both technical work and adaptive work. Type III situations require adaptive work. There is a continuum represented by these basic concepts. Knowing where a situation is located along this continuum can be helpful in formulating an appropriate response.
4.2 Application of the Framework

The technical/adaptive work framework described previously will be applied now to the melt shop and the issue of insufficient capacity.

4.2.1 Problem Definition

The problem definition is clear. The melt shop has difficulty meeting current demand for metallurgical product orders. It will not be able to satisfy the anticipated future demand for these products without expansion. More melting capacity is required. There is general agreement on this problem statement.

4.2.2 Solution

The solution to the problem is not clear. There are several options to consider. All of them are investments of one sort or another. Some of the choices are: buy another company, build a new plant, use current assets more effectively or a combination of these.

Given that the management of the company has recently purchased another company and is planning to move the operation, there is clarity about what they believe to be the best solution. This solution will take several years to implement. In that time, there may be significant lost sales due to the present under-capacity. For this reason, a complementary solution of using the current melt shop more efficiently should be considered.

4.2.3 Implementation

The implementation of any of the solutions mentioned above will require that employees of the company alter their activities. Consider two different situations.

First, consider the case of the new facility. It will require some people to drive much further on their commutes or even move their families if they want to keep their jobs.
There will be new machines, new processes and new physical surroundings. This change will no doubt require leadership on the part of management to help employees make the transition while minimizing the disruption to the business. The workload will be very heavy during this transition period. These changes are more than a year away, however. They are not immediate and do not affect employees today.

Consider a second scenario: implementing a major change to the processes in the melt shop to increase its capacity. The benefits and costs of the change will be more immediate. If successful, there will be a significant increase in the melt shop's capacity within a year. Accomplishing this change will require work. Engineering testing needs to be completed. New SAP recipes need to be written. Money needs to be spent to upgrade some of the equipment. There is a litany of tasks that would need to be done. The number of tasks, however, will certainly be less than will be required to move an entire production operation.

Why the resistance to the second solution? There are two. First, it requires action and changes in behavior today, not a year from now. Second, and more importantly, it requires that people change the way they think about the melting operation. For several decades the melting operation has processed thousands of ingots using the same technology, the same set of processes and the same physical surroundings. Using the plasma furnace to replace sintering and the first melts on the EB furnace represents a departure from the familiar routine. Doing so feels uncertain and can be perceived as a threat to meeting current production requirements.

4.2.4 Observations

Increasing the capacity in the melt shop is a Type II situation, in the technical/adaptive work structure of Heifetz. The problem statement is clear: increase the capacity of the melt shop. The solution and its implementation will require that the company approach this problem differently. It is not as simple as adding another shift or hiring a new
employee. Regardless of the solution chosen, people will need to alter their behaviors in order for the solution to be implemented successfully.

A Type II situation requires that the leader not only be an expert but also a visionary. Those affected by the change need to be able to imagine the future desired state that will result from the change. Remember the patient with heart disease. Why would he or she give up fried food and their La-Z-Boy if they did not believe that eating more healthfully and exercising regularly would make their lives better? What is their vision? For a patient with a life-threatening disease, they might want to see their kids graduate from college or get married. Similarly, a vision of the future needs to be created by the leader. This vision helps motivate people to participate in the change process and learn what is required to make it successful.

4.3 Barriers to Change

The melting operation within H. C. Starck does not appear to have much experience or interest in "adaptive work." There are significant barriers to change. The evidence to support this claim will be presented by looking at the company from three different perspectives. The three lenses are the cultural lens, the political lens and the strategic design lens. Each lens will be described and examples given from the company.

4.3.1 Cultural Barriers

The cultural lens focuses on the meaning that people assign to their work. (Ancona, et. al., 1999). From the cultural perspective, people take action based on what a situation means to them. In this context, change might be prohibited by some of the cultural beliefs held by members of the company. Here are three observations. First, "the business is successful." Second, "we are comfortable." Finally, "I don't trust them. We can do it better ourselves anyway."
The business is successful. It is very profitable without the extra effort required by adaptive work. It participates in niche markets, specialty metals, with few competitors. These markets have been growing steadily over the last few years. This growth is expected to continue. The profit margins for their products are generous. There is little pressure on these margins because demand exceeds supply. While business success is the desired outcome, organizational changes that may be needed to further improve the business are difficult in this climate. There is no motivation to change.

People seem comfortable continuing to do things the way they have been done for the past few years. The culture of the company is stable. It is a 60 year-old company. There are 400 people on site. Many of them have been there for a decade or more. The production processes are stable. These processes have been successful at meeting the demands placed on them until now. Why change? Again, feeling comfortable with business processes is desirable but it can make organizational change difficult because there is little motivation to change even though the business would benefit from the change.

The working relationships between the melting operation and some other key groups are contentious. These relationships are characterized by a lack of trust. An example of this occurred during the upgrade of the EB furnace last year. The engineering group and the melting operation needed to work closely together to design and install the new system. Communication broke down and the newly installed equipment made the EB furnace run worse, not better. Production in the melt shop suffered for most of 2000 as a result. The remedy is for the melting operation to take control of the whole project and fix the problem. While this breakdown in teamwork is improving, the fact that it exists indicates that there are issues of people working together to implement change—even change that is not supposed to affect the way people do their jobs.
4.3.2 Political Barriers

The political perspective views an organization as a composite of "stakeholders," both individuals and groups. Each one contributes resources to the organization and also depends on the organization's success. Each stakeholder also may have different interests and goals and bring different amounts and sources of power to bear in her or his interactions (Ancona, et. al, 1999). In this context, change might be prohibited by the way stakeholders chose to use their power in the organization. Three examples are given. First, company management focuses on the powder business. Second, the melt shop is run on a "command and control" basis with a focus on short-term issues. Finally, the process engineer in the melt shop does not support using the plasma furnace in the way suggested.

