Project Number: ZAZ-11AB

GE Aviation-Rolls-Royce Stator Assembly Improvements

A Major Qualifying Project Report

submitted to the Faculty of the

WORCESTER POLYTECHNIC INSTITUTE

in partial fulfillment of the requirements for the

Degree of Bachelor of Science

by

Ewelina Czekaj ___________________________

Melanie Dexter ___________________________

Ethan Granoff ___________________________

Rebekah Socha ___________________________

Edward Spofford ___________________________

Matthew Tassinari ___________________________

Date: 12/16/2011

Approved:

____

Professor Amy Zeng, Major Advisor

Table of Contents

List of Figures

Acknowledgments

The team would like to thank the employees of General Electric Aviation in Manchester, Connecticut, primarily Samantha Cote, Cell/Product Group Leader, for their endless help throughout this project. The team would also like to thank project advisor, Professor Amy Z. Zeng at the WPI School of Business.

The subgroup working on Issue #3 would like to thank Professor Richard Sisson for his expertise and his time in assisting with the project, as well as Dr. Boquan Li for his help with the SEM analysis. The team would also like to thank Russ Colburn at Praxair for being so accommodating in providing the information needed to evaluate the brazing process.

Abstract

This project examines the manufacturability of compressor stator vane assemblies at GE Aviation in Manchester, CT. Three major issues – excess copper brazing, the need to recamber vanes, and discoloration experienced in honeycombed stators are investigated to identify root causes and areas for improvement. A variety of engineering techniques such as statistical analysis, process redesign, and qualitative study are employed, resulting in a range of recommendations for reducing lead time and costs for this GE facility.

Executive Summary

GE Aviation is a leader in the manufacturing of aircraft engines and parts. The GE Aviation facility in Manchester, Connecticut produces compressor stator assemblies which are contract manufactured for Rolls-Royce. These stators undergo extensive manufacturing processes, and are machined to standards that far exceed the tolerances of most manufacturing facilities. GE Aviation approached our MQP team with three quality issues regarding processes related to the stators. The first problem occurs when the joint between the vane and the stator is brazed with copper in excess, and must be manually removed. Removal of excess copper is both time consuming and costly, due to the high probability of damaging the part. The second issue dealt with the recambering of vanes in the stator. This occurs when the hot upset machine welds the vanes at an improper angle. Like excess copper brazing, recambering vanes is both expensive and time consuming because vanes must be adjusted individually. The final issue, discoloration of the stator, occurs after a heat treatment brazing process. This problem raises quality concerns among GE's customers, and parts with these issues are often rejected and scrapped.

To analyze the first issue, excess copper brazing, our MQP team developed a series of experiments. The cause of excess copper brazing was believed to be the same issue that resulted in vane angle deviation. As a result, the experiments served as information both issues. The first focused on the width and length of tangs, a small tab that comes off the top and bottom of the vane. These tangs fit into the pierced slot and therefore, if there is an incorrect fit between the two, the copper is more easily allowed to pass through in excess. In addition, if the fit is incorrect, the vanes have the ability to shift inside the slot and become welded at different angles. Those who focused on the issue measured fifty tangs that were fixed and numbered, as well as two hundred and fifty random samples. The fixed measurements acted as a control for the experiment to determine operator measurement differences, while the random sample moved to describe the pattern of variation. The second experiment focused on slot size, and was done using a spectrograph. Slots were measured in three different locations for width, as well as one for length. Variation and range of the sample was then derived for the data statistically using SAS. When compared with the tang experiment, conclusive data could be extracted about how tangs were joining with the slots. The last experiment, focused on a factor called trumpeting. This issue occurs when the die, which punches slots into the ring, becomes blunt and causes uneven punches with respect to depth. This results in one side of the punched slot being larger than the other. This was analyzed qualitatively with a digital microscope that allowed the operator to see edges of the punched slot and analyze it on a computer. A final analysis was also done on brazing process itself, which was is outsourced by GE Aviation, and performed by a company called Bodycote Ipswich, in Ipswich, MA.

The results that came from these experiments lead to many different conclusions. With regard to tang size, it was determined that the length did not very enough to be significant, although the widths of the tangs showed variation, that by our conclusions, exceeded acceptable standards. The slot sizes were similar in their response, with length being inconsequential and width showing large variation. The images from the microscope showed that trumpeting did occur, but a scale that was much smaller than anticipated. The conclusion is that trumpeting was not an active factor of any of the given issues.

We noticed variance in the ways different operators ran some machines, such as the hot upset machine. These differences, though many seem slight, make a large impact on the final product. As some operators do not load the hot upset machine properly, the vanes can get bent to inconsistent angles, ultimately adding time, effort and money into the recamber process. By creating Standard Operating Procedures, the machine workers will be able to follow strict guidelines on the use of the machines as to prevent issues at the recamber and final inspection stages. Between 25% and 100% of vanes must be recambered due to angles outside of the specifications. This hurts the company by adding a great deal of lead time and costs large sums of money. By controlling the input, the output can be controlled. Standard Operating Procedures will also allow the business to smoothly continue the process if an operator leaves, is out sick, or takes a vacation. Other workers would be able to more smoothly transition into other roles.

As a result of these experiments, our MQP team recommends that the tolerances regarding tang size be tightened, purchase stronger dies that won't dull after repeatedly punching slots, create a fixture to hold vanes at the proper angle during hot upset. In addition, our team also recommends that Bodycote Ipswich use an automated process to distribute copper to the tangs during the brazing process, and that the width of pierced slots be reduced. It is our hope that these recommendations will cooperatively solve the excess copper brazing and vane recambering issues.

For the third and final issue, the discoloration of the honeycombed stator assemblies, we used the Six Sigma DMAIC methodology. The issue was known to arise after a heat treatment brazing process at an external vendor. We focused its analysis on the manufacturing processes at GE, the heat treatment processes at the vendor, and the materials comprising the stators. We had little experience with heat treatment or material science, but was able to obtain consultation and input from industry professionals and WPI professors. We quantitatively evaluated the issue by running an Energy Dispersive x-ray Spectroscopy (EDS) analysis on a specimen of the stators using a Scanning Electron Microscope.

We quickly learned that there were a number of variables which can alter the result of the heat treatment process. From stakeholder and professional feedback, we were able to determine that the most likely cause for the discoloration was either issues with the brazing ovens, such as vacuum leaks, or a material vaporizing (offgasing) during the heat treatment. Oven leaks allow oxygen into the heat treatment environment, which can cause discoloration through oxidation, and undesired offgasing of materials can adhere to the assemblies at lower temperatures, causing a layer to form on the parts. The SEM analysis showed the elemental composition of the surface of the assemblies, but further analysis is required for more conclusive results.

It was discovered that through alternative processes the discoloration after heat treatment can be avoided, but this process is very expensive. A simpler process is being developed which significantly decreases the vendors operating costs and will result in much shorter lead times for GE. We was unable to scientifically determine the root cause of the discoloration issue, but from the new brazing processes the issue has far less of an impact. Further study by subject experts is required to determine exactly what is causing the discoloration.

We also evaluated GE's business practices and operating costs. At the time of this project, GE was 2,000 assemblies overdue in their orders, which is about 1.5 million dollars in revenue that has not been produced yet. Many of the orders are about two to three months behind schedule. The shop costs $110 per hour to run, while each employee makes on average $20.80 per hour. By adding a second shift to straightening and a third shift to recamber, wash and lathe, the shop would have to spend an additional $1,545.60 per day to account for the utilities and the payroll hours, but this has the potential to allow the shop to make 840 stators more per month than they currently are outputting. If these shift additions were continued the stator assembly could bring in 8 million more dollars in revenue each year. Overall creating a business continuity plan and adding a few new employees would allow for a higher quantity and quality of products.

Throughout the course of the project we were able to develop significant insight into the root causes of the three quality issues. From this analysis, we developed solutions which can have a real impact on the overall goal of decreasing manufacturing costs and reducing lead times for the GE Aviation Manchester facility.

1. Introduction

1.1 Company Background

General Electric (GE) is a multinational conglomerate that operates through four main divisions: Capital Finance, Consumer & Industrial; Energy; Technology; and Infrastructure. General Electric is currently the sixth largest firm in the United States, incorporated in Schenectady, New York and headquartered in Fairfield, Connecticut.

GE Aviation is the top supplier of aircraft engines in the world, supplying the military, civilian, and marine markets. GE Aviation initiated jet engine development in 1941 when Frank Whittle began designing the W.1 turbojet engine. Headquartered in Evansdale, Ohio, GE Aviation owns several subsidiaries and has locations across the United States.

GE has a strong presence in Connecticut with a total of fourteen facilities located in nine cities throughout the state. GE employs over 5,425 people in its Connecticut facilities. In addition, GE pays over $900 million per year to suppliers, which helps to maintain 4,005 jobs at the companies GE is dependent upon. To further aid the needs of the community, GE has provided almost $17 million to outreach programs and employees have devoted 23,900 hours of service to their communities.

The GE Aviation facility in Manchester, CT produces a number of aircraft engine components for commercial and military applications. Five separate manufacturing facilities comprise the Manchester campus, each location hosting different manufacturing processes and products. Unique to other GE Aviation locations, the Manchester plant sells products to many different customers including Rolls-Royce and Pratt & Whitney, rather than producing exclusively for GE engines. GE Aviation began operating in Manchester after acquiring Smith's Aerospace in April of 2007 and has since made a substantial investment in the location.

Building #3 of the five-facility Manchester campus hosts the manufacturing line for compressor stator assemblies, which is the product this project will be focusing on. The facility has equipment for laser processing, heat treatment, and brazing. Some of the main products made in Building #3 include turbine exhaust cases, bearing housings, compressor supports, and finally the stator assemblies.

1.2 Problem Descriptions

There are three issues GE Aviation in Manchester, CT is experiencing associated with the compressor stator assemblies. The first issue is the accumulation of excess copper brazing on the assemblies. The second issue is the need to correct angle deviation in the vanes that occurs during manufacturing. And finally, the third issue deals with the discoloration found on the honeycomb stators.

1.2.1 Issue 1 – Excess Copper Brazing

Ethan Granoff and Rebekah Socha are responsible for the first task which is to analyze the effect of excess copper brazing on the stator assemblies and develop possible solutions. All stages of the stator are outsourced by GE to Bodycote Ipswich, in Ipswich, MA, for copper brazing. Excess copper brazing occurs on a significant number of stators and cannot be left unaddressed on the final product. Removal must be done manually back at the GE Manchester facility, using a small filing tool. This process leaves room for operator error, possible damage, and adds to the total cycle time. Due to the complexity of the removal, the majority of excess copper brazing is removed by one employee who is skilled with the process.

Excessive brazing can be addressed from two sides: the removal and the source. Creating an efficient way to remove excess copper would allow the facility to make better use of their employees but at an astronomical cost. The second approach would focus on adapting the copper brazing process at the source, thereby eliminating the need for a removal step. To solve this issue a root cause must be determined, and in turn possible solutions for GE must be created while accurately analyzing the full effects that would result from their implementation. Currently, it is believed that excess could be caused by errors made during the piercing process. In connection with the improper placement or movement of vanes, this can cause excess to form. This issue is closely tied with the second issue as they both may have the same root cause.

To determine the root cause, the steps in the assembly process leading up to the brazing will be studied and the locations where potential faults could be made will be determined. The facility that performs the brazing will also be visited to see what problems could cause excess copper buildup during the brazing process. To begin gauging the problem, it will be important to determine how many occurrences of stators with excess copper brazing happen per given time or lot. It will also be important to determine how long it takes to remove excess copper and the operator error rate. This information will put the magnitude of the problem into perspective, while also providing a full spectrum analysis of the effects of possible solutions. To determine where the problem is occurring, it will be important to analyze the steps that lead up to brazing to determine if one or more factors add to the occurrence of excess copper brazing. Areas of possible interest include the turning, piercing, burring, milling holes, and EDM splitting. A third area of focus would entail a profile of excessive copper brazing cases (i.e., where is it located, how much excess, and other notable cues) in order to identify correlations and the root cause. Using the information gathered, solutions to appropriately deal with excess copper in the assembly process will be suggested and total rework cost and overall cycle time for the company will ultimately be decreased.

1.2.2 Issue 2 – Vane Angle Deviation Correction

Melanie Dexter and Edward Spofford will be investigating the second issue, more specifically the recamber process for the stator assembly. The recamber process is necessary because the angle of the vanes changes during the manufacturing process. The angle of the vanes needs to be precise to perform properly in the engine and meet the specifications of the customer.

The GE Manchester plant currently measures and recambers the vanes several times during the manufacturing process. This process is time consuming and slows overall cycle time. The recamber process begins with placing one half of a stator onto a measuring jig that measures the angle and camber of several vanes. After measuring a sample of the vanes, the stator either passes and moves down the line or fails and gets recambered. When a stator is recambered, every vane is clamped in jaws and pressed into the correct position. This is a slow process that must be repeated several times if it is not successful.

In order to solve this problem it is necessary to locate the specific process that changes the camber of the vanes. The goal of the team is to analyze that process and find a solution for the recamber problem that decreases lead time and rework costs. The hope is that this will decrease overall cycle time for the product line and increase the rate of production.

Two processes have been identified as potential contributors to the recamber problem. The first process is hot upset, which heats the vanes with electrical current to weld them into place. While this process is happening, the vanes are loose and can change pitch before they are welded in place. Hot upset will be investigated by Melanie Dexter. The second process that has been identified as a potential contributor is the piercing process, which has been increased several years ago and several problems are attributed to this change. There are no existing records that state how or why the new size was chosen; nor are there records that contain the original piercing size. The piercing process will be investigated by Edward Spofford.

In order to meet the goals specified by GE Aviation the root cause of the recamber issue must be identified. The team plans to use Six Sigma and statistical analysis to correctly identify the problem and formulate a solution.

1.2.3 Issue 3 – Honeycomb Stator Manufacturability

Ewelina Czekaj and Matthew Tassinari are responsible for investigating the third issue, in which there are two main problems associated with the honeycomb treated stator assemblies.

First, the honeycomb feature is more difficult to manufacture in comparison to the coated feature. The honeycomb coating is applied to the stators at an external vendor, Praxair, which is also located in Manchester, CT. By the time that the stators are shipped back to the GE plant, time is already lost in the production of the final product. In addition to outsourcing the stators to Praxair, the honeycomb stators are also more difficult to recamber because they are heat treated multiple times. These additional steps in applying the honeycomb feature onto the stator make the production time much longer than that of the coated stators due to the fact that there are more steps to take in the process.

Second, honeycomb assemblies are experiencing what appears to be oxidation or discoloration, resulting in the need to refurbish the product and yet again adding to production time. The source of this discoloration is unknown, and the assemblies will not pass internal inspection if they are covered with this possible “oxidation.” In order to remove the foreign entity, the product must undergo a vapor blasting process which adds twenty extra minutes per assembly.

The first goal for this issue is to identify the root cause of the discoloration and at what point of the production process it occurs. Second, solutions that will prevent the discoloration from continuing to arise will be provided, which will in turn, reduce production time. Once these goals are met, the focus will be on implementing further improvements in order to enhance the manufacturability of the honeycomb assemblies.

In order to meet the goals specified, it is important to familiarize oneself with the product. Aircraft engines require extremely tight manufacturing tolerances and the production process must be virtually flawless to ensure that there are no defects. To find the root cause of the discoloration, it is crucial to identify what materials are involved in the assembly and any foreign contaminants that they may come in contact with throughout the manufacturing process. Once these specific materials are identified, a thorough analysis will be conducted on the product to reveal the chemical makeup of the discoloration, which will assist in determining where in the process it takes place. Finally, once the root cause has been identified the focus will be on prevention and correction of the undesired discoloration.

1.3 Overall Project Goals and Objectives

The overall goal for the project is to reduce the lead time for the Rolls-Royce stator assemblies. By addressing the excess copper brazing, recambering, and honeycomb discoloration, the team hopes to streamline the production process, thereby reducing manufacturing costs. In order to meet this goal, the team must first determine the root causes of these issues. Once the root cause or causes have been identified, the team will investigate what solutions could be implemented to prevent the issues and provide recommendations to the sponsors.

