

# An Investigation of Laser Drilling Variation and the Application of a Knowledge Management Framework

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Submitted to the Sloan School of Management and the Department of Mechanical  
Engineering in Partial Fulfillment of the requirements for the Degrees of

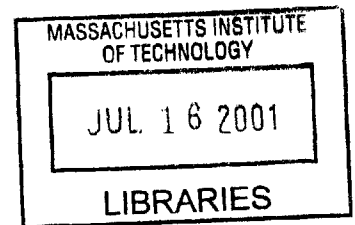
~~[M.S.]~~  
Masters of Science in Management and  
Masters of Science in Mechanical Engineering

In conjunction with the Leaders for Manufacturing Program  
at the Massachusetts Institute of Technology  
June, 2001

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## **Abstract**

Customer requirements for efficiency in the gas turbine industry are driving designs that require increasingly complex and precise manufacturing processes. One such process employed at Alstom Power is the laser drilling holes in gas turbine blades and vanes. The complexity of such advanced manufacturing techniques requires a disciplined approach toward process improvement. In addition, manufacturing knowledge management systems must be put in place to provide the foundation for improvement initiatives.

This thesis attempts to advance the understanding of laser-drilling variation sources on gas turbine nickel-based alloy blades and vanes. It also illustrates the importance of a disciplined approach to reducing variation in advanced manufacturing processes.

For illustrative purposes, this thesis consists of two main sections. The first focuses on efforts to reduce laser drilling variation. A historical view of the process highlights the need for a rigorous improvement plan. A disciplined approach is then proposed, incorporating a variety of tools to focus on key issues. Finally, testing and analysis provide the quantitative insights for improving the process.

Rigorous test data showed the drilling process to be significantly impacted by energy and focus variations. The sensitivity was greater than anticipated and highlights the need for improved setup techniques and instrumentation for successful production runs.

The second section of the thesis takes an organizational perspective of managing process improvement knowledge. The historical perspective shows that there were not sufficient systems in place to facilitate the necessary learning. The three key elements of a knowledge management system (creation, capture, and transfer) and the implementation of such a system are discussed.

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Daniel Whitney

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## **Acknowledgement**

I would first like to thank the Leaders for Manufacturing program and its supporters for providing me with the opportunity to study at MIT and perform this work.

I would like to thank my advisors – Dan Whitney and Roy Welsch for their guidance throughout this process. Their ability to ask tough questions and explore topics from a variety of angles is greatly valued.

I would like to thank ABB-Alstom Power for allowing me to explore their company and technology which provided a mutually beneficial learning experience.

Finally, I would like to thank my wife, Andrea, for accompanying me on this journey (both literally and figuratively) and for her support.



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## **Section 1: Laser Drilling Variation Investigation**

### **2. Introduction**

#### **2.1 Company Introduction**

Alstom Power is a \$10 B per year business with a complete range of power generation and service offerings. The power division of Alstom was built through a number of acquisitions and sales over the past few years.

In March, 1999 ABB and Alstom combined their power businesses in a new joint venture called ABB-Alstom Power. This created the largest power corporation in the world with ~\$10B in revenue. In April of 2000, it was announced that Alstom would buy out ABB's share of the joint venture. ABB intends to concentrate on IT and service development, while Alstom is pursuing power generation as a core business.

The work for this thesis was performed in the Gas Turbine business segment. Alstom Power has a full range of gas turbine power plants ranging from <5MW to >200MW. The gas turbine market has seen explosive growth in the past three years – spurred by deregulation and increased demand for cleaner, more efficient power sources. Alstom is currently behind GE and Siemens in world wide gas turbine market share. Alstom is trying to gain market share by leveraging its new GT24B/26B product line.

## 2.2 Group Introduction

This project was initiated by the manufacturing engineering group (ME). This newly formed group was chartered with supporting the design department with manufacturing knowledge and guidelines, and improving supplier performance through process improvement.

The group was formed in August of 1999 and had eight members as of June 2000. The group is functionally split between precision cast components and large castings. The former includes the blades and vanes with which this project is concerned. The latter includes housings and vane carrier rings.

The ME group began with a fairly loosely defined role and responsibility. The group had only loose connections with design, quality, and logistics and no formal relationship with suppliers. The lack of power and incentives to move projects forward hindered the group's initial effectiveness. However, in mid-March of 2000, supply and quality problems led to greater involvement and appreciation of the manufacturing group. The members of the group became involved in a number of improvement and investigative teams during this crisis time.

Manufacturing Engineering originally reported through Design and Manufacturing to the Turbomachinery business center, which in turn reports to the head of the Gas Turbine business unit.

Under a recent re-organization (July 2000), the ME department was merged with a quality group who also originally reported to Design and Manufacturing. The new group, Quality and Process Engineering reports to Logistics (supply chain and procurement), which then reports to the Turbomachinery business center. This new reporting structure has the benefit of placing Quality and Process Engineering closer to those who have the power to influence suppliers. The disadvantage is that there is a conflict of interest in having the quality group report to the group responsible for on-time component delivery.

The merger with the quality organization will provide greater sharing of information and synergies in training and analysis. The union of the two departments was a logical step since the quality department had become more focussed on quality control, variation reduction, and process improvement. Other leading power generation manufacturers have made similar organizational changes in the past few years. The merger of manufacturing engineering and quality departments can be seen as a natural progression based on technology. As manufacturing processes become more complex, pushing the bounds of technology and incorporating more automation – the core manufacturing process cannot be developed on the factory floor. Manufacturing process development is occurring in R&D laboratories and equipment suppliers. Thus, the traditional manufacturing department has focussed more on process improvement and workflow using statistical methods. A similar progression has occurred in quality departments. Information technology allows much of the paperwork to be generated and processed automatically. In addition, ever increasing amounts of data are available for review.

Thus, quality personnel have increased their focus on variation reduction through the use of statistical tools.

The incorporation of the expanded quality group into the logistics group provides a boost for process improvement teams. The logistics group controls relationships with suppliers through contracts and payment. Closer communication between process improvement teams and logistics personnel will better align supplier incentives for project success.

## 2.3 Problem Statement

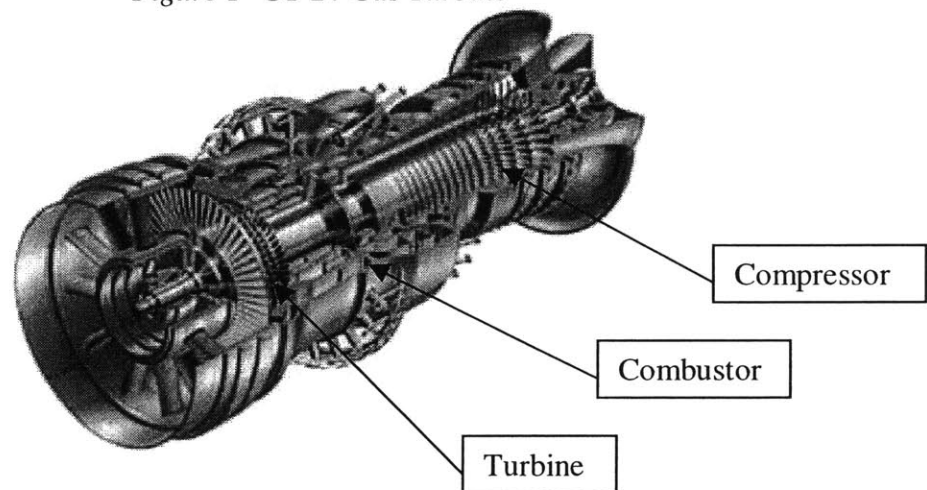
The purpose of the project was to reduce the airflow variation in precision cast components, thought to be due to laser drilling. Airflow variation had been causing unacceptable levels of scrap components and reduced turbine performance.

In an effort to put this problem in context, a brief description of the machine, component, and acceptance criteria follows.

### *Background*

The components of concern are key elements of the GT24 industrial gas turbine shown in *Figure 1*.

*Figure 1- GT 24 Gas Turbine*

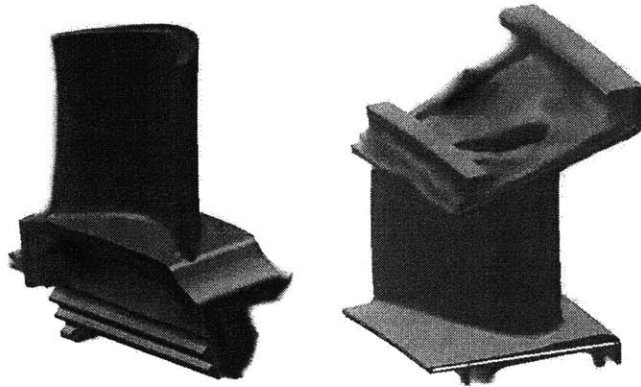


The industrial gas turbine is in the same family as the jet engine. Industrial gas turbines of this size are primarily used for electrical power generation.

The turbine inlet is on the right hand side of *Figure 1*. The gas is then compressed, and fuel added and ignited in the center section – known as the combustor. The hot gas then exits through the left side (hot section) of the turbine, creating the motive force to turn the shaft.

The components of concern for this project are the most crucial components in the turbine, blades and vanes. These components see the highest temperatures and are those that extract the work from the high temperature and pressure gas. Pictures of a typical blade and vane are shown in *Figure 2*.

*Figure 2 – Typical Blade and Vane*



In order for these components to survive the harsh environment, they must be supplied with a continuous source of cooling. The cooling air is pumped into the components and escapes from small holes (~1mm diameter) on the surface of the components. The amount of air flowing from these components determines their lifetime. The airflow must be within strict limits in order to be accepted. If airflow is too low, high temperatures will cause premature failure, while excessive airflow reduces overall turbine efficiency. To achieve the specified airflow, the process used to drill the holes must be strictly controlled. These parts are carefully inspected, and those that do not pass are subjected to lengthy, costly review, and/or are scrapped.

#### *Importance of Problem*

The blades and vanes are the pacing item for turbine completion and are among the most expensive in the engine. Airflow problems were causing unacceptable scrap levels and Non-Conformance Reports (NCR's) which delay shipments of finished parts. With individual part costs on the order of thousands of Swiss Francs (Sfr), scrap costs from laser/airflow variation are particularly severe. Shortages of blades and vanes cause delays in assembly and shipment of the turbine, leading to punitive penalties. These penalties can be a significant percentage of the machine purchase price.

## **2.4 Approach**

The approach taken for this project was to develop a structured methodology for quantifying improvement opportunities using quality tools and statistical methods.

This approach is mirrored in the following chapters, which discuss each step in detail.

The first step in the process was to investigate the process and understand the context of the problem. Process maps of the manufacturing process were created to illustrate each step and provide an understanding of the interactions between steps. These maps provided a tool for conceptualizing the manufacturing supply chain and the opportunities for variation reduction.

In an effort to understand the current state of the process and prevent repetition of past actions, a historical summary of the problem was compiled.

Baseline statistical information was captured to show how the process behaved. This information was used as a reference for improvement activities.

Statistical and process information was combined to form a business plan for the project.

The testing plan follows, which is the most crucial element of the plan. An Ishikawa (fishbone) diagram was used to display the relationships between various parameters and laser hole/airflow variation. The diagram was used to focus on key drivers for testing. In designing the testing plan, statistical relevance was ensured using standard guidelines.

## **2.5 Summary**

This chapter discussed the setting and framework for this thesis. A brief introduction of the problem set the stage for the discussion, followed by some background on the company and division in which the work was completed. The approach to the problem set out a framework in which to complete the investigation of the laser drilling variation. The next chapter provides detail on the components and manufacturing processes in question. A brief history of the laser drilling variation problem completes the chapter.



### **3. Process Investigation**

#### **3.1 History of the Problem**

Laser drilling is new to Alstom power and generally new to the gas turbine industry. Most suppliers and laser producers consider Alstom to be leading the advance into laser drilling technology.

The aircraft engine industry has been using lasers for a number of years, however this knowledge has not transferred to the industrial gas turbine segment. Aircraft engine manufacturers utilizing this technology have developed their knowledge internally and there are few details available in the literature<sup>1</sup>. Even if the information was made available, aircraft engine components are an order of magnitude smaller and thinner than industrial gas turbine parts, and thus easier to produce successfully. The thickness of industrial gas turbine components causes geometry and energy distribution complications since the focal spot length of the laser beam is comparable to the material thickness<sup>2</sup>. Larger parts and longer holes create a much more complex recast layer and heat affected zone dynamics in the material, which impact material properties and hole geometry.

The semi-conductor industry has used lasers extensively in various manufacturing operations. However, the scale of those operations makes a different class of lasers applicable. The thinner materials and lower energies allow use of smaller lasers whose behavior does not scale to the power levels required for gas turbine applications.

Alstom's pursuit of laser drilling was necessitated by the recent design developments, which in turn were driven by market demands for higher efficiency. Higher efficiency requires higher gas temperatures, which have lead to the development of ceramic coatings to help maintain the life of the blade. The ceramic coatings are non-conductive, thus the traditional method of electro-discharge machining (EDM) cannot be used.

The new design of the GT24/26 turbine began production in early 1999. Starting in 1998 and expected to continue through 2003, there has been a boom in the gas turbine market. Production volumes are expected to reach approximately 4x their values in the early 90's.

This increase in volume and production pressures has left little time or manpower for process investigation and improvement. Unfortunately, the laser drilling process is significantly more complex than standard machining technologies and significant variations in process capability lead to numerous production problems.

Compounding the problem is the fact that the suppliers do not have strong incentives to improve. Due to the manner in which contracts were structured, Alstom has not had enough power to convince the suppliers to improve.

Beyond issues of incentives, the suppliers did not have systems in place for continuous improvement. When suppliers were asked what actions they were taking to improve their processes, there was no response. The only attempts at process improvement were driven and controlled by Alstom engineers in Baden. The engineers would specify tests and

measurements to gain information on the process. There are two problems with this approach. First, process improvement should be led by those who know the process the best, not by those who know the design the best. Second, Alstom's suppliers seem to rely on Alstom for improvement initiatives and take no action or responsibility on their own.

Through recent changes in management at some of the suppliers, there appears to be an effort to focus on improvement

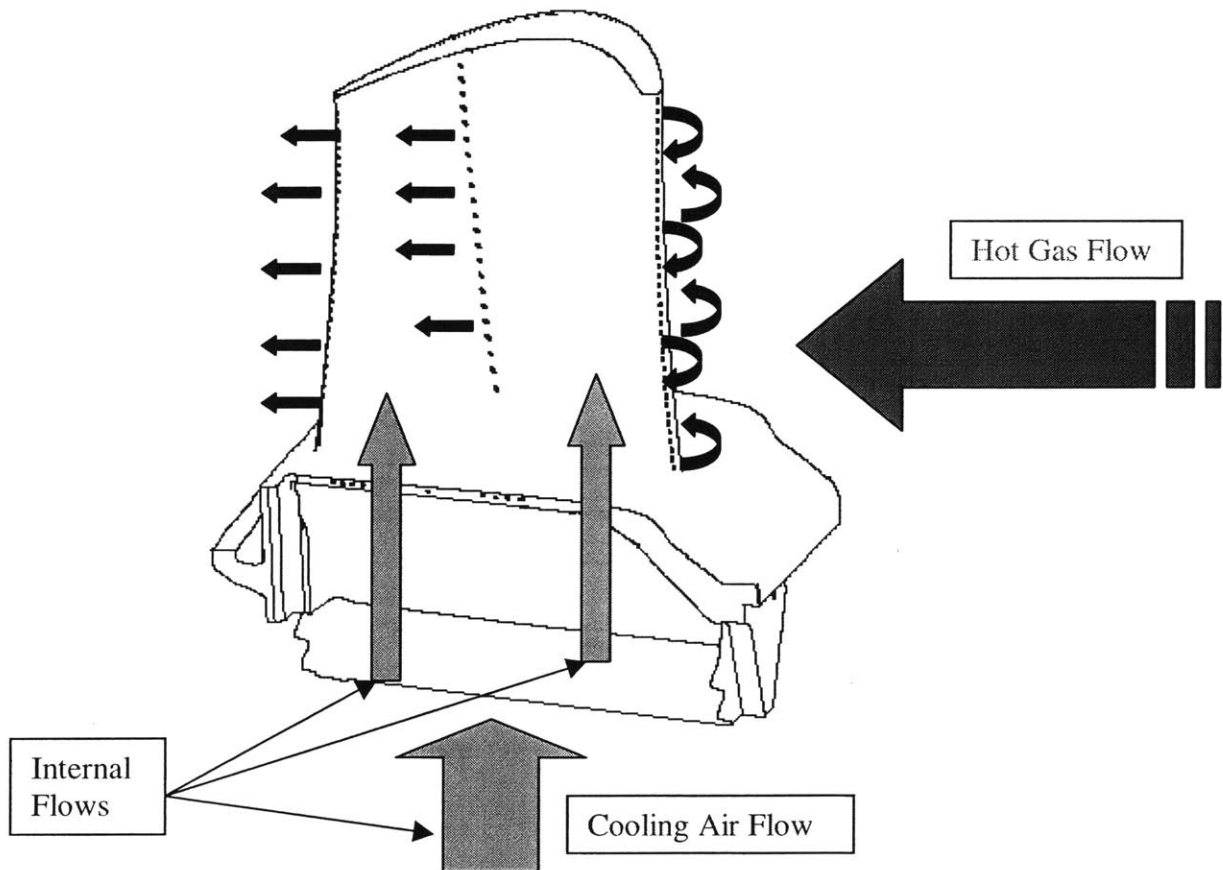
### 3.2 Focus Component Description

In an attempt to limit the scope of data collection and number of interface points, the decision was made to focus on a single component. Focussing efforts on a single component allowed an in-depth examination of factors influencing the outcome, and then transfer the lessons learned to other components.

The GT24 Blade 1 was chosen as the focus component because it had the most problems. The advantages of choosing the blade 1 over any of the vanes is that it does not have additional parts incorporated into the casting, which can also contribute to airflow variation. This eliminated adding factors that could confound results of a statistical analysis of past data. The Blade 1 is made primarily at a local internal supplier, which simplified logistics and testing execution. There are external vendors that perform laser drilling on Blade 1 and other components in the engine.

A picture of the blade is shown in *Figure 3*. When mounted in the engine, the hot gasses flow from right to left over the blade. Cooling gas is supplied from underneath the blade and passes through internal cooling passages and out through the holes. The holes are grouped into specific rows. Each row contains similar hole types and is targeted to cool a specific section of the blade. The Blade 1 has approximately 200 holes total.

*Figure 3 – GT24 Blade 1*



The blade is made of a nickel based super alloy and is partially coated with a ceramic material, helping to insulate sections of the part from the hot gas.

This component requires a number of tests in order to be deemed engine ready. For the purpose of this investigation, only tests related to the laser drilling process will be discussed.

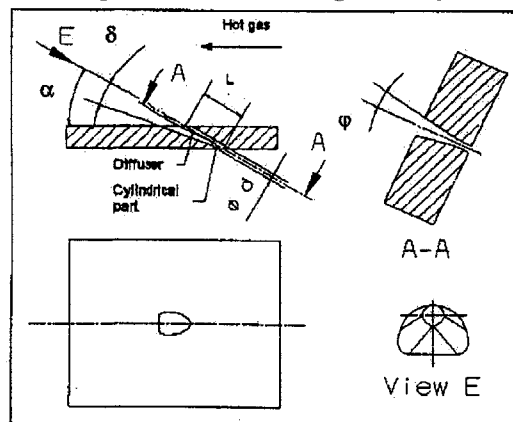
Airflow testing is the first critical test that we will discuss. In an airflow test, air at ~1.4 bar is supplied through the bottom of the component and flows out through the various holes. A number of possible airflow test configurations may be performed. Total airflow measurements are performed on 100% of components. In the total airflow test, all of the holes are open and the airflow is measured.

On a smaller percentage of the parts, a number of tests are performed with air flowing only through specific holes. These tests are referred to as "sector flows". Testing numerous sectors on a component is a time and labor intensive operation.

The sector flow data provides information on the distribution of flow around the component. In order for the blade to perform properly, the balance of this flow must be within certain specifications, otherwise some areas of the component may be too hot, causing reduced part life. In addition, temperature gradients in the part will increase the severity of the thermal cycling the part encounters. Thus, sector flow data is valuable for determining part performance.

Two types of holes will be discussed. The first are simple cylindrical holes, which may be drilled at a variety of angles to the surface. The second type is known as fan shaped. The geometry of these cooling holes provides specific advantages for certain locations. However these advantages will not be discussed here. *Figure 4* is a diagram of a fan shaped hole. Typical holes are ~1mm in diameter and are drilled at an angle of 30° to the surface, through ~3mm of material, with a hole depth of ~6mm. Some holes have up to ~80° angle to the surface and material thickness range is ~2-4mm.

*Figure 4 – Fan hole geometry*



### 3.3 Component Manufacturing

In order to understand the sources of variation in the component it was first necessary to map the process steps. *Figure 5*, on the following page, shows the path that the components follow as they are manufactured.

The first section of the diagram describes the casting process. Casting is the most expensive step in the manufacturing process and requires the most detailed knowledge base. The casting suppliers have been in the business a long time (most having developed the technology through government contracts), and there are few that know the process as well. Due to the sensitivity of their knowledge, the casting suppliers generally do not allow outsiders to investigate their process.