The company places most of its emphasis on the powdered tantalum business. It accounts for 42% of the revenue. Metallurgical (Ta-metallurgical and Mill & Fabricated), on the other hand accounts for a total of 19% of the business. Recently, however, metallurgical has received much more management attention. There are two reasons. First, the on-time shipping performance is so bad during 2000 that it dragged the company-wide metric down. Second, the sales group has identified new markets for metallurgical products that require more capacity.
The melt shop is operated by "command and control." Furthermore, the focus seems to be on "fighting fires" to meet the demands of today. Having this type of focus and structure does not engage people in thinking about how to do things differently or better. One example is that there is little effort exerted on how scrap contamination might be mitigated even though it is one of the biggest sources of variation in the operation. Another example is that there is no intention to develop a production plan tied to demand and attempt to build to that plan.

The process engineer in the melt shop is not in favor of making the change to use the plasma furnace to process all un-sintered bars. His opinion is highly valued by others in the company. As a result, the urgency to complete the needed installations and testing is dampened. The plasma furnace is not viewed as a solution to the issue of insufficient capacity.
4.3.3 Structural Barriers

The strategic design perspective focuses on understanding the design of an organization and how this design helps the organization reach its strategic objectives (Ancona, et. al., 1999). Here are three examples where the structure of the organization may not be in line with the larger goals of the company. This mismatch might prohibit needed changes. First, the incentives of the melting and milling operations are not aligned. Second, there is not enough information flowing between the two operations. Finally, this internship is not sponsored by the melting organization.

The flow of material from the melt shop is the life-blood of the milling operation. They are in the same value stream. From a structural perspective, one would like the incentives of these groups closely aligned and an easy flow of information between the groups. The company is grouped by activity, however. Each functional area operates as a separate organization. There are some cross-functional teams that span these organizations to solve specific problems. The formal reporting structure is hierarchical. As a result of the functional structure, there are different managers and organizations responsible for melting and milling.

The first example is that the two organizations, melting and milling, are evaluated separately. On one hand, this is effective given that they perform very different operations. On the other hand, the milling operation is completely dependent on melting. Poor performance in melting will negatively affect milling. To remedy this it might be useful to evaluate the two groups as a single entity on metrics related to throughput, quality and delivery. Tying the performance of the two operations together will make the role played by the melting operation more visible.

Secondly, there is a lack of communication between the two groups. The melt shop uses a policy that can best be described as "build-what-you-can." Every month there is a demand forecast provided by the milling operation to the melting operation. There is no indication that this is actually used to plan and schedule production. This seemed to be
the state of affairs until this past year. The production planner for the milling operation began taking part in the daily production status ("drumbeat") meetings in the melt shop. As a result, the information linking the melting and milling operations together now takes place on an informal basis. This needs to be strengthened.

The supply chain group and not the melting operation sponsored this project. The focus at the outset is to improve on-time performance of metallurgical products. Analysis of the issue led to the melting operation and the need to increase its capacity. While the project is aligned well with the goals of the company at a high level, there are three functional groups affected by the work. Supply chain is the project sponsor and is responsible for meeting deliveries to customers but not responsible for melting. Melting is the department whose operations are most affected by the suggested changes did not sponsor this project. Finally, milling operations are the largest customer of melting and most adversely affected by the lack of material from the melt shop.

4.4 Intern's Role

The intern approached the project as if it were a Type I situation. The assumption is that by pointing out a solution, it would automatically be implemented. This is a mistake. Obviously, this is unrealistic.

There needed to be greater recognition of the kind of activities that would actually ensure the adoption and implementation of the solution. There are several activities that would have led to greater success. Building stronger relationships with the project stakeholders would have facilitated better communication and mutual understanding. This, in turn, may have helped the proposed solution gain greater acceptance and led to a better transfer of knowledge, both from intern-to-company and vice versa. Next, focusing on smaller wins throughout the internship would have help to build credibility and momentum for larger recommendations later.
Another feature of the internship, similar to the doctor-patient example from Heifetz, is that of time. The internship is short, 6 months. It is difficult to learn the organization, identify a problem, devise a solution and implement that solution in this time. Implementing a solution is particularly difficult because of the adaptive work aspect. It demands an investment in time and energy that seems beyond the six month of the internship.
Chapter 5: Conclusions

A focused effort designed to bring the plasma furnace on-line as a productive asset is important to the capacity expansion of the company. Choosing not to do so represents a wasted opportunity. To date there is no urgency to complete the needed process verification to use the plasma furnace. This needs to change.

5.1 Technical Conclusions

The central conclusion of this work is that the company should invest the time and effort to develop a process that utilizes the plasma furnace to increase the capacity of the melt shop. There are three areas of the operation that are affected by this change. They are interconnected. Making this change will increase the throughput of the current melt shop by 20% while simultaneously reducing average cycle time and work-in-process inventory by 84% and 81% respectively.

Increasing the throughput of the melt shop 20% will enable the company to sell more product. The gross profit contribution is estimated to be $1.1 million per year. Having the increased capacity during the next three years in the current production facility is important for two reasons. First, demand for metallurgical products exceeds capacity now and is expected to grow (Figure 22). Given this growth and the three years to complete the new facility, lost sales of approximately $15.1 million will result (Figure 23). Using the plasma furnace as recommended will enable the company to reduce the lost sales during this time by $3.0 million to $12.1 million (Figure 24). See Appendix C for the economic analysis that led to these figures.