In accordance with the overall goal to reduce the production lead time for the stators, the team has a number of other objectives which will hopefully assist in improving the manufacturing process. The team aspires to reduce the manufacturing costs of the stators, reduce waste, and reduce the number of reworks that must be done. By the end of the project, the team aims to provide recommendations that will accomplish all of these objectives.

1.4 Project Plan

This team of six was divided into three pairs of team members, each of which have focused on one of the three issues. Ethan Granoff and Rebekah Socha addressed the excess copper brazing issue. Melanie Dexter and Edward Spofford investigated the angle deviation correction. Finally, Ewelina Czekaj and Matthew Tassinari looked into the honeycomb discoloration.

The project was conducted over the period of two seven-week terms during the fall semester of 2011: A Term and B Term. There are two main phases which characterize the progression of the project. A Term was devoted to defining and researching the three issues, and B Term was dedicated to implement procedures and offer solutions.

During A Term the team initially toured the Manchester plant, observing and studying the manufacturing process for the stator assemblies. The team also visited external vendors who perform various services for the production of the stators. Background research was conducted on issue specific topics and general process improvement. Using the knowledge of the production processes and the background research, the team formulated methodologies to determine the root causes of the quality issues, which will be implemented during B Term.

B Term was devoted to implementing the methodologies formulated during A Term. The team worked closely with the GE Manchester plant and their external vendors to perform various tests and analyses on different aspects of the manufacturing process. Taking the data accumulated through the tests, the team assessed the results and provided recommendations for what GE can do to avoid these issues in the future.

2. Background and Literature Review

2.1 Aerospace Manufacturing

The aerospace industry is characterized by extremely complex products which demand the utmost precision. Aircraft engines experience extreme forces throughout their lifespan. Some components can operate at temperatures of nearly 1200^0C and must withstand incredible pressures (Clarke and Bold). Turbine speeds for commercial engines can be in the 10,000's of revolutions per minute (RPM) as well, with military engines often operating at much higher speeds (Boeing 502-6 Turboshaft Engine). Reliability, safety, and more recently minimizing emissions are also key criteria. In the aerospace industry the stakes are very high, and any sort of error or equipment malfunction can be catastrophic.

In order to withstand these conditions and maximize efficiency, turbine manufacturing demands extremely tight tolerances (Clarke and Bold). Choosing materials and ensuring the quality of components are major concerns for the aerospace industry. In terms of manufacturing, the demands on precision are very high. Because there is so little margin for error there is a high likelihood that parts will need to be reworked or may be scrapped altogether. Any added time to the manufacturing process cuts into the producer's profit margin and can easily set them behind schedule. It is therefore a major concern to ensure the manufacturing process is as efficient and precise as possible.

2.2 Jet Engine Background

The basic turbine powered jet engine was originally developed in the 1930s to overcome the inefficiencies of piston powered propeller driven aircraft. As propellers spin faster and the blades approach the speed of sound, they lose efficiency. Aircraft performance reached a barrier and a new type of power plant needed to be developed to increase performance. Although the idea for a jet turbine engine was patented in England in 1791, sustained operation was not achieved until 1903. At this time metallurgy, weight, and safety prevented the engine from powering an aircraft until the 1920s.

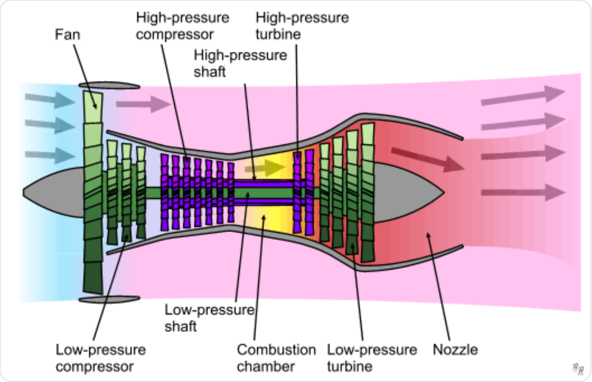


Figure 1: Diagram of jet engine internal components.

A jet engine is a broad term used to identify an engine that operates by using jet propulsion. In a typical atmospheric environment jet engines typically use internal combustion, which consists of turbines powering rotary compressors in the Brayton Cycle (Sawyer). In order to understand the Brayton Cylce, it is important to note that a jet engine is self-sustaining; the combustion is continuous, unlike a piston powered engine where the combustion is pulsed between cylinders. The power turbines in the back section power the compressor at the front of the engine. The rotary compressor takes in the air, compressing it over several stages. After the air is compressed, fuel is added in the combustor and is burned. This burn causes the compressed air to expand rapidly. This high pressure hot air continues through the engine and flows over the power turbines. This converts the high pressure air in the rear section to rotational energy over several stages and provides thrust via a propelling nozzle. (GE Aviation)

There are several different types of jet engines. A turbojet engine is the oldest type of air breathing jet engine that produces thrust. This type of jet engine only takes enough power from the thrust to sustain its own operation. Turboshaft engines operate on the same principles as turbojet engines, however instead of producing thrust the goal is to harness the thrust and convert it to shaft power (Rolls Royce). In a turboshaft engine almost no thrust is produced. All of the power is harnessed from extra power turbines called the free turbines that are connected to the power shafts (Rolls Royce).

The team's goal is to improve the engine stator, a stationary ring concentric with the rotating power shaft that directs the air flow through the power turbines. These stators precisely angle the high pressure air to maximize the efficiency of the free turbines.

2.3 Process Improvement

The team will be evaluating different areas of process improvement to accomplish the project goals. Lean manufacturing, lean principles, quality control, lead time reduction, and Six Sigma Analysis are all areas that can contribute to improving manufacturability of the stators at the Manchester GE plant.

2.3.1 Lean Manufacturing

Lean manufacturing is an important production practice that works to create value while eliminating waste. This process is widely used throughout many large manufacturing firms and allows them to optimize the use of their resources in value-adding steps. Reducing the amount of waste within given processes is an extremely important step to lean manufacturing. In particular, defective parts can cause a massive amount of waste beyond the monetary cost of material in the part. A single defective part will undergo a series of processes that take companies resources like electricity, employee time, and material costs. Many times the defect will go unnoticed until inspection, which means that the product underwent processes that could not add value to the part but still utilized resources that are therefore wasted. This process is particularly important to the excess brazing issue, because excess brazing has no efficient way to be removed. There is a high chance of damaging the part and therefore there is a potential for waste reduction by influencing factors that reduce excess braze (Hi TecMetal Group, Inc.); (Akinlawon); (Krajewski).

2.3.2 Lean Principles

Process improvement involves a great deal of investigation, analysis, and implementation in the world of manufacturing. In 1913, Henry Ford identified the need for a more efficient manufacturing process for the vehicles his company produced and through this realization he introduced to the world the moving assembly line. In the 1930s, Kiichiro Toyoda carried on Ford's idea and introduced new techniques that would improve the quality and overall production of the process (A Brief History of Lean). Since those years, Ford and Toyoda's ideas have accrued innovative changes to make the process as a whole more varied, efficient, and effective and developed into what are today called lean principles.

First and foremost, identifying the value of the product from the customer's standpoint is key. With a full understanding of what the customer seeks and expects in a specific product, a manufacturing plant will know what modifications they need to make so that they can next map the value stream. Mapping the value stream allows the chance for a stronger understanding of what steps in the process contribute zero value to production, and thus displaying what steps to eliminate. This creates the chance to create flow through making the sequence of steps faster and more efficient and as flow is introduced the manufacturing floor may establish pull between these steps wherever it is possible to create continuous flow. The final principle is to seek perfection by repeating all of these steps. Continuously identifying value, mapping the value stream, creating flow, and establishing pull will help to eliminate impractical steps that add no value to production and achieving perfection in the end (Principles of Lean).

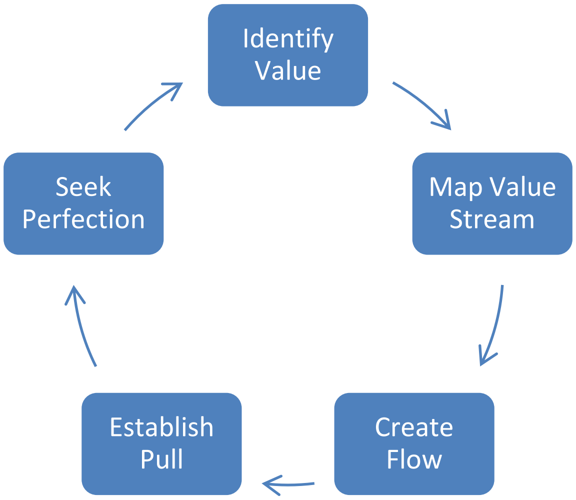


Figure 2: Lean principles.

2.3.3 Quality Control

The use of quality control ties in closely with lean manufacturing techniques by ensuring that parts are within the specifications that they need to be and ensuring that the item operates as expected. Quality control also works to reduce waste by reducing the chances of faults and defects in the item being produced. Quality control potentially contributes to some of the issues at the Manchester GE plant, such as vane recambering and excess copper brazing, because the piercing process may be inexact.

2.3.4 Lead Time Reduction

The total time between purchase of a specific product and its delivery to the customer is known as lead time. Because fast delivery of a final product can set a company apart from its competitors, lead time is an important factor that many manufacturers constantly look to reduce through various methods including Six Sigma Analysis or lean principles.

2.3.5 Six Sigma Analysis

Six Sigma Analysis is a business strategy that seeks to improve a process by identifying the cause of variability (defects) and eliminating it. Although Six Sigma uses several different methods to improve the quality of any process, it is most well-known for its statistical analysis of a manufacturing process. These powerful analytical tools support a well-defined problem solving method. The Six Sigma approach is to take small steps forward and no steps backwards; this drives the goal of continuous improvement. All improvement efforts are aimed at better serving the needs and expectations of the customer; however it requires a deep commitment from a company because it could question the way tasks have been done in the past. Because Six Sigma is designed to improve a process and not generate a new one, there must already be a process in place. This process must be brought under control statistically in order for Six Sigma to be effective and variability reduced.

Six Sigma has a six-step structured approach designed to lead an organization through process improvement. The six steps are: Define, Measure, Analyze, Improve, Implement, and Control. These steps are known as DMAIIC.

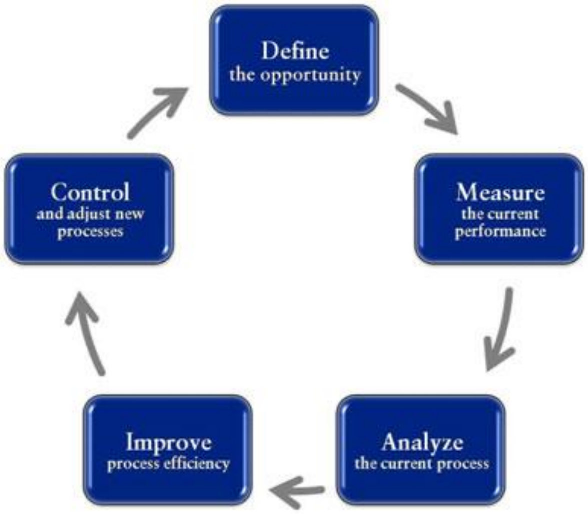


Figure 3: Six Sigma Process

The DMAIIC process breaks down the Six Sigma process into easy, clearly defined steps. This simplifies the process so that it can be adapted to many different processes easily and applied without significant changes.

The first step in the process is to define the opportunity, which is when the opportunity for improvement is recognized and the goals for improvement are set. The goals for improvement need to be realistic and within the bounds of the opportunity; for example it would be unrealistic to try to reduce the cost of a process below the cost of raw materials. Not only is this not possible and therefore a poor goal, but the cost of the materials is not controlled or effected by the process and is not within the bounds of the project.

Once an opportunity has been defined it must be measured, which is intended to benchmark the current level of performance so that it may be compared to the improved process later on. This step is also important because not only does it map the current process, but it also identifies the factors that are critical to the goals of the project.

The next three steps in the process are closely related to one other. The current processes must be analyzed to identify the problems and the reasons behind them. Cause and effect analysis are performed to help determine the reasons for gaps. After the data is analyzed the process must be improved. Once the data is analyzed and interpreted new processes are designed and breakthroughs are found by reviewing the analyzed data. Well analyzed data should show the problems clearly and show evidence how to improve them. Once improvements have been made they need to be implemented in the processes. This may require further training for workers to change the way they do things. This can be difficult because workers can be resistant to change if they do not agree or understand the benefits and necessity of it.

The final step in the process is to control and adjust the new processes as they need to be modified until they reach their full potential. Once they do reach their full potential, the new processes need to be benchmarked and compared to the original process. This will allow any improvements to be measured and identified, as well as help show the strengths and weaknesses of the new system.

With these steps it is easy to reduce variation in almost any process and bring it up to a Six Sigma level of quality. Six Sigma is a business strategy that can successfully reduce costs and waste and improve the general efficiency of a company. It is a repeatable process that allows a process to be quantified and statistically analyzed in order to find room for improvement (Institute Of Industrial Engineers).

3. Preliminary Analysis

3.1 Turbine Engine Stator Assemblies

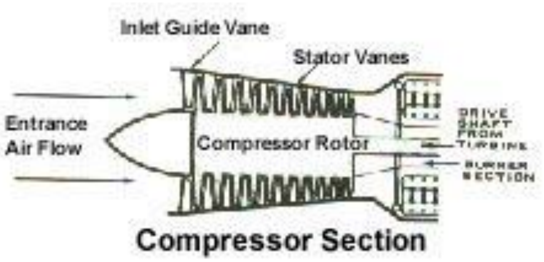


Figure 4: Diagram of compressor section of turbine engine. Stators are located in between the different stages of the compressor rotor. (Thai Technics)

Stator assemblies are a key component of modern aircraft engines. Stators are fixed features which complement the rotating blades of the turbine. Stators act as aerodynamic diffusers, ensuring the rotating turbine blades receive the correct airflow and capture the greatest amount of energy possible. Engines contain many rows of stator-rotor pairs. The stators follow the diameter of the turbine case, and therefore become more and more narrow deeper into the engine. The different sized stators are referred to as stages (AirCav: Compressors).

As air enters the turbine, it picks up the rotational direction of the spinning rotor blades as it passes through the first stage. After passing through the rotors, the air meets a stator assembly. The rotational direction of the air is halted and corrected to a straighter direction. This corrected air then gets picked up by the next stage of rotors, and so on, building up pressure and velocity with each passing stage. The assemblies being evaluated in the project are known as compressor stators, so named because they are part of the compressor component of the engine (Heppenheimer).

3.2 Manufacturing Process Flow Chart

The stators undergo a number of processes from initial machining to final inspection. Below is a flow chart of the main processes relevant to the issues of the project. They are explained in greater detail in the following sections of the Preliminary Analysis.

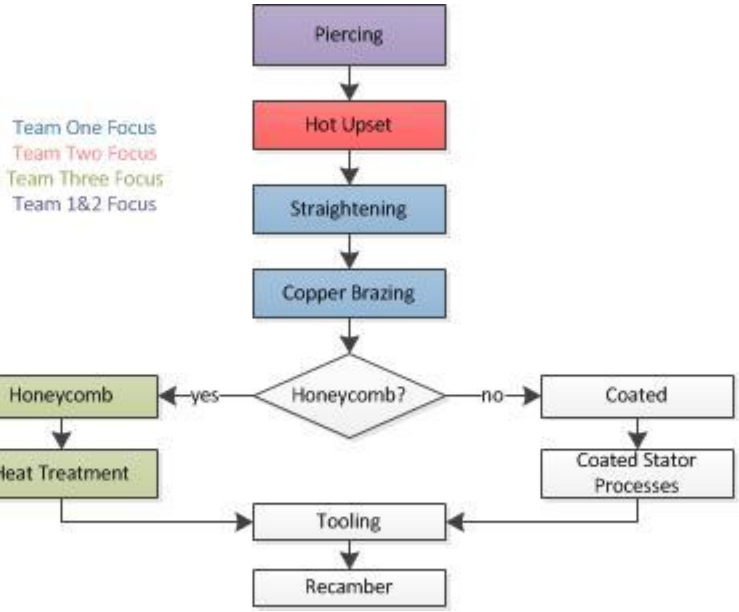


Figure 5: Stator manufacturing process flow chart.