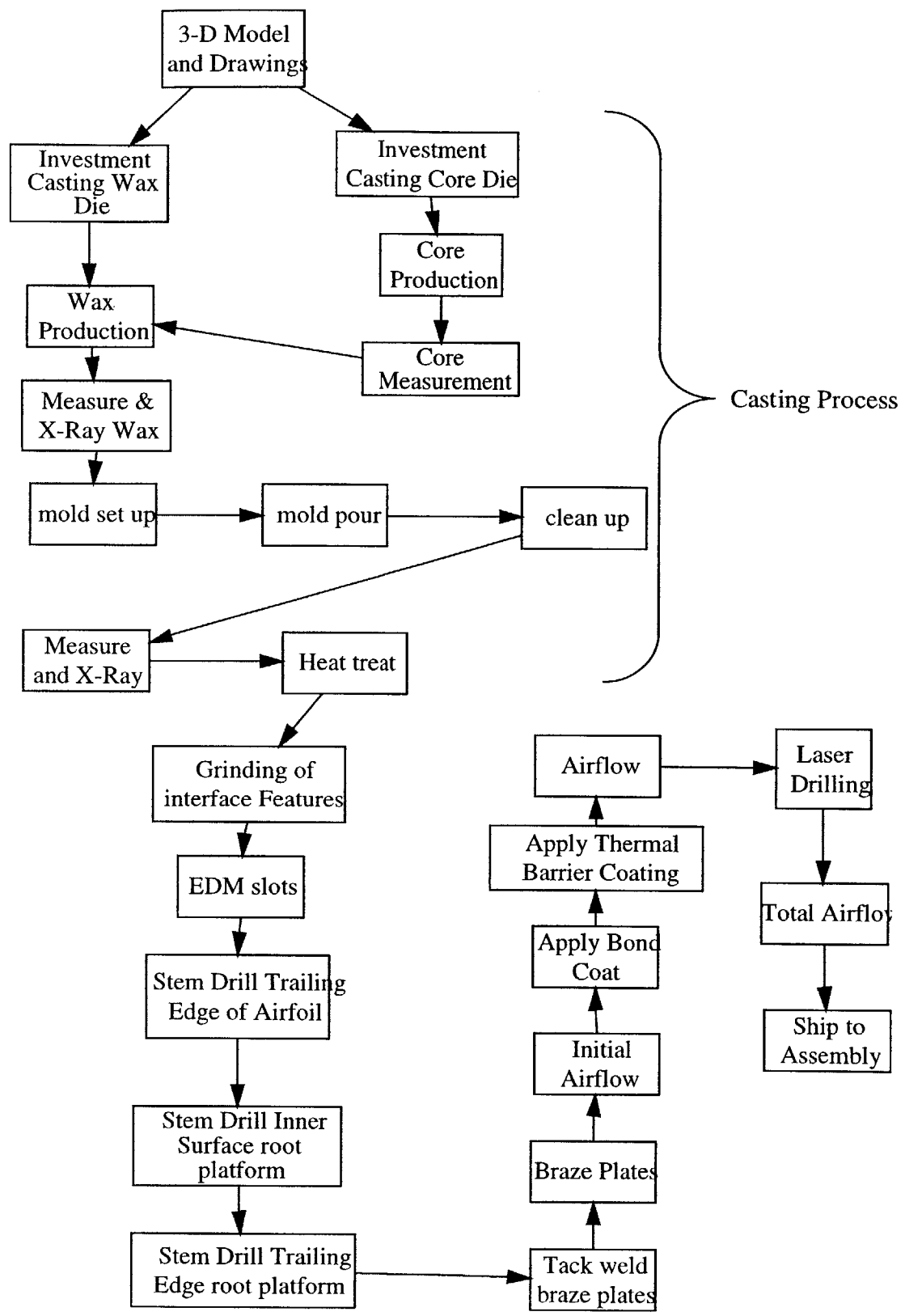
In the investment casting process, a wax form of the part is used to create each mold. Ceramic cores are often used to create the internal cavities of the part. Thus, two dies are required – one for the core and one for the wax form. The core die is used to create the ceramic core. The ceramic core is then placed in the wax die, and wax is injected around it. The wax form is then used to create the mold for the investment casting process.

The casting process forms the external shape and internal cavities of the component. Due to the size of the internal cavities with respect to the size of the holes, cavity variation will not have a significant impact on total airflow.

There are a number of grinding operations that prepare the mating surfaces of the component, but in no way effect airflow.

The STEM (Shaped Tube Electrolytic Machining) process is used to drill the holes in the trailing edge of the airfoil. This process has been shown to vary significantly, but it only impacts 15% of total airflow. Available data at the time showed no evidence of correlation between stem drilled airflow variation and total flow variation. The conclusion from the data was that the variation in laser drilling was overwhelming the STEM variation. The laser drilling process drills a quantity of holes that account for 78% of the total airflow. Based on historical data, the remaining drilling techniques can only account for a small portion of the total variation, due to their contribution to total airflow. From this data, it is clear that the laser drilling process is the key process to focus on for the improvement of airflow performance.

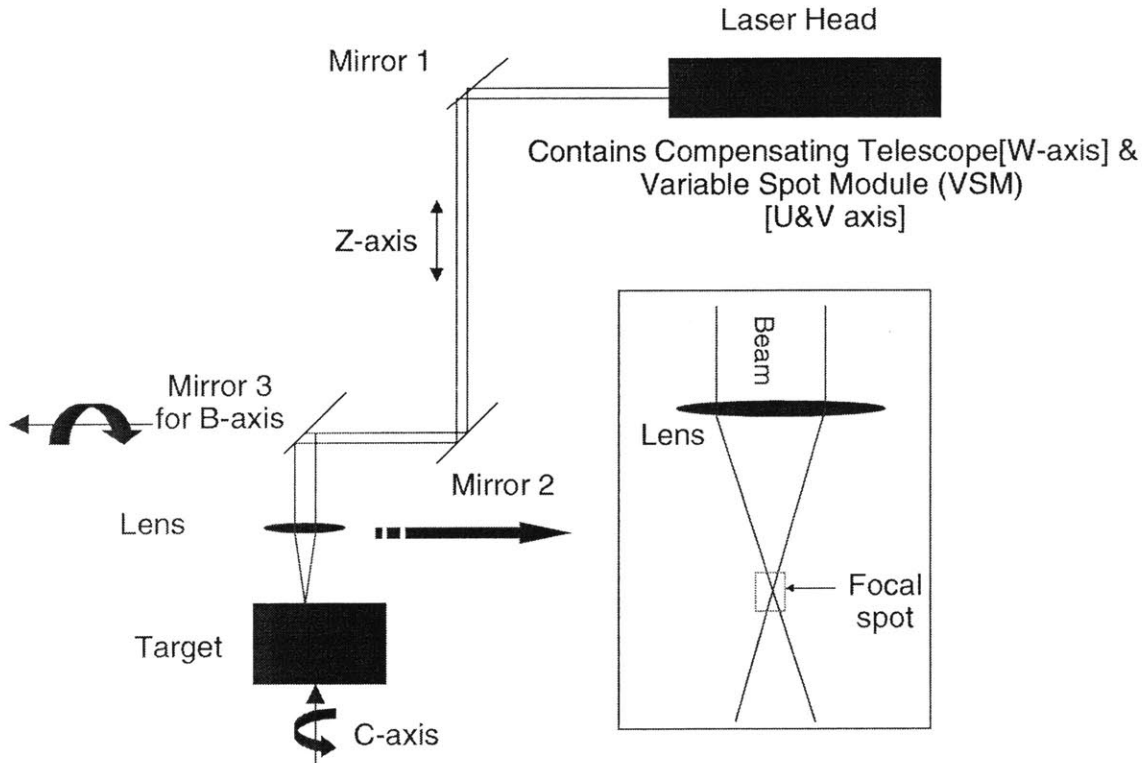
**GT 24b Blade 1 Manufacturing** Figure 5 – GT 24 Blade 1 manufacturing process



### 3.4 Detailed Description of Laser Process

The laser drilling process uses a focussed laser light to vaporize material. Laser drilling is still a relatively new process. There are many parameters to control and methods for drilling the parts. In addition to the 5 axis controls and feed rate of conventional machines, there is also energy, frequency, laser pulse shape and duration, beam size, focus position, assist gas, and beam divergence. All of these parameters will affect hole size, quality, and repeatability. *Figure 6* shows the layout of the laser tool and its axes.

*Figure 6 – Laser Machine Schematic*

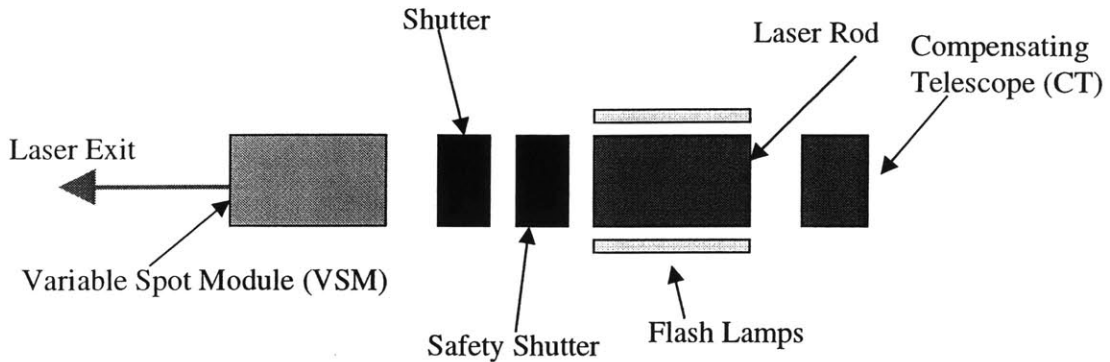


The beam is generated in the laser head and directed to the work piece via the “beam path”. The beam path is a series of mirrors that allow the beam to be rotated and focused as necessitated by the component design. One of the most critical factors of hole quality is focus position. Focal position is dependent on the CNC program, the focus of the beam (which changes over time as the optical components get dirty), fixturing, and component variation.

A schematic of the laser head itself is shown in *Figure 7*. The basics of operation are as follows: The flash lamps pump energy into the laser rod – once sufficient energy has been input to the rod, lasing occurs within the material. The energy is contained within the chamber until the shutter opens, releasing the energy in a single pulse. The compensating telescope adjusts the effective length of the lasing chamber, which affects the energy of the pulse. The variable spot module (VSM) is composed of a pair of diverging/converging lenses that control the diameter of the beam. The beam diameter is

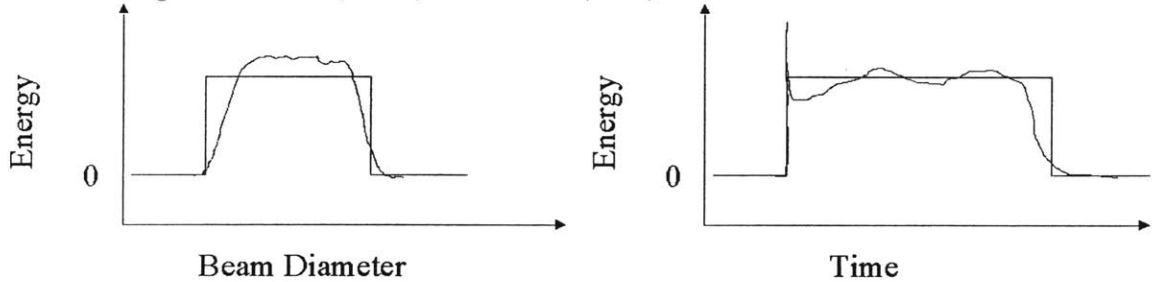
controlled by adjusting the relative distance between the two lenses. The intention of the device is to adjust size of the beam and ensure a parallel output beam.

Figure 7 – Laser Head Schematic



Ideal and typical pulse energy within a laser pulse would be shown in Figure 8.

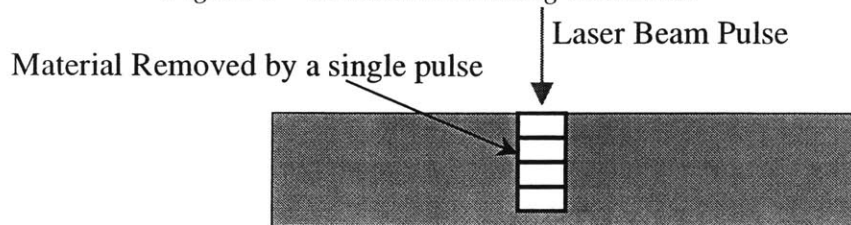
Figure 8 – Ideal (black) and Actual (blue) Laser Pulse Characteristics



Unfortunately, the laser in question, a Convergent Energy – Aurora P50, does not have the ideal properties. Thus, the adjustment of the CT and VSM impact the energy distribution within the laser pulse. The machine itself is not capable of measuring these parameters, but some measurements were taken with specialized equipment and are summarized later.

The process of drilling a hole can be performed with two methods. The first is known as percussion and the second as trepan. In percussion drilling, the laser beam diameter is equal to the size of the hole. As Figure 9 shows, successive pulses remove material further into the material. It can take anywhere from 4 to 20 pulses to penetrate the material depending on the depth of the material and beam properties (energy, spot size etc...).

Figure 9 – Percussion Drilling Schematic



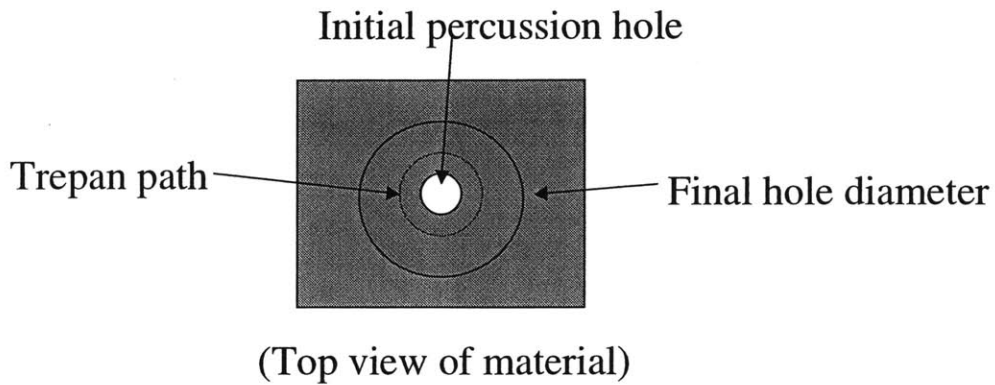
(Side view of material)



The benefit of percussion drilling is the speed at which holes can be drilled. The disadvantage is that the beam must be manipulated to match hole size.

In trepan drilling the beam spot size is significantly smaller than the intended hole size. As shown in *Figure 10*, a percussion hole is first drilled in the material; then the beam is traversed around the hole to expand its size to the desired diameter. Trepan drilling, while slower, maintains a constant beam size for all holes. Trepan drilling generally produces holes with better metallurgy and geometry, and can generate fan shaped holes.

*Figure 10 – Trepan Drilling Schematic*



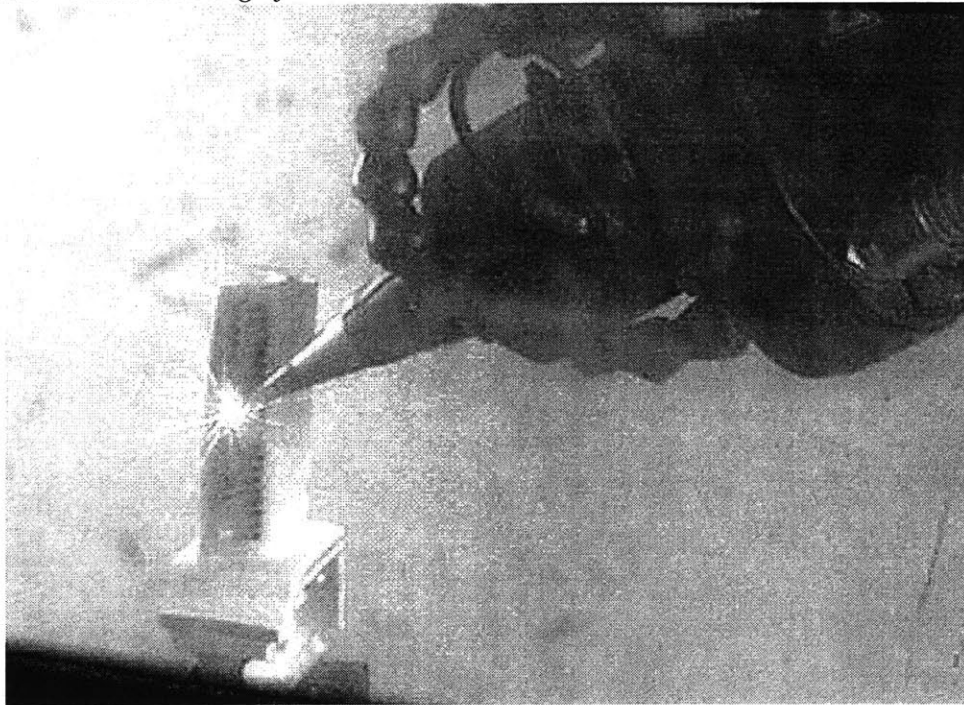
*Figure 11* shows the tool drilling a sample piece:

*Figure 11 – Laser Drilling of a Test Piece*



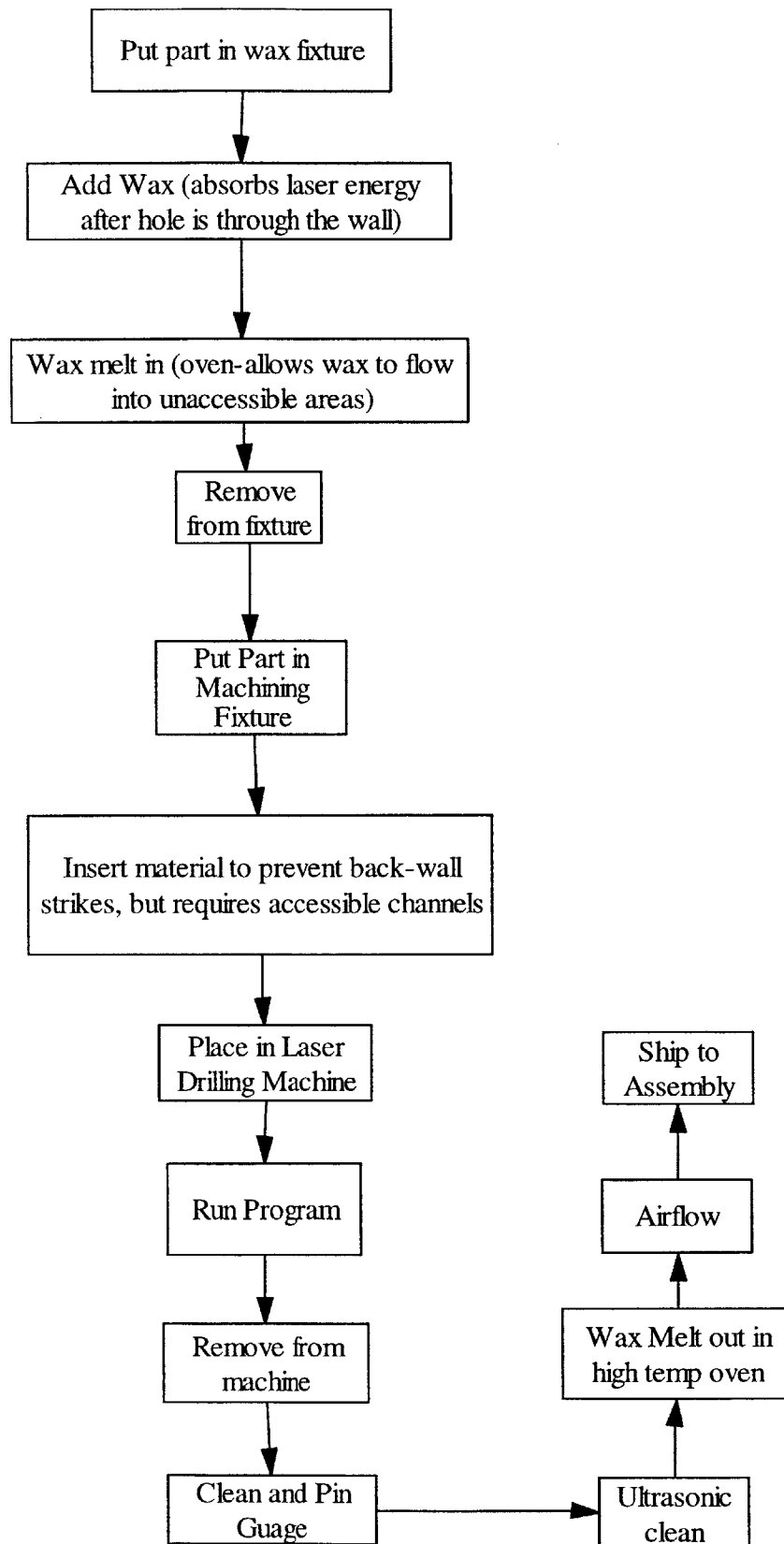
*Figure 12* shows a Blade 1 being drilled on the laser drilling machine.

*Figure 12 – Laser Drilling of a Blade 1*



*Figure 13* on the following page shows the process map for the Blade 1 at the internal supplier.

Figure 13 -- Laser Drilling Process Steps at the Internal Supplier



### **3.5 Summary**

This chapter focussed on the details of the component and manufacturing processes related to the variation problem. This information, along with the history of the problem provides the insights necessary to develop a testing plan for improvement.

Prior to developing the improvement plan, baseline statistics and financial information were gathered to justify testing and development. Chapter 4 quantifies the variation in the process, and provides a baseline for improvement measurement. A business case is then presented which justifies further expenses in testing and process improvement.