There will be an 81% reduction in work in process inventory. This one time reduction is estimated to be $1.3 million. This represents a decrease in working capital requirements, more cash and better asset utilization.
Finally, there is estimated to be an 84% reduction in process cycle time from 72 days to 11 days. Having a process that is this short would enable the company to be more responsive to shifting customer demands and schedule production more accurately.

Figure 22: Historic and Projected Demand for Metallurgical Products
Figure 23: Planned-for Capacity Results in Lost Sales of $15.1M

Figure 24: Using the Plasma Furnace Reduces Lost Sales by $3.0M
5.2 Organizational Conclusions

Realizing the benefits of the changes recommended here is contingent upon committing to its implementation. To achieve this commitment, the recommendation needs to be accepted by the organization and viewed as valuable. There are several dimensions on which the value of the change can be communicated. First, there is the economic argument that is presented in the previous section. Second, there are structural changes that can be made to highlight the interconnected nature of the melting and milling operations. The pressure that results from tying the two organizations closer together could be used to build the consensus needed to find new ways of using existing assets. Third, the cultural aspects of this change would need to be addressed. It is a Type II change in the language of Heifetz. Recognizing this highlights the fact that the change will affect the culture of the melting operation. Culture changes are often difficult because of the meaning people assign to their jobs and the way they do their work. Finally, the key stakeholders of this change will need to be involved and become advocates for the change. This may be accomplished by forming a cross-functional team that has a clear goal and timeline and has the autonomy to make the needed changes to the melt shop processes.
References


Appendix A: Queueing Network Model

This appendix will provide background information and a detailed explanation of the application of queuing networks to a flow shop. The approach described here is an implementation of the work by Suri, et.al. (1993).

A.1 Background

The goal of modeling a production system in this way is to calculate several important measure of production effectiveness: cycle time ($CT$), work in process inventory ($WIP$) and throughput ($TH$). Little's Law relates these three measures to one another: $WIP = (TH)(CT)$.

One way to determine these measures is through the application of queueing theory. If we can estimate two of them, we can use Little's Law to find the third. A steady state queueing network can be used to find the total process cycle time ($CT$) for a given arrival rate. For a system in steady state, the arrival rate will equal the throughput ($TH$). With these two measures, we calculate the WIP of the process using Little's Law.

The sections that follow will provide the notation and governing equations used in the queueing model to determine the process cycle time ($CT$).
A.2 Notation

\( r_{aj} \)  The rate of arrivals to a station \( j \).

\( r_{pj} \)  The processing rate or capacity of station \( j \).

\( t_{pj} \)  The processing time of station \( j \). Same as \( \frac{1}{r_{pj}} \).

\( \mu \)  The average time of either inter-arrival time or processing time.

\( \sigma \)  The standard deviation of the inter-arrival time or processing time.

\( c^2 \)  Squared coefficient of variation. It is defined as, \( c^2 = \left( \frac{\sigma}{\mu} \right)^2 \).

\( c_{aj}^2 \)  Squared coefficient of variation of the time between arrivals to a station \( j \).

\( c_{pj}^2 \)  Squared coefficient of variation for the processing time at station \( j \).

\( c_{dj}^2 \)  Squared coefficient of variation of the time between departures from station \( j \).

\( m_j \)  Number of parallel machines at station \( j \).

\( u_j \)  Utilization of station \( j \).

\( I \)  The identity matrix.

\( P_{ij} \)  The probability that a job will go from station \( i \) to station \( j \).

\( P_0 \)  The probability matrix containing all \( p_{ij} \) for the network.
A.3 Governing Equations

What follows in a description of the method used to determine the throughput ($TH$), process cycle time ($CT$) and the work in process inventory ($WIP$) in this paper. The steady state average $WIP$, $TH$ and $CT$ of a process are found by applying Little's Law.

$$WIP = (TH)(CT)$$

Before this can be done, two of the three variables need to be determined. Start with the throughput, $TH$. In a steady state system, i.e. no accumulation or generation, the rate of arrival will equal the output rate or throughput. In our system there are three arrival streams from outside the melt shop. We denote an arrival stream, $r_{0j}$, as the rate of arrival to station $j$ from outside the system. Adding all of these arrival streams together gives the total arrival rate to the system and thus the throughput.

$$TH = \sum_j r_{0j}$$

Calculating the cycle time is more complex and requires the use of queueing theory. Observe the equation below. It is the summation of the queue time and processing time at each workstation $j$.

$$CT = \sum_j (CT_{oj} + t_{pj})$$

The processing time, $t_{pj}$, is easy to determine. It is the average time it take the workstation to complete a single job. It is the inverse of the stations processing rate, or $1/r_{pj}$.

The time a job spends in queue is determined using the Kingman equation. It is given below. Notice that it has three terms. The first is an increasing function of variability. The greater the variation in the arrival of jobs to the system, measured by $e_{o}^{2}$, or the
variation in the processing time at station $j$, measure by $c_{pj}^2$, the longer the queue at the station $j$. The second term is an increasing function of utilization, $u_j$. If workstation $j$ is busy most of the time, the length of the queue will be long. A bottleneck operation is defined as the one with the greatest utilization. This term captures this behavior. Finally, the third term is an increasing function of the processing time. The longer the station takes to process a job, the longer the queue.

$$CT_{aj} = \left(\frac{c_{aj}^2 + c_{pj}^2}{2}\right)\left(\frac{u_j}{1-u_j}\right) \left(1 \right)$$

Looking at the equation above, there are four variables that determine the cycle time in a queue at each station $j$: $r_{pj}$, $c_{pj}^2$, $u_j$, and $c_{aj}^2$. Each of these variables will be discussed below.

The average processing rate of each station, $r_{pj}$, is a variable that is determined via observation or by using SAP data. The inverse, $1/r_{pj}$, is the processing time of the station. In the context of the queue at a station, it makes sense that the time a job will wait to be processed will depend on the time the station takes to process a job.