3.3 Piercing

The piercing process punches slots through the inner and outer rings of all stages of the stator assemblies. An individual ring is laid horizontally and rotated as pierces are punched. The die that pierces through the rings is unique to each stage and must be changed before a new stage is pierced. Each stage has two dies, one for the inside rings and one for the outside. This task is greatly dependent on operator experience which can affect the number of lots completed per day and the downtime that occurs when changing dies. An operator with relatively little experience can produce three to four lots of sixteen rings per day while an operator with more experience can produce four to five lots. It takes ten to fifteen minutes to change dies, depending on operator experience.

There are a couple of issues that arise during the piercing process that can cause variability in the final product. The first is the tendency of the piercer assemblies to break after a certain number of uses. There is no exact measure but the time before the assembly breaks depends on the number of pierces performed and the thickness of the rings. For example, stages 6-9 have a total of eighty pierces on each ring and stages 10-14 have ninety pierces. Thickness decreases with the stage number, and because of this the stage 6 piercers need to be repaired most often. Although they pierce fewer holes, the larger thickness causes more wear on the assembly over time. When a piercer assembly breaks down it must be sent off-site to Building #5 of the Manchester plant for repair. It typically takes three days to return: two days for travel to and from Building #3 and one day to be repaired.

Another issue with the piercing process is inspection, which is performed on the first ring in a lot. If the ring passes inspection the operator continues with the lot, but if there are problems with the first ring the follow-up inspections are performed. This process adds to total lead time as operators do not perform inspection and must wait for an inspector.

Although inspection is performed using a shadowgraph, there are reservations about the reliability of its measurements as there is room for inspector error. Light is shone through the slots and on to a projection depicting the current slots' dimensions and tolerances. Before inspection can begin the projection must be focused and lined up with the light of the first slot. This can lead to variation between inspections of the same stages. Since there are a total of six inspectors that may use the shadowgraph, variations in measurements are apt to occur. There is also a question of whether the shadowgraph's measurements are even accurate. The light shown on the dimension projection is shone from the far side of the ring and through two slots before it reaches the projection. There is concern that this may skew some of the measurements and cause inspectors to miss otherwise bad piercings. Additionally there is no knowledge of the effect trumpeting has on measurements in the shadowgraph. Trumpeting may cause one side of the slot to be slightly larger than the other and it occurs naturally during the piercing process. Further investigation using other measurement techniques is needed to determine if the effect of trumpeting can be proven negligible in accurate measurements on the shadowgraph.

3.4 Straightening

The straightening process is the last process that the stator undergoes before it is shipped to Bodycote Ipswich for copper brazing. Straightening ensures that the ring is flat and perfectly symmetrical. The operator will place the ring on two pegs and turn the stator around them. Where the pegs come too close or too far away, the operator will take the ring and place it on a special stand. He then strikes the inner ring of the stator causing it to bend outwards slightly where he strikes it. After the ring has been fitted within the given constraints, the ring is laid flat on a slab of flat stone. A thin, flat piece of metal is slid between the rings and the stone. The width of the metal on the tool matches the maximum constraint for deviation from being perfectly flush with the stone. At any place where the tool does not touch the metal of the stator, adjustments are made in a similar fashion to previous check. Straightening also occurs after the ring is sent back from Bodycote Ipswich. It is notable that after discussion with the technician, stators need more adjustment after they are received from Bodycote Ipswich. In addition to straightening the stator, the operator also looks for excess brazing on the inner ring and vane.

3.5 Copper Brazing

Bodycote Ipswich brazes copper on the tang that protrudes from the inner ring of the stator. The copper passes through the gap between the tang and the pierced hole and creates a weld holding the vane in place. This process is done for every pierced slot. The copper is applied before brazing by the current operator. The amount of braze deposited is controlled by a foot pedal switch that the operator uses. As it currently stands, the equipment is unable to deposit a set amount of copper at each slot, which leaves room for variance and potential operator error. This unstandardized process may be creating enough variance in the amount of copper applied that it may be causing excess to form.

Issues with the current copper brazing process include the development of excess copper and the lack of copper braze development at all. Excess copper may form if there is too much copper applied or if the gap between the tang and the slot is too large. Copper may fail to pass through leaving a gap in the weld or no braze at all if the distance between the tang and the slot is very tight. If this occurs, the process can be repeated an additional two times. Afterwards, if the copper has failed to create a weld that meets the specifications of the customer, a defective tag is placed on the stator and it is then shipped back to the Manchester GE plant.

Typically GE Aviation in Manchester sends out one or two lots of stators to Bodycote Ipswich every day. After copper is applied, the brazing process takes about eight hours or one full work day to complete. Once Bodycote Ipswich has finished approximately three to five lots, they send a shipment back that is received by the Manchester GE plant roughly twice a week.

3.6 Coated and Honeycombed Stators

The Rolls-Royce stators are treated by one of two ways: a coated application or honeycomb feature on the interior ring of the assembly. The coated stators have an abradable nickel graphite coating applied at the outside vendor Metallizing Service Co Inc. located in West Hartford, CT. The honeycombs are applied at Praxair Surface Technologies located nearby the GE plant in Manchester, CT.

Both the coated feature and the honeycomb serve the same function in the engine, which is to create a seal between the turbine shaft and the stator to ensure that no air slips through without travelling across the airfoils of the assembly (Kay). The nickel graphite coating is comparatively very soft, as is the honeycomb, which by design allows it to wear down slightly as the engine is broken in, thus ensuring there is as tight of a seal as possible. The final customer, Rolls-Royce, uses the two kinds of stators for different engine applications, depending primarily on the environment the engines will be operating in.

As mentioned earlier, the nickel graphite coating is applied at Metallizing Service Co Inc. When the stators first arrive at the vendor, they undergo a visual inspection and are covered in a special tape. The tape protects the areas of the stator which will not be receiving the coating. Then the parts undergo a grit blasting process which roughens up the smooth aluminum rings to give the coating a better surface to adhere to. The actual coating is applied using a plasma gun. In its raw form, the coating is a powder which is vaporize passing through the plasma gun and adheres to the part. After a few coats are applied the tape is removed, any burrs of excess coating are removed, and the part is inspected again before being shipped back to the Manchester GE plant.

The honeycomb feature is brazed onto the stator assemblies at Praxair Surface Technologies. The untreated stators and the honeycomb material are shipped to Praxair from the Manchester GE plant. A braze tape of adhesive material is placed between the honeycombs and the stator and is TAC welded into place. The stators are then placed into a braze furnace and undergo a series of three heat treatments to fully adhere the honeycombs onto the assemblies and allows the honeycombs to harden and become more durable. A “leak down” test is conducted to ensure there is no gap between the stator and the individual honeycomb cells. After another set of inspections, the honeycombed stators are shipped back to the GE plant.

3.7 GE Aviation Manchester Plant Operations

GE Aviation Building #3 in Manchester, CT started off as a small, family run shop. As the demand for stators and some other products went up, they began producing more products for companies such as Rolls-Royce, General Electric, Volvo, Turbomeca, and many more. About four years ago GE Aviation purchased this facility and grouped it with GE Manchester. The original shop was a single, simple operational shop and therefore did not have the same standards, protocol, and regulations that a much larger company would have enforced. The transition has left some gaps which overall is creating a variety of problems, both internally and externally.

When this shop began, GE only had to comply with their customers’ standards. A customer would send them the exact specifications of a product including tolerances, sizes, procedure, and material composite. The shop would simply set their machines to comply with these given specifications and would be able to produce a product. Often times the machines would not give an exact product and reworking would be done along the way as well as after the first inspection to assure quality. With a smaller volume of products the shop was able to spend time fixing any issues, such as a deviation in the angles of a vane on a stator. As time went on, and especially after GE bought the business therefore expanding its needed output, the time it took to fix mistakes after the fact began causing a bottleneck in the overall production line. By the beginning on the teams' projects, the cell is several months behind in orders, costing them thousands of dollars, not to mention the unhappy and anxious customers they are constantly reporting to. Previously the factory only relied on the given measurements and specifications given by a client to produce parts, but now that they are at a much higher capacity with a record number of parts being ordered, they must begin looking at their productions and engineering from an internal perspective.

Previously records were not kept about machine maintenance, piercing blade sharpening, piercing size changes, different measurement tools, and many other important functions within the cell. This worked for the company for many years, but it left them at a huge loss once GE bought them and the demand skyrocketed. The current system is at maximum capacity, but it could handle more with some changes made within the factory, which is what the teams were sent out to look at. Like many other large corporations, GE expects documentation. For example, several years ago the size of the piercings in the stators was changed as the people assembling the stators were having a difficult time getting the vanes into the piercing slots. The piercing size was changed, most likely due to careful calculations, but none of this change was documented. Currently there is no record of the piercing dimensions or angles from before this change, nor are any of the calculations attainable. This lack of documentation makes it difficult for the teams to look at how that may be affecting extra copper brazing for example. The reason GE and many other large corporations require very detailed and accessible documentation is because they desire business continuity. If the person operating the hot upset machine who has been doing so for the last twenty years can no longer do so and someone else must come in to take over that job, will he or she be able to smoothly transition without operator error? Having data of angle deviation from before the piercing size change would help in the investigation of the deviant angles, because the data could easily be analyzed. Without proper documentation many people have to do the same process, such as changing a piercing size and taking new data, in order to solve a problem or make improvements. Essentially GE is paying their employees to do the same thing repeatedly. This lack of documentation has the potential to cost a company millions of dollars in payroll alone.

Many of the same people who worked for the cell twenty years ago are still currently working there. They have dealt with the transition in a different way. A common problem in a large corporation buying a small shop situation is that the workers who have been there for a long time are set in their ways. For example a man working in the cell doing piercings may not find it necessary to record his data or to follow new protocol because he had been doing it his way for so many years and did not see a problem with the way it was done. There are often undertones of hostility or stubbornness towards new management in these situations because the managers and people higher up running this facility are all new and often younger than those working in the cell on the machines. Issues of seniority and experience can be questioned. While in this case this does not seem to be outwardly present, it is still a definite possibility that some workers do not follow all of the new regulations carefully. Concrete evidence of this could be gloves. In the safety manuals the Manchester GE plant provides, all persons in the cell must be wearing steal toed shoes and safety glasses, and persons running certain machines must wear gloves, earplugs and/or more protective eyewear. Many machine operators do not wear gloves.

While this may seem like a small breach in protocol, they are still breaking the regulations. Someone who has worked on a particular machine for twenty years and did not have to wear gloves in the past is highly unlikely to wear them now even if the operator's manual for that machine requires the operator to wear gloves.

The customers of this production line expect quality products in a timely manner. Quality does not appear to be an issue, as there are several inspections for parts along the way and a final inspection which sends parts to be fixed if they are not up to standards. The reworking process, however, does take up a great deal of time and ultimately causes many, if not most, products to be delivered later than their original scheduled date of arrival. The clients send the facility specifications, such as tolerances, which can be different for every part for every client. The batches of same parts for same customer travel together with their design and specifications to each stage so that all operators involved clearly know what they are working on and what the tolerances and specifications are each step of the way.

There are several machines on location in Building #3 that the teams are looking at. Most of these steps only have one machine, but each machine may have several operators. There are standard first and second shifts, but there are also a few part time workers while talk of adding a third shift within the cell takes place. The recamber and inspection areas do have several stations. While generally speaking there is only one of each machine, there are parts within the machine that there are multiples of which must be constantly worked on, such as sharpening and making new pieces, by the workers in the machine shops. The piercing blades must be constantly sharpened to give the best results. The mounting rings must be constantly checked to make sure the location key slot is the perfect size, because if it is too large, the stator can and most likely will move around during production. Again, there really is no documentation or standards as to when the location key must be checked and measured or when the blade is too dull; these judgments are simply left to the operators, leaving large gaps for operator errors.

4. Issue #1 & #2: Excess Copper Brazing and Recambering Vanes

4.1 Methodology

The team's goal is to eliminate the occurrence of excess copper brazing on stator assemblies. Inspection does not occur until the stator is fully assembled making it costly to GE if rework fails or is impossible. To gauge the effect this issue has on the entire process, it is important to determine how long it takes on average to rework each affected vane and what effect this has on total lead time. Since excess does not occur on each vane, one can assume that there is some variation occurring during the process that is causing excess to form. To address this, the team will investigate the most likely root cause, the piercing process, in depth to examine all possible causes of variation. After collecting data, the team will analyze it to determine where, if any, variation is occurring. Finally, the team will provide recommendations to minimize or eliminate variation or offer other possible root causes of excess.

4.1.1 Project Plan

The following is a list of objectives and specific tasks the team will use to accomplish the steps outlined above. The order and flow of these objectives is shown in Figure 4.

- Perform preliminary problem analysis
    - Determine copper removal lead time
    - Common characteristics of excess copper brazing
- Identify and collect data for possible causes of variation in the piercing process
    - Prove that trumpeting is negligible
    - Collect data regarding die bluntness
    - Collect data regarding slot size
    - Collect data verifying consistency in tang sizes
- Analyze data to determine where variation is occurring

  - If yes, confirm that the found variation is impacting the copper brazing process
  - If no, look for other causes of copper excess
- Provide recommendations
  - Identify ways to minimize or eliminate occurrences of excess brazing
  - Identify other areas to analyze in depth that could be possible root causes

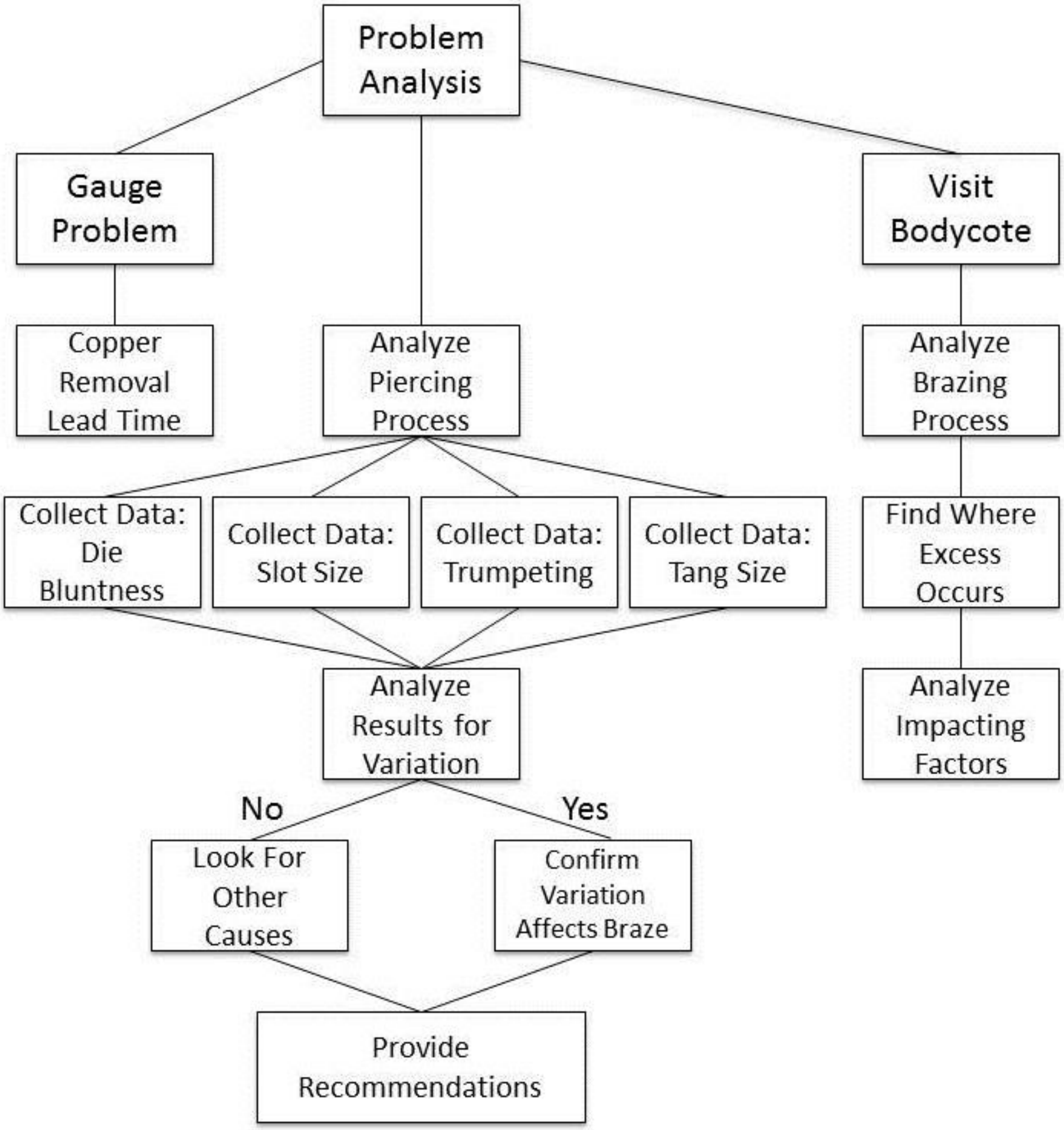


Figure 6: Issue 1 project plan.