## 4. Measurements and Business Impact

### 4.1 Baseline Statistics

In order to have a sound basis for proceeding with the project, it was necessary to gather information on the current state of the process on various component and suppliers. This task was complicated by the fact that an integrated part/data tracking system did not exist. There was no available data on specific causes of scrap and scrap rates, or throughput time for components. Airflow data was only received for parts that were out of spec and there was no common storage method or retrieval system. However, there was an airflow data tracking project in progress, which hoped to create a central storage and retrieval system. (The airflow data tracking system was not operational by the end of the airflow project. The IT solution was in beta testing, but the database was incomplete. There were a number of problems regarding data reporting, consistency, and formatting with both internal and external suppliers, which hindered progress.)

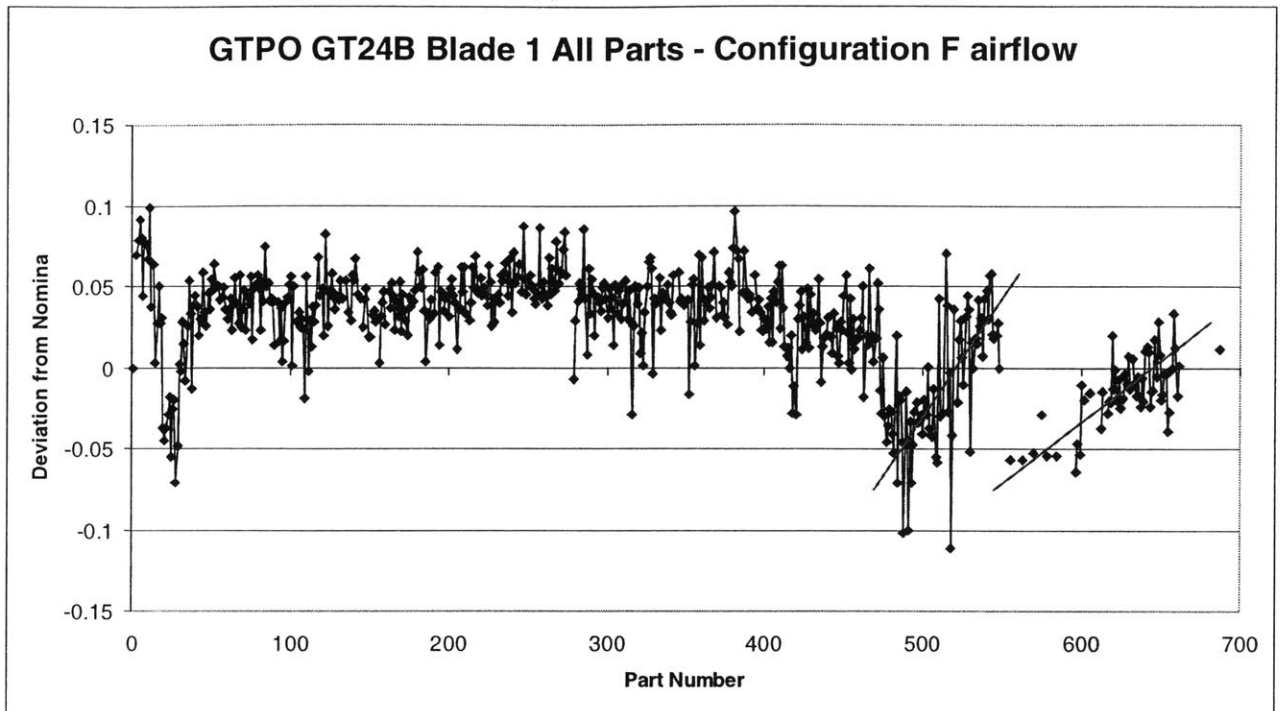
To provide a reasonable baseline for the project, the author gathered a sample of total flow data from various suppliers to understand the state of the process. It was found that standard deviation of total airflow for each component within an engine set of parts (approximately 80) fell between 2 and 4%, yielding a  $3\sigma$  range of +/-6% to +/-12%. The specification for the components originally required +/-5% or a standard deviation of 1.67%. Total airflow specifications were expanded for each component to ~ +/-10% range (standard deviation of 3.3%) when it was found that the laser process was not capable of +/-5%. The quality department had adopted tools defining a capable process as one with a  $C_p \geq 1.33$ .  $C_p$  is defined as the range of the specification divided by 6 times the standard deviation of the process. 
$$C_p = \frac{USL - LSL}{6\sigma}$$

Thus with the deviations found in the sample of data, the laser process was not capable for either specification at a first glance. It became clear through interviews with suppliers, that they did not have a thorough understanding of the driving factors behind this variation.

In order to understand variation at a more detailed level, individual row flows were also examined. It was found that the rows varied in the range of +/-15 to +/-30%. There was not enough data to make any statistical or qualitative correlation between the row flows. The row flow variations appear to be independent from one another.

An examination of the behavior of the machines over time showed significant trending. *Figure 14* shows overall airflow over time for the internal supplier, for the timeframe of February through April 2000.

Figure 14 Internal Supplier Total Airflow History



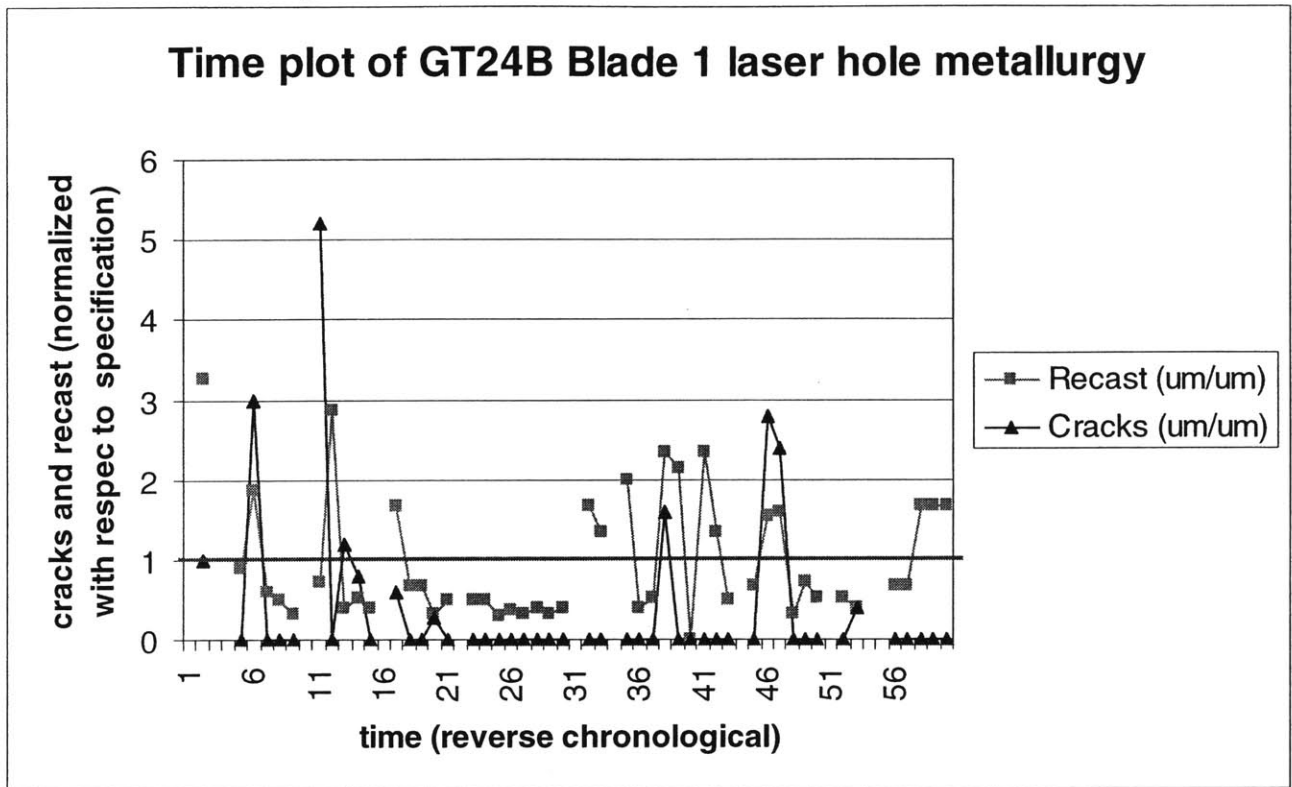
From *Figure 14*, we can see the progression of the production. Over the first 450 parts, there were a number of process changes as programs were adjusted to improve hole quality and airflow distribution between rows. These were relatively short runs with testing, measurements, and adjustments made within the processing of a single part and between parts. After ~450 components, the process parameters were fixed and serial production began. The serial production components exhibit upward trending in airflow, as machine behavior changes. There is a clear trend from ~450 to 550 – an adjustment was made to the machine in an attempt to re-center the process, and another clear trend is seen from ~550 to 670. As parts are drilled the behavior of the flashlamps in the laser change. Also, the optics can change which leads to an increased focal diameter of the beam. These two factors account for the increase in airflow over time. However, this behavior had not been correlated in such a way that proper adjustments to the machine could be made to reduce this variation.

One of the over-arching concerns with the laser drilling process is metallurgical quality. Since the laser process adds heat to the material, there are concerns about the impact on metallurgical properties. The biggest concerns to date deal with cracking and recast layer.

The data on metallurgy for these components is sparse, since a component must be cut-up in order to gather the data. The cost of the component and the metallurgical investigations themselves are high, thus limiting the practical number of samples. *Figure 15* shows recast layer and base metal cracking in the holes. The recast layer is classified as the material on the walls of the hole, which was melted and then re-solidified. Re-cast material has inferior properties, and therefore must be minimized. Base metal cracks can

form when the material surrounding the hole is heated and cooled quickly. These cracks are a serious concern, since the high vibratory operational environment could cause these cracks to grow – potentially causing a failure.

Figure 15 – Metallurgy of Laser-Drilled Holes



While the majority of the recent components are within the specification, the primary concern is the variation of results. This data represents an extremely small sample of all holes, and yet shows the variation of metallurgical quality. As the process repeatability is improved via airflow measurements, the metallurgical variation will also improve, since laser parameters affecting geometry also affect metallurgical quality.

## 4.2 Business Case for Improvement

With an understanding of the process and background statistics, it was possible to develop a business case for investing in the laser process.

Two major categories dominate the costs in this area. Scrap is the number one cost consideration. The scrap rates driving these numbers are much higher than those expected from traditional machining (~3% vs. <1%). Engineering costs were significant for this year, estimated at 500k Sfr. Engineering time is required to disposition parts that are outside of specified tolerances. Engineers spent significant time interacting with the suppliers, requesting additional tests, and developing recovery plans for late blades due to laser drilling problems.

Improvements in the laser drilling process can generate savings that amount to 2% of total part cost assuming that the rework rate could be halved on the GT24B blade 1. Once the laser drilling process is improved and stabilized, throughput time can be reduced by optimizing flow through the shop. Throughput time could be reduced from 18 days to 5 days, resulting in inventory carrying cost savings on the order of 100's kSfr/year for the GT24B blade 1 and vane 1 alone.

With numbers as overwhelming as these, it would be hard to believe that the suppliers would not jump at the chance to improve their process. However, the savings presented are those that can be realized by Alstom Power, and not by the suppliers. Suppliers in this context could be either external or internal. The incentives for and interactions with the internal supplier are identical to those of an external supplier. The scrap costs are extremely high for Alstom because laser drilling is the last manufacturing step, so the scrapped part is valuable. The supplier on the other hand only loses their cost to drill it, which accounts for only 5% of total part cost. The engineering time is that spent by Alstom engineers, and there are no penalties for applying that time to the supplier. The inventory carrying cost savings also apply to Alstom, since at no point does the supplier take ownership of the components.

Not considered in the analysis are the potential late fees paid to utilities for late delivery of turbines due to insufficient blades or vanes. Such numbers are difficult to calculate with any certainty, can change through negotiations, and are tightly held within the company. Thus, late penalties must be thought of in terms of a risk factor, which would favor process improvement.

Although there is a strong incentive from Alstom's perspective to improve the process, there are none for the supplier. There are not even late penalties for the supplier. Thus it is critical for Alstom to provide incentives for their suppliers to improve. Without incentives in place, the suppliers will not take action.



### **4.3 Summary**

This chapter provides the quantification of variation and costs which justify further process improvement efforts. The following chapter develops the testing plan used to gain insights into the laser drilling process. The results are discussed in detail, and recommendations are made for improving the production process.

## 5. Testing and Results

### 5.1 Testing Plan

After discussions with the suppliers and industry representatives, it became evident that without a rigorous testing plan, there would be no process improvement. The first step in sorting out the data was to organize it in a palatable format. I chose to show the sources of variation in the visual format of a fishbone diagram (see *Figure 16*). This diagram, although not all encompassing, shows the breadth of the problem and allows initial filtering of the attributes. The five circled elements were those targeted for testing, based on the discussion that follows.

The first step in managing the problem was elimination of aspects that were expected to produce small variations (cooling flow, frequency, pinning). The cooling flow for the laser nozzle is regulated from a supply line pressure approximately four times higher. In addition, no pressure supply problems had been identified to date, and the regulators are a standard, proven technology. The laser pulse frequency had not shown variation in operation. The power supplies have limitations in the energy that can be supplied at various frequencies, but the frequency of the pulses themselves is controlled by the shutter logic, which is fully capable. Pinning is a technique for measuring the size of the holes in the components. Typically go-no go gauges are used for these measurements. There were concerns that the pinning process would dislodge portions of the recast layer, which would influence component airflow. However, this was shown to have only a minor impact, ~1-2%, on total airflow. Procedures had been implemented to ensure that all components were pinned in a consistent manner.

Items that are outside the realm of influence for this project were also eliminated. Items related to casting (metal, hole depth, positional tolerance) were removed according to this criterion. The investment casting process has been refined for many decades such that the expected change in capability is second order with respect to the problem at hand.

An extensive literature search was performed on lasers and laser drilling to understand current trends and approaches. The literature is generally focussed on correlating beam parameters to hole geometry and metallurgical quality<sup>1,4,5</sup>. This work provides some guidelines for setting laser parameters for achieving specific hole sizes, but provides no information on variation. Little mention is made about the overall repeatability of the lasers. In one case, a figure of +/-10% airflow was given as the variation range, which would be unacceptable for the components in question<sup>4</sup>. Such variation was acceptable (sometimes not even measured) in earlier gas turbine and aircraft engine designs – however the newer, more efficient designs require more precise knowledge of cooling flow.

Since most (if not all) of the research is sponsored by industry, the most interesting results are confidential. Thus insights and approaches to the issue were found, but detailed solutions must be worked out internally.

The literature indicates that focus and energy are significant drivers of hole geometry and quality<sup>1,4,5</sup>. These items and operator adjustments became the overwhelming choices for attention.

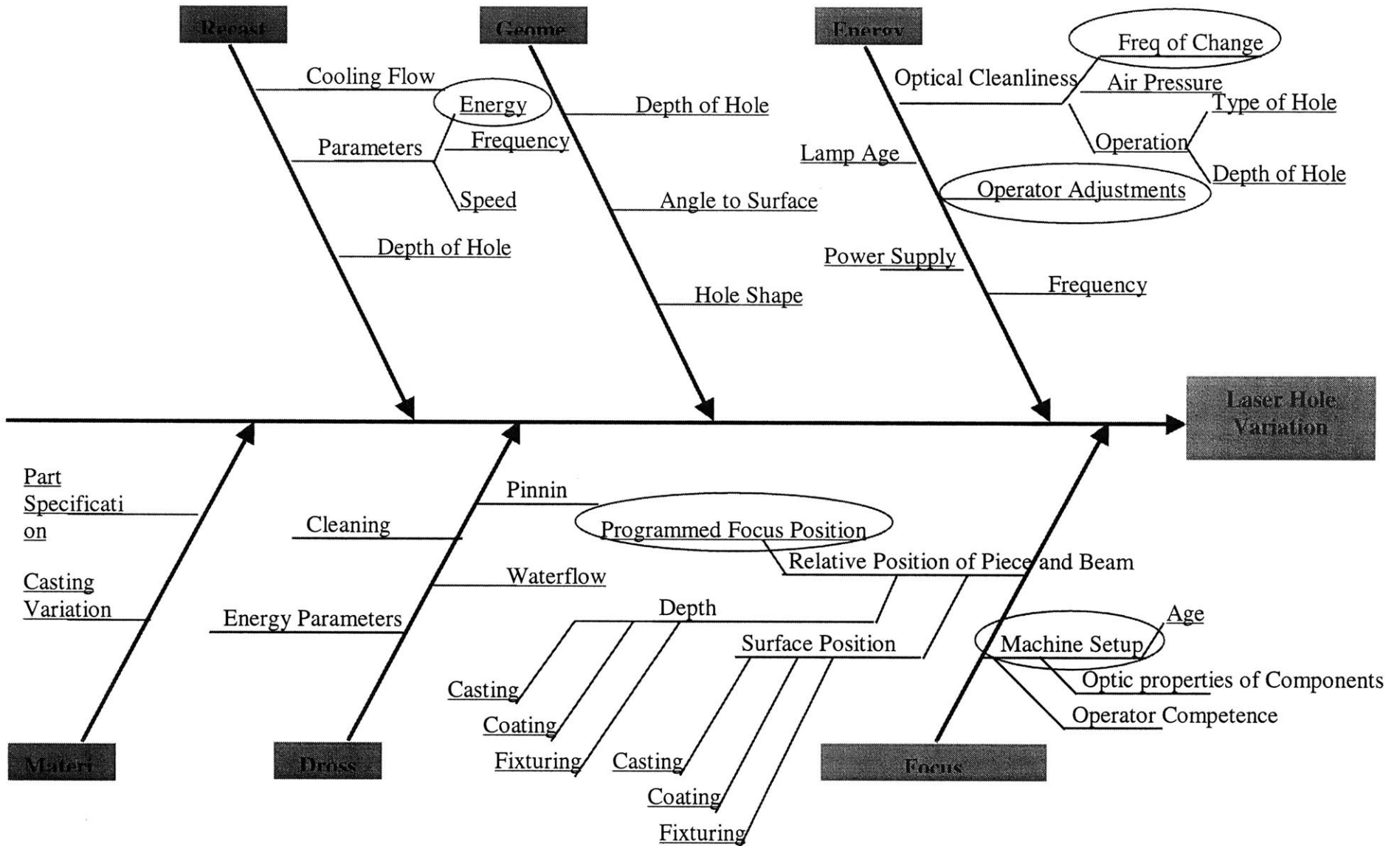
To eliminate part to part variation and allow a number of tests to be completed cost effectively, flat plates were used in the testing. Two types of plates were utilized during the testing. Single crystal plates were used on those tests that were expected to be dependent on material. Hastelloy X was used on the remainder of the tests. Hastelloy X is much cheaper than the single crystal material and the geometry of the available material allowed use of fewer plates.

The testing plan that was developed is shown and described in Appendix A. The tests were designed so that useful statistics could be gained while minimizing the number of tests.

The characteristics of the test plates and holes were chosen to be within the typical range of those found on the blades and vanes in question. All holes are approximately 0.8mm in diameter and drilled at an angle of 30° to the surface of the test plate. The test plates are all 3.2mm thick, yielding a hole length of 6.4mm.

The details of the airflow setup, including instructions for test setups are shown in Appendix B.

Figure 16 --Fishbone Diagram



## 5.2 Results

### Single Hole Airflow

The single hole airflow results are summarized in *Figure 17*:  
*Figure 17 – Single Hole Airflow Test Results from Test Plates*

|                    | Hole Type              |                |                           |
|--------------------|------------------------|----------------|---------------------------|
|                    | Cylindrical<br>Treppan | Fan<br>Treppan | Cylindrical<br>Percussion |
| Flow Variations    |                        |                |                           |
| %StDev             | 8.1%                   | 1.4%           | 11.8%                     |
| min max spread     | 23%                    | 11%            | 55%                       |
| Diameter Variation |                        |                |                           |
| %StDev             | 2.6%                   | 3.4%           | 3.0%                      |
| min max spread     | 13.2%                  | 8.5%           | 15.0%                     |

Since the data was not normally distributed, the estimated standard deviations were calculated by subtracting the first from the third quartile values and dividing by 1.25 to provide an estimate<sup>15</sup>.

This data set provides information on the hole to hole variation expected from the machine, with all energy and focus parameters held constant. With this data set, it is possible to build a statistical model of a row of holes and the entire blade. The model generated assumed that the holes were independent and that successive rows of holes were independent. Independence was assumed based on available data of short-term variation. Two types of data were analyzed for possible trends. The individual hole data from this experiment did not show any trends for hole size or airflow. Pinning of a number of production blades (a time consuming manual process, which can take over an hour for one blade) also showed no signs of trends. Row to row variation was assumed to be independent based also on the pinning of a number of production blades and production airflow data from a number of components.

The variation for a total row (*Figure 18*) is calculated by multiplying the variation of a single hole (from *Figure 17*) by the square root of the number of holes in a row. The number of holes per row was between 32 and 80.

$$\text{Equation 1: } \sigma_{row} = \sigma_{hole} * \sqrt{n_{holes}}$$

In this calculation, the  $\sigma$  is in the units of airflow, not %. So, to get the numbers in *Figure 18*, the percentages in *Figure 17* must first be converted into airflow by multiplying by single hole airflow, then aggregated per the above formula and finally converted back into percentage form. An example calculation is shown below.

$$\text{Equation 2: } \sigma_a = (8.1\% * .00118671) * \sqrt{32} = .000544 \longrightarrow \sigma_a \% = .000544 / .038 = 1.4\%$$

These calculations show that the hole-to-hole variation is only responsible for a small percentage of the row variations observed. Thus, it is necessary to find additional sources of laser-drilling machine variation, which cause the observed behavior.