The squared coefficient of variation for each station's processing time, $c_{pj}^2$, is determined via observation or by using SAP data. For most stations a value of 0.50 was chosen. This indicates that the process has low variability. Some of the workstations are more variable and the data was readily available. In these cases the $c_{pj}^2$ was calculated and used in the model.

The next term is the utilization of the workstation, $u_j$. If the station is busy most of the time, jobs arriving to it will have to wait for the job currently in process to finish before they can be serviced. The utilization is defined as the ratio of arrivals to the workstation, or inter-arrival rate, to the processing rate of the station. If there are more than one
machine at a station, the processing rate will be the product of the number of machines, \( m_j \), and their individual processing rates, \( r_{pj} \). The formula for the utilization is given below.

\[
\mu_j = \frac{r_{aj}}{m_j r_{pj}}
\]

The inter-arrival rate to each station, \( r_{aj} \), is the vector \( \vec{r} \). It is calculated by multiplying the vector or the arrival rates to each station from outside the system, \( \vec{r}_0 \), by the transpose of the matrix formed by subtracting the probability matrix, \( P_0 \), from the identity matrix, \( I \). The probability matrix formed by the inter-station transition probabilities. For example, if all jobs from station 1 go to station 2, the probability is 1.0. The equation for the inter-arrival rates is given below.

\[
\vec{r} = \vec{r}_0 (I - P_0)^{-1}
\]

Finally, the last term we need to determine is the variability associated with the inter-station arrivals, \( c_{aj}^2 \). The determination of the inter-arrival rate variability is complicated by the fact that this system is a network. Consider two cases. In the first case the system is a simple line of stations where the output of one station arrives directly as the input of the next station. A schematic of such a system is shown below. The arrival variability of this system is relatively easy to determine. It is discussed by Hopp and Spearman (2000).

![Figure 25: Simple Queueing Network](image)

The second case is more complex and requires a more involved set of calculations. The work of Suri, et. al. (1993) is used to develop the inter-arrival variability. In this case
there is one station, G, that is fed by two different stations, D and F. Also, there is station B whose departures are split between C and E. The ratio of jobs that go to C and E is determined by the transition probabilities mentioned earlier. If \( \frac{1}{4} \) of the jobs go to C then the transition probability on this arc will be 0.25. These routing probabilities are given in Appendix B.2.

![Figure 26: More Complex Queueing Network](image)

The equations to determine the \( c_{aj}^2 \) for each of the stations in a more complex system (like the one in Figure 26) are given below. Interested readers are referred to the paper by Suri, et. al. for a description meaning of each of the terms.

\[
c_{aj}^2 = a_j + \sum_{i}^{M} c_{ai}^2 b_{ij},
\]

where

\[
a_j = 1 + w\left[q_{0j}^2 c_{0j}^2 - 1\right] + \sum_{i=1}^{M} q_{ij} \left[(1 - p_{ij}) + p_{ij} u_i^2 x_i\right]
\]

\[
b_{ij} = w_j p_j q_{ij} (1 - u_i^2)
\]

and where

\[
q_{ij} = \left(\frac{r_i}{r_j}\right) p_{ij}
\]

\[
x_i = 1 + m_i^{-0.5} \left(\max\left[c_{ij}^2,0.2\right] - 1\right)
\]

\[
v_i = \left[\sum_{i=1}^{M} q_{ij}^2\right]^{-1}
\]
\[ w = \left[ 1 + 4(1-u)^2(v-1) \right]^{-1} \]

Departures

\[ c_d^2 = 1 + (1-u^2)(c_a^2 - 1) + \frac{u^2}{\sqrt{m}}(c_p^2 - 1) \]

Splitting of departure streams

\[ c_i^2 = p_i c^2 + 1 - p_i \]

Merging of arrival streams

\[ r = \sum_i r_i \]

\[ c^2 = w \sum_i \left( \frac{r_i}{\sum_i r_i} \right) c_i^2 + 1 - w \]

where

\[ w = \left[ 1 + 4(1-u)^2(v-1) \right]^{-1} \]

and

\[ v = \left[ \frac{\sum_k \left( \frac{r_k}{\sum_k r_k} \right)^2}{\sum_k r_k} \right]^{-1} \]
Appendix B: Melt Shop Model

Figure 27 is a schematic of the melt shop model that is used in this paper. Using this model, each station $j$ can be characterized by the 5-tuple, $\{ c_{0j}^2, c_{pj}^2, r_{o,j}, r_{pj}, m_j \}$. $c_{0j}^2$ is the squared coefficient of variation (scv) of the inter-arrival times to the network from the outside. $c_{pj}^2$ is the scv of the processing time of station $j$. $r_{o,j}$ is the inter-arrival rate of jobs to the network from outside. $r_{pj}$ is the processing rate of station $j$. Finally, $m_j$ is the number of servers/machines at station $j$.

![Figure 27: Schematic of Melt Shop Model](image)

The sections that follow will illustrate how each of these variables is determined for each station. After showing the calculations for each of the variables that characterize the stations the three scenarios are shown: Current, 50% to Plasma and 100% to Plasma.

B.1 Current Arrivals to the System

This section describes the arrivals to the system. The calculations for the arrival rate, $r_{o,j}$, are based on SAP data and are shown. The squared coefficient of variation, $c_{0j}^2$, are
assumed to be 1.0 because the arrival processes have high variability. Sensitivity analysis indicates that the value of $c_{oj}$ affects the performance of the system little.