4.1.2 Tools

To take measurements, the team will need to use tools that are precise enough to detect tiny deviations in measurement. Below is a list of tools the team will use:

- Calipers
- Mylar graph paper
- Shadowgraph
- Statistical process control (SPC) chart

4.1.3 Preliminary Problem Analysis

To perform preliminary problem analysis, the team will begin by quantifying the effect that excess copper brazing has on the assembly process. By finding the average removal time, the effect rework has on overall lead time is found. Any addition to lead time is detrimental but it is important to know just how much it is affecting the process. This may be difficult to do as GE does not have a standardized and easily searchable system. It would be tedious to sift through all of the existing records to find pertinent ones for stators deemed defective due to excess copper brazing. For this aspect of our project, we may be forced to go by the word and experience of our project contacts rather than develop our own quantitative evidence. It would be more beneficial for our team to focus our efforts on measuring the potential variation.

Also, the team will visit Bodycote Ipswich, the facility that performs copper brazing, to determine where excess occurs and under what circumstances. Bodycote’s current process for applying the copper braze will also be evaluated. The team will look at cases of excess copper brazing to determine if there are reoccurring characteristics, such as crooked vanes or improper slot size. These occurrences should be noted to distinguish which, if any, characteristics are contributing factors to the root cause.

4.1.4 Data Identification and Collection

To identify possible causes of variation in the piercing process, the team will collect data regarding trumpeting, die bluntness, slot size, and tang size. Variations in slot size will be measured using the shadowgraph. The shadowgraph is currently used by GE to inspect slot sizes on all stages of the stator assemblies. The process for measuring using the shadowgraph is not accurate enough to identify exact measurements of variations. To rectify this, the team designed its own system to provide more accurate measurements. The team printed a Mylar graph paper sheet with measurements in millimeters so the readings can be as accurate as possible. Using GE's current inner slot size drawing for the stage six rings, the team will align the Mylar sheet to easily measure four points located along the slot outline and the intersections on the Mylar. The first point the team is measuring is the length or the slot. Since the slot curves along its length, the team will measure the width of three points distributed along the left side of the slot. The x and y-axis, as well as other noticeable markings, will also be noted on the Mylar so it can be lined up to provide consistent measurements. Using the x and y-axis, specific measurements of each of the four points can be taken so that variation will be noticed at its first occurrence. Any occurrences of trumpeting can also be noted by comparing the measurements of the inside and outside slot diameter. The team will measure the first, middle, and last ring of ten lots of the stage six inner rings. Only 10% of slots evenly distributed on each ring will be measured to provide a well-balanced sample. Since there are ninety slots on each stage six inner ring, every ninth slot will measured and noted.

Regarding die bluntness, GE already has a system for documenting how often dies are repaired and how many punches they make before they break. This information compared with our measurements of slot size could help determine warning signs of die bluntness. If the team can determine warning signs that occur just before the die breaks, GE will be able to anticipate a repair and send dies out for maintenance before they add to total lead time or ruin a ring.

The team will also measure stage six tang sizes to identify any variance that occurs. After identifying a reasonable sample size of 50 fixed and 250 random tangs per each of the three team members, the team will use calipers to measure and record each tang's length and width. It is important to measure tangs to determine the degree of variance that occurs. Depending on the severity of the variance, we can provide suggestions to reprimand the problem or to leave the process as it currently is. To determine if trumpeting may be a contributing factor, our team will use the equipment in the surface metrology lab located on the WPI campus. Trumpeting occurs when the slot on one side of the ring is larger than the other. It is believed to be caused by a dull die during the piercing process. The more a die is used, the blunter the die becomes. This causes the pierces to lose their sharpness and edge and may create slight variations in slot size. The trumpeting that may occur passes inspection as long as the slot size is still within the acceptable tolerances. However, this slight difference in size can cause problems for vane and tang placement within the slot. Also, the added surface area may make the slots more susceptible to developing excess copper brazing, the issue we are trying to quantify and correct.

Before measuring, the team cut a scrapped stage six stator into smaller pieces to make it less cumbersome, flatter, and easier to measure under the microscope. The team cut each stator at every third slot leaving 60 slots for measurement. Then the vanes were removed from the inner ring. Since excess brazing typically occurs on the inner ring, this was the piece of the stator that was kept to measure. Using the microscope, the team noted the size of each slot on the inner and outer sides of the inner stator ring.

The measurements collected during this test prove whether or not trumpeting exists and to what degree. This experiment provides the group with a greater knowledge of the trumpeting that may or may not be occurring on the stator rings. From there, the team can determine whether or not the trumpeting experienced is negligible or if suggestions to minimize the occurrences should be made. The team was also able to determine if slot size increases as the ring is turned clockwise during piercing by checking for trends in the data. This paired with our slot size measurements collected by using the shadowgraph helped us develop accurate conclusions regarding the effect of trumpeting on excess copper brazing.

4.1.5 Analysis of the Data

After collecting the data mentioned above, the team will analyze it for occurrences of measurements outside of the provided tolerances and special cause variation. Using statistical analysis software or SAS, the team will input all of our collected data and generate graphs for the measurements gathered from each of our respective experiments. SAS will also provide accurate calculations for important values such as the mean, mode, standard deviation, and coefficient of variation, quartile divisions, and other information that will be helpful in analyzing the collected data. The team will analyze these graphs for trends within the individual measurements and collectively as a whole. If a significant variance does occur, it will be noted and elaborated upon in the analysis section. Options to reduce or eliminate variation will also be discussed in our recommendations and conclusions sections. If there are no noticeable variances in the collected data, other areas that may be the root cause will be identified and discussed as potential future project topics.

4.1.6 Recommendations & Conclusions

Finally, the team will draw conclusions and provide recommendations to end the occurrence of excess copper brazing. If variance is a factor found in one or more of our measurement analyses, the team will suggest changes in procedures or equipment that will decrease or eliminate this variance. If no noticeable variance is occurring, the team will provide possible methods to test other steps in the assembly process that may be contributing to the excess copper brazing. Also, the limitations of our study will be discussed, as well as suggestions to improve results and areas of future interest for other project teams or for GE itself.

4.2 Analyses and Results

The results of our data collection for the tang, slot size, and trumpeting experiments are detailed in graphs and figures located in Appendices A, B, and C. The following analysis will reference these graphs and figures and allow the team to develop a greater understanding of the strengths and shortcomings of each process and what is being produced. The team will evaluate data from each aspect of our experiments to find areas of variance that may be disrupting the assembly process and causing excess copper brazing to form.

4.2.1 Tang Size Analysis

The graphs created using the tang size data are located in Appendix A. The first section of graphs depicts the fixed tang lengths and widths collected by each respective operator. The first operator was Ethan Granoff, the second, Ed Spofford, and the third, Rebekah Socha. The fixed sample data is then compared to the other operators in multiple residual graphs. Then the samples of each operator are analyzed. Finally the total length and width measurements are depicted collectively in one graph and analyzed for trends resulting from special cause variation.

4.2.1.1 Fixed Tang Samples

In order to analyze the effects of human error on our measurements of tangs, a fixed set of 50 tangs was numbered and measured by each of the three operators. Each individual measured the length and width of each of the tangs, and the residuals were recorded. The purpose of these results is not to define the characteristics displayed in a sample of tangs, but rather to characterize the expected difference in measurements between operators. From the three operators that were taking measurements of length, three means were derived: 0.19589, 0.19592, and 0.19584 inches, respectively. This data shows that the average difference in the mean of length measurements from each of the 50 samples is 0.000053334 inches. The means of width measurements taken by the three operators were 0.04646, 0.04642, and 0.04584 inches, respectively. This shows that the average difference in the mean of width measurements is 0.0004334 inches. From an analysis standpoint, this data suggest a greater level of error from the width. This could be caused by multiple factors, although it is more than likely that the width measurements faced higher residuals because the tang has a tendency to widen as it moves closer to its attachment to the vane itself. These two average errors can be solely attributed to human error of measurement, which occurs naturally as a result of differences in measurement reading and tool placement on the tang.

After the measurements were taken, residuals data tables were created to compare the operators' length and width measurements. These calculations are located in, "Fixed Tang Length Residuals," and, "Fixed Width Residuals," sections of Appendix A. The residuals tables calculate the absolute value of the difference between the measurements of two operators. This shows for each specific tang how far apart the two estimated values were from each other. There are three comparisons for the length and width measurements: operator 1 vs. operator 2, operator

2 vs. operator 3, and operator 1 vs. operator 3. The average residuals for length were 0.00024, 0.00046, and 0.00038 inches. This information shows that operator error is negligible and will allow the data comprised of random samples to be more easily interpreted accurately.

4.2.1.2 Random Tang Samples

Each of the three operators was also required to measure a random sample of 250 tangs. This sample could not include any of the fixed tang measurements and also could not include tangs that had also been measured by another operator. The length and width measurements were inputted and graphs of the distributions were created and analyzed by each operator. Operator 1 is Ethan Granoff, operator 2 is Ed Spofford, and operator 3 is Rebekah Socha.

4.2.1.2.1 Operator 1 Length

The results of the sample measurements taken by operator 1 suggest a mean length of 0.19594 inches. Of the sample taken, 90% lied within the range 0.1955-0.1962 inches, leaving the excess 10% outside of that range. The data for this analysis can be found under “Operator 1,” in the, “Random Length Measurements by Operator,” section of appendix A. The bell curve shown in the histogram illustrates a rather small deviation from the curve, which implies that the majority of the samples taken were close to mean. One notable fact that can be observed by the data is the negative skew of the graph, a value of -0.6473. This suggests that should an observation be drawn from the samples measured by operator 1, there would be a more likely chance that the observation length would be smaller than the mean. In other words, the samples taken by operator 1 suggest that there is a trend for the tangs to be smaller than the mean rather than larger. All of the measurements of length taken by operator 1 remained inside the tolerances provided by GE Aviation. The first quartile was marked at 0.1959 inches, while the third quartile was marked at 0.1961 inches. This means that the middle 50% of the data lies within 0.0012 inches of each other. This would be considered a tight margin with respect to the tolerances and does not issue cause for alarm. The highest margin found was 0.1965 inches and the lowest at 0.1953 inches. The box and whiskers plot shows a good representation this. It is noticeable that there are three outliers to the plot outside the left whisker and only one outside on the right. This would further the suggestion of a positive trend in skew. While the data is conclusive in nature, it is important to consider the possibility that the observation in this sample could have been unusual, and therefore the data collected and the results and analysis interpreted by the other operators must be taken into account as well.

4.2.1.2.2 Operator 1 Width

To begin the initial analysis of operator 1's width measurements, the histogram suggests that the data is bimodal. Two distinct modes can be seen, the first mode in the interval 0.0460 to 0.0461 inches and another between 0.0470 to 0.0471 inches. This places the mean in the middle of the two at 0.04663 inches. Although the mean lies at that point, there are fewer observations around that interval because the mean represents more of an average of the two modes. There are a variety of reasons that could explain why the graph is bimodal. The first possibility is that there were multiple machines that were cutting tangs in the sample. One of these machines could have been freshly sharpened and the other could have been fairly blunt. Another possibility could be error in the operator measurement technique or measurement tool. To discount this as a possibility, the other operator's samples must be analyzed. The sample from operator 1 states a skew of 0.6316. Because this value is positive, it is considered negatively skewed and more likely to pull a sample that is above the mean. This also means that the greater of the two modes mentioned before is more likely to dominate over the lower mode. This tendency is important to remember and compare with the measurements of other operators. A final suggestion from operator 1’s width measurements is that the tail after the larger mode extends out much farther than to the left of the smaller mode. This means that it is not very likely to find a tang which is smaller than the smaller mode, but rather, it is much more likely that the tang is larger than the second mode.

4.2.1.2.3 Operator 2 Length

The results of the length measurements suggest that the stage six tangs have a mean length of 0.1957 inches. The standard deviation is 0.0004 inches. This number is an acceptable deviation within the measurements of the tang lengths. It is within the specified tolerance called for in the Rolls-Royce drawings. This assures that on average, the tangs are within 0.0004 inches of the specified size called for in the drawings. The bell curve on this data set is centered high in the middle with a slight skew to upper side of the range. The box and whisker plot is relatively centered. The box is larger on the lower side of the mean; however, the whisker is longer on the upper side of the mean. There are also three outliers on the upper side of the range, one of them significantly more distant from the mean. The mode of the sample is at 0.1958 inches. The Q3 is 0.1960 and the Q1 is 0.1955 inches. This means that the Q3-Q1 spread is only a range of 0.0005 inches. This is a small range. The overall range for all measurements is 0.0026 inches. This is larger than expected but is not problematic because the standard deviation and Q3-Q1 spread is small. The length of the slot size called for in the drawings is 0.2004 inches. This is larger than the mean value plus the calculated standard deviation, or 0.1957 + 0.0004 = 0.1966 inches. This is still 0.0038 inches smaller than the 0.2004 inch specified in the drawings. This leaves a gap of 0.0038 inches between the slot in the inner ring and the tang. This data was collected prior to the hot upset process that expands the vanes to form a press fit in the ring. This gap is acceptable;

however, it is on the larger side given that the gap specified for the width on the stage 6 drawings is 0.000 to 0.010 inches.

4.2.1.2.4 Operator 2 Width

The results of the width measurements suggest that the stage 6 tangs have a mean width of 0.0468 inches. The standard deviation is 0.0006 inches. The bell curve is non-standard on this data set because it is skewed to the lower side of the range. The box and whisker plot is well centered on the mean. The whiskers also reach approximately equidistant from the mean on both the upper and lower sides. There are two outliers on the upper side of the range as well as three outliers on the lower side. The mode of this sample is 0.0470 inches. The largest data point in this sample is 0.04850 inches. This is significantly larger than the mean. The Q3 is 0.0472 inches and the Q1 is 0.0465 inches. This means the total Q3-Q1 spread is 0.0007 inches. This is still a small range however it is a larger variance than was found in the length measurements. The entire range of the total sample is 0.0037 inches. The range is larger than expected, especially because the range on the length of the tang is so tight. The number of samples that match the mode is significantly higher than that of the length. This means that although the distribution is heavily centered over the mode, the spread is still larger than that of the length. This means that during manufacturing, although a high percentage of the vanes are close to the mode there are some extreme outliers.