Figure 18 – Row Flow Variation: Predictive Model vs. Actual Data

| Row                                     | a    | b    | c    | d    |
|---|------|------|------|------|
| % Variation Predicted by Model          | 1.4% | 1.3% | 1.2% | 1.5% |
| % Actual Variation from Production Data | 7.0% | 7.0% | 4.0% | 4.2% |

A statistical model of the entire part was made by combining the row variations as shown in Equation 3. The resulting expected variation of the component based on hole-to-hole variation would be 0.88%.

$$\text{Equation 3: } \sigma_{part} \% = \frac{(\sigma_{Row1}^2 + \sigma_{Row2}^2 + \dots)^{\frac{1}{2}}}{TotalFlow}$$

Each  $\sigma_{Row}$  was calculated per Equation 1. Figure 19 shows the calculations (actual numbers disguised).

Figure 19 – Statistical Model of Entire GT 24 Blade 1 Airflow Variation

| Row # | # Holes | Type of Holes | % Dev/Hole | Hole Flow | Expected Dev/Hole | Expected Row Variation | Expected Row Variance |
|-------|---------|---------------|------------|-----------|-------------------|------------------------|-----------------------|
| a     | 30      | treppan       | 8.1%       | 0.0010    | 8.09E-05          | 4.43E-04               | 1.97E-07              |
| b     | 50      | percussion    | 18.2%      | 0.0012    | 2.18E-04          | 1.54E-03               | 2.38E-06              |
| c     | 40      | percussion    | 18.2%      | 0.0012    | 2.18E-04          | 1.38E-03               | 1.90E-06              |
| d     | 60      | treppan       | 8.1%       | 0.0012    | 9.72E-05          | 7.53E-04               | 5.67E-07              |
| e     | 35      | fan           | 1.4%       | 0.0013    | 1.86E-05          | 1.10E-04               | 1.22E-08              |
|       |         |               |            |           |                   | Total Variance         | 5.06E-06              |
|       |         |               |            |           |                   | Total StDev            | 0.002249              |
|       |         |               |            |           |                   | Total Flow             | 0.25655               |
|       |         |               |            |           |                   | %StDev                 | 0.88%                 |
|       |         |               |            |           |                   | 3 sigma                | 2.6%                  |

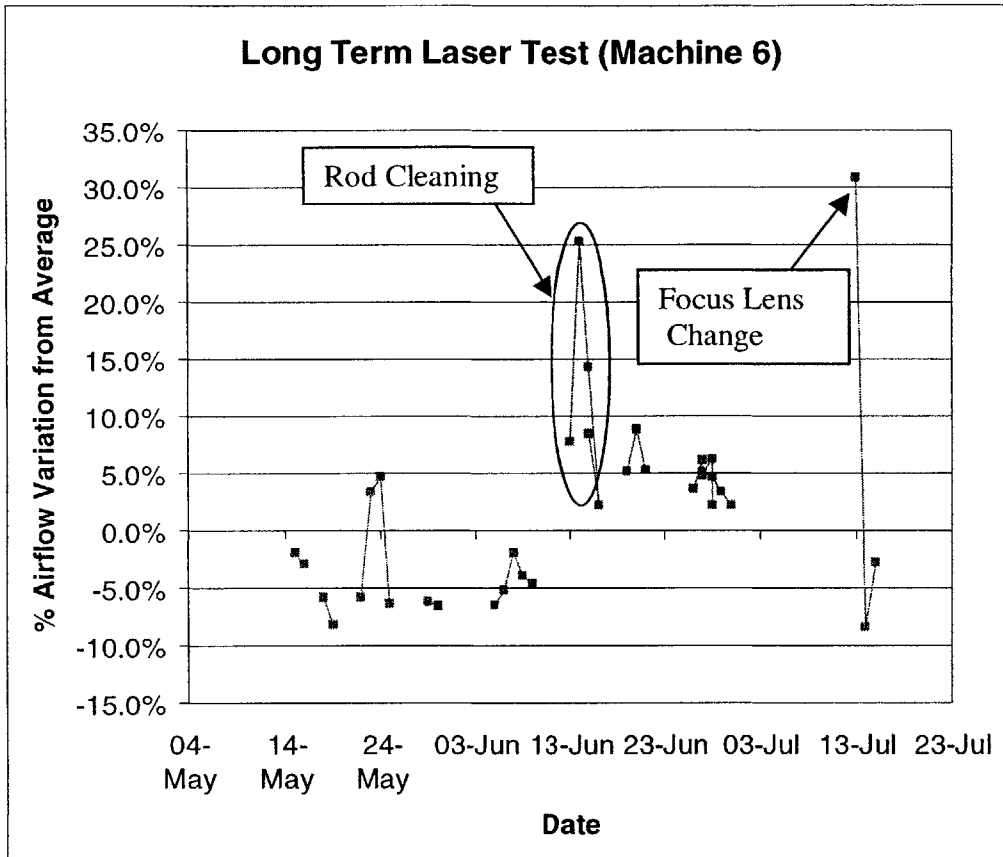
This model is again based on independence of the individual rows.

With this information, a lower limit for airflow variation can be identified. If laser characteristics and pulse repeatability remained constant over time (i.e. consistent machine setup) – hole-to-hole, short term variation would result in a process capability (Cp) of 1.9 (based on a +/-5% specification range).

## Long Term Test

The intention of the long-term test was to understand laser-drilling machine behavior over time using test plates. The resulting plot of airflow variation in the long-term test is shown in *Figure 20*:

*Figure 20 – Long Term Laser-Drilling Machine Test*



*Figure 20* shows that the machine itself is varying significantly over time. This indicates that a significant amount of variation can be removed if the machine is set up properly prior to drilling. This would require additional equipment on the machines, which would allow the operators to adjust beam parameters such that defined energy and intensity distribution requirements were met.

The first spike in the graph was due to maintenance on the machine. Adjustments were made to the machine prior to drilling components to bring the energy level in spec. However, we still saw an increase in plate airflow of 10%.

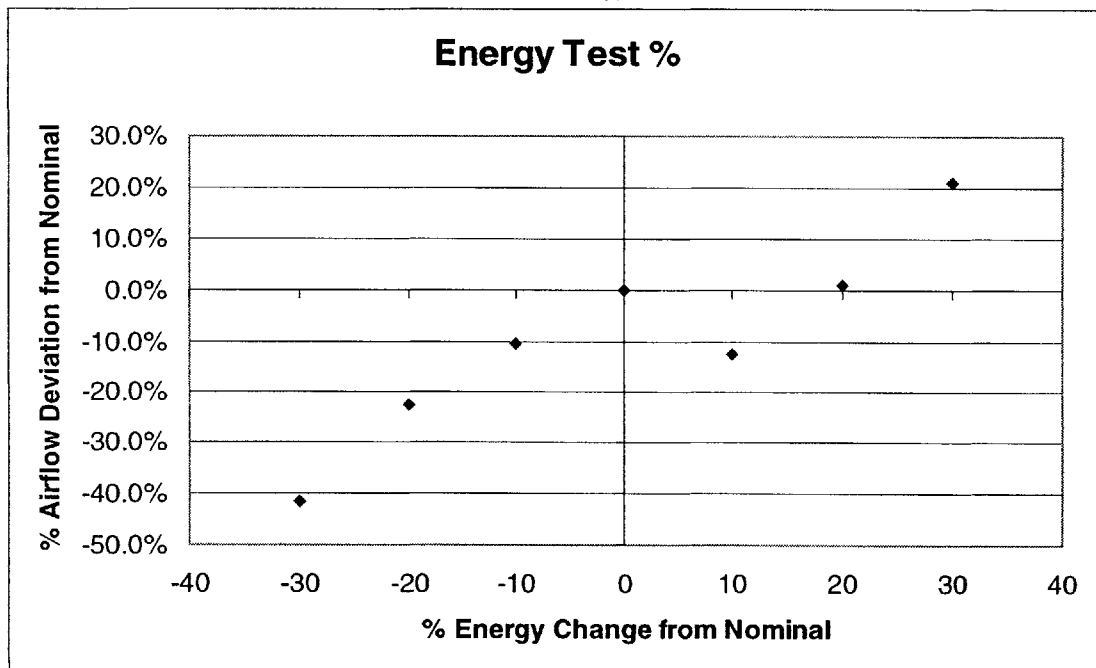
The second spike was due to changing the focal lens on the machine. Two parts were scrapped before proper adjustments were made to correct for the energy distribution and focal position associated with the new focus lens. After adjustments were made, the airflow was lower than expected and only further corrected after another day.

## Energy Tests

The energy tests were intended to quantify the variation in airflow due to energy fluctuations. Operators had previously noticed that energy could vary as much as +/-10% during production. Although this was known to impact airflow, there had been no prior attempts to quantify it.

The first round of energy tests (*Figure 21*) showed that airflow varied significantly with changes in energy and that there is nearly a 1 to 1 correlation. This result was much higher than expected by resident laser experts. The dip at +10% was due to the manner in which energy was adjusted. In general, as the power input to the laser is changed, the intensity distribution and size of the beam changes. To optimize the beam characteristics for various energy levels, there is a device called a compensating telescope (CT). When this test set was performed, the compensating telescope was not re-optimized for the various energy levels. One setting was used for nominal energy and below, while another was used for those above nominal. The change in CT position changed the beam shape, thus resulting in the dip at +10%.

*Figure 21 – Energy Test #1*



Based on the above discussion, it is clear that the adjustments to energy also affect beam characteristics such as beam size and intensity distribution. In addition, the CT position also affects beam characteristics – thus both CT position and energy level must be controlled to ensure proper delivery of energy to the work piece.

To further understand this situation, a new round of testing was conducted. This round was more closely centered around nominal to allow better characterization of the behavior in the most relevant region, and provided for optimization of the compensating telescope. The operator optimized the compensating telescope position by adjusting the compensating telescope to obtain maximum energy for a given input power.



The second round of testing (*Figure 22*) again shows the strong dependence of airflow on energy with approximately the same relationship as in the first round (*Figure 21*). For the drilling of the nominal energy position (0.0%), the operator did not attempt to optimize the CT position. He assumed it would be optimal, since it contained the settings used in production. However, the nominal energy data point (0.0%) appears to show that the production parameters have the compensating telescope at a non-optimal position. *Figure 23* is a graph of compensating telescope (CT) position vs. input power (pulse height) that shows the relationship for optimal energy and clearly shows the "nominal" condition as a non-optimal pair.

*Figure 22 – Energy Test #2*

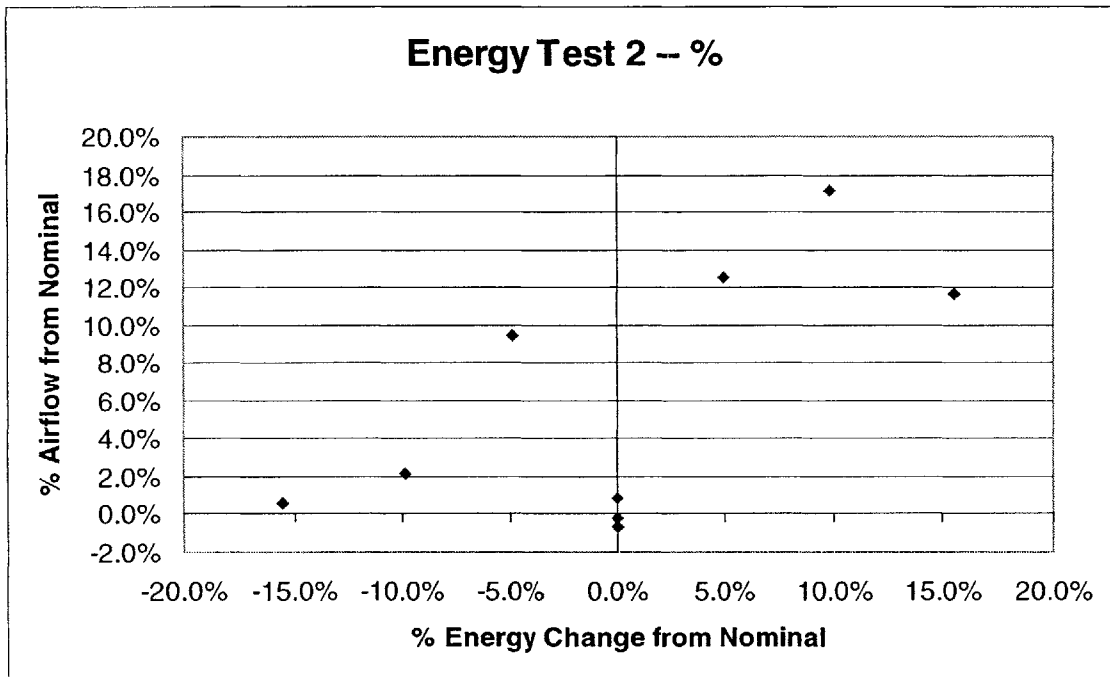
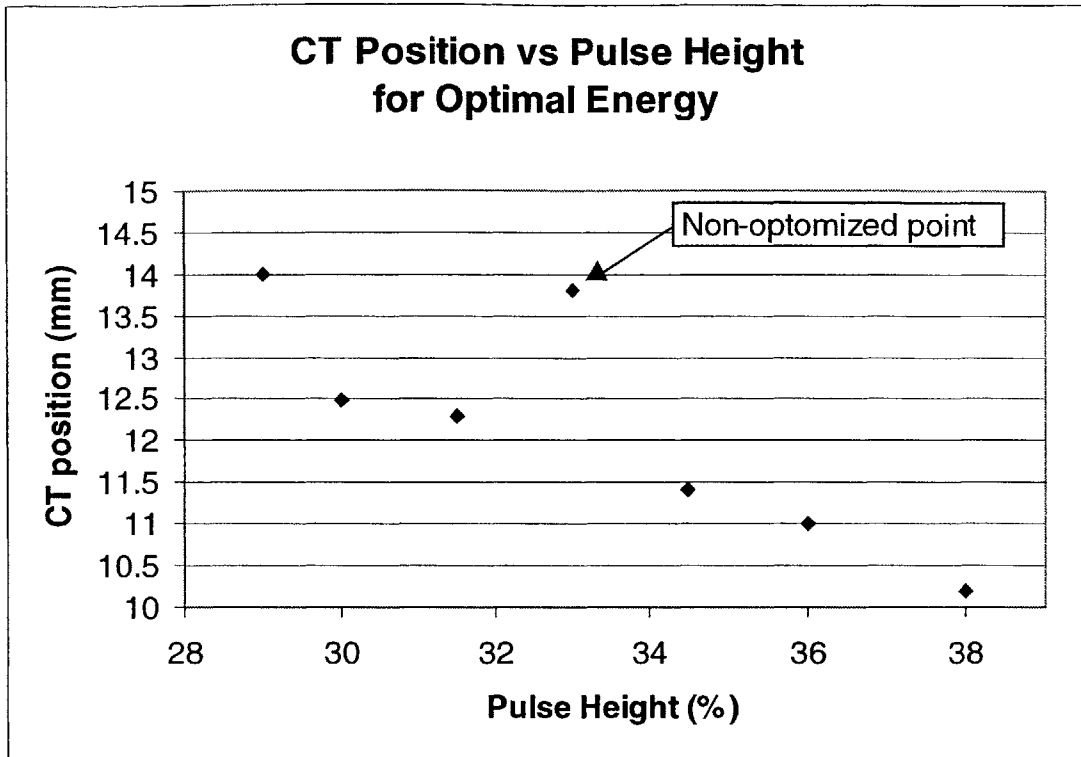


Figure 23 – Plot of Optimal CT Position vs. Pulse Height



## *Focus Test*

The focus tests were designed to answer questions on two fronts. Quantifying the effect of focus point movement can provide guidelines for machine setup, since focal position can change as optics and laser rods age. Secondly, focal point sensitivity allows us to quantify the contribution due to component (blade/vane) variation. As the component surface varies, the focal position will vary from that intended in the program. The surface variation in question is the variation in the surface away from the fixture locations. The components are located by a six point nest when placed in the fixture. Thus the location of those six points matches the expectation of the program. However, if the surface of the part away from the fixture locations vary, the focal position will not be properly positioned. By quantifying the focal point sensitivity of the machine, we will know how much part variation can be tolerated by the machine, and can justify programming changes to compensate for the component variation.

The first round of testing was performed on a test plate made of single crystal MK4, identical to the material for the blade 1. This provides for a direct correlation of component to airflow variation. Metallographic examination will allow us to understand the relationship between focal position and cracking/recast layer. The focal position is measured relative to the surface of the material being drilled. Thus, +1mm implies that the focal spot will be 1mm above the material surface.

*Figure 24* clearly shows the relationship between focal position and airflow. The troublesome point for round 1 was located at +1mm. This point is off the general upward trend that is expected. It was determined that the particular plate was incorrectly drilled at -1mm instead of +1mm. With that resolved, the clear trend shows ~8% change in airflow for 1mm in focal position. As expected, the airflow drops off as the focal point moves past +2mm since the intensity at the outer edges of the beam is no longer high enough to vaporize the metal.

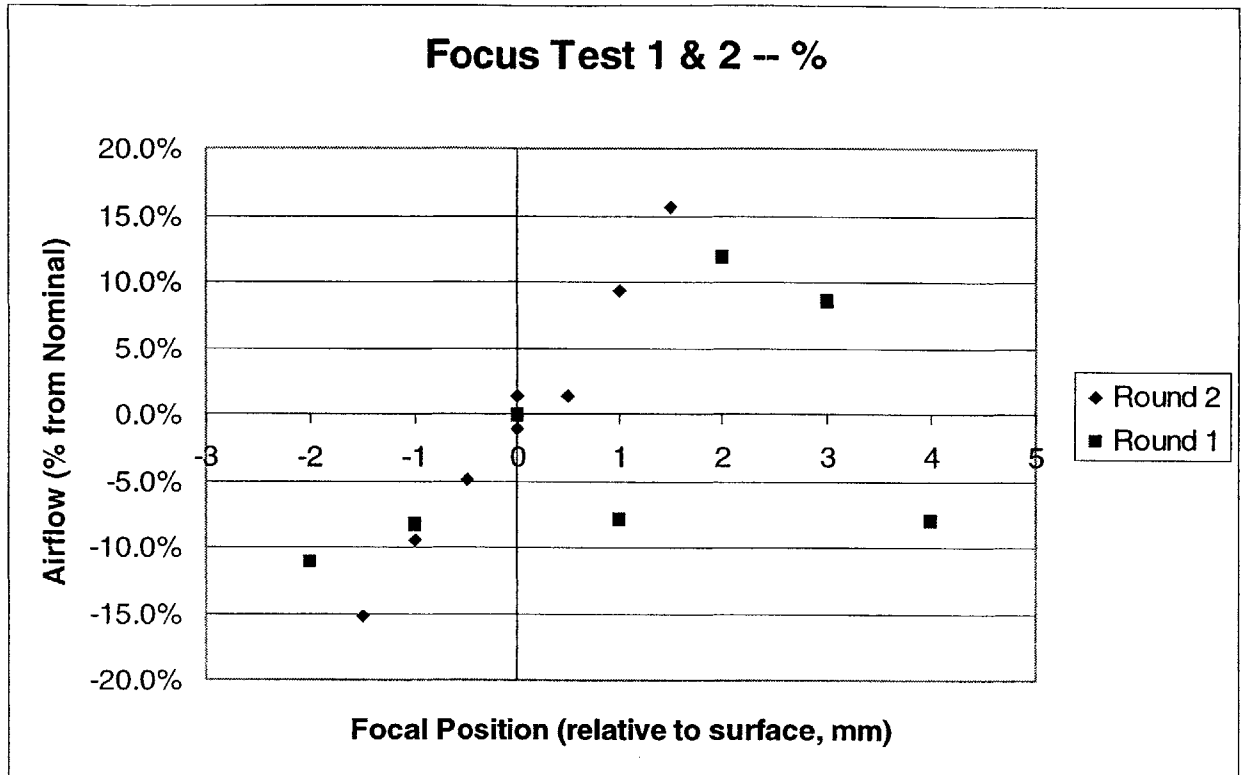
The second round of testing was further concentrated around nominal and was performed on Hastelloy X plates. This test confirmed the high impact of focal position on airflow. The Hastelloy X plates show greater sensitivity to changes in focal position than the single crystal material, due to its lower melting point.

There are two competing effects that influence the shape of the graph shown in *Figure 24*. As the focal point is moved away from the surface, the beam spot size impacting the work piece increases, which would tend to yield a larger hole. However, as the beam expands, the intensity of the beam, particularly at the edges is weakened. Lower beam intensity at the edges may prevent the material on the edge of the hole from vaporizing, resulting in a smaller than expected hole.

Further work should be done to characterize the behavior of the beam near the focal point. Laser supervisors generally believed the beam diameter to be effectively constant with a 10mm range surrounding the true focal position. Thus, the variation seen in these tests far exceeded expectations. Future work should concentrate on determining the true

focal position and the effective beam size surrounding the true focal position. Improved understanding of the effective beam size will provide further insights into the variation problems. Perhaps more importantly, this understanding will lead to better understanding of hole formation and geometry.

Figure 24 – Focus Test Results



Significant airflow variations within +/-1mm are particularly troubling since the tolerance stack-up on the surface of the component allows for +/-0.9mm.

Historical data confirms this trend. The author found that rows furthest from the fixture points locating the part are the most variable. This was observed on both the GT24B Blade 1 and Vane 1. The data shows that variation away from fixture locators causes airflow variation.