**B.1.1 Route I, Alloys E & D**

Based on SAP data, there are an average of eleven process orders for blends each month. That is eleven arrivals to Route I each month. Each blend, weighing 2,250 pounds, is the equivalent of two jobs in this analysis because the ingot is cut into two pieces later and each piece is a single unit of processing. Below is the processing rate that results from these data.

\[
\text{arrival rate} = \frac{11 \text{ arrivals}}{\text{month}} \cdot \frac{2 \text{ jobs}}{\text{arrival}} \cdot \frac{1 \text{ month}}{22 \text{ days}} = 1.00 \text{ jobs/day}
\]

\[
\text{arrival scv} = 1.00 \text{ (assumed)}
\]

**B.1.2 Route II, Alloy Q**

Based on SAP data, there are an average of four process orders for alloy Q each month. That is four arrivals to Route II each month. Each of these weighs approximately 800 pounds and is the equivalent of one job in this analysis because the ingot is cut into two pieces later and each piece is a single unit of processing. Below is the processing rate calculated from these data.

\[
\text{arrival rate} = \frac{4 \text{ arrivals}}{\text{month}} \cdot \frac{1 \text{ job}}{\text{arrival}} \cdot \frac{1 \text{ month}}{22 \text{ days}} = 0.20 \text{ jobs/day}
\]

\[
\text{arrival scv} = 1.00 \text{ (assumed)}
\]
B.1.3 Route III, Alloy W& S

Based on SAP data, there are an average of seven process orders for Route III each month. That is seven arrivals each month. Each of these weighs approximately 1,000 pounds and is the equivalent of one job in this analysis. Below is the processing rate calculated from these data.

\[
\text{arrival rate} = \left( \frac{7 \text{ arrivals}}{\text{month}} \right) \left( \frac{1 \text{ job}}{\text{arrival}} \right) \left( \frac{1 \text{ month}}{22 \text{ days}} \right) = 0.32 \text{ jobs/day}
\]

\[
\text{arrival scv} = 1.00 \text{ (assumed)}
\]
B.2 Routing Probabilities

The figure shown here is a schematic of the melt shop model. Each arc connects two stations. The flow of material through the model is determined by the transition probabilities. The transition probability is the percentage of a station's output that flows to another station. The method for calculating these factors is given in the table below for each of the three scenarios. The terms "r's" are rates. For example, \( r_{I,1} \) is the rate of material arriving from I to station 1.
Table 5: Routing Probabilities for the Three Scenarios

<table>
<thead>
<tr>
<th>Probability (from-to)</th>
<th>Current</th>
<th>50% Plasma</th>
<th>100% Plasma</th>
</tr>
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<tbody>
<tr>
<td>P_{1-2}</td>
<td>1.0</td>
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</tr>
<tr>
<td>P_{2-3}</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P_{3-4}</td>
<td>(0.20) \left( \frac{r_{I-1}}{r_{I-1} + r_{II-3}} \right)</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>P_{3-5}</td>
<td>(0.80) \left( \frac{r_{I-1}}{r_{I-1} + r_{II-3}} \right)</td>
<td>(0.50) \left( \frac{r_{I-1}}{r_{I-1} + r_{II-3}} \right)</td>
<td>0.0</td>
</tr>
<tr>
<td>P_{3-6}</td>
<td>0.0</td>
<td>(0.50) \left( \frac{r_{I-1}}{r_{I-1} + r_{II-3}} \right)</td>
<td>\left[ \frac{r_{I-1}}{r_{I-1} + r_{II-3}} \right]</td>
</tr>
<tr>
<td>P_{3-11}</td>
<td></td>
<td>r_{II-3} \left/ \left( r_{II-3} + r_{III-11} \right) \right.</td>
<td></td>
</tr>
<tr>
<td>P_{4-7}</td>
<td>1.0</td>
<td></td>
<td>0.0</td>
</tr>
<tr>
<td>P_{5-7}</td>
<td>1.0</td>
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<td>P_{6-7}</td>
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<td>1.0</td>
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<tr>
<td>P_{6-11}</td>
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<tr>
<td>P_{7-8}</td>
<td></td>
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<td>P_{8-9}</td>
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<td>P_{9-10}</td>
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<tr>
<td>P_{10-11}</td>
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</tr>
<tr>
<td>P_{11-out}</td>
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<tr>
<td>P_{12-12}</td>
<td></td>
<td>1.0</td>
<td></td>
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<tr>
<td>P_{12-9}</td>
<td>1.0 - \left( \frac{r_{II-3}}{r_{I-3} + r_{II-3} + r_{III-11}} \right)</td>
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<td></td>
</tr>
<tr>
<td>P_{12-out}</td>
<td>\left( \frac{r_{II-3}}{r_{I-3} + r_{II-3} + r_{III-11}} \right)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


**B.3 Current Processing Rates**

This section describes the processing rates of each workstation in the Current scenario. The calculations for the processing rate, \( r_{ij} \), are based on SAP data or observations and are shown. The squared coefficient of variation, \( c_v^2 \), of most stations are assumed to be 0.50 because the processes have low variability. For workstations that have highly variable processes, the \( c_v^2 \) is calculated and is shown.