4.2.1.2.5 Operator 3 Length

The data analysis produced by SAS can be found in appendix A, “The length data collected by operator 3 found the mean of the sample of 250 tangs to be 0.1958 inches. Most of the data points that were collected were close to the mean with more outliers on the higher rather than lower side of the taken measurements. This is evidenced by the low standard deviation of

0.0005 inches. The low deviation means that the majority of data points are located relatively close to the mean. However, one could argue that the data is in fact multimodal and that the true means occur at 0.19525 and 0.1954 inches respectively. Since the data can be perceived as multimodal, our team can assume that tang length is not always consistent and centered on one mean. The lengths of the tangs could vary based on when they were produced and on which particular machine. Despite the two peaks on the graph, it seems that the variance should not cause too much concern. The entire range of the data spans only 0.0022 inches. This range is certainly acceptable and well within GE's given tolerances. Also, the distance between Q3 and Q1, or the range of data concentrated between the 25th and 75th percentiles, is only 0.0008 inches. Comparatively, that is a very small distance. The fact that the distance where the majority of data points are is so small means that the variance in length can be viewed as negligible. Random variation will always occur with any process. The data Operator 3 collected provides no evidence that can strongly support the argument that length is contributing to variance, which, in turn, may be contributing to excess copper brazing. The data on the graph is positively skewed at 0.2345, meaning that if a tang was chosen at random, the lengths would most likely be larger than the mean and therefore located on the right or higher valued side. This simply means that the data is not evenly distributed. Since most data is not evenly distributed and skew is always a positive or negative value between 0 and 1, the measured skew of 0.2345 is within reason. The kurtosis value for the graph is -0.7172 inches. A negative value indicates that the distribution of the data is flatter and there is less of a peak in the data points. The value -0.7172 is very close to zero which is the common kurtosis value for a normal distribution curve. This means that the data distribution is flatter than most but is not experiencing so much variance that the range is abnormally large and the data is unacceptable.

4.2.1.2.6 Operator 3 Width

The data for this analysis can be found under “Operator 3,” in the, “Random Width Measurements by Operator,” section of appendix A. The width data collected by operator 3 found the mean of the sample to be 0.0474. This graph is relatively flat except for a tall peak at one point meaning one measurement was more common than all the others. The kurtosis value is given at 1.0044 inches. This indicates that there is a peak in the data points which is clearly shown in the figure. This point is located at 0.0472 inches and is the mode of the collected data points. This data set has a wide range at 0.0039 inches. While the standard deviation is relatively low at only 0.0006 of an inch, the wide range indicates that there are many varying measurements. This means that while the distribution of data is very vast, the measurements do not vary much between themselves. However, the vast data could be cause for concern since it may indicate special cause variation and not common cause variation. The short distance between Q3 and Q1 at 0.0007 inches is also evidence for special variation. The range is over 5.5 times larger than Q3-Q1, or the middle portion of the collected data points. One can assume that this means there are many outlying data points that contribute to a higher variation. The data displayed is negatively skewed at a value of 0.5956, meaning that the data tails to the left or to the negative side of the graph. It also means that a tang chosen at random will most likely be at the higher end of the measurements. Since skew is always a number between 0 and 1, the given value of 0.5956 indicates that the data is fairly skewed and could contribute to variance of tang width sizes. All of these points indicate that there are a wide range of measurements that were collected for tang widths. While all of the points are within the acceptable tolerances as set by GE, the wide range of acceptable widths can make it difficult to produce a quality product. The current state allows for variance to occur and does nothing to prevent it. It would be a different story if there was a wide range of data points but they produced a normal curve. Based on the current data points, the data is skewed and does not produce any shape remotely close to a normal curve. This variation combined with potential slot size variation may be leaving gaps or creating blocks between the tang and the slot that cause problems when the copper braze is applied. The variation in tang width should be noted as a potential factor that may be contributing to excess copper brazing.

4.2.1.2.7 Total Length and Width Analysis

The following analysis looks at the total length and total width measurements to see if a trend in variance is visible on a larger rather than smaller scale. The data included in this analysis is limited to the 250 random sample lengths and widths measured by each operator.

4.2.1.2.7.1 Total Length

The data for this analysis can be found in the, "Overall Tang Length Measurements," section of appendix A. The histogram shows a dominant mode at interval between 0.1959 and 0.1961 inches. Because it is clear that the there is a greater mass of samples that are smaller than this mode, the mean valued at 0.1958 inches, is slightly smaller than the mode. Because of this bias to the left of the mode, the skew is smaller than it should be. The tail to the left, or smaller side of the graph, shows a strong tendency for the tangs length to be smaller than the mode rather than larger. This is shown by the quartiles. The first 25% of the data is below 0.1955 inches. The 75% mark reaches 0.1960 inches which just barely exceeds the mean. This is a good way to show the tendency of the sample because it shows the middle 50% of the data is mostly below the mean. The box and whiskers plot also shows a good visual representation, with the box representing the mid 50% and the line through it representing the mean.

4.2.1.2.7.2 Total Width

The data for this analysis can be found in the, “Overall Tang Width Measurements,” section of appendix A. Immediate impressions of the histogram show an objectively even distribution in the shape of a bell curve. However, this bell curve is only seen when the intervals are set at 0.004 inches. With this knowledge, it is apparent the distribution of the graph has a large amount of variance. The mode and the mean are relatively equal to each other with a mean of 0.0470 inches and mode from 0.0470 – 0.04740 inches. Since the mean is at the beginning of the mode interval, the value of the calculated skew is slightly higher than the normal value of 0.3419. What is significant about the data is that there is a much larger amount of variation in width when compared to the variation seen in the length. This is important to notice because the excess brazing occurs on the width section of the tang as opposed to the length.

4.2.2 Slot Size Analysis

The graphs displaying the data from the slot size analysis begin in Appendix B. The initial graphs in the series are broken down by lot and then by ring. The first letter of the graphs is denoted with either the letter “l,” for length, or “w,” for width. The number after the “l” or “w” represents where the point was measured. Length was measured uniformly from the same point each time. Width was broken down into the three categories w1, w2, and w3. W1 represents the width located at the top of the slot, w2 represents the width at the middle of the slot, and w3 represents width at the bottom of the slot.

4.2.2.1 Total Length

The data for this analysis can be found under “Total Length,” in the, “Total Length and Widths,” section of appendix B. The histogram of the data shows three dominant intervals. These intervals are almost equal in height, although at the largest, the mode is placed at the interval between 0.202 to 0.204 inches. The mean of the data, 0.202742 inches, is found on the smaller side of the interval due to a slightly larger amount of length observations that are smaller than the mode. The present data would suggest marginal amounts of variation, although to support this visual assumption, it is important to analyze the quartile calculations. The first 25% of the data was smaller than 0.201280 inches and the largest 25% of the data was above 0.204724 inches. This leaves the middle 50% of the data between the two, a difference of 0.003445 inches. In addition, the quartiles plot also shows that the sample had a maximum measured length of 0.206693 inches, and a minimum measured length of 0.200787 inches. This makes the total range of the 108 observations sample 0.005906 inches. The data noted in this section will be important to determine whether there is an underlying issue with variation in the length of the tang when compared to the variation seen in the width measurements.

4.2.2.2 Total Width

As detailed in the methodology, the width measurements include an evenly distributed 10% of the slots from the first, ninth, and last ring, from four different lots of 16 rings total. This experiment was meant to capture data that illustrated variation in slot size due to sharpness of the piercing die. Before measuring, the team assumed that the die would be duller while piercing the last ring than while piercing the first ring of any given lot.

The first graph of width measurements was w1. The data for this analysis can be found under “Total Width 1,” in the, “Total Length and Widths,” section of appendix B. A first look at these graphs and data reveals predominant mode is found between 0.0492 and 0.0506 inches. When compared to the mean, 0.048839 inches, and a skew value of 0.2349, we can assume that there is a tendency for the data points to be larger than the mean. This is because the tail extends fairly far out on the smaller side of the mode, causing the mean to therefore also become smaller. In order to quantify variation in the data sample, the quartile values for data must be analyzed to determine how far apart the data is spread. The first 25% of the data for the total w1 measurements is smaller than 0.047982 inches. The last 25% of the data is larger than 0.049213 inches. This means that the middle 50% of the data is within these two values. From that, it is easily calculated that the middle 50% of the data covers an area of 0.001230 inches. In the sample, there is a maximum measured value of 0.05315 inches and a minimum value of 0.04527 inches, which means that the total range of the sample was 0.00787 inches. Factoring all of this together, it is safe to assume that the sample has a relatively large amount of variation when compared to the total length data. To confirm the results as consistent, total w2 and w3 measurements must also be analyzed.

The data for this analysis can be found under "Total Width 2," in the, "Total Length and Widths," section of appendix B. The histogram provided in the figure shows a mode at the interval of 0.0508 to 0.0516 inches. An immediate impression that can be taken from the graph is the tail that extends to the left or smaller side of the mode. This tail causes the mean to be smaller than the mode at 0.051026 inches with a skew value of -0.254382. This result varies slightly from the skew of w1, which as stated before, was 0.2349. This is most likely a result of the longer tail extending from the mode of the sample. The lowest 25% of the data is below 0.50197 inches. The 75% percent mark of the data lies at 0.51427 inches. This means that the middle 50% of the data has a range of 0.001230 inches. This is slightly less than the middle 50% range of the data in w1, but is not enough to cause concern of consistency within the sample set. Lastly, the maximum measurement taken was a width of 0.53150 inches, while the minimum measurement taken was a width of 0.47244 inches. Therefore the range of the entire sample is 0.005906 inches.

The last of the width measurements, w3, is a measurement of the width at the lower section of the slot. The data for this analysis can be found under “Total Width 3,” in the, “Total Length and Widths,” section of appendix B. Unlike the histograms for the first and second width measurements, the third width measurement is bimodal. The first mode lies in between 0.051 and 0.052 inches, while the second mode lies in between 0.053 and 0.054 inches with reference to the current interval setting of the graph. As a result, the mean is located in the margin of the first mode at 0.051272 inches. This means that the graph balances out around the first mode. Because the graph is bimodal, it is important to consider whether or not a specific lot of rings could be causing the data to very so widely. The analysis of the third width measurements from lot four is most likely the cause of the two modes seen in the total third width data. The data for this analysis can be found under “Lot 4: Width 3,” of appendix B. More than 50% of the data from this graph is located at a value of 0.53150 inches. This value was also the maximum point on the graph. This identifies two possible causes for the difference of the fourth lot from the first three. The first possibility is that there was a form of human error or measurement error. Based on the way that the experiment was designed, it would be difficult to justify a difference of this magnification, although it is not out of the question. The second possibility is that the data is accurate and that the die punched slots in the ring that were larger near the bottom of the slot. One factor that supports this possibility is that the first and second width measurements from this lot did not dramatically vary from other lots. This suggests that the variation could be from the die because the third width measurements were taken at the same time as the first and second width measurements for any given punched slot.

4.2.3 Trumpeting Analysis

The data for this analysis can be found in appendix C. The results of the trumpeting analysis are not quantitative like those of the tang analysis. They are qualitative because the machine used to take the measurements was unable to focus on the entire part at once.

The trumpeting analysis shows that trumpeting is occurring in the middle of and on the inside of the punched ring. Close inspection shows that the outside of the ring shows a slight indent and a clean punch at the slot. This is exactly what is supposed to be occurring when the slot is punched in the ring. This shows that the punch is making a good entry into the ring. The punch slots measured from the front of the ring had a range from 1235.409 to 1332.265 nanometers across. The punch slots measured on the inside of the ring had a range from 1314.642 to 1546.548. The slots are consistently bigger on the inside of the ring however the amount of trumpeting is inconsistent.

Although this data shows that trumpeting is occurring on the inside of the punched slots, the pictures from the electronic microscope at five and ten times magnification show that there are two stages of trumpeting. The first stage of trumpeting is happening in the middle of the punched slot and is causing the walls of the slot to be angled so that the slot on the inside of the ring is larger than the slot on the outside of the ring. This stage one trumpeting is contributing to the copper braze build up around the veins. This is occurring in the middle of the punched slot along the punched axis. It is causing the braze, which pulls through the cracks like water when at temperature in the oven, to pull through too much, causing a buildup of excess braze at the base of the vein. The second stage of trumpeting is occurring on the inside surface of the ring. There appears to be a chipping effect that breaks away chips from the areas adjacent to the slot. This is a normal phenomenon when punching through a material with a blunt object. This suggests that the die may be blunt when piercing the slots. Unfortunately our sample was limited to two rings and it is not known how new the die was when each particular ring was pierced. This second stage may also be contributing to the copper braze buildup. Once excess copper braze has been pulled through ring, the second stage of trumpeting acts like a trough for the braze to sit in, allowing it to accumulate around the vein.

The first stage of trumpeting appears to be consistently deeper than the second stage; however, the second stage appears to be consistently wider and reach laterally farther away from the defined slot opening. Even though trumpeting is present, we have determined that it is not contributing to the excess copper braze. The trumpeting is not severe enough to cause a problem during the hot upset or copper braze process. It is possible that a blunt die could exacerbate the problem; this would cause severe trumpeting and would cause a large increase in the excess copper braze issue. Because of this the die needs to be kept sharp so that trumpeting does not increase. Overall it was determined that the trumpeting was not severe enough and was too inconsistent over each individual slot to be considered an issue.

4.3 Conclusions and Recommendations

Our group has spilt the conclusions and recommendations section into goals for the short-term and long-term. Short-term goals should be able to be completed within the next year or two. Long-term goals can be accomplished within five to ten years.

4.3.1 Short-Term

Based on our analysis of the tang measurements, our group was able to draw the following conclusions regarding the current tang production. The variation in length measurements can be dismissed as negligible. All collected measurements were well within GE's given tolerances. The minimal variance that did occur can be considered common cause variation that occurs naturally during any manufacturing process.

However, the variation in width should be further investigated. Each set of data that was collected had a wide range and a high coefficient of variance. Although none of the sampled tangs included a measurement for width that was outside of GE's specified tolerances, there is not enough consistency in the data to conclude there is nothing wrong with the tang widths as they are currently. In addition to the wide range and high coefficient of variance, the majority graphs are multimodal and represent either a positive or negative skew of data. Since the modes and curves of the data are so inconsistent, our group would be wrong to assume the variance in width is negligible.

To rectify the variance in tang width, our group's recommendation is to tighten the current width tolerances. Tighter tolerances will lead to less acceptable variation and, ideally, a more normal mean and mode. This change will most likely lead to a higher percentage of scrapped tangs. If the rejection rate climbs to high, GE may want to consider investigating the current production process. Equipment should be checked to determine whether it is just one machine or all machines that produce tangs of varying widths. If there are only a few machines that produce tangs at a statistically higher or lower mean, perhaps those can be tinkered with and made to produce tangs of the correct mean regularly instead of sporadically. This change will create a better, more uniform fit between the tang and vane and will help reduce the number of occurrences of excess copper brazing.

With regard to our slot size analysis, our group found that variance in the length of the slots is negligible. However, we were able to determine that the variance in width was not negligible and steps should be taken to prevent and eliminate it. This variance was noticeable on all three width measurements but most detrimental on the third width.

To rectify this, we recommend that GE should purchase a sharper die made from a stronger material to pierce the slots. If all the dies cannot be replaced at once, the replacements should start at the thickest stage, or stage six, and go in order from there. A sharper die will lower the variation in slot width and will stay sharper longer. This will decrease overall lead time for GE in two aspects. The first is a sharper die made from a stronger material will blunt less often and will not need to be sent out as often for repairs. The second is a die that punches clearer, more accurate slots will create less variance and will prevent many future cases of excess copper brazing. This change would allow GE to experience lower lead times immediately especially with regard to the stage six rings which are the thickest and whose die breaks most often.

We were also able to conclude that the amount of copper braze paste applied to the outside of the ring is inconsistent because the operator currently uses an on demand application valve that is activated by a foot pedal. Our team recommends that this be upgraded to a time release valve that, when activated, releases a predetermined amount of copper braze paste. This will help prevent over application and place the proper amount of braze in the area needed. This will help reduce the excess braze issue; if there is no extra braze that can accumulate at the base of the vane, then it cannot cause excessive braze build up.