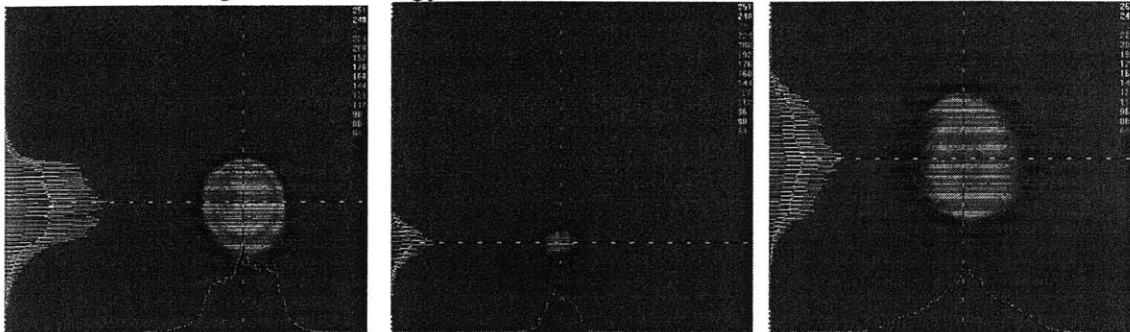
**Laser Characterization Work**

In parallel with the testing completed for airflow variation, work was completed with an in-house laser expert and outside consultant, characterizing the behavior of the laser beam itself. The goal was to quantify the intensity distribution, temporal distribution (shape of a single pulse over time), their variations over time, and sensitivity to laser settings.

We found that the energy distribution of the pulse across the diameter was not as uniform as expected (see Figure 25). It follows that as the beam converges and diverges along the focal length, the non-uniform energy distribution will also change. Thus, depending on where the component lies within the focal spot, it will see a different pulse energy

distribution. The non-uniform energy distribution reinforces the results from the previously discussed focus test.

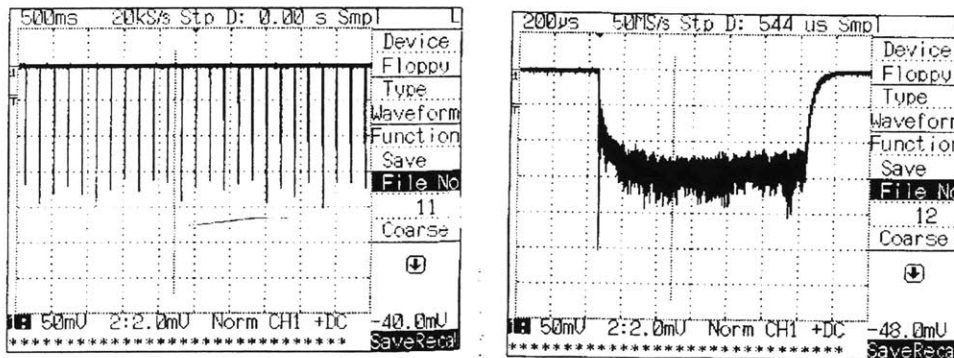
Figure 25 – Energy Distribution Across the Pulse Diameter



This figure shows energy distribution at three different focal distances. The first picture is in front of the focal position, the second is near the true focal point, and the third is well behind the focal point. Note that the color scale, which represents energy intensity, is not common between the three pictures.

The temporal energy distribution of the pulse was also less uniform than anticipated, as shown in Figure 26. The pulse itself was ~15% shorter than indicated by the on-machine measurement. In addition, there is a spike at the beginning of the pulse, which is of particular concern. The spike is apparent in most pulses, but the height of the spike varies by a factor of two. Initially, it was felt that the spike may not be a problem. Upon further review, it was determined that the spike could cause unwanted plasma formation<sup>3</sup>. When plasma forms early in the pulse life, the plasma will absorb much of the remaining pulse energy that was intended for material vaporization. The result is a less efficient pulse with greater heating. The excess heating contributes to the recast layer and cracking problems, creating metallurgical and dimensional problems.

Figure 26 – Temporal Pulse Distribution



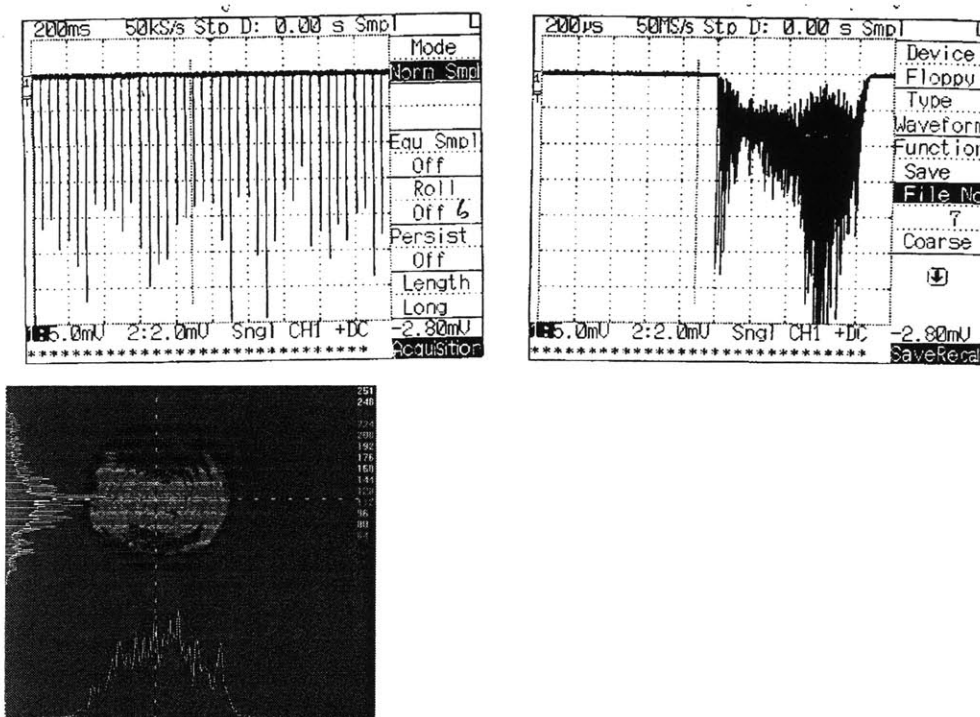
The first picture shows a number of pulses throughout time. The second shows the energy distribution of a single pulse.

The temporal pulse variation severity could be reduced with a stepped pulse. The stepped pulse would begin with a smaller energy for the first ~200ms and then increased to full

energy for the remaining 800ms. Unfortunately, we were not able to conduct experiments on stepped pulses during this study.

The last significant finding was that CT position strongly influenced both the diametric and temporal energy distributions (see *Figure 27*). Thus, it is critical to have the CT position optimized for each energy and pulse duration used while drilling. This also implies that the optimal position will change over time, as the flash lamps and laser rod age. This finding again mirrors the information found in the energy tests performed on flat plates.

*Figure 27 – Compensating Telescope Effects on Energy Distribution*



*The three pictures composing Figure 27 shows the adverse effect of non-optimal CT position on temporal pulse distribution – between pulses and within a pulse, and poor energy distribution across the diameter.*

It is satisfying to note that the recommendations from the detailed laser characterization align with those of the airflow tests. The laser characterization work provides an example of the measuring equipment required to properly set up and maintain a laser to reduce variation. It also provides some insight into the laser characteristics that are affecting material properties.

It is interesting to note that this information was unsettling to the laser machine suppliers. They had never performed such tests, and were nervous that Alstom now had the ability to ascertain the capability of the machines with respect to the specifications.

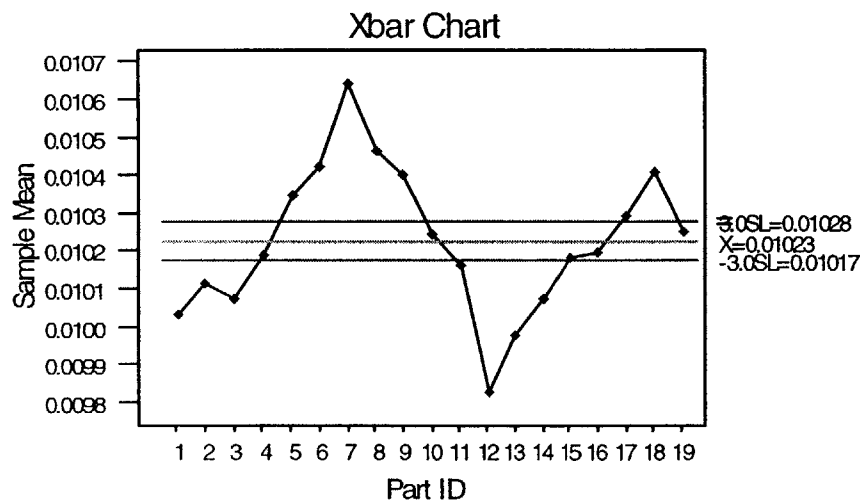
## Gauge Repeatability

An important aspect of a disciplined testing process is the assurance of repeatable measurements. In this case, the most sensitive measurements to gage error are the single hole measurements. In order to allow enough air volume to pass through the test stand, a bypass hole was created in the fixture which was approximately 5 times the flow of the single hole to be tested. Thus there was concern that repeatability errors in the test stand would influence the results.

The test stand had a manufacturers repeatability rating of  $\pm 0.25\%$  of the measurement. Due to the bypass hole created to create sufficient flow for a measurement, our total flow was  $\sim 6$  times the flow of the single hole itself, yielding an expected repeatability of  $\pm 1.5\%$ . This range of repeatability error was sufficient, but a gage repeatability test was completed to double-check the manufacturers specifications and include the test specific fixtures.

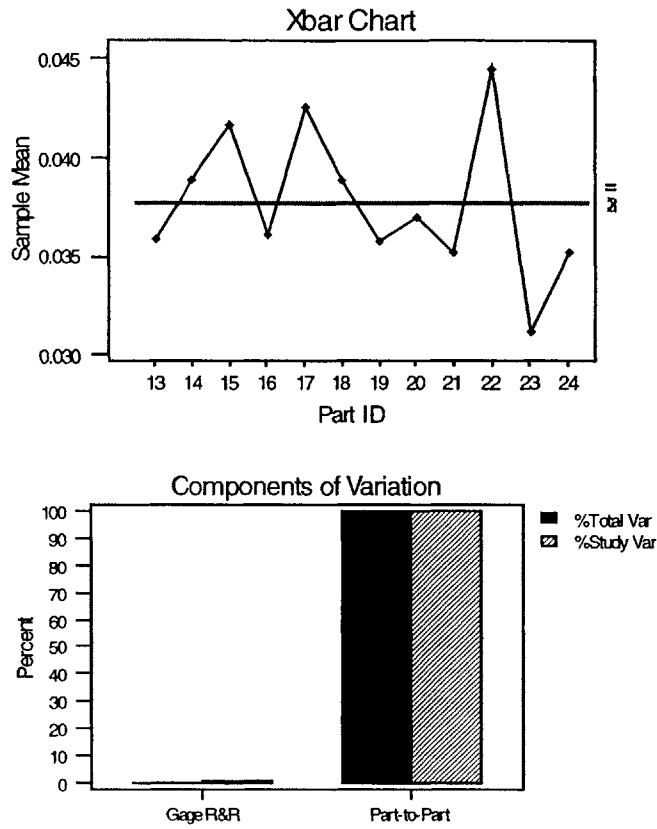
Nineteen holes were used in the study and a ANOVA analysis was completed using MiniTab, a well known statistical package popular with companies focussing on  $6\sigma$  methodologies. The results of the analysis showed that about 1.8% of the variation was due to the gage. This result is consistent with the manufacturers guidance, and provides confidence in the results. The Xbar chart (Figure 28) shows the relative variation between the parts and the repeatability range of the measurement system.

Figure 28 – Xbar chart for single-hole test measurements



Though not expected to be an issue, a similar ANOVA gage repeatability test was completed for the test plates used in the energy, focus, and long-term tests. The result showed that there was virtually no influence (0.01%) of gage variation on the results as shown in the graphs of Figure 29

Figure 29 – Xbar chart and component variation graphs for test plates



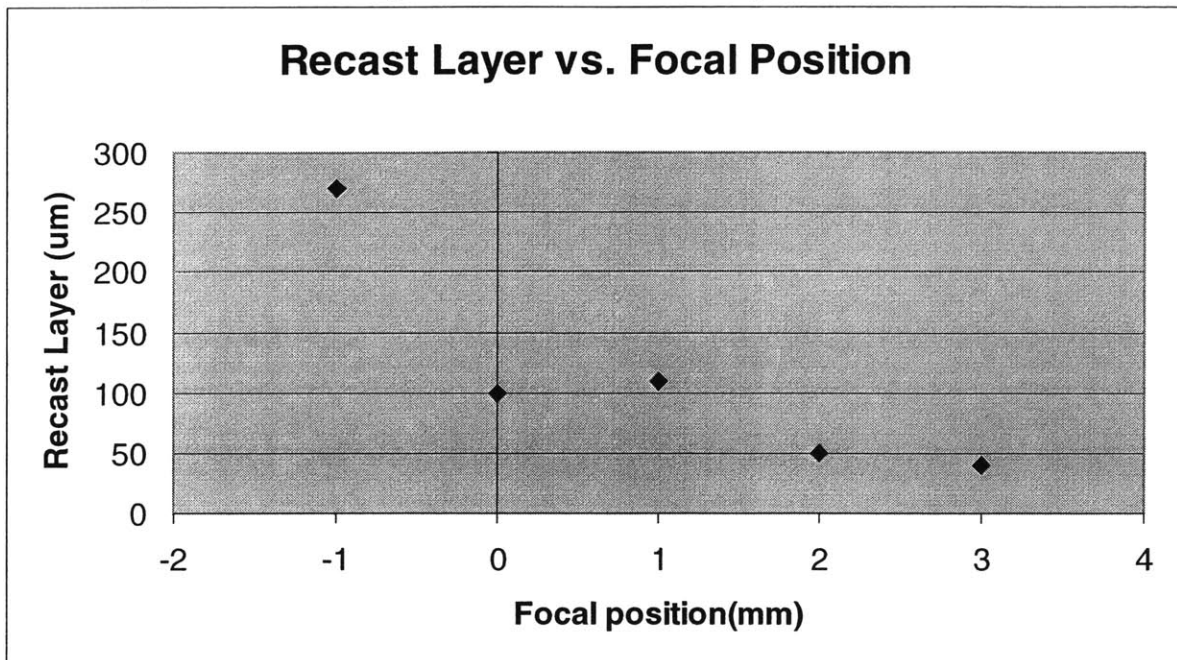
### Metallurgy

As mentioned earlier, metallurgical quality is a concern due to the rapid local heating and cooling of the material. The most relevant measurements are cracking and recast layer thickness.

The literature suggests that the best metallurgy will occur with a focal position of 1-2mm above the surface. Initial data from the airflow plates suggests the same trend as shown in Figure 30.



Figure 30 – Metallurgical Correlation: Recast Layer vs. Focal Position



This preliminary graph shows the same trends observed in prior literature and qualitatively shows the impact of focal position on hole quality.

### ***Recommendations***

Through disciplined testing, it has been shown that the laser-drilling machine varies over time and that these variations significantly impact the quality of the product. In order to improve the process, the machine must be properly set-up. To date, this has not been possible with the installed diagnostic equipment.

Proper machine setup is attainable with currently available technologies<sup>1</sup>. Equipment must be procured to allow operators to properly tune the focal position and energy of the beam. The equipment must be capable of measuring pulse energy, temporal distribution, and intensity distribution. These characterization measurements will allow the operator to tune the beam to maintain proper operation.

Characterization equipment will provide the capability to accurately measure and tune the beams of all the machines to the same standard. Currently, each machine must be qualified (individually tested and programs modified to meet each machines needs) on a component due to the differences known to exist in beam behavior. Characterization equipment will allow the operator to see and tune the beam to deliver expected results.

In addition to machine variation, component variation within specifications can also lead to unacceptable variation at the drilling process. To counteract blade/vane surface variation, probing routines can be installed which will allow the machine to adjust the program based on the true position of the component.

In the long term, it is critical that Alstom maintain some laser expertise in house. The laser producers are generally small companies that can only justify development programs with strong industry support. Thus, Alstom must know when and how to guide the suppliers toward adoption of new technology. One such technology is Q-switching<sup>6,7</sup>. This technology uses pulses that are an order of magnitude or two shorter than what is currently used, but with higher peak power. Although none of these lasers have been produced for drilling applications similar to the gas turbine industry, the technology shows excellent potential for improved geometry and material properties.

As Alstom expands its laser-drilling capacity, it must specify acceptable variation of the laser machine and ensure tests are designed that can accurately quantify the variation.

### **5.3 Summary**

This chapter discussed the importance of a rigorous testing plan and developed such a plan for the laser drilling variation problem. The plan focussed on short-term (hole-to-hole) and long-term variation, and the effects of energy and focus variation. The results showed that variation in energy and focal position was significantly affecting the performance of the machine and should be addressed with specific recommendations of: improved machine set-up, touch probing components on the machine, and development of in-house laser expertise.

The following section takes an organizational perspective on improvement and specifically, knowledge management.

## Section 2: The Knowledge Management System

### 6. Knowledge Management

The charter of the manufacturing group is focussed around gathering and dispersing manufacturing knowledge for the company. Being a newly formed group, there were no existing systems or guidelines in place to define a knowledge system. With blades and vanes becoming increasingly complex, pushing the leading edge of manufacturing technology, knowledge of manufacturing processes is essential for success. Knowledge is in effect the "product" that this group provides to the company. Therefore, the group must make sure that its product is carefully built, maintained, and available to its customers.

With this in mind, this thesis project expanded into the development of process improvement guidelines and a knowledge management system, using the laser-drilling problem as a proof of concept.

The knowledge system itself must envelop three concepts

1. Knowledge creation -- developing process improvement frameworks, guidelines and tools.
2. Knowledge capture -- systems to collect and store data and knowledge such that it is not lost and projects are not repeated; includes data storage and manipulation techniques, guidelines for project write-ups
3. Knowledge Transfer -- ensuring the knowledge is accessible to all and that efforts are made to train others, through web based storage and searching of reports and traditional presentations

This knowledge creation/capture/transfer cycle has taken many forms in recent literature<sup>10,11,12</sup>. It is not surprising that knowledge management systems differ in various applications, since a vital key to successful implementation is the integration with culture of the application<sup>10,11,13</sup>. Diverse organizational cultures and objectives will result in different embodiments of similar concepts with emphasis and detail shifted per the specific needs of the application.

The field of knowledge management is still young, and as such the literature is still evolving. An interesting commentary on the state of evolution is provided by Bontis and Girardi : "Despite the feverish interest and exponential growth in this field, the majority of literature has an introductory flavor, lacking substance and tends to quickly become repetitive."<sup>14</sup>

The challenge with a knowledge management system is that it requires discipline to ensure that the knowledge is captured and transferred efficiently. The capture and transfer pay dividends in the long run, so it is up to management to ensure that knowledge management remains a priority and is not overrun by daily fire-fighting. It must be recognized that it is far more cost effective to spend a couple of days wrapping up a project than to have to repeat a few months worth of effort later on. In addition to the cost savings, timesavings are equally, if not more important. Properly documented and

controlled projects will allow quicker reactions to future situations. Fast reactions will improve time to market, help meet delivery schedules, and prevent further scrap parts or NCR's.

Efficient knowledge transfer is becoming increasingly important as employee turnover increases. Since employees do not stay in the same position or department for long, it is crucial to have materials available which will reduce the time required for new members to come up to speed. Traditionally, project reports have been kept in binders which travel around the office and end up on a non-descript shelf or electronically in files with non-descriptive filenames in ambiguous directories. With the coming of the web, documents can be arranged in a logical, easy to find manner and quickly accessed from any employee's desktop. With employees and manufacturing facilities all over Europe and North America, it is crucial to have a system which allows this knowledge transfer to occur anywhere and at any time. The development of a department web-page will not only aid knowledge transfer within the department, but will also help to share this information with other disciplines.

However, the thrust of this thesis is not on the technology/IT solution to the knowledge management problem. The intention of this work is to create a workable framework on a pilot project level. This system would fit the needs of the current department and provide a model for future scalable systems. There are an abundance of companies currently offering and developing complex IT solutions for enterprise wide knowledge management. Large consulting and automotive corporations have popularized these systems. Large, successful rollouts of integrated enterprise knowledge management systems have taken as long as three years to successfully implement – far beyond the scope of this project<sup>9</sup>.

In addition to web based solutions, the human element of knowledge transfer cannot be eliminated. There is still no better way to communicate with and influence people than in person. It is important to have presentations discussing completed projects such that lessons learned and best practices can be shared with many people in a short period of time.

The quality department (whose members are resident at various suppliers) currently holds bi-monthly workshops where they share best practices, lessons learned, and production data. They also use this opportunity to provide training on continuous improvement, influencing people, and project management. These workshops provide a perfect forum to exchange manufacturing knowledge.

## 6.1 Knowledge Creation

Creating knowledge is the core of the manufacturing and development groups. Engineers toil every day to create or learn something that did not exist the day before. In order to develop knowledge most efficiently, it is important to have systems or procedures in place, which help to organize thoughts and actions. A disciplined approach not only helps the individual to tackle highly complex tasks, but more importantly, it allows others to provide input and feedback. In the same manner in which common jargon allows people to communicate quickly, a common process allows people to understand where you are in the project, and what the goals and next steps are. Common processes also make life easier for leadership since they have a common form to understand the progress and issues associated with various projects.

Many companies have had large-scale corporate initiatives on quality and process improvement. TQM programs such as those at Analog Devices and 6sigma initiatives at GE and Motorola have been replicated at thousands of businesses. Alstom does not have such a program. Thus, it is up to the individual business units to develop a common language and guidelines for process improvement. The approach in the gas turbine division was to provide various process improvement tools, but not the strict structure of the GE 6sigma program or Analog's TQM efforts. The quality department has developed a number of training modules on specific process improvement tools. The intention of this work was to provide a basic framework for project planning – to aid knowledge creation, and reporting – to facilitate knowledge transfer.