**Mill (1):**

\[
\text{processing rate} = \left( \frac{16 \text{ hours}}{1 \text{ day}} \right) \left( \frac{\text{lot}}{1 \text{ hour}} \right) \left( \frac{150 \text{ lbs}}{\text{lot}} \right) \left( \frac{2 \text{ jobs}}{2,250 \text{ lbs}} \right) = 2.14 \text{ jobs/day}
\]

\[
\text{process scv} = 0.50 \text{ (assumed)}
\]

**Blender (2):**

\[
\text{processing rate} = \left( \frac{16 \text{ hours}}{1 \text{ day}} \right) \left( \frac{\text{lot}}{13 \text{ hours}} \right) \left( \frac{2,250 \text{ lbs}}{\text{lot}} \right) \left( \frac{2 \text{ jobs}}{2,250 \text{ lbs}} \right) = 2.46 \text{ jobs/day}
\]

\[
\text{process scv} = 0.50 \text{ (assumed)}
\]

**1500T Press (3):**

\[
\text{processing rate} = \left( \frac{16 \text{ hours}}{1 \text{ day}} \right) \left( \frac{\text{lot}}{8 \text{ hours}} \right) \left( \frac{2,250 \text{ lbs}}{\text{lot}} \right) \left( \frac{2 \text{ jobs}}{2,250 \text{ lbs}} \right) = 4.00 \text{ jobs/day}
\]

\[
\text{process scv} = 0.50 \text{ (assumed)}
\]
ABAR Sintering Furnace (4): The ABAR sintering furnace has a long cycle time. It is the only sintering furnace that can process raw material AA. A typical sintering lot is 750 lbs and requires 3 separate runs to complete the batch of 2,250 lbs. Completely sintering a batch takes one week, with all of the non-productive time taken into account. This behavior can be characterized by the following set where each number indicates the number of jobs that are completed on a given day. This set is assumed to repeat. In this way an estimate of the mean and variance for the process are possible.

Set: \{0, 0, 0, 0, 0, 2\}.

\[
\text{processing rate} = \left( \frac{3 \text{ lots}}{7 \text{ days}} \right) \left( \frac{750 \text{ lbs}}{\text{lot}} \right) \left( \frac{2 \text{ jobs}}{2,250 \text{ lbs}} \right) = 0.29 \text{ jobs/day}
\]

\[
\text{process scv} = \left( \frac{\sigma}{\mu} \right)^2 = \left( \frac{0.76}{0.29} \right)^2 = 7.00
\]

GCA & AC Sintering Furnaces (5): There are other sintering furnaces used to prepare the raw materials of type MG and HY. These are the GCA and AC sintering furnaces. There is one GCA and two AC furnaces. Their processing rates are slightly different. Their variability is observed to be similar. Instead of treating them as separate servers, they will be treated as a group of three servers, \(m = 3\), whose processing rate is their weighted average.

\[
\text{GCA furnaces:}
\]

\[
\text{processing rate} = \left( \frac{16 \text{ hours}}{1 \text{ day}} \right) \left( \frac{\text{lot}}{21 \text{ hours}} \right) \left( \frac{750 \text{ lbs}}{\text{lot}} \right) \left( \frac{2 \text{ jobs}}{2,250 \text{ lbs}} \right) = 0.51 \text{ jobs/day}
\]
AC furnaces:

\[
\text{processing rate} = \left( \frac{\text{16 hours}}{1 \text{ day}} \right) \left( \frac{\text{lot}}{2.75 \text{ hours/lot}} \right) \left( \frac{\text{150 lbs}}{\text{2 jobs/2,250 lbs}} \right) = 0.78 \text{ jobs/day}
\]

Combined (1 GCA furnace and 2 AC furnaces):

\[
\text{processing rate} = \frac{1}{3} (0.51 \text{ jobs/day}) + \frac{2}{3} (0.78 \text{ jobs/day}) = 0.69 \text{ jobs/day}
\]

\[
\text{process scv} = 0.50 \text{ (assumed)}
\]

Plasma Furnace (6): NOT USED

EB Furnace (7): The EB furnace is managed using campaigns. A typical campaign is four ingots that are melted two times in the EB furnace before being passed to the next station. This behavior can be characterized by the following set where each number indicates the number of jobs that are completed on a given day. This set is assumed to repeat. In this way an estimate of the mean and variance for the process are possible.

Set: \{0, 0, 0, 4, 4, 0\}.

\[
\text{processing rate} = \left( \frac{4 \text{ lots}}{7 \text{ days}} \right) \left( \frac{2,250 \text{ lbs}}{\text{lot}} \right) \left( \frac{2 \text{ jobs}}{2,250 \text{ lbs}} \right) = 1.14 \text{ jobs/day}
\]

\[
\text{process scv} = \left( \frac{\sigma}{\mu} \right)^2 = \left( \frac{1.95}{1.14} \right)^2 = 2.92
\]
Quality Control (8): Quality control is assumed to behave like a pipeline delay. In an attempt to model this delay, the processing rate is set so that the total cycle time (queue time and processing time) for this station is at least four days. The variability is assumed to be less than the EB furnace but still significant.

processing rate = 1.14 jobs/day (assumed)

process scv = 0.50 (assumed)

Lathes (9): There are two lathes. Both of them operate with the characteristics identified below. In the model, both lathes will be used, \( m = 2 \).

\[
\text{processing rate} = \left( \frac{2 \text{ shifts}}{\text{day}} \right) \left( \frac{0.75 \text{ jobs}}{\text{shift}} \right) = 1.5 \text{ jobs/day}
\]

process scv = 0.50 (assumed)

2000T Press (10): The 2000T press works on a mixture of job types that have varying process times. Data compiled from daily shop floor meetings from Aug-Nov 2000 give the following results:

processing rate = 3.81 jobs/day

process scv = 0.65
Welding (11): There are two welding stations in the melt shop. The model, however, will use only one machine, \( m = 1 \). This is done for two reasons. First, there is only one welder. Second the machines do not work on all incoming jobs. Alloys S and W are welded in one machine. Alloys D and Q are welded in the second machine.

\[
\text{processing rate} = \left( \frac{2 \text{ shifts}}{\text{day}} \right) \left( \frac{2 \text{ jobs}}{\text{shift}} \right) = 4.00 \text{ jobs/day}
\]

\[
\text{process scv} = 0.50 \text{ (assumed)}
\]

Arc Furnaces (12): There are two arc furnaces in the melt shop. The model, however, will use only one machine, \( m = 1 \). This is done for two reasons. First, only one furnace can be operated at a time because of a limitation imposed by the plant’s electrical infrastructure. Second the machines do not work on all incoming jobs. Alloys S and W are melted in one machine. Alloys D and Q are melted in the second machine.