The team also investigated the Hot Upset process at GE Manchester. We determined that some of the vanes were loose in their slots prior to the hot upset process. This could cause a recamber issue if the vanes are frozen at the wrong angle. In order to decrease rework and lead-time for the recamber process, our team is recommending that a fixture be created to hold the veins at the proper angle in the slots for the hot upset process; a visual of this fixture may be found in Appendix E. We feel that this fixture is the best way to combat misaligned vanes before and during the hot upset process. This fixture requires minimal investment and little to no modification of the hot upset machine; this will minimize the down time of the machine during the conversion process. We feel that it is worth the down time of fitting the new fixture to the machine, as well as training the operators with the new procedure in an attempt to decrease rework time farther down the production line.

4.3.2 Long-Term

In the long term our team recommends that GE reduce the piercing slot size. This will increase the interference fit that occurs during the hot upset process and hold the vanes tighter before hot upset takes place. This could either eliminate the need for a fixture, or augment its holding capability. We also recommend that GE begin the process of finding new manufacturing machines. The machines that are currently being used are antiquated and well-worn in. We think that by upgrading the machines GE could remedy the reliability and variability issues that the old machines are introducing. Purchasing new equipment is a large investment and may be far down the road, however GE Manchester should have new machines selected incase GE decides to spend more capital to upgrade the production line.

4.4 Limitations

Our team encountered several limitations during the course of our project with GE aviation Manchester. The first limitation was time. Our team did not have enough time to perform some of the experiments we wanted to perform. While some of the experiments were off site at GE vendors, some of the experiments were long-term studies at the GE facility. These tests could easily be performed by a GE employee. This caused the team to have to reduce the sample size for several of the experiments. This also caused the team to eliminate several of the experiments that would have investigated certain specific issues in depth. With respect to the experiments that were conducted, many were performed with a smaller than expected sample size because the team was unable to take live parts off of the production line to do destructive testing because of the expense each part.

Another limitation was the absence of a budget for this project. Although GE offered to support our team financially if necessary, there were no reasonable opportunities to take advantage of this. Unfortunately we had to eliminate a slot size experiment because we were not able to get the necessary supplies needed in time to perform the test.

5. Issue #3: Honeycomb Stator Discoloration

5.1 Methodology

To accomplish the project goals for the issue of manufacturing the honeycombed stator assemblies and discovering the root cause of the discoloration, the Issue #3 team used the Six Sigma DMAIC methodology.

- **Define** the scope of the issue and what stakeholders are involved.
- **Measure** when the issue occurs.
- **Analyze** factors that could contribute to the issue.
- **Improve** production process by eliminating issue.
- **Control** the issue by documenting interventions and continuously improve process.

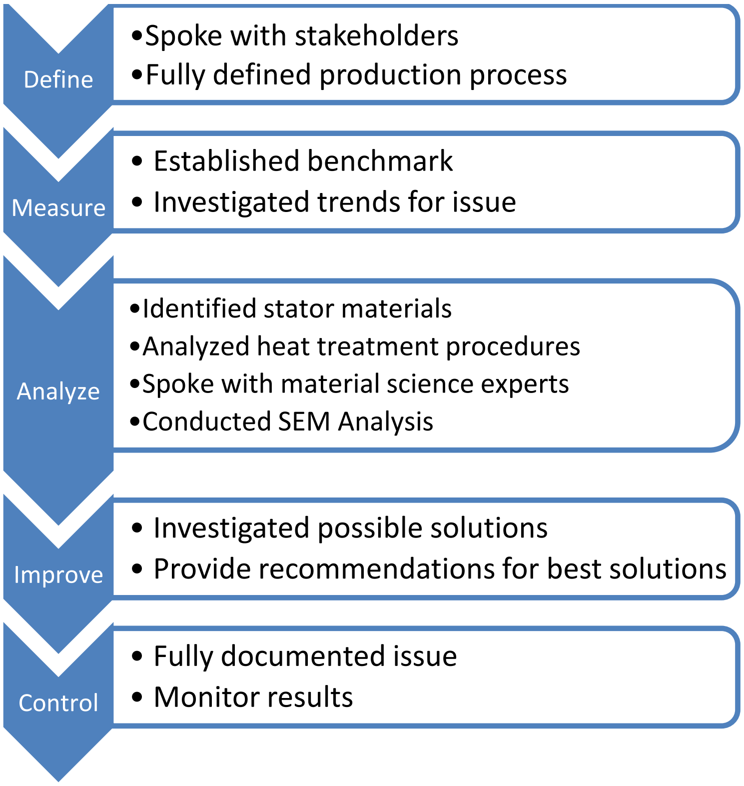


Figure 7: Issue 3 project plan

5.1.1 Scope of Issue

In order to fully understand the issue, the team fully defined what it entails. The scope of the project encompassed all parties that have a stake in production and use of the stator assemblies as well as what the implications of the issue are. The team's main contact at the GE Manchester plant was Samantha Cote. Ms. Cote is responsible for the production of the Rolls Royce stators that the project is focusing on. Ms. Cote, other employees at the Manchester GE plant involved with the manufacturing of the stators, the vendor who brazes the honeycomb feature onto the stators (Praxair Surface Technologies), and the customer (Rolls-Royce) are the primary stakeholders in the process.

The first step in defining the issue was to tour the manufacturing facility and become familiar with how the stators are made and where specifically the discoloration is noticed. Information was gathered about what processes are used in manufacturing, and the different steps required to produce a finished assembly. The team spoke with stakeholders directly involved in manufacturing at GE, specifically the product inspectors. Praxair was also a main focus for the project, since there were clear indications that the discoloration was noticed on the stators after the brazing process at their plant. By defining the impact of the issue, the team was able to better gauge what interventions were necessary and how to best mitigate the problem.

5.1.2 Quantifying and Measuring Discoloration

The next step for the team was to quantify the issue through careful measurement. Through stakeholder interviews, the team established a baseline for when the discoloration began occurring and if there were any evident historical trends. Knowing when and where the issue developed and if it has changed at all over time provided useful clues towards its origin. The team also examined the entire production process in greater detail, paying close attention to any steps that could be contributing to the quality issue. By mapping out where the discoloration first occurs in the process and the steps preceding this identification point, the team had a better idea of where to focus the investigation of the issue.

It was important to quantify the problem as much as possible. Figures of how many assemblies are affected by the discoloration would need to be gathered as well as the severity of how much their appearance has changed. This again could be a powerful indicator of what key factors exist that may be contributing to the problem. This data can also be used to statistically model the effect the discoloration has on the total output from the plant, which will help gage the impact the issue has. An issue in the identification process has been the perception of the discoloration by those inspecting them. A definitive measure will need to be established to avoid ambiguity.

5.1.3 Analysis of Honeycomb Manufacturing Process and Discoloration

The team analyzed all factors involved in the stator assembly process in order to gain a better understanding of why and where this issue occurs. Analysis began with first identifying all foreign materials that the stators come in contact with and the alloys which comprise the sections of the parts of the assemblies. By cataloging these materials, the team aimed to recognize all possible contaminants that may be a potential cause of the issue. A list of these materials and their chemical makeup could be created in order to compare the foreign contaminants to the material of the stator assemblies. By doing so, a pattern or indication of where the discoloration originates may be noticeable.

Once all of these materials were identified, the next step was to closely examine heat treatment procedures to help determine if the discoloration occurs during one of these processes, and to gain a better understanding of how the treatment works. The honeycombed stator assemblies go through a heat treat process at two external vendors, Bodycote Ipswich where the copper brazing is applied, and Praxair where the honeycomb feature is applied.

Following the study of heat treatment procedures, the team spoke with WPI material science professors to seek advice and opinions on the issue, given what was known thus far. With the aid of these professors the team was able to conduct a chemical analysis on the discoloration to determine its chemical structure, which was accomplished using a Scanning Electron Microscope (SEM).

A Scanning Electron Microscope uses a beam of electrons to produce extremely high resolution images. An analysis method using a SEM known as Energy-Dispersive x-ray Spectroscopy (EDS) measures how electrons are reflected off of the specimen being examined. These reflected electrons can be used to determine the elemental composition of the specimen. An EDS analysis was an extremely helpful tool for the project, because from this technique the team was able to determine which elements were appearing on the surface of the assemblies.

5.1.4 Improving & Controlling Manufacturability of Honeycomb Stators

Following the in-depth analysis of the issue, the next steps were to compile the results and to determine what can be done to solve the issue of discoloration. The results of the analysis provided the team with tools and knowledge that helped investigate possible solutions that were options to resolve the issue. If the proposed solution and further recommendations are implemented, it is important to document all outcomes that arise as a result. Documenting the outcome is extremely important so that the team may recognize if the solution did in fact make the process more efficient in the end. Documenting such accounts will help the manufacturability in the long run because it will allow for continuous improvement as new suggestions and interventions arise in the entire process. The objective of this chapter is to document the process the team took to investigate that is relevant to the discoloration issue and to provide grounds for future research.

5.2 Analyses and Results

5.2.1 Brazing Process at Praxair

Over the past years, the relationship between the Manchester GE plant and Praxair Surface Technologies has been a successful interaction. Due to the good relations, GE's concern with the discoloration of the honeycomb stator assemblies equates to just as much as a concern for Praxair. Because their customer is unsatisfied with a product that does not meet their standards, Praxair realizes the severity of this issue and is open to help resolve it.

The braze cycle at Praxair is the technique which applies the honeycomb segment onto the inner ring of the stator assemblies. Through the braze cycle, the stators undergo temperatures of 1900°F for three minutes per lot. After the cycle is complete the stators go through heat treatment, which consists of precipitation hardening and temperatures of 1150°F for four hours. Because the past method that Praxair underwent with their oven heat treatment showed discoloration on the stators after the heat treatment, the company recently chose to change their method to experiment. Presently Praxair puts the stators through a single oven technique, and although the discoloration is still apparent after this change, it does reduce total time by eleven hours.

After tours of their facility and interviews with their employees, it is evident that Praxair is looking into their options of what they can do to help avoid discoloration in the future. They have made mention of a *Praxair Fast Team* that is composed of corporate employees that can help further investigate the issue, and they have also made strides in adjusting their techniques in regards to brazing and heat treatment.

5.2.2 Scanning Electron Microscope

One of the main initiatives for the team was to analyze the surface of the stators to determine the chemical composition of any surface layers which may exist on the assembly. To accomplish this, the team used WPI resources to conduct an analysis using a Scanning Electron Microscope (SEM).

A SEM device projects a beam of electrons on a specimen and can form extremely high resolution images based on how they are reflected. Each chemical element reflects electrons differently and releases x-ray energy. Based off of this released energy, the SEM can determine the chemical composition of the sample. This process is known as an Energy Dispersive x-ray Spectroscopy, or EDS.

The team performed an EDS analysis on a section of a honeycombed stator which had been cut from the assembly in order to fit into the SEM machine. Three sites were analyzed on the specimen: an edge of the airfoil, the honeycomb material, and finally the outer ring. See Figure 8 for a diagram of the sites evaluated on the sample. Prior to conducting the analysis, the specimen underwent a twenty-minute acetone bath to ensure the surface was free of contaminants.

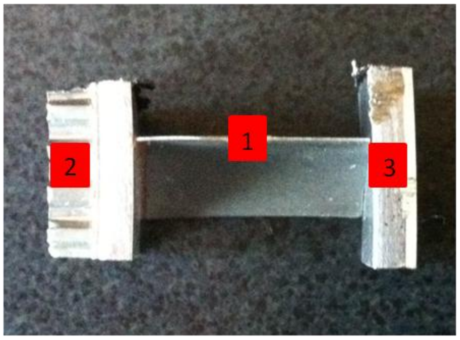


Figure 8: The sample evaluated in the SEM and the areas analyzed.

The following sections show some of the results of the EDS analysis. For the full results please see Appendix F. The scale on the bottom of the graph (keV) is a measure of the energy emitted by the SEM. When examining the graphs it is important to note: the higher the peaks of the graph, the greater the concentration of the respective element.

5.2.2.1 Site 1 – Airfoil Results

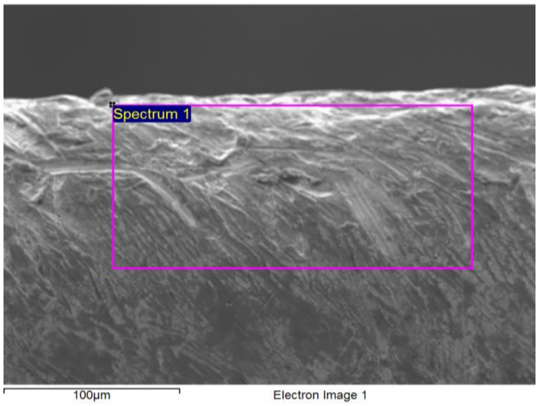


Figure 9: The surface of the airfoil as captured by the SEM.

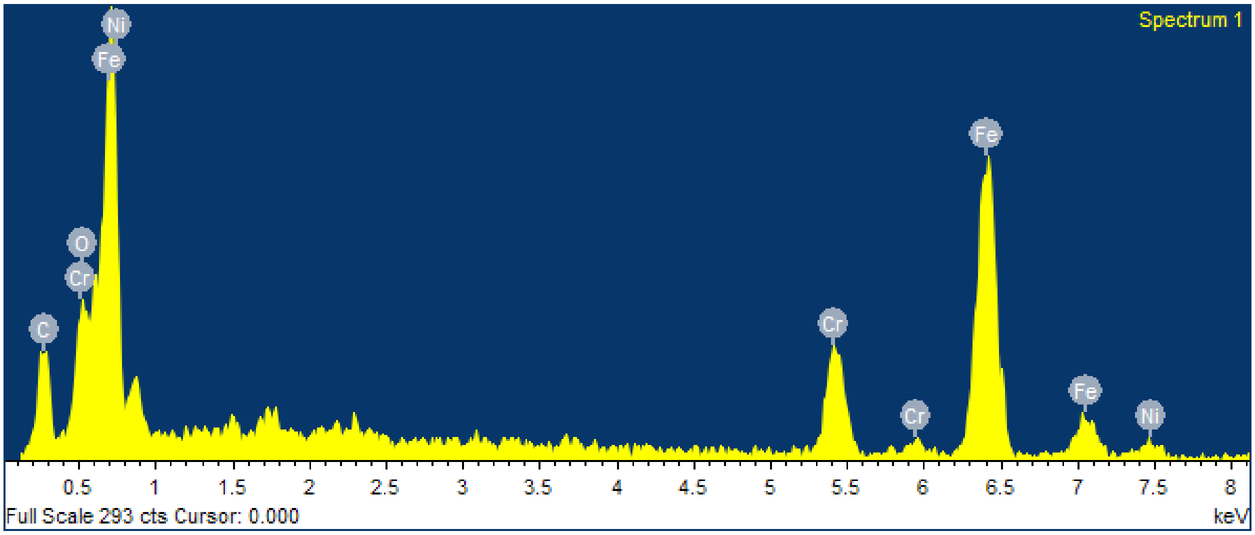


Figure 10: EDS graph of the surface elements on the airfoil.

The results of Site 1 show high concentrations of iron and chromium, which is to be expected from the alloy of stainless steel as it is comprised of (EMS 70755). Between the range of 1 keV and 5 keV, there is some noise in the graph, signifying that there are trace elements being picked up by the analysis. Due to limitations in the precision of the EDS analysis, the team was unable to identify what there materials were. A more sensitive analysis method would need to be utilized in order to accurately determine the composition of these trace materials.

5.2.2.2 Site 2 – Honeycomb Results

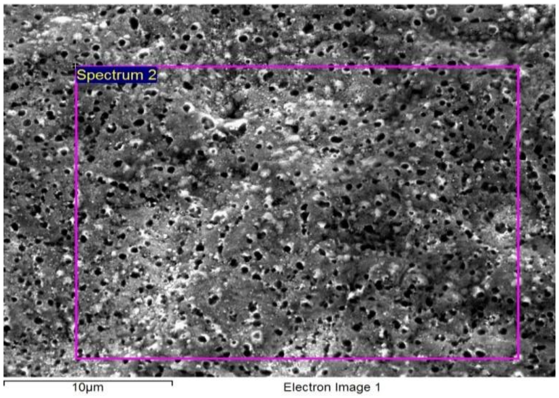


Figure 11: The surface of the honeycomb material as captured by the SEM.