Efficient knowledge creation at the operational level requires a disciplined approach to the problem. The first step is to create a plan for the project. This plan need not be task by task, but should include the objectives and logically follow from beginning to end.

The next important step is that of filtering information. Having the plan and clear objectives helps one to sift through the enormous amounts of data available today and focus in on the information most relevant to the goals of the project.

When it comes to testing and gathering new information, it is equally, if not more important to plan the data collection. Measurements must be chosen which provide insight on the process and not just the final product performance. In addition to choosing the proper measurements, the resulting data must be in a useful and reliable format such that it can be put to good use.

As important as the plan is, once developed, it is not perfect. Therefore, one must expect to react to new information and adjust the plan accordingly. However, when adjusting the plan, it is crucial that the new plan still fulfill the goals of the project.

These aspects of knowledge creation were illustrated in the first section of the thesis where a disciplined plan incorporating process improvement tools and methodologies was executed.

## 6.2 Knowledge Capture

Having completed a project, it is essential that the information be captured in a suitable manner. Without guidelines to reference, project reports will vary from person to person based on the time they have available, individual abilities, and whether they think management will read it. Even with the best of intentions, reports may not document the details necessary to capture the knowledge. Creating proper guidelines shows employees that the knowledge they create is important and that the manner in which their knowledge is captured is important. When developing the guidelines, emphasis should be placed on aspects that are critical for organizational learning<sup>8</sup>. A report containing results is only useful if the exact same problem occurs in the future. However, a report that contains relevant background information, assumptions, thought processes, and lessons learned will allow the reader to adapt results and methods to a host of new problems.

The document in Appendix D was developed with group members to provide direction in report writing.

A recent illustration of ineffective knowledge capture concerns airflow data for precision cast components. Neither the suppliers nor Alstom had systems in place to archive airflow data in a useful format. As a result, three people have spent the better part of four months gathering all the airflow data for the previous year and a half and entering it into the new database. The task is currently unfinished as there have been numerous problems with the data including incorrect serial numbers and multiple data sets for single parts. Such inconsistency in data has led to potentially defective parts being shipped. This increases the risk of engine fatigue and heavy financial penalties.

Another example was documented at one of the suppliers. Airflow data was stored on a network, but the system was insufficient to handle the data, resulting in lost and corrupted data. For example, blade 1 parts are to be airflowed prior to and after machining 2 operations. Thus, there should be at least two measurements for every part. When trying to retrieve the data, 561 Blade 1 total airflow measurements were found for the pre-machining 2 test, while 612 measurements were found for the post-machining test. Furthermore, when the pre and post machining 2 data were aligned, it was found that only 137 serial #'s had both measurements! From this we can conclude that at least 900 parts have missing data. Since the manufacturing processes are not so out of control that these measurements would not have been made, it is clear that the data capture system does not function properly.

In addition, the current data capture and retrieval system does not provide convenient means for data analysis. The data is organized strictly by shipping lots. Thus, there is no way to perform machine or time series analysis. Data must be manually exported from the system, transferred to Excel and further manipulated in order to perform any useful analysis. Thus, the time series plots used on the shop floor are usually at least a week old.

### **6.3 Knowledge Transfer**

The knowledge transfer implementation centered around information accessibility in a convenient format. An intranet page was developed for the department to provide an archiving structure for projects and training that is easy to navigate. It also provides descriptions of department initiatives and accomplishments.

The concept of the web page began with the desire to share manufacturing knowledge developed by the group. The intended focus was expected to be on current and past projects and training material. Discussions with the quality department revealed that there were training materials that should be included in the website. Further synergies in direction and scope seemed to warrant the development of a joint web-page. Upper management recognized these synergies between the two departments, resulting in the their merger.

The quality department had developed an audit system to help control supplier quality, through use of word templates. While a good start to help identify issues and share lessons learned within the quality group, it was not sufficient to provide adequate follow-up on supplier actions, and the transfer of ideas. Thus, it was crucial to develop a database system that could be used to track and catalog audits, action items, and lessons learned. A web based database application was created to track supplier audits. The database is searchable by a number of parameters and will provide necessary information to help manage the suppliers more effectively.

The web page also allows for promotion of department initiatives such as Initial Sample Inspection (supplier qualification efforts) and Total Quality Management.

The following few graphics show the structure and implementation of the web page.

Figure 31 shows the home page for the Quality Manufacturing group. Per Alstom convention, the global intranet structure remains visible at all times. The department specific structure is placed to the left. The tree structure is highlighted as one progresses through the site.

Figure 31 – Quality Manufacturing Home Page

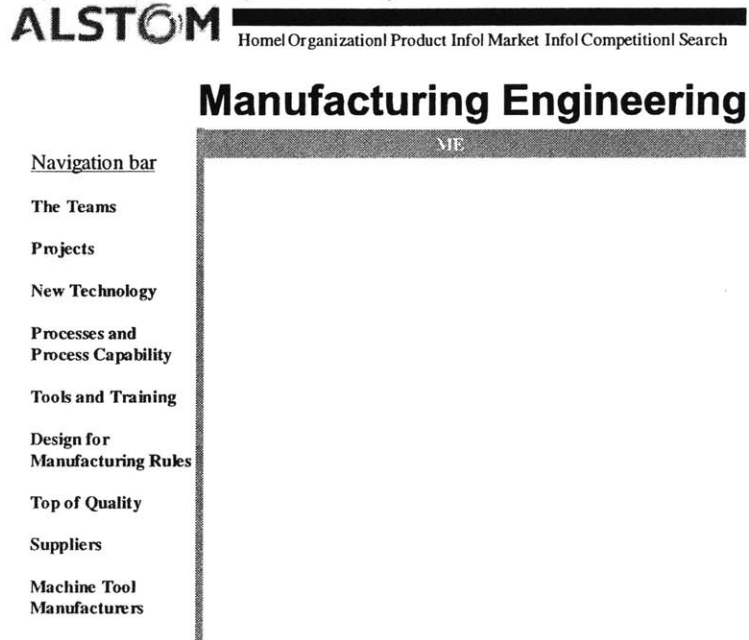


Figure 32 shows the “Past Project” page within the “Projects” section. The projects shown in the main window link directly to the source documents for the project as shown in Figure 33.

Figure 32 – Past Projects Page

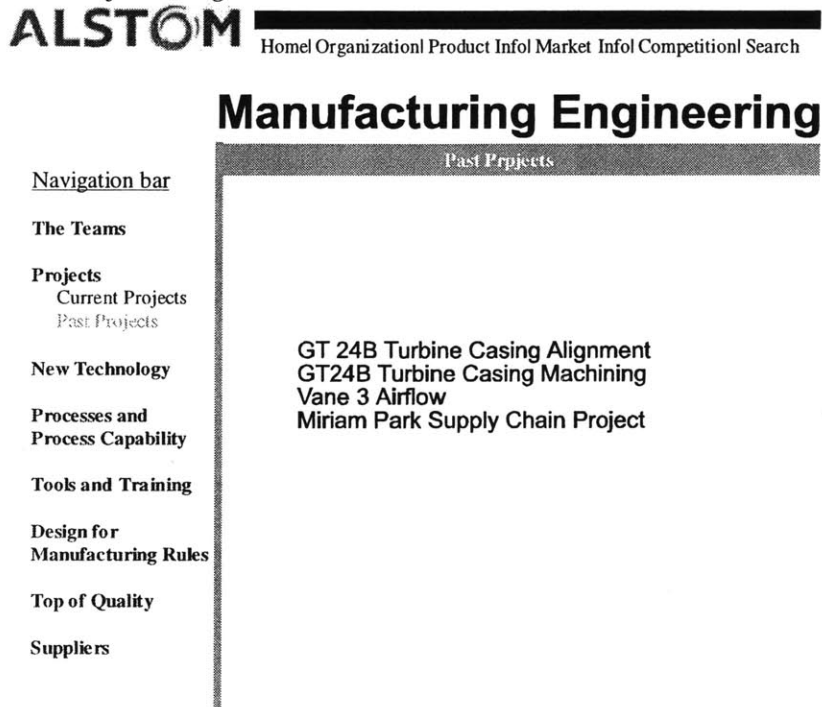




Figure 33 – Source Document Links

## Manufacturing Engineering

Navigation bar

The Teams

Projects

Current Projects  
Past Projects

New Technology

Processes and  
Process Capability

Tools and Training

Design for  
Manufacturing Rules

Top of Quality

Suppliers

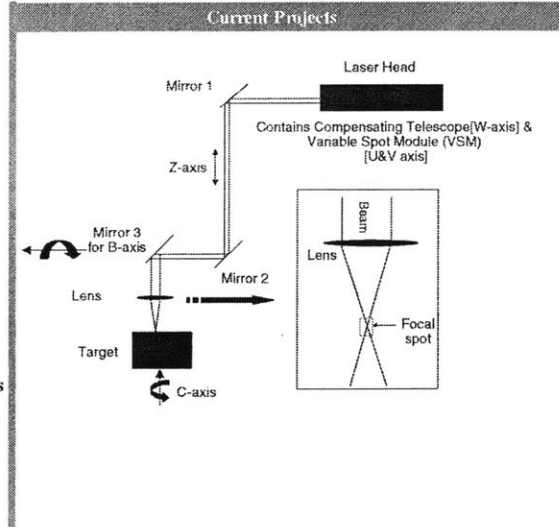


Figure 34 illustrates the structure of the “Tools & Training” section. The current view is of the Improvement Philosophies, which falls under the Training category.

Figure 34 – Tools and Training

## Manufacturing Engineering

Navigation bar

The Teams

Projects

New Technology

Processes and  
Process Capability

Tools and Training

Q Workshops  
Tools  
Training  
Audits  
Communication  
Gurus  
Improvement  
Philosophies  
Techniques  
Tools – training

Design for  
Manufacturing Rules

Top of Quality

Suppliers

Machine Tool  
Manufacturers

**Tools and Training**

**Concurrent Engineering\_Dresden 1099**  
**Daily Management 5's**  
**Improving the Business**  
**JIT jargon and notes**  
**Kano Modeling**  
**Understanding Variation**

## **7. Additional Benefits of a Knowledge System**

One of the benefits of an integrated knowledge system is that once the system is developed, additional knowledge gathering requires less effort. An example of this benefit was realized during this project.

When the components for this project were originally designed, reference sizes for holes were given as a starting point for manufacturers. The hole size could be adjusted to meet the airflow requirement. The resulting manufacturing processes required smaller diameters than those suggested by design. In some cases, the diameters in production were 25% smaller than originally called for. In order to help the design community improve their estimates, a testing plan was developed to measure airflow with various hole sizes over a range of pressure ratios. This testing was completed within 2 weeks of the initial discussion and required minimal resources. The results were passed on to the cooling group to be incorporated into their models.

This system can also be used to compare drilling techniques. Plates can be drilled on various machines (laser, EDM, water-jet) and their repeatability and absolute flows can be measured. Disciplined testing would provide the data necessary to make an informed decision about various drilling technologies.

Once the knowledge system is in place, the marginal cost of creating, storing, and retrieving knowledge is greatly reduced. New categories of knowledge can be accommodated quickly to meet the needs of the environment. In this case, a category called "Design Lessons Learned from Manufacturing" could be created in an effort to communicate lessons learned that affect product design, to the design community. Such economies of scale with knowledge and knowledge systems works to the advantage of large firms such as Alstom Power.

## 8. Summary

This thesis attempted to advance the understanding of laser-machine variation and show the financial and intuitive benefits of a knowledge management.

The results of the investigation into laser drilling show that in order to reduce variation, the following three actions must be taken:

- 1) Introduce component touch probing on the machine to ensure consistent focal position is achieved.
- 2) Procure equipment to allow characterization of the laser beam. This will allow all machines to be set up in a consistent manner
- 3) Continue long term testing until laser-drilling machine repeatability is proven.

In the future, variation concerns should drive changes in laser-drilling machine design and procurement. Future machines must incorporate instrumentation and software to ensure proper setup. In addition, machine procurement and acceptance documents must require demonstration of repeatability.

The knowledge management system echoed the disciplined approach to the laser-drilling project as it was created. The system will help support the Quality Manufacturing group's efforts in transferring knowledge throughout its operations.

There are some questions that merit investigation, but were not addressed in this thesis.

Component surface variability was identified as a concern with respect to focal position, but the variation has not been quantified. Estimates were made based only on drawing tolerances. Measurements could be made after the coating process to determine the surface variations that occur away from the fixture points. Due to large overhanging platforms, the author expects surface variation to have even greater influence on the vanes than on blades.

Though touch probing is expected to neutralize the surface variation problem, quantitative evidence is not yet available. Once touch probing is implemented, variation in rows away from the fixture points can be compared to historical data to quickly assess the reduction in variation. Studies should also be made to determine the optimal procedure for probing the surface in the shortest possible time.

Though differences between percussion and trepan holes were discussed, no recommendation was made as to the superiority of one over the other. The data available suggests that trepan holes have better repeatability and metallurgical properties. However, percussion holes have the operational benefits of significantly shorter drilling times, and reduced back wall protection requirements. Most of the work performed here focussed on trepanned holes, since they are the most common holes used on current components. Future work could investigate the sensitivity of focus and energy on percussion holes.

After an initial investigation of short-term variation, the topic was de-emphasized due to its relatively small impact on component variation. As long-term laser drilling machine variation is improved, short-term variation may become more important. Once short-term repeatability becomes limiting, Alstom will be best served by forming a partnership with the laser manufacturers to improve power supplies and laser components, which limit laser capability.

Little attempt was made to relate laser parameters or drilling procedures to geometry due to the overwhelming affects of variation. Once long-term variation is improved through machine setup and touch probing, design of experiments and other robust design techniques can be utilized to improve laser-drilling performance. A number of investigations should be made to understand the effects of:

- Ramped laser pulse on geometry and metallurgy
- Movement of the focal position along the axis of the hole during drilling
- Hole depth on geometry and metallurgical quality
- Optimizing energy for improved metallurgy
- Interactions between energy, focus, and CT position on geometry and metallurgy

Work done to answer these questions, using disciplined approaches such as that exemplified in this thesis, would generate competitive advantage in the marketplace through improved turbine performance and reduced manufacturing lead-times and scrap rates.

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### **1) High Speed Laser Diagnostics at 1.06 Micron with Simultaneous Percussion Hole Drilling of Aerospace Materials**

Cunningham, P.R.; Fahndrich, M.; Oliver, J.W.; Bertlesen, T.; Frye, R  
SPIE Vol 1871 1993

This article describes the details of equipment installed on a laser drilling machine to characterize the laser beam. It shows that it is possible to drill and characterize the laser at the same time, but the equipment is relatively expensive. Although it clearly states that all data is confidential, this paper stresses the importance of characterizing the beam and the influence of beam shape on hole repeatability and quality.

This work was completed for United Technologies

### **2) The influence of material thickness on the efficiency of laser cutting and welding**

J. Powel

Proceedings of 6<sup>th</sup> International Conference on Lasers in Manufacturing, May 1989

### **3) Investigation of the Nd:Yag laser percussion drilling process using high speed filming**

PW French, DP Hand, C Peters, GJ Shannon, P Byrd, WM Steen  
www.liv.ac.uk

### **4) An experimental investigation of the airflow characteristics of laser drilled holes**

Author Disimile, P.J.; Fox, C.W.; Lee, C.P.

Author Affiliation: Cincinnati Univ., OH, USA

**Journal: Journal of Laser Applications 1998 vol.10, no.2 p. 78-84**

**Publisher: AIP for Laser Inst. America ,**

This article describes a DOE approach to understanding parameter impacts on airflow. There are three important results from this work:

1. Focal position was found to have the strongest impact on airflow
2. Manufacturing variations were  $\sim \pm 10\%$  (Not very good)
3. Irregularity of holes makes it difficult to determine hole diameter accurately

This study was conducted for General Electric.

### **5) Investigation of the Nd:YAG laser percussion drilling process using factorial experimental design**

French, PW; Hand, DP; Peters, C; Shannon, GJ; Byrd, P; Watkins, K; Steen, WM

This article is concerned with correlating parameters to hole quality and has the following relevant conclusions:

35. Ramped pulse shape provides for the fastest drilling speed
36. Lower energy pulses gives a better hole quality
37. Optimal focal position is above the surface

This work was sponsored by UK Aerospace Group and Lumonics

**6) Title: Processing of Ni-based aero engine components with repetitively Q-switched Nd:YAG-lasers**

Author Bostanjoglo, G.; Sarady, I.; Beck, T.; Weber, H.

Author Affiliation: Laser- und Medizin-Technol. Berlin gGmbH, Germany

**Journal: Proceedings of the SPIE - The International Society for Optical Engineering Conference Title: Proc. SPIE - Int. Soc. Opt. Eng. (USA)**

vol.2789 p. 145-57

This paper attempts to show the viability of Q-switched lasers for hole drilling in aerospace materials. Q-switched lasers produce laser pulses approximately 1000 times shorter than conventional lasers. The paper convincingly shows improved hole quality with respect to geometry and metallurgy.

When laser producers were questioned about this technology, they expressed that industry was not pushing this technology enough for anyone to invest in bringing the technology to market. Best estimates were that Q-switched lasers could be production ready in the 3 to 5 year time frame.

**7) Machining with high brightness lasers**

X Chen

SPIE Conference on High-Power Laser Ablation, April 1998

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**8) The house that knowledge built**

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Vol 20, 2000, p545-555

**15) Exploratory Data Analysis**

John W. Tukey

## Appendix A

### Test Plan to reduce laser variation

The holes will be ~1mm diameter (disguised) at 30° to the surface. The plates will be 3.2mm thick, yielding a hole length of ~6.4mm. All plates should not be cleaned or pinned in any form.

1. **Short Term Laser Capability** – Before we attempt to control the sources of variation in our laser drilling process, we must first understand the process capability of the machine. Once we have proven that the laser machine is inherently capable, we can confidently investigate the production process. If the machine is found to incapable, we will have to revise future steps to focus specifically on the laser itself.
  - 1.1. *Trepan drilling*
    - 1.1.1. Standard cylindrical hole – 3 plates, 8 holes per plate
    - 1.1.2. Fan shaped hole – 3 plates, 8 holes per plate
  - 1.2. *Percussion Drilling* – 3 plates, 8 holes per plate
  - 1.3. *Other Suppliers* – In order to make a comparison between our suppliers, we will have the suppliers drill plates to test their capability
2. **Beam Profile/Quality** – To fundamentally understand some of the observed variation, we must know the quality of the cutting tool. In this circumstance, the cutting tool is the laser beam. We will perform test to characterize the beam. This includes pulse to pulse variation and beam intensity profile.
3. **Long Term Laser Capability** – In order to understand how the machine behaves in the long term, we must collect data in a controlled fashion. Drilling one plate per day with 30 identical holes and identical parameters, will help us understand the behavior of the machine. With this data, we should also be able to make correlations to maintenance activities. This data can then be used for ongoing statistical process control of the machines.
  - 3.1. **Plan**
    - 3.1.1. Procure Material – Material (Hastelloy X) to be delivered and marked by 9 May
    - 3.1.2. Program Holes – Program to be ready by 9 May
    - 3.1.3. Drill Holes – Drilling to begin on 10 May. One part will be drilled per day (always on the same machine) between 8 and 10am and promptly transferred to airflow.
    - 3.1.4. Airflow Plate – Ensure plate is airflowed within 2 hours of drilling
    - 3.1.5. Store Results – Airflow results should be stored in such a way that instantaneous statistical analysis is possible.
    - 3.1.6. Interpret Results – All
    - 3.1.7. The test will continue for a 2 month period. At the end of this period, the results will be reviewed and we will determine whether the test should be implemented as part of the production process on all machines.
4. **Energy Variation over time and Effect of Energy variation on hole size** – The amount of energy transferred to the part changes as lamps age and as optics get dirty.



By determining the effects of energy changes on hole size/airflow in a disciplined manner, correlations can be drawn to lamp aging and optical cleanliness to help schedule maintenance. Rules based on this data would remove some of the variation due to individual operator's interpretations for machine maintenance. To accomplish this, we will drill plates with 30 holes each at varying levels of energy. The energy will be changed at 10% intervals up to +/-30% from nominal.

5. **Focus Compensation** – It has been shown in papers and from experiences in the field that focus is a critical variable. One report showed that flow could vary by up to 50% on aircraft engine type holes due to a change in focus of 2.54mm on a 1.27mm deep hole. We need quantify the effects of focus variation on airflow for our holes (since our holes are ~5 times deeper ). Once we have this knowledge, we can compare the quantified process variation to the surface deviations resulting from casting and coating processes (per the drawing, the surface location could vary by ~1.2mm from nominal and still be in spec). We can then determine if it is necessary to develop a scheme to compensate the focal distance for part variations, and how precise (expensive) the scheme would have to be. The testing would consist of 9 flat plates, each drilled with 25 identical holes. The focus distances will consist of (all distances are focal point relative to material surface): -2, -1, 0, 1, 2, 3, 4 mm.
6. **Cleaning Effects** – A few people have noticed that pinning or cleaning a part can affect the airflow. However, no one has quantified the effects. With three simple tests, we will quantify the effects of pinning, waterflow, and waterblast on airflow. These samples will also be used to determine the metallurgical effects of pinning on the holes. We will pin a row of holes and cut the sample through the pinned row and a non-pinned row and investigate the differences.
  - 6.1. *Pin* – Drill one plate with 30 holes: Airflow⇒Pin⇒Airflow⇒Pin⇒Airflow
  - 6.2. *Waterflow* – Drill one plate with 30 holes: Airflow⇒Waterflow⇒Airflow
  - 6.3. *Waterblast* – Drill one plate with 30 holes: Airflow⇒Waterblast⇒Airflow
7. **Parameter Effects** – Once the sources of variation are understood, we can explore parameter optimization. Using designs of experiments, we will determine the effect of various factors on hole performance. The key metrics are: airflow, crack length, recast layer thickness, out of round. The factors expected to influence quality are: energy, pulse length, feed rate, frequency, focus position, VSM setting, feed rate, assist gas, depth. The design of experiments will attempt to determine the first order effects of each variable along with the first order interactions between the variables. This will require approximately 32 plates.
8. **Process Changes** – We may also need to investigate changes to the laser drilling process itself. This may consist of changing the types of pulses we use and investigating new methods of programming. A couple of ideas so far include “preheating” the hole with a shaped pulse having a low initial energy or varying the pulse energy throughout the hole to achieve different end effects for the hole.
9. **Design Information** – Currently, designers do not have proper correlations for laser hole size and airflow. The drawing nominals are approximates and do not end up being used in production. By testing a number of diameters and relating them to airflow, the designers will be capable of better specifying the holes which should lead to reduced manufacturing development time. We will test hole sizes from .65 to 1.05mm in 0.10mm intervals.