The arc furnaces work on a mixture of job types that have varying process times. Data compiled from daily shop floor meetings from Aug-Nov 2000 give the following results:

\[
\text{processing rate} = 2.44 \text{ jobs/day}
\]

\[
\text{process scv} = 0.40
\]
**B.4 50% Plasma Processing Rates**

This section describes the processing rates of each workstation in the 50% to Plasma scenario. Most of the rates, \( r_{pj} \), are the same as the Current scenario. For instances where this is not the case the calculations based on SAP data or observations and are shown. The squared coefficient of variation, \( c_{pj}^2 \), of most stations are assumed to be 0.50 because the processes have low variability. For workstations that have highly variable processes, the \( c_{oj}^2 \) is calculated and is shown.

*Mill (1):* Same as current process

*Blender (2):* Same as current process

*1500T Press (3):* Same as current process

*ABAR Sintering Furnace (4):* NOT USED

*GCA & AC Sintering Furnaces (5):* Same as current process

*Plasma Furnace (6):* The Plasma furnace is not currently being used. The figures used for the calculations below are estimates of the expected performance of the plasma furnace.

\[
\text{processing rate} = \left( \frac{16 \text{ hours}}{1 \text{ day}} \right) \left( \frac{1 \text{ lot}}{10 \text{ hours}} \right) \left( \frac{1,950 \text{ lbs}}{1 \text{ lot}} \right) \left( \frac{2 \text{ jobs}}{2,250 \text{ lbs}} \right) = 2.77 \text{ jobs/day}
\]

\[
\text{process scv} \quad = 0.50
\]
**EB Furnace (7):** Same as the current process. The EB Furnace will need to continue processing first and second melts in batches. As a result, the queue time will remain long and the variation in departure times will also remain the same.

**Quality Control (8):** Same as current process

**Lathes (9):** Same as current process

**2000T Press (10):** Same as current process

**Welding (11):** Same as current process

**Arc Furnaces (12):** Same as current process
B.5 100% Plasma Processing Rates

This section describes the processing rates of each workstation in the 50% to Plasma scenario. Most of the rates, $r_{pj}$, are the same as the Current scenario. For instances where this is not the case the calculations based on SAP data or observations and are shown. The squared coefficient of variation, $c^2_{pj}$, of most stations are assumed to be 0.50 because the processes have low variability. For workstations that have highly variable processes, the $c^2_{pj}$ is calculated and is shown.

Mill (1): Same as current process

Blender (2): Same as current process

1500T Press (3): Same as current process

ABAR Sintering Furnace (4): NOT USED

GCA & AC Sintering Furnaces (5): NOT USED

Plasma Furnace (6): The Plasma furnace is not currently being used. The figures used for the calculations below are estimates of the expected performance of the plasma furnace.

\[
\text{processing rate} = \left( \frac{16 \text{ hours}}{1 \text{ day}} \right) \left( \frac{1 \text{ lot}}{10 \text{ hours}} \right) \left( \frac{1,950 \text{ lbs}}{1 \text{ lot}} \right) \left( \frac{2 \text{ jobs}}{2,250 \text{ lbs}} \right) = 2.77 \text{ jobs/day}
\]

process scv $= 0.50$
**EB Furnace (7):** In the proposed process, the EB furnace would not be operated using campaigns. Ingots would be melted only once. The figures used below are estimates of the expected performance of the EB furnace if it are operated in this way.

\[
\text{processing rate} = \left( \frac{16 \text{ hours}}{1 \text{ day}} \right) \left( \frac{1 \text{ lot}}{10 \text{ hours}} \right) \left( \frac{1,950 \text{ lbs}}{1 \text{ lot}} \right) \left( \frac{2 \text{ jobs}}{2,250 \text{ lbs}} \right) = 2.77 \text{ jobs/day}
\]

\[
\text{process scv} = 0.50
\]

Note that the number of hours per day drops from 24 to 16 but the processing rate increases from 1.14 to 2.77 jobs per day. This is attributable to the elimination of campaigns with the associated elimination of long queue time and increase in throughput.

**Quality Control (8):** Quality control is assumed to be a pipeline delay. In the 100% plasma scenario the processing rate is changed from 1.15 jobs/day to 1.49 jobs/day, a 30% increase in capacity. This is done to keep the utilization below 85%. It is assumed that this change could be made.

**Lathes (9):** Same as current process

**2000T Press (10):** Same as current process

**Welding (11):** Same as current process

**Arc Furnaces (12):** Same as current process
B.6 Actual Data: Current

SAP Data: January 1999 to June 2000

18 month period
22 days/month

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<tr>
<th>Mat'l No</th>
<th>Description</th>
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Calculations

Work In Process Inventory
(process orders per month = jobs)

Blends 15
Scrap 7
Ingots 48
Sheetbars 32
WIP = 101 jobs

Throughput
(Sheet Bars Shipped per day = jobs/day)

32 Sheet Bars Shipped divided by 22 days/month
TH = 1.44 jobs/day

Cycle Time
Little's Law: CT = WIP/TH

WIP = 101 jobs
TH = 1.44 jobs/day
CT = 70 days
### B.7 Scenario #1: Current

#### Current Performance Measures

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#### Network Reliability Matrix

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#### Previous Performance Measures

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</tbody>
</table>
B.8 Scenario #2: 50% to Plasma
B.9 Scenario #3: 100% to Plasma

- [Diagram of a process flow chart showing various machines and processes.]