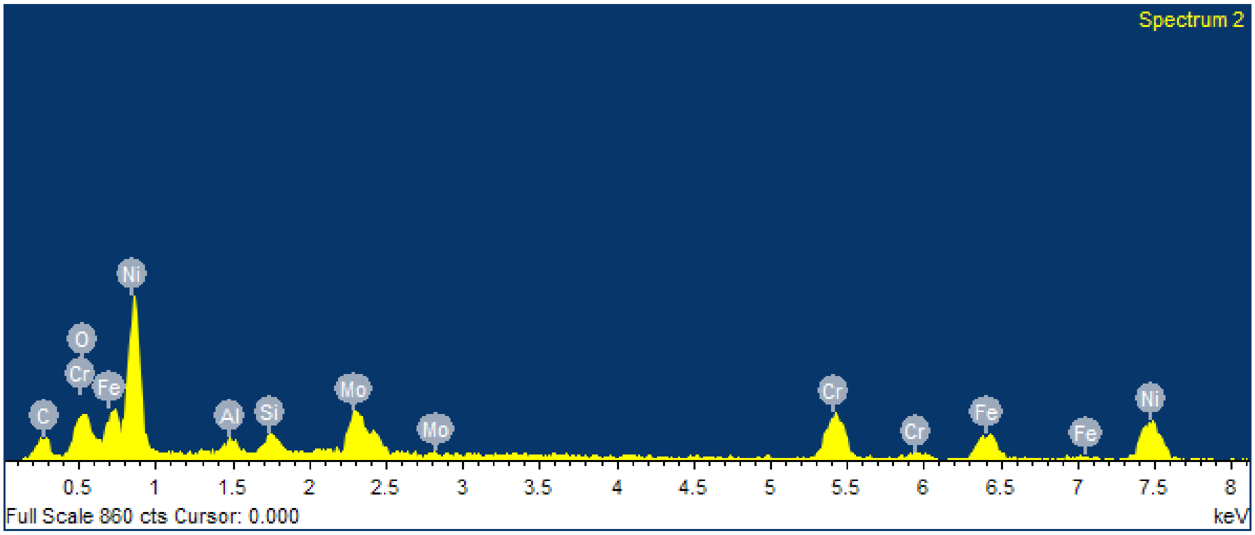


Figure 12: EDS graph of the surface elements on the honeycomb material.

Based on the surface analysis of Site 2, the honeycomb, it is apparent that there are lesser concentrations of more materials. The honeycomb is comprised of a nickel based alloy (AMS 5536M). As with the airfoil examination, the same energy range (1 keV – 5 keV) shows traces of other elements. There were four spectrums recorded of the honeycomb, the other graphs are available in Appendix F.

5.2.2.3 Site 3 – Outer Ring Results

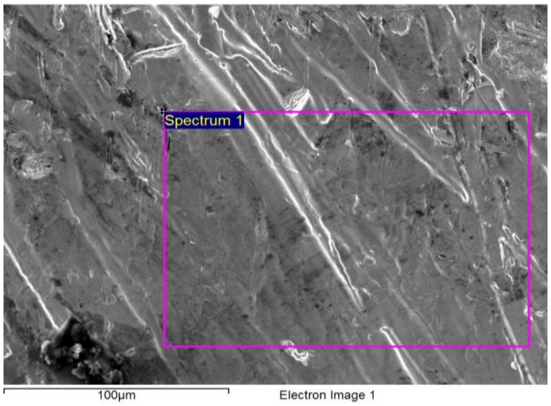


Figure 13: The surface of the outer ring as captured by the SEM.

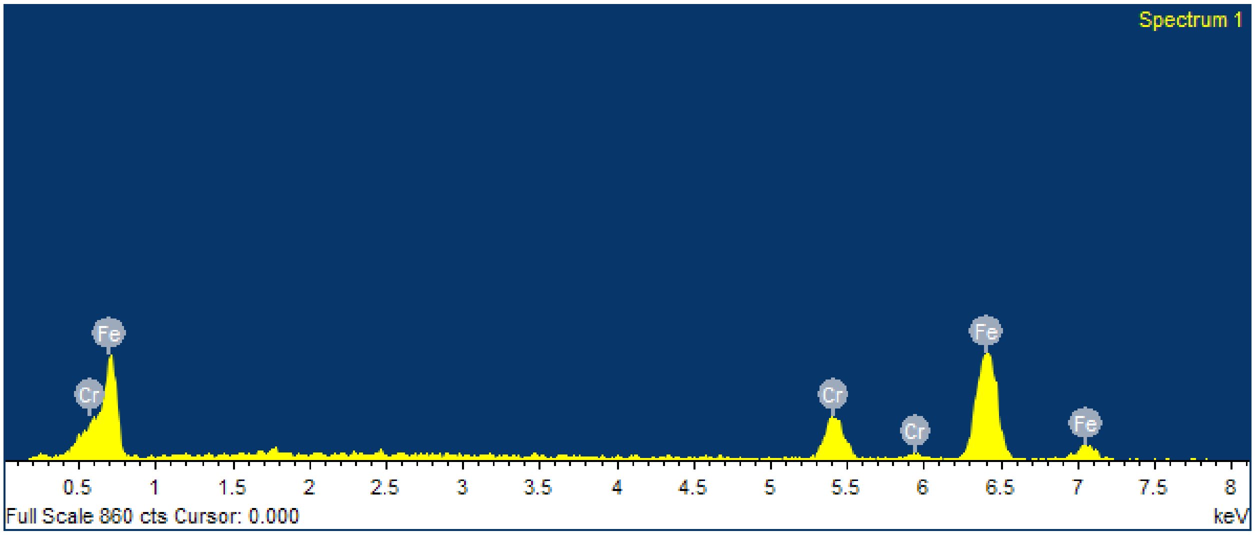


Figure 14: EDS graph of the surface elements on the outer ring.

The results of the EDS on Site 3, the outer ring of the assembly, exhibited much clearer peaks and significantly less noise than the other spectrums. There were three spectrums recorded of the honeycomb, the other graphs are available in Appendix F.

5.2.3 Expert Consultation

The team recognized that a large component of the analysis for the project consisted of in depth material science topics and the study of heat treatment processes. Having only an introductory knowledge of material science and no experience in the field of brazing and heat treatment, the team sought help from experts in those respective fields. The project team is very thankful for the input and assistance of WPI Professor Richard Sisson and Dr. Boquan Li, the inspectors at the GE Manchester plant, and the brazing experts at Bodycote Ipswich.

From the feedback of the various experts who were interviewed during the extent of the project the team was able to identify a number of potential problem areas or factors that could be contributing towards the discoloration issue.

5.2.3.1 WPI Professors

Professor Richard Sisson is the Director of the Manufacturing Engineering and Material Science programs in the WPI Mechanical Engineering department who also has extensive experience in metallurgy and heat treatment. The team met with Professor Sisson a number of times throughout the course of the project for consultation. After visually inspecting a sample stator the team was able to provide and providing background information towards the issue, Professor Sisson's first impression was that it is a surface issue, meaning that through some means a layer of oxidation or other material is building up on the assemblies.

There are many different variables to control during heat treatment processes, leaving a number of possibilities for unwanted discoloration to arise from. As was stated, Professor

Sisson’s first impression was that there is something that is either reacting on the surface of the assemblies or a buildup of material that is concentrated on the surface. There are a number of causes which could account for this, but Professor Sisson’s take was that there is a gas in the oven environment that is adhering to the parts. The stainless steel alloy used in the assemblies (AMS 5627G) has a high concentration of chromium. A thin layer of chromium oxide could be forming on the assemblies, which is potentially a cause for at least some of the discoloration.

The color of the discoloration can be an indication of what material is causing it. The stators have been known to be a dark cobalt blue, yellow, as well as simply dull or gray. The thickness of the layer of discoloration can be an indicator as well. Professor Sisson was focused on how the assemblies are cleaned. Any contamination on the stators could certainly cause discoloration, as well as if there is any residue left on the surface as a result of cleaning.

Directly following the first meeting with Professor Sisson, he reached out to Roger Fabian, a colleague of his who is an expert at vacuum brazing. Mr. Fabian’s take on the issue is that there is a problem with the ovens at Praxair, particularly during the back fill process where argon is pumped into the vacuum environment to raise the pressure back to normal and cool the parts. Mr. Fabian was concerned that there may be leaks in the back fill system or the argon used to repopulate the vacuum is impure. Impure gas or ambient air entering the ovens during the vacuum phase both contain impurities which can adhere to hot parts and are common sources of discoloration. Professor Sisson advised examining the ovens at Praxair and investigating whether they are having any issues with leaks or impure argon.

After having conducted more research on the project, the team met again with Professor Sisson to discuss the findings and follow up with conducting a SEM analysis. In the interim, the team had revisited Praxair and discussed Professor Sisson’s thoughts. Praxair assured the team that the ovens are well within specs for their leak tolerances and that the argon is certified pure from the manufacturer. Given the absence of any conclusive information related to oven issues, Professor Sisson agreed with Praxair's view that there is a material in the assembly which is offgasing during the braze cycle and reacting during the precipitation heat treatment. His main suspect for the offgasing material is the braze tape which binds the honeycomb onto the part. The braze tape undergoes liquefaction during the process and could very well be releasing gasses as well. Professor Sisson also mentioned that small changes in the metallurgy or alloy chemistry could cause the material to react differently, and could be the cause of random off-gassing.

Professor Sisson suggested that the best course of action would be to run quantitative analyses on sample assemblies in order to determine what composition of the discoloration. He put the team in contact with Dr. Boquan Li who is the manager of the Materials Characterization Laboratories at WPI. Dr. Li assisted the team with the Scanning Electron Microscope (SEM) Energy Dispersive x-ray Spectroscopy analysis (EDS).

In addition to the EDS, Professor Sisson suggested other analytical methods that can be used to gain insight towards the discoloration issue. A mass spectrometer is an effective tool for determining the elemental composition of a material. A mass spectrometer directly attached to a vacuum oven would be an effective method for determining which gasses are emitted as the sample is heated, and could determine what is off-gassing. This however is a very specialized application of a mass spectrometer and is difficult to find this sort of device. Similar to EDS analysis, X-ray Photoelectron Spectroscopy (XPS) and Auger Electron Spectroscopy (AES) are both analyses which can be used to determine the elemental composition of the surface of the samples. XPS and AES are more precise measurements, and are able to detect smaller amounts of elements than is possible through an EDS analysis.

Throughout all of these analyses the best results can be achieved by analyzing a significantly discolored specimen. The more a part is discolored, the thicker the layer of material in question and the more there is to analyze.

5.2.3.2 GE Inspectors

The team also made it a point to speak with the inspectors in Building three who have a firsthand look at the finished assemblies. The inspectors of Building #3 have the final say on whether or not an assembly is discolored enough to merit the vapor blasting process. The team was able to speak with three product inspectors and ask them what they have seen in terms of discoloration over time and if they noticed anything that may contribute towards the issue.

The first inspector the team spoke with mentioned that the discoloration was very inconsistent; there would be times when there would be no discoloration in any shipments, other times there would only be some discolored parts, and sometimes the entire lot would be discolored. They would also go long periods without seeing any discoloration, only to have more become apparent in lots later on. He mentioned that roughly one in every twenty lots was discolored. The first inspector’s take was that if the discoloration was arising from something at GE then every lot would be discolored. He suggested studying Praxair’s heat treatment process in detail, particularly that the proper procedures were taken.

The second inspector the team had the chance to speak with was very confident that the discoloration is a result of something happening at Praxair as well. Her suspicion was that since the stainless steel in the assemblies is subject to a great deal of stress during the brazing and heat treatment processes, the properties of the materials change and they lose some of their corrosion resistance. She also mentioned that she notices three out of every five lots which require vapor blasting.

The final inspector that was interviewed had yet another perspective. He informed us that most of the complaints from Rolls-Royce were that the assemblies were experiencing rust. There has been difficulty in the past determining whether the issue is rust or discoloration, but he believed that rust or some other form of oxidation was the cause of the discoloration issue.

From the GE product inspectors the team learned that there are differing opinions on the extent of the discoloration issue and how much of an impact it has. The team was able to gather important information relevant to the issue from those who were directly handling the products, and gained more insight into what could be causing the issue.

5.2.3.3 Bodycote Ipswich

The Bodycote facility in Ipswich, Massachusetts is the vendor GE utilizes to braze the copper material on the inside edge of the airfoils on the stators. Bodycote Ipswich also conducts brazing operations, including honeycomb brazing for their customers other than GE. The team asked the engineers at Bodycote if they experience any discoloration in their operations. According to the engineers, there is inherent discoloration in any sort of heat treatment procedures.

Through the input from the engineers at Bodycote, the team was able to identify a number of other potential contributing factors. They stressed that the parts absolutely must be clean prior to the heat treatment process. Foreign contamination from the parts themselves or from some other means, such as dirty seals on the oven doors, can certainly cause discoloration. They also mentioned that the pump system for maintaining the vacuum in the ovens must be in good working order. Any oxygen that leaks into the ovens can adhere to the part and will cause a blue layer to form on the parts. Another consideration is that there may be a gap between the thermal coupling temperature gages and the actual temperature of the parts. Exposing hot parts to ambient air can result in discoloration as well. They specifically mentioned that the braze tape for the honeycombs has a tendency to offgas, which may be very similar to what is happening at Praxair.

It was very helpful for the project team to speak with another brazing facility and get a better view of discoloration on a wider scale. The team took Bodycote Ipswich’s feedback and used this to further analyze Praxair’s brazing process.

5.2.4 Cause and Effect Analysis

From the various techniques and interviews conducted through the analysis phase of the project the team was able to determine a number of contributing factors which can result in discoloration for the vane assemblies. The results were combined and summarized into the Ichikawa Diagram shown below.

The most suspect areas are the issues related to the ovens and material vaporization, or offgasing. The diagram is divided into internal factors and external factors. Internal factors are those for which the stakeholders (GE and Praxair) have direct influence over, whereas with external factors they may have less control.