The testing matrix, updated for changes along the way is shown on the following page.

| Test # | Complete | Test Type            | Specific Test        | Description   | Plate Labeling     | Data Acquisition File | Material | Airflow Tests required                                   | Test Specifics  |
|--------|----------|----------------------|----------------------|---|--------------------|-----------------------|----------|--|---|
| 1.1.1  | YES      | Short Term           | Trepanning           | 24 holes on 3 plates (8 holes per plate)  | jb 1.1.1 p1...3    | jb_1.1.1              | MK4      | PR of 1.2, 1.3, 1.4,...1.8 for each hole                 | ~1mm diameter (disguised) holes. 30 degree angle to the surface. 3.2mm thick plates. Parameters are constant for all holes.   |
| 1.1.2  | YES      | Short Term           | Fan Shapes           | 24 holes on 3 plates (8 holes per plate)  | jb 1.1.2 p1...3    | jb_1.1.2              | MK4      | PR of 1.2, 1.3, 1.4,...1.8 for each hole                 | ~1mm diameter holes. 30 degree angle to the surface. 3.2mm thick plates. Parameters are constant for all holes.   |
| 1.2    | YES      | Short Term           | Percussion           | 24 holes on 3 plates (8 holes per plate)  | jb 1.2 p1...3      | jb_1.2                | MK4      | PR of 1.2, 1.3, 1.4,...1.8 for each hole                 | ~1mm diameter holes. 30 degree angle to the surface. 3.2mm thick plates. Parameters are constant for all holes.   |
| 1.3.1  | YES      | Short Term           | Trepanning?          | Plates drilled at NGV   | jb 1.3.1 p1...3    | jb_1.3.1              | MK4      | PR of 1.2, 1.3, 1.4,...1.8 for each hole                 | ~1mm diameter holes. 30 degree angle to the surface. 3.2mm thick plates. Parameters are constant for all holes.   |
| 1.3.2  | YES      | Short Term           | Trepanning?          | Plates drilled at Vickers   | jb 1.3.2 p1...3    | jb_1.3.2              | MK4      | PR of 1.2, 1.3, 1.4,...1.8 for each hole                 | ~1mm diameter holes. 30 degree angle to the surface. 3.2mm thick plates. Parameters are constant for all holes.   |
| 2      | YES      | Beam Profile/Quality | 5 rows of Percussion | Test to accompany the beam profile equipment  | jb 2               | jb_2                  | Hast X   | PR of 1.4  | Percussion drilled holes of unspecified size with wave tool 13, 90 degrees to surface   |
| 3      | YES      | Long Term            | Trepan               | 30 holes per plate. One plate drilled per day                                       | jb 3 d08-05        | jb_3                  | Hast X   | PR of 1.4  | ~1mm diameter holes. 30 degree angle to the surface. 3.2mm thick plates. Parameters are constant for all holes.   |
| 4      | YES      | Energy               |                      | Plates drilled with varying energy levels   | jb 4 p1...7        | jb_4                  | Hast X   | PR of 1.4  | ~1mm diameter holes. 30 degree angle to the surface. 3.2mm thick plates. 7 energy levels will be tested: Nominal, +10%, +20%, +30%, -10%, -20%, -30%.   |
| 5      | YES      | Focus                |                      | Plates drilled with varied focal position   | jb 5 p1...7A and B | jb_5                  | MK4      | PR of 1.2, 1.3, 1.4,...1.8 for each plate                | ~1mm diameter holes. 30 degree angle to the surface. 3.2mm thick plates. 7 focus levels will be tested (2 plates, each with 14 holes) for each focus position: At surface, +1,+2, +3, +4, -1, -2mm.   |
| 6      |          | Cleaning             |                      | Plates cleaned with pinning/water and then airflowed                                | jb 6 p1...3        | jb_6                  | Hast X   |  |   |
| 7      |          | Parameter Effects    | DOE's                | DOE's to determine influence of various factors                                     |                    | jb_7.1,2,3            | ?        | ?  |   |
| 8      |          | Process Changes      |                      | Undefined   |                    |                       |          | ?  |   |
| 9      | YES      | Design Information   | Trepan               | Holes drilled at various diameters and then airflowed to provide design information | jb 9 p1...5        | jb_9                  | Hast X   | PR of 1.05,1.1,1.15,1.2, 1.3, 1.4,1.5,1.6 for each plate | ~.60,.7,.8.1.1.2mm diameter holes. 30 degree angle to the surface. 3.2mm thick plates. Parameters are constant for all holes. Last two plates are .60mm and .70mm holes at 90 degrees to the surface. |
| 10     | YES      | Energy 2             | Trepan               | Plates drilled with varying energy levels   | jb 10 p1...7       | jb_10                 | Hast X   | PR of 1.4  | ~1mm diameter holes. 30 degree angle to the surface. 3.2mm thick plates. 7 energy levels will be tested: Nominal, +5,10, 15%.   |
| 11     | YES      | Focus 2              | Trepan               | Plates drilled with varied focal position   | jb11 p1...7        | jb_11                 | Hast X   | PR of 1.4  | ~1mm diameter holes. 30 degree angle to the surface. 3.2mm thick plates. 7 focus levels will be tested (2 plates, each with 14 holes) for each focus position: At surface, +-5,1,1.5mm.               |
| 12     | YES      | Environmental        | Trepan               | Plates drilled at various times throughout the day                                  | jb12 p1...6        | jb_12                 | Hast X   | PR of 1.4  | ~1mm diameter holes. 30 degree angle to the surface. 3.2mm thick plates. These plates will be drilled at various times throughout the day to determine the effect of temperature on the laser.        |

## **Appendix B -- Airflow Test Setup**

# Airflow Testing of Laser Drilled Plates

### **Purpose**

The testing of flat plates to investigate laser drilling performance serves two major functions:

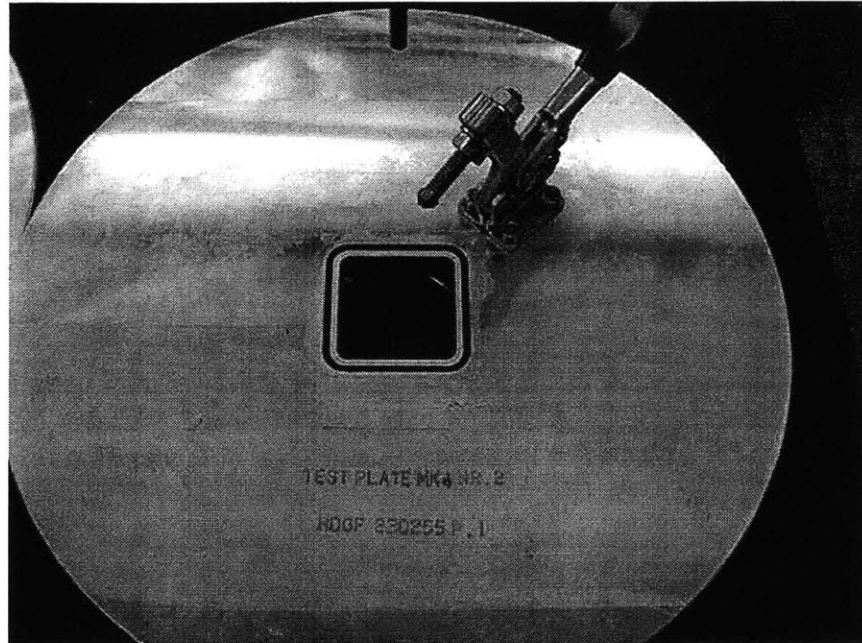
1. Testing of plates separates laser machine variation from component variation
2. Provides the capability of performing a large number of tests quickly and cheaply

These two elements will allow statistical process control data to be gathered as well as rigorous testing to facilitate continuous improvement.

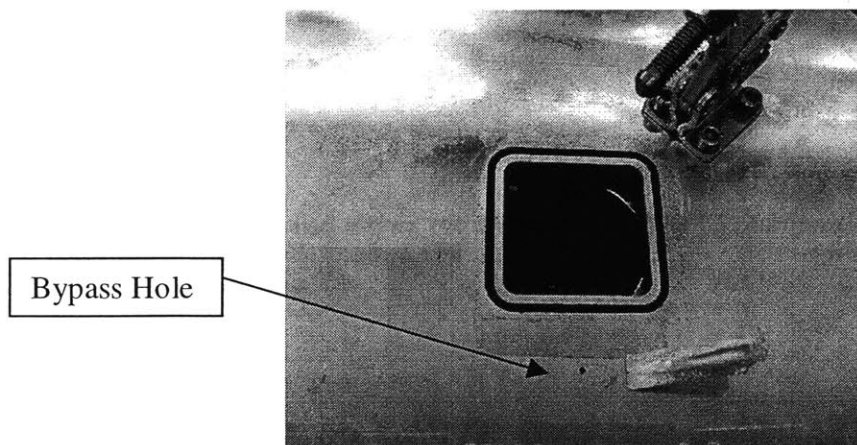
## Equipment

### *MK4 NR.2 (HDGF 230255p.1)*

This is the base plate for airflowing 70mm x 70mm Hastelloy X plates and single holes.

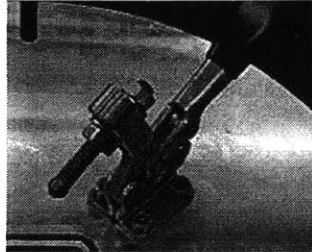


This test plate has a bypass hole in it for use in testing single holes. The purpose of the hole is to allow enough flow through the flow bench to attain an accurate reading. This hole should be taped closed for testing Hastelloy X plates and only open when airflowing single holes. The bypass hole is 1.9mm in diameter and was drilled using a conventional drill press. The hole is perpendicular to the surface and is 15mm deep. The following is a picture of the bypass hole in the base plate.



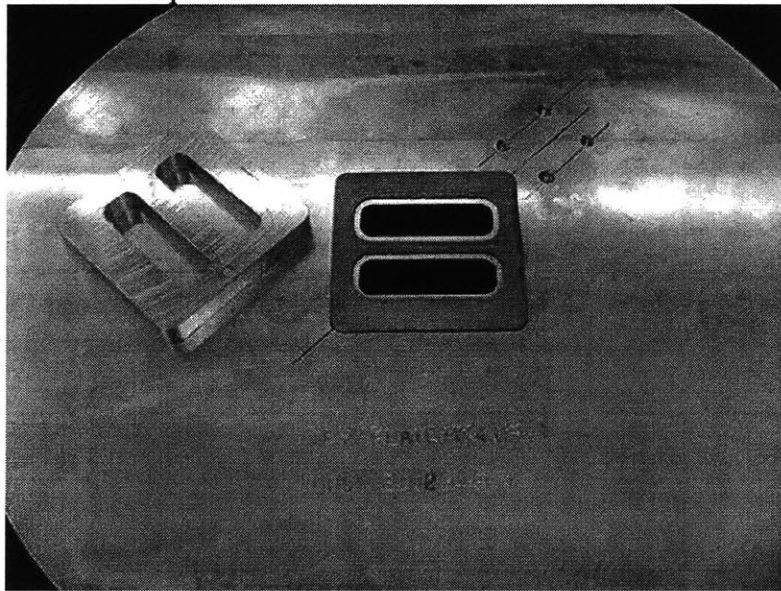
### ***Clamp***

This clamp is used for both base plates (MK4 NR.1 and MK4 NR.2). Be careful when switching the clamp from one plate to the other, as the metal screws are much harder than the aluminum plate. The screws should only be tightened enough to hold the clamp in place. They should not be torqued down.



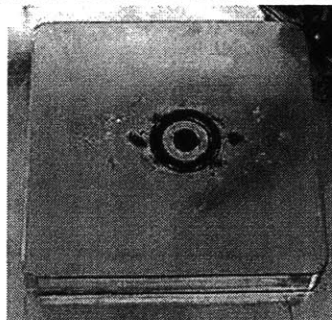
### ***MK4 NR.1 (HDGF 230254p.1)***

This is the baseplate and mask for airflying the MK4 plates with 16 holes in each. Two plates are tested simultaneously in order to have a statistically significant number of holes. This allows for adequate cancellation of individual hole variation.



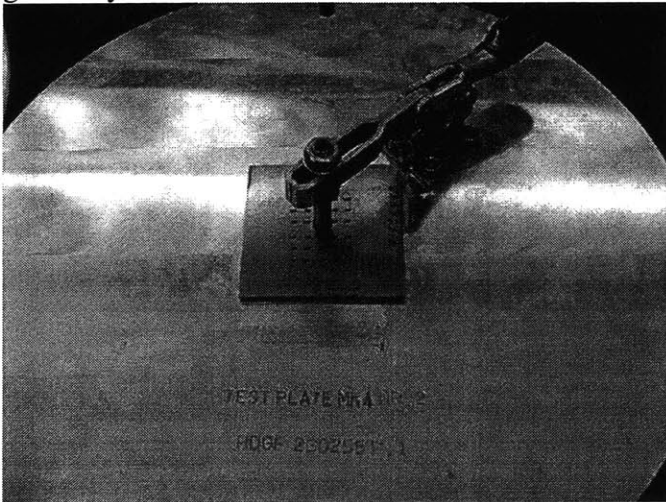
### ***Single Hole Airflow Mask***

This mask is used on baseplate MK4 NR.2 to allow for single hole airflow testing



### Test Setup -- Hastelloy X plates

1. Place baseplate MK4 NR.2 into the flowbench. Ensure bypass hole has been taped closed
2. Place un-drilled plate over the opening. Ensure the seal is fully covered.
3. Clamp the plate in place
4. Perform standard leak test on the fixture
5. Remove un-drilled plate from fixture
6. Place test plate over the opening. Ensure the seal is fully covered. The system is fairly robust, so exact positioning of the plate is not critical. The clamping point should be in the middle (where the gap between rows of holes is the largest) and generally in line with the middle hole of the two flanking rows. It should look like:

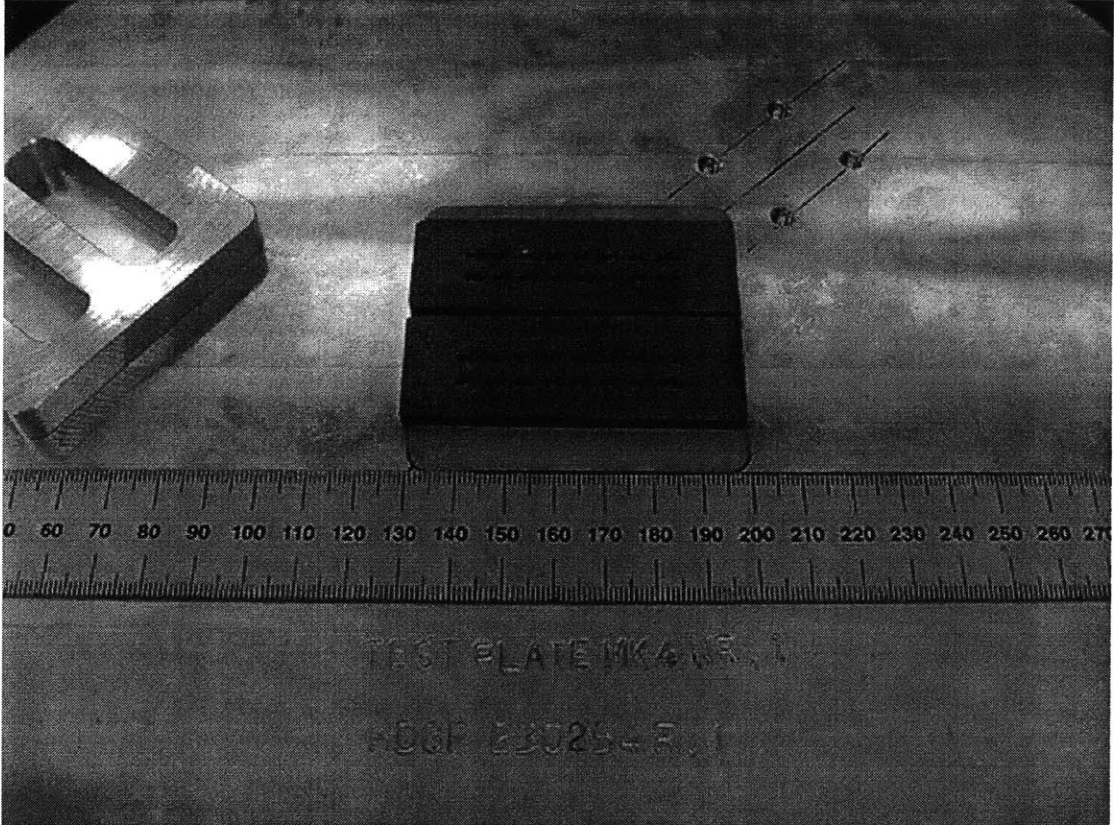


7. Clamp the plate in place. The clamping height may need to be adjusted using the two nuts in order to get a proper seal.
8. Airflow the plate.

### Test Setup -- MK 4 Plates

1. Place baseplate MK4 NR.1 into the flowbench.(Note: pictures shown here do not include the clamp. Prior to beginning this procedure, the clamp must be screwed into the baseplate.)
2. Leak test the fixture using un-drilled plates. The plates should be placed in the fixture as shown in steps 4-5.
3. Remove un-drilled plates from fixture

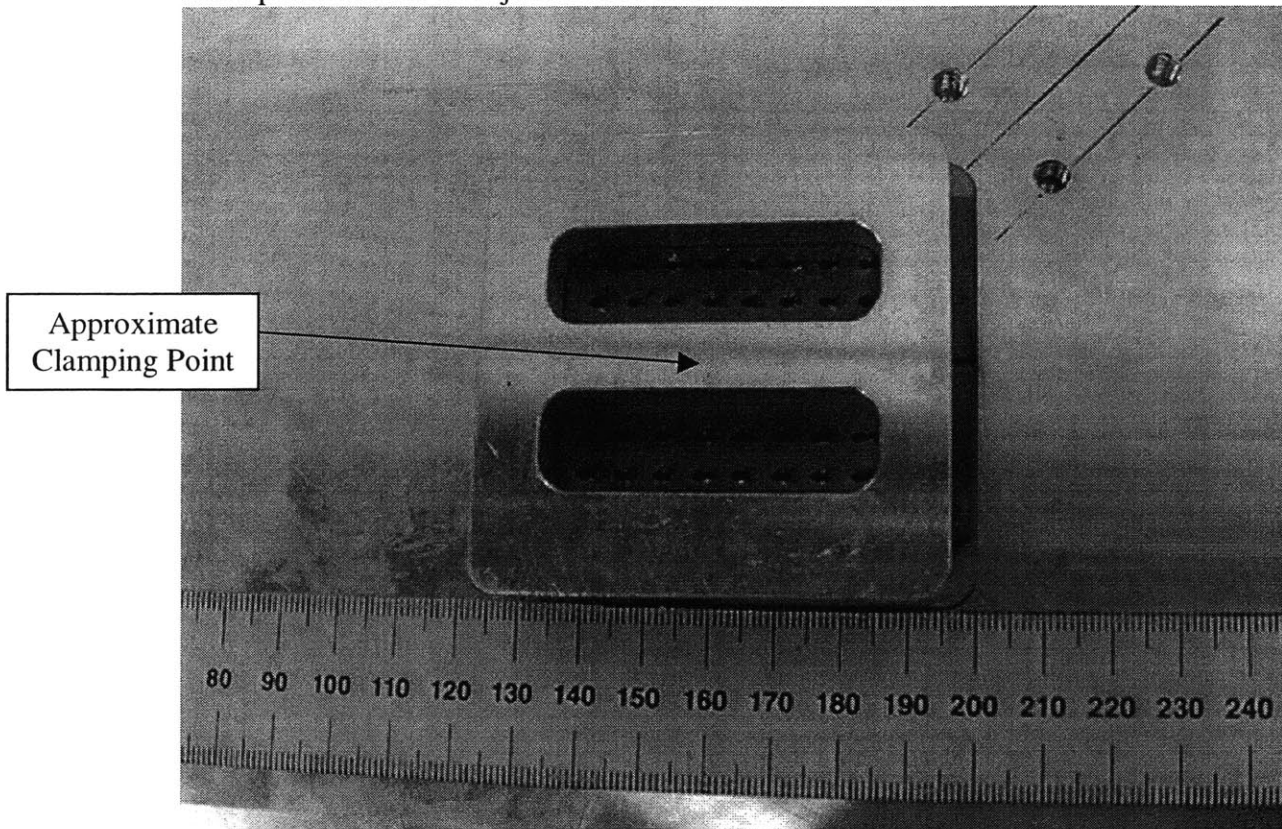
4. Place plates on fixture as shown. The plates should be placed on the fixture such that the air will flow to the left of the fixture.