<table>
<thead>
<tr>
<th>Machine</th>
<th>1M</th>
<th>2M</th>
<th>3M</th>
<th>4M</th>
<th>5M</th>
<th>6M</th>
<th>7M</th>
<th>8M</th>
<th>9M</th>
<th>10M</th>
<th>11M</th>
<th>12M</th>
<th>13M</th>
<th>14M</th>
<th>15M</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arrival Rate</td>
<td>1.27</td>
<td>1.27</td>
<td>1.27</td>
<td>2.08</td>
<td>2.08</td>
<td>1.05</td>
<td>1.53</td>
<td>1.53</td>
<td>1.53</td>
<td>1.53</td>
<td>1.53</td>
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<td>1.53</td>
<td>1.53</td>
<td>1.53</td>
<td></td>
</tr>
<tr>
<td>Utilization</td>
<td>50%</td>
<td>50%</td>
<td>50%</td>
<td>40%</td>
<td>40%</td>
<td>50%</td>
<td>70%</td>
<td>70%</td>
<td>70%</td>
<td>70%</td>
<td>70%</td>
<td>70%</td>
<td>70%</td>
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</table>

- [Table showing network probability and identity values.]
Appendix C: Economic Analysis

ASSUMPTIONS

<p>| | |</p>
<table>
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<tbody>
<tr>
<td>Gross Margin</td>
<td>$20</td>
</tr>
<tr>
<td>Discount Rate</td>
<td>10%</td>
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</table>

DEMAND (lbs)

<table>
<thead>
<tr>
<th>Year</th>
<th>Demand</th>
<th>% diff</th>
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</thead>
<tbody>
<tr>
<td>1993</td>
<td>201,271</td>
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</tr>
<tr>
<td>1994</td>
<td>233,943</td>
<td>16%</td>
</tr>
<tr>
<td>1995</td>
<td>264,453</td>
<td>13%</td>
</tr>
<tr>
<td>1996</td>
<td>345,658</td>
<td>31%</td>
</tr>
<tr>
<td>1997</td>
<td>286,228</td>
<td>-17%</td>
</tr>
<tr>
<td>1998</td>
<td>256,116</td>
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</tr>
<tr>
<td>1999</td>
<td>309,205</td>
<td>21%</td>
</tr>
<tr>
<td>2000(P)</td>
<td>361,999</td>
<td>17%</td>
</tr>
<tr>
<td>2001(F)</td>
<td>419,289</td>
<td>16%</td>
</tr>
<tr>
<td>2002(F)</td>
<td>475,950</td>
<td>14%</td>
</tr>
<tr>
<td>2003(F)</td>
<td>642,784</td>
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</tr>
<tr>
<td>2004(F)</td>
<td>707,063</td>
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</tr>
<tr>
<td>2005(F)</td>
<td>777,769</td>
<td>10%</td>
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</tbody>
</table>

CAPACITY (lbs)

<table>
<thead>
<tr>
<th>Year</th>
<th>Current</th>
<th>Current</th>
<th>New Facility</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>300,000</td>
<td>300,000</td>
<td>300,000</td>
</tr>
<tr>
<td></td>
<td>300,000</td>
<td>300,000</td>
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<tr>
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REVENUE ($000)

<table>
<thead>
<tr>
<th>Year</th>
<th>Potential Sales</th>
<th>Current</th>
<th>Current</th>
<th>Current</th>
<th>Current</th>
<th>Current</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>+New Facility</td>
<td>+Plasma</td>
<td>+New Facility</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>7,240</td>
<td>6,000</td>
<td>6,000</td>
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<tr>
<td>2001</td>
<td>8,386</td>
<td>6,000</td>
<td>6,000</td>
<td>7,208</td>
<td>7,208</td>
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</tr>
<tr>
<td>2002</td>
<td>9,519</td>
<td>6,000</td>
<td>6,000</td>
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<tr>
<td>2003</td>
<td>12,856</td>
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<td>6,000</td>
<td>7,208</td>
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<tr>
<td>2004</td>
<td>14,141</td>
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<td>12,000</td>
<td>7,208</td>
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<tr>
<td>2005</td>
<td>15,555</td>
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<td>7,208</td>
<td>12,000</td>
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</table>

NPV: $51,706

Lost Sales: ($22,962) ($15,138) ($18,382) ($12,134)

Additional Sales Possible by adding Plasma to Current+New Facility: $3,004

INVESTMENT ($000)

<table>
<thead>
<tr>
<th>Year</th>
<th>Current</th>
<th>Current</th>
<th>Current</th>
<th>Current</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>+New Facility</td>
<td>+Plasma</td>
<td>+New Facility</td>
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<tr>
<td>2000</td>
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<td>0</td>
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<td>0</td>
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<td>1,000</td>
<td>3,000</td>
</tr>
<tr>
<td>2002</td>
<td>0</td>
<td>2,000</td>
<td>0</td>
<td>2,000</td>
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<tr>
<td>2003</td>
<td>0</td>
<td>2,000</td>
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<tr>
<td>2004</td>
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<tr>
<td>2005</td>
<td>0</td>
<td>2,000</td>
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NPV: $0

SUMMARY

<table>
<thead>
<tr>
<th>NPV of Project</th>
<th>Current +New Facility</th>
<th>Current +Plasma</th>
<th>Current +New Facility</th>
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<tbody>
<tr>
<td></td>
<td>$28,745</td>
<td>$28,987</td>
<td>$32,415</td>
</tr>
<tr>
<td>Subtracting lost sales</td>
<td>$5,783</td>
<td>$13,849</td>
<td>$14,933</td>
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