5. Place mask on top of fixtures as shown. The mask should be offset from the rubber by 5mm. This offset compensates for the 30 degree angle at which the holes are drilled. The top and bottom of the mask should be lined up with the rubber as shown. All holes should be visible as shown below. If any of the holes are not visible, the



MK4 plates should be adjusted such that all holes are visible.

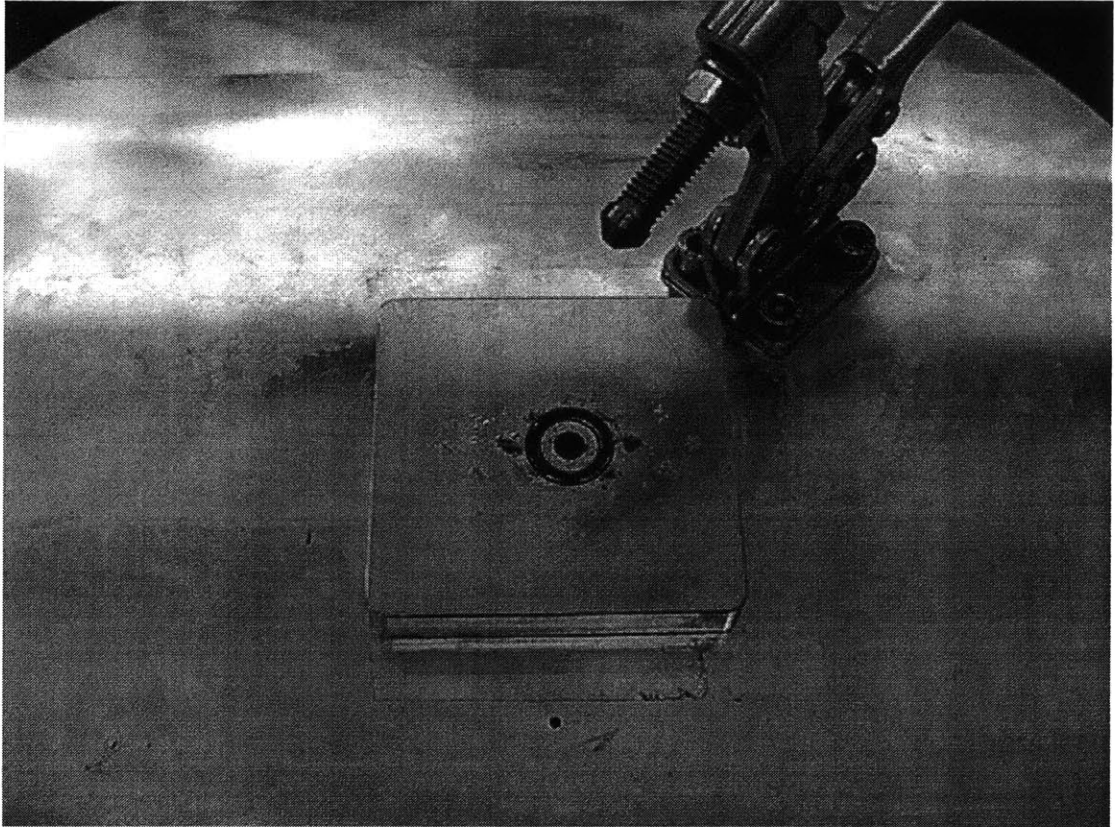


6. Clamp the mask and plates in place. The clamping point should be in the middle of the mask.
7. Airflow the plates

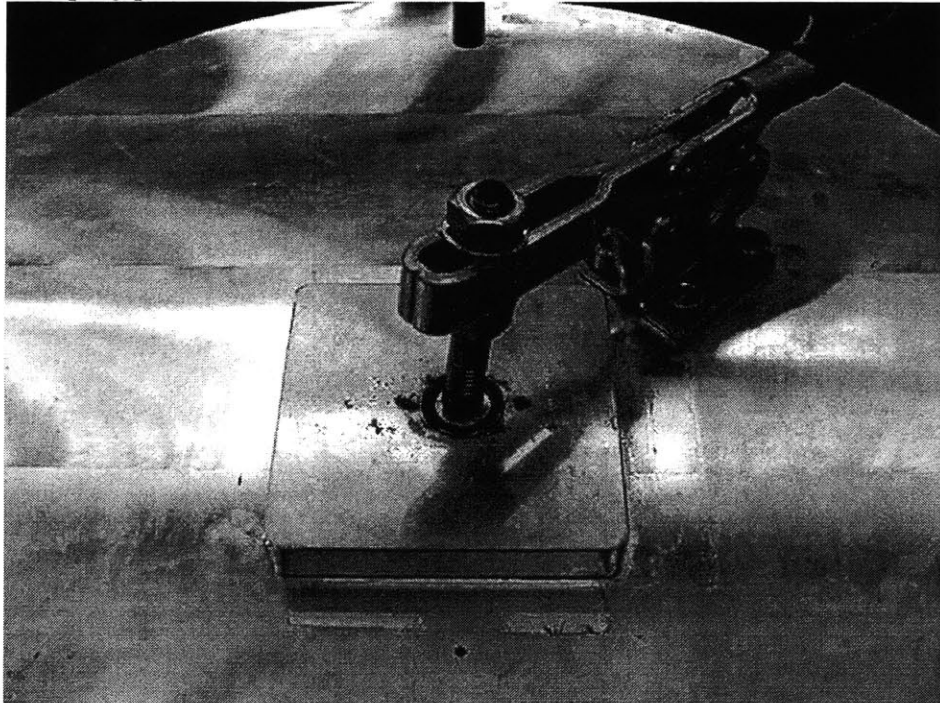
#### **Test Setup -- Single Hole Airflow**

1. Place baseplate MK4 NR.2 into the flowbench. Ensure bypass hole has been taped closed
2. Place un-drilled plate over the opening. Ensure the seal is fully covered.
3. Clamp the plate in place
4. Perform standard leak test on the fixture
5. Remove un-drilled plate from fixture
6. Uncover the bypass hole

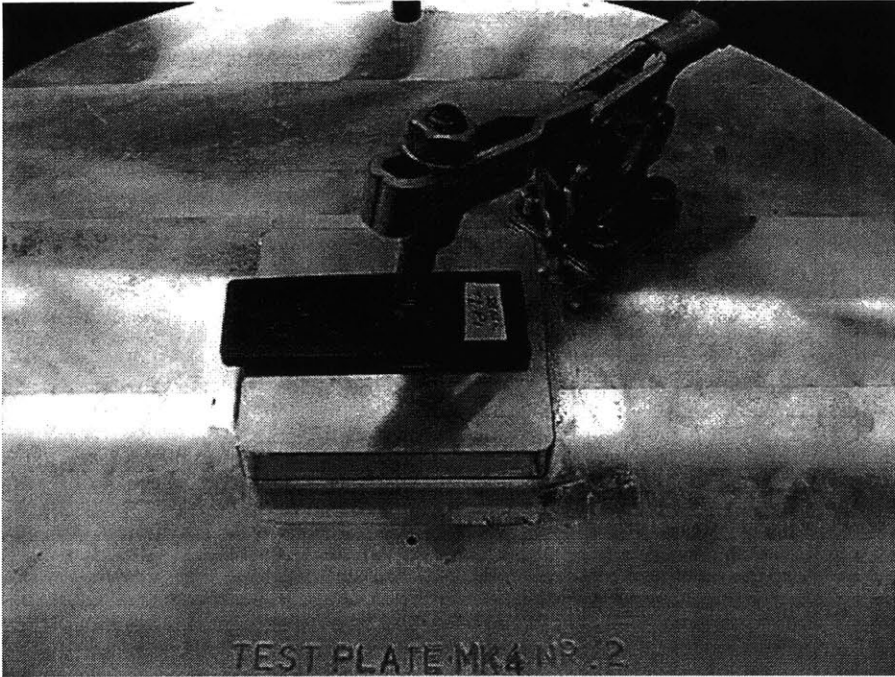
7. Place single hole mask over the plenum opening as shown



8. To aid in aligning of the single hole plates, align the mask to the clamp so that the clamping point is in the center of the mask hole as shown:



9. Place the hole to be tested over the mask hole. The plate must be positioned such that the air exits to the left of the fixture as shown. The hole exit should be 5mm to the left of the clamping point (assuming a 30° angle to the surface). This will ensure that the hole entrance is well aligned over the mask hole and that there is sufficient sealing area around the hole.



10. Airflow the single hole.

#### **Tips for Airflow Testing:**

- ◆ Visually inspect plates prior to testing. Ensure that all holes are unblocked. It has been found that slight blockage in a hole can reduce the flow in that hole by 25%.
- ◆ CCDI flow bench: Although the flow bench uses a PID controller to help settle the measurement quickly, the algorithm is very sensitive to the "Rtyp" value. The closer the "Rtyp" value is to the actual measurement, the faster the bench will lock in to the correct value. When testing plates, the operator should be aware of this fact and adjust the "Rtyp" as necessary to improve testing cycle time.
- ◆ All fixtures were made by Unifer at the Birr facility. They have all the CAD models for the plates and should be able to make any necessary modifications to meet future needs.

## Appendix C -- Guidelines for Report Writing

### Intro

The intention of this guideline is to improve information-sharing efficiency by establishing a standard. By creating a common format, team members will be able to assimilate the information quickly. This guideline should not be seen as limiting the creativity or content of the report, but merely providing initial structure.

The goal of the project write-up is to effectively capture the knowledge created during the project. The created knowledge is not merely the data and answer, since that is only the end result of a knowledge initiative. It is equally important to capture the planning process of the project and the amount of data available prior to project initiation. The thought process used to determine testing or action priorities is also important. The way we work is a process itself and should be recorded and improved such that each project runs smoother and quicker than the last. Lessons learned are key elements of any project documentation. We must describe what could have gone better or went wrong, so that the next project can benefit.

### Sections

The following sections should be incorporated into the document in order to provide the background, thought process, and data necessary for comprehension by those not familiar with the problem addressed.

#### *Problem Introduction*

What is the problem?

Why is this problem important to the business?

What are the goals of the project?

These questions must be answered to base the reader in the correct business context.

#### *Baseline Statistics and Data*

This section should document the status of the problem at project initiation. This helps answer the question: How bad was it?

#### *History*

A thorough understanding of the history can provide insights into the current state of the problem, potential roadblocks, and potential starting points. Unless we understand the history of a problem, we risk repeating the mistakes that created it. The historical perspective also helps separate issues that are "because we've always done it that way" and "band-aid" fixes from factors that have a true purpose or can't be changed.

#### *Past Work*

Prior to initiating actions, a search should be made of prior work done in the area. The search should include both internal and external sources. In addition to contacting local departments, internal documents should be searched. The benefits of leveraging internal work include more detailed information than that found externally and those who did the work might still be around to help.

External research papers can also help significantly. These papers will allow one to understand what is cutting edge in the field, who is doing it, and how they are approaching the problem.

External searches can be performed with a variety of tools. There are a number of web-based pay per usage services available. Two common services are Web of Science and Compendex. The CRC uses DialogWeb, which also provides comprehensive search capabilities.

### *Approach to Problem*

Should include a well designed plan to attack the problem and the reasoning behind the plan. It is instructive to have a copy of the plan at the beginning of the project and a copy of the plan as completed to note the differences.

### *Results*

Results of the investigation should be summarized along with the conclusions reached.

### *Actions*

Description of the actions taken based on the above conclusions and how those actions are expected to impact relevant measurements.

### *Stabilization*

The resolution to the problem should include a system or process to ensure that the problem does not recur. This is particularly important for future work. If the problem recurs and it is found that the stabilization measures were not maintained, a great deal of time and effort can be saved. This will also provide ideas for future projects that may require similar control methods.

### *Lessons Learned*

This section should include items that the author believes are the critical learnings from this project. Lessons learned can be technical, process, communication, or motivationally oriented.

## **General Guidelines**

- ◆ Pictures are worth a thousand words! So, find a digital camera and make good use of it.
- ◆ It is important to learn from failures. Don't be afraid to include mis-steps along the way. Mistakes are only evil when they are repeated!

## **Control**

1. Write-ups should be completed within 2 weeks of project completion. Any longer and there is a risk that it won't be done.

2. Write-ups should be approved by leadership. It is the leader's job to ensure that knowledge is being captured in the proper manner and consistent with the goals of the department.
3. Write-ups must be posted on the department web page within 1 week of leadership approval.

### **Why is this Important?**

It must be recognized that it is far more cost effective to spend a couple of days wrapping-up a project than to have to repeat a few months worth of effort later on. In addition to the cost savings, time savings are equally, if not more important. Properly documented and controlled projects will allow quicker reactions to future situations. Faster reaction will improve time to market, help meet delivery schedules, and prevent further scrap parts or NCR's.

Efficient knowledge transfer is becoming increasingly important as employee turnover increases. Since employees do not stay in the same position or department for long, it is crucial to have materials available which will reduce the time for new members to come up to speed. Having employees scattered across the globe increases the need for knowledge capture and transfer systems. Our world-wide colleagues must have access to the knowledge at any time and in any place. Our department's effectiveness is determined by its knowledge base and the application of this knowledge. The only way to maintain the knowledge base in our ever changing environment, is to have systems in place to capture it.

The challenge with such a system is that it requires discipline to ensure that the knowledge is captured and transferred efficiently. The capture and transfer pay dividends in the long run, so it is up to management to ensure that knowledge management remains a priority and is not overrun

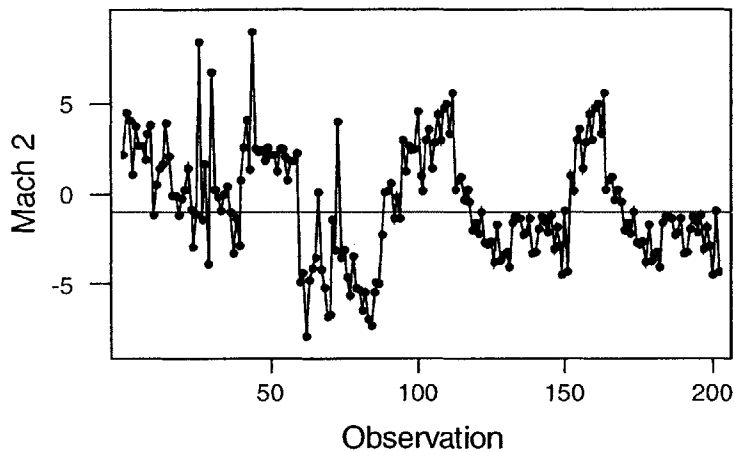
## Appendix D -- Summary of Recent Laser Drilling Data

Recent data (as of June 30, 2000) from an internal supplier shows some improvement in the control of airflow. However, the data does not show that the process is in control.

The vane 1 data shows a nearly capable process over the last 300 parts. However, on a machine by machine basis, this accounts for less than one set per machine. Run charts of the last 150 parts on each machine suggest that there could continue to be problems. The problems are likely to occur after a maintenance activity, as shown in the long-term flat plate tests.

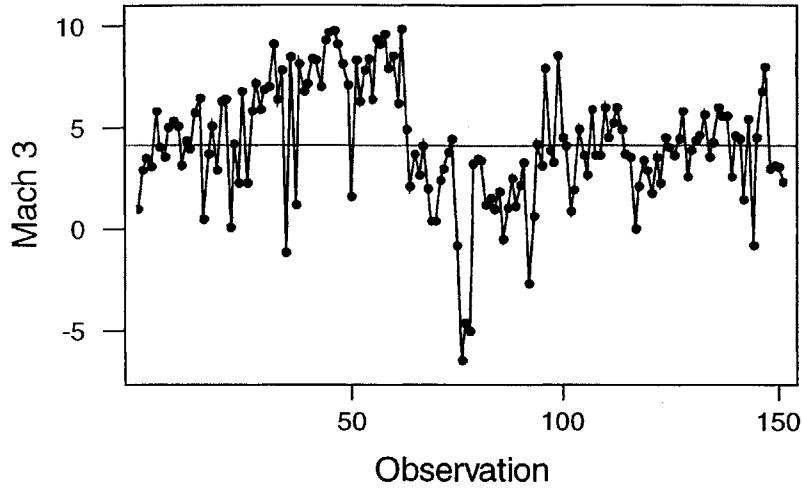
Note: Charts show % Deviation from airflow vs. part number for the most recent 150 to 200 parts.

### Machine 2 Run Chart



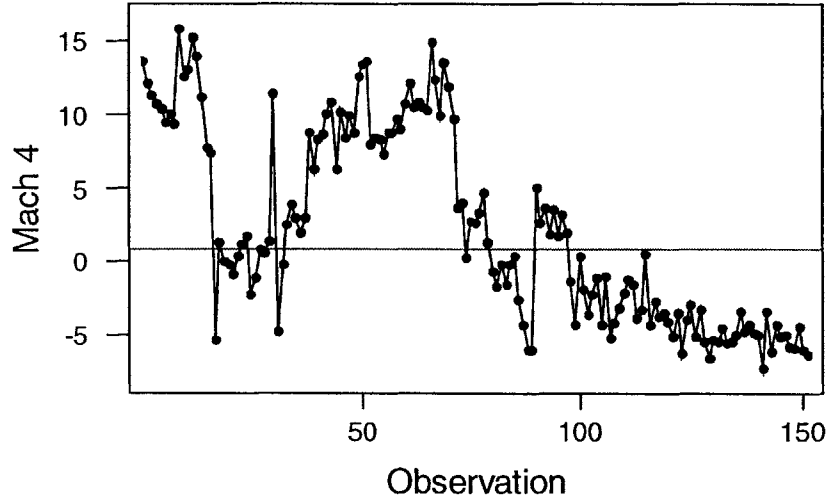
|                                |         |                                 |         |
|--------------------------------|---------|---------------------------------|---------|
| Number of runs about median:   | 34.000  | Number of runs up or down:      | 132.000 |
| Expected number of runs:       | 102.000 | Expected number of runs:        | 134.333 |
| Longest run about median:      | 27.000  | Longest run up or down:         | 4.000   |
| Approx P-Value for Clustering: | 0.000   | Approx P-Value for Trends:      | 0.348   |
| Approx P-Value for Mixtures:   | 1.000   | Approx P-Value for Oscillation: | 0.652   |

### Machine 3 Run Chart



|                                |        |                                 |         |
|--------------------------------|--------|---------------------------------|---------|
| Number of runs about median:   | 55.000 | Number of runs up or down:      | 96.000  |
| Expected number of runs:       | 76.497 | Expected number of runs:        | 100.333 |
| Longest run about median:      | 19.000 | Longest run up or down:         | 5.000   |
| Approx P-Value for Clustering: | 0.000  | Approx P-Value for Trends:      | 0.200   |
| Approx P-Value for Mixtures:   | 1.000  | Approx P-Value for Oscillation: | 0.800   |

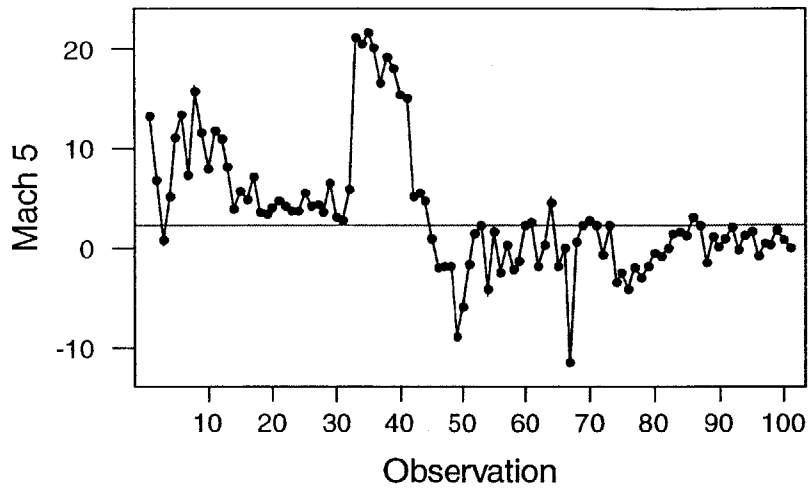
### Machine 4 Run Chart



|                                |        |                                 |         |
|--------------------------------|--------|---------------------------------|---------|
| Number of runs about median:   | 14.000 | Number of runs up or down:      | 93.000  |
| Expected number of runs:       | 76.497 | Expected number of runs:        | 100.333 |
| Longest run about median:      | 54.000 | Longest run up or down:         | 5.000   |
| Approx P-Value for Clustering: | 0.000  | Approx P-Value for Trends:      | 0.077   |
| Approx P-Value for Mixtures:   | 1.000  | Approx P-Value for Oscillation: | 0.923   |



### Machine 5 Run Chart



|                                |         |                                 |         |
|--------------------------------|---------|---------------------------------|---------|
| Number of runs about median:   | 16.0000 | Number of runs up or down:      | 65.0000 |
| Expected number of runs        | 51.4950 | Expected number of runs         | 67.0000 |
| Longest run about median:      | 41.0000 | Longest run up or down:         | 4.0000  |
| Approx P-Value for Clustering: | 0.0000  | Approx P-Value for Trends       | 0.3169  |
| Approx P-Value for Mixtures:   | 1.0000  | Approx P-Value for Oscillation: | 0.6831  |

The blade 1 data also shows improvement over the data from April. However the data also shows that the most recent 200 parts show noticeably more variation than the previous 200 ( standard deviation of 1.8% versus 2.4%).