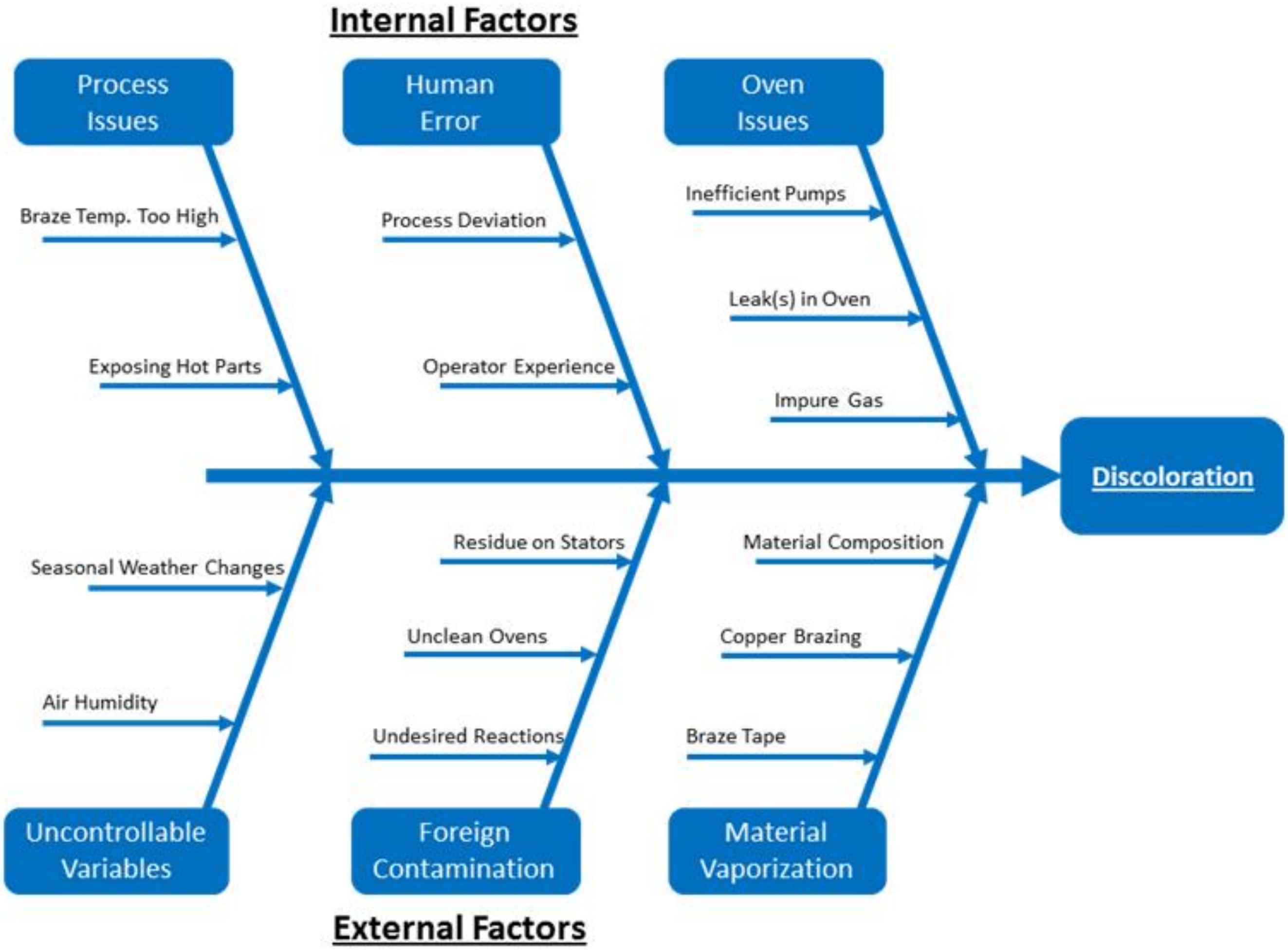


Figure 15: Ishikawa Diagram summarizing potential causes of discoloration.

5.3 Conclusions & Recommendations

From the analysis component of the project, the team was able to identify some key focus areas contributing toward the discoloration as well as rule out what is likely not causing the issue. Issues related with the ovens at Praxair and the possibility of a material in the stators offgasing are likely causes of the discoloration.

5.3.1 Discussion

Through feedback from the various stakeholders and subject experts, discoloration is often the result of issues with the brazing ovens. Oxidation building up on materials is known to cause discoloration. Oxygen can enter the vacuum brazing environment through leaks in the oven or the backfill component. Praxair has had issues with oven leaks in the past, but when asked if they had any recent issues they replied that the oven pressures are within specifications. While the team was not able to quantifiably confirm or rule out oven leaks as a contributing factor, it is certainly a possibility which must be considered.

The team determined that the most likely cause of the discoloration is a material offgasing during the braze process. Praxair observed that the discoloration appears only after the precipitation hardening and can be avoided by doing an oven burn out of the fixtures prior to this process lead. This leads the team to believe that a material is offgasing during the braze cycle, contaminating the fixtures, and adhering to the parts during the heat treat to cause the discoloration. The copper brazing on the vanes and the nickel based braze tape for the honeycomb are suspect materials. Bodycote Ipswich has had issues with braze tape offgasing in the past during their operations, and both the copper braze and braze tape are designed to liquefy during their respective braze cycles. It is very likely that some gasses are released during the process.

While the team was unable to identify what the specific root cause of the discoloration issue was, a solution was found to solve the issue. By including the second burn out of the ovens with the fixtures included the parts experience little to no discoloration. This process is very costly and time consuming though, and utilizing the single oven technique will greatly reduce the cost for Praxair and improve the lead time for GE.

Through research, testing, and stakeholder input the team was able to identify some areas which are likely not contributing towards the issue. It was suspected that there may be some residue on the stators going into the heat treatment process. The braze cycle runs at 1900°F, which is high enough to incinerate any residue that may be on the stators. During the early steps of the project it was suspected that the discoloration may be the result of exposure to various chemicals throughout the manufacturing process, but it was determined that the discoloration occurred after the heat treatment phase.

5.3.2 Short Term Recommendations

There are a number of options that the Manchester GE plant and Praxair Surface Technologies may choose to explore in response to the stator discoloration that can help both companies in the short run. In order to satisfy their respective customers and improve lead time, the following recommendations have been made.

5.3.2.1 Recommendations for Praxair

During a visit to Praxair Surface Technologies, it was mentioned by a Praxair employee that the company has an option to contact their company headquarters and request a team of professionals to travel to their plant and investigate issues that the location may be experiencing; this was referred to as a *Praxair Fast Team*. It would be in Praxair's best interest to invest time into this option as it would help not only their location to save time and money through solving this issue, but it would also help them to maintain good relations with their customers, one of which is GE Aviation.

Although discoloration of the honeycomb stators still occurs with the change of the oven techniques at Praxair, it is recommended that the plant stay with this new method. With both the original and alternative processes the ovens produced discoloration on the honeycomb stator assemblies. The main distinction between these two processes is the difference in time. Because the new process that Praxair has chosen to explore is reduced by roughly eleven hours, it would be more efficient for the company to continue this new technique due to the fact that an extreme amount of time and energy would be saved. The reduction in time also reduces production costs by approximately $100 per hour, which could help the company financially and perhaps invest in new ovens for the future as well. Likewise, this would also save time and money for the Manchester GE plant since they would be receiving their lots a lot earlier, allowing them to complete production, inspection, and vapor blast, if needed, much sooner than in the past.

5.3.2.2 Recommendations for GE Aviation Building #3

For further study of the elemental composition of the honeycomb stators, it is recommended that the employees at the Manchester GE plant look into locating a mass spectrometer that may analyze all the materials that compose the stators. As Professor Sisson said during his interviews, this specialized application could help provide more detailed results in regards to elemental compositions. Likewise, XPS and AES analyses would provide much more precise results. With these results the Manchester GE plant may identify the elements that could possibly help them to identify what it is that is causing the discoloration.

5.3.3 Long Term Recommendations

Just as with the short term recommendations, there are opportunities that GE may pursue over a longer period of time that could help identify and eliminate the discoloration issue. The following recommendations are ones that may help prevent discoloration of the honeycomb stators in the future.

5.3.3.1 Purchasing of New Equipment

Although a costly option, it may be a good idea to investigate the possibility of purchasing new machines and equipment that are involved in the manufacturing of the stator assemblies. Because the equipment at the Manchester GE plant is comparatively older than that of present technologies, there is a good chance that newer machines will be more likely to produce better results. Likewise, it is recommended that Praxair look into either fixing or purchasing new ovens since it is assumed that the discoloration is forming as a result of the heat treatment.

5.3.3.2 Potential Further Study

It is recommended that there be further study of this issue. A future Major Qualifying Project (MQP) team that has a good background knowledge and understanding of materials, elements, and metals would provide strong candidates for further investigation of the discoloration issue. Because time and resources were very limited within one fall semester, this project should be continued as another MQP.

It is recommended that the future MQP team further analyze the ovens at Praxair to identify whether or not a leak exists and how severe it is. They should also take the time to take a closer look at the cleaning of the stator assemblies prior to outsourcing them to Praxair. There is a chance that there may be some foreign materials that remain after the cleaning that may be reacting with other chemicals during the heat treatment. If experienced with analyses such as ones performed by a SEM, mass spectrometer, XPS, or AES the future MQP team would also be able to better analyze the results that these analyses would produce.

5.3.3.3 Explore Other Vendors

An option for the Manchester GE plant to explore is to investigate the possibility of choosing to use another vendor instead of Praxair. Although the relationship between the Manchester plant and Praxair may have proved to be successful in the past, it may be time for General Electric to seek other vendors that will produce products without discoloration. Unless Praxair actively investigates their oven issues and produces positive results relatively soon, it is recommended that GE Aviation look to apply the honeycomb application on their stator assemblies at other locations.

5.3.3.4 Analyze Metals that Compose the Stators

It is also recommended that the metals that the stator assemblies are composed of be investigated. There is the possibility that there may be some type of deviation in the metal composition, changes in vendor processes over the past few years, or perhaps something that has not yet been thought of, and it would be a good idea to further investigate the metals as a whole in case the issue were to be originating from their composition.

5.4 Limitations of Study

The team did their best to conduct as complete of an analysis on the discoloration issue as possible, but was ultimately limited in the amount they were able to accomplish during the course of the project. The temporal boundaries of the project, limitations of resources, and scope of expertise were constricting factors.

With heat treatment there are many variables to examine in order to fully understand the process. The complexity and sensitivity of heat treatment processes leaves many opportunities for something to go wrong and possibly result in discoloration. The team was unable to fully investigate every possibility laid out in the analysis section simply because of time restraints.

Over the two terms the project was conducted, the lots received from Praxair showed very little discoloration. With very few samples of the issue the team was unable to conduct as thorough of an analysis as was intended, particularly with the SEM. In order to achieve the best results a highly discolored sample would need to be analyzed, which the team was unable to procure. The team was limited in the amount of observation of the actual process at Praxair as well. Being separate from the GE sponsor, the team did not want to interfere with Praxair's operations and did not have access to fully examine the ovens where the heat treatment is conducted.

It is important to note that while process evaluation was the main component of the project, there was a great deal of material science study required as well. Being from the School of Business at WPI, the team only had an introductory knowledge of material science. More expert review would be required to more accurately assess the materials component of the project.

6. Creating a Business Continuity Plan

6.1 Standard Operating Procedures

6.1.1 Methodology and Purpose

The team has created several standard operating procedures for the cell workers to use as a reference. While there is generally only one machine for each task, there are often multiple operators including some people who are known as "floaters." These people work wherever they are needed to help decrease the numbers of bottlenecks in the process or to cover for people who are out for the day or a significant amount of time. Most of the people who run the machines as their main job each day follow the proper guidelines on how to maintain protocol and get the parts to be within the specifications by the time they are done, but often times other operates, be they floaters or new employees, just observe how to run the machine or feel as though they know how to run the machines, but this may change the outcome of each part, especially in running machines such as the hot upset machine. By creating standard operating procedures for stages like the hot upset machines, many continuity issues could be resolved before they would have to get reworked. If an operator were to retire or leave the company, having these procedures would allow the new people to learn the correct processes on how to run the machines or stations.

The everyday operator applies all of the pegs before starting the machine. She applies them to the ends of each half first, then applies them to the centers of each stator. After applying all screws, she tightens them then starts the machine. This is the proper technique on how to run this machine. Other operators apply one peg to each half, start the machine and then apply the other pegs. This improper technique can result in the angles being permanently changes because the pressure does not line up correctly and evenly. This seemingly small difference in technique can add a great deal of lead time to the product when it gets to the recamber stage. In addition to taking longer to recamber, as more and more stators need to be significantly recambered, queues begin to form, causing a bottleneck in the production.

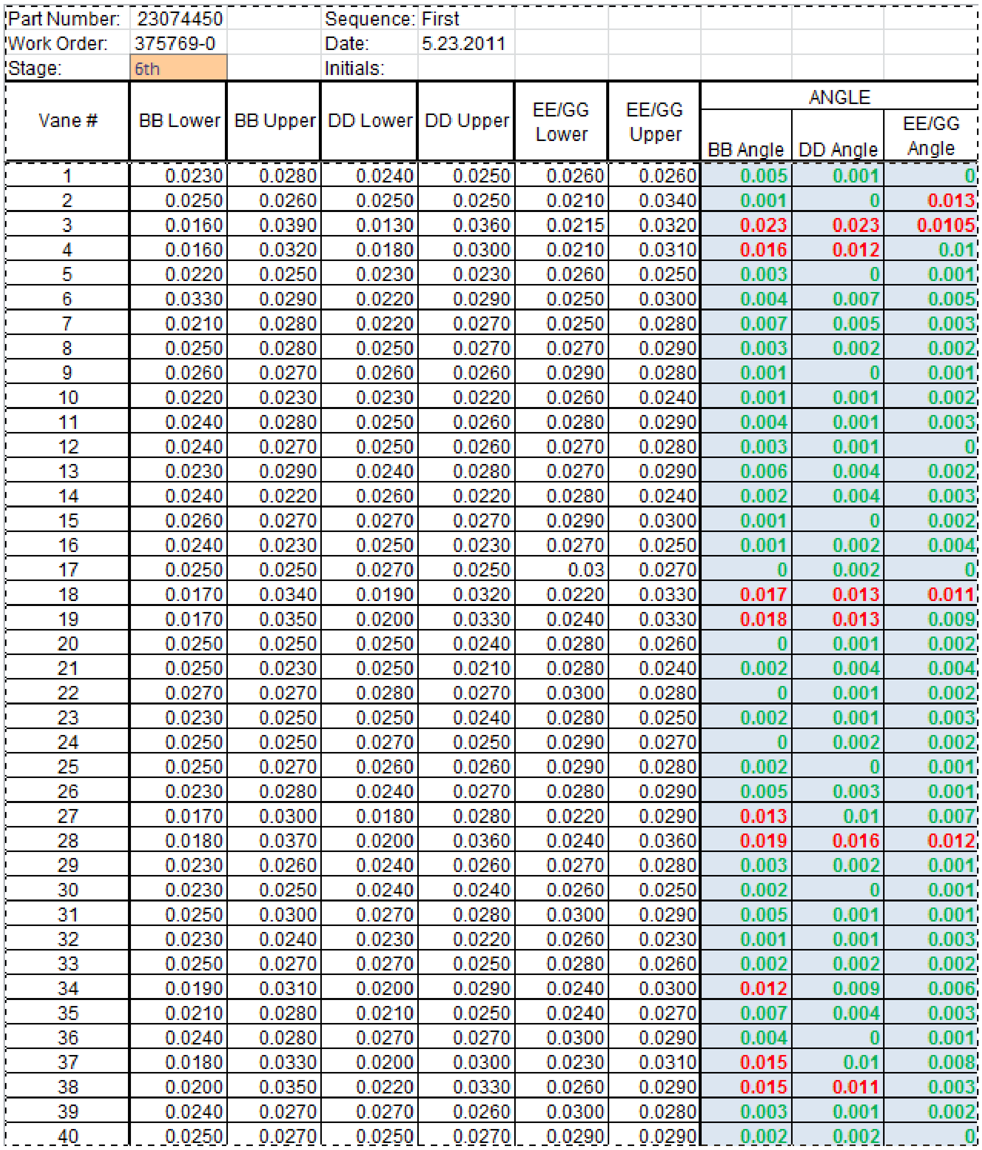
The standard operating procedures were created by working with machine operators, engineers and the current standards. Each of these resources helped contribute with what they are doing, what others are doing and what each believes the proper technique is. The everyday operator was the most useful resource in this endeavor, as this is the person who runs the machine or station day in and day out and they, for the most part, are knowledgeable about their procedure and the results of their job directly and indirectly. As they are not available to help other's learn or operate their machines if they are absent, others just do as they see fit. Many operators were excited with the potential to have standard guidelines for others as to ensure the job is done right.

6.1.2 Future Benefits

If the hot upset process is not done correctly, the vanes are set at the wrong angles. Recamber on average take about 30 minutes per stator. Each stator is half of the product that go on the hot upset machine. Ten minutes on the hot upset machine with operator error will result in one hour of recamber time which costs about $20.80. This may seem small at first, but this number very quickly adds up. One entire shift of hot upset with operator error results in 480 hours of recamber which is equal to about $10,000 lost by the company. This is a significant amount of money which can easily be reduced if all operators of all machines at any given time are well educated on how to properly run their machine or tools. Over the course of a year, these errors have the potential to cost the company an unnecessary two million dollars.

6.2 Recamber Analysis

Between May and June 2011, someone at the recamber station measured each angle and camber of 12 stators of 5 different stages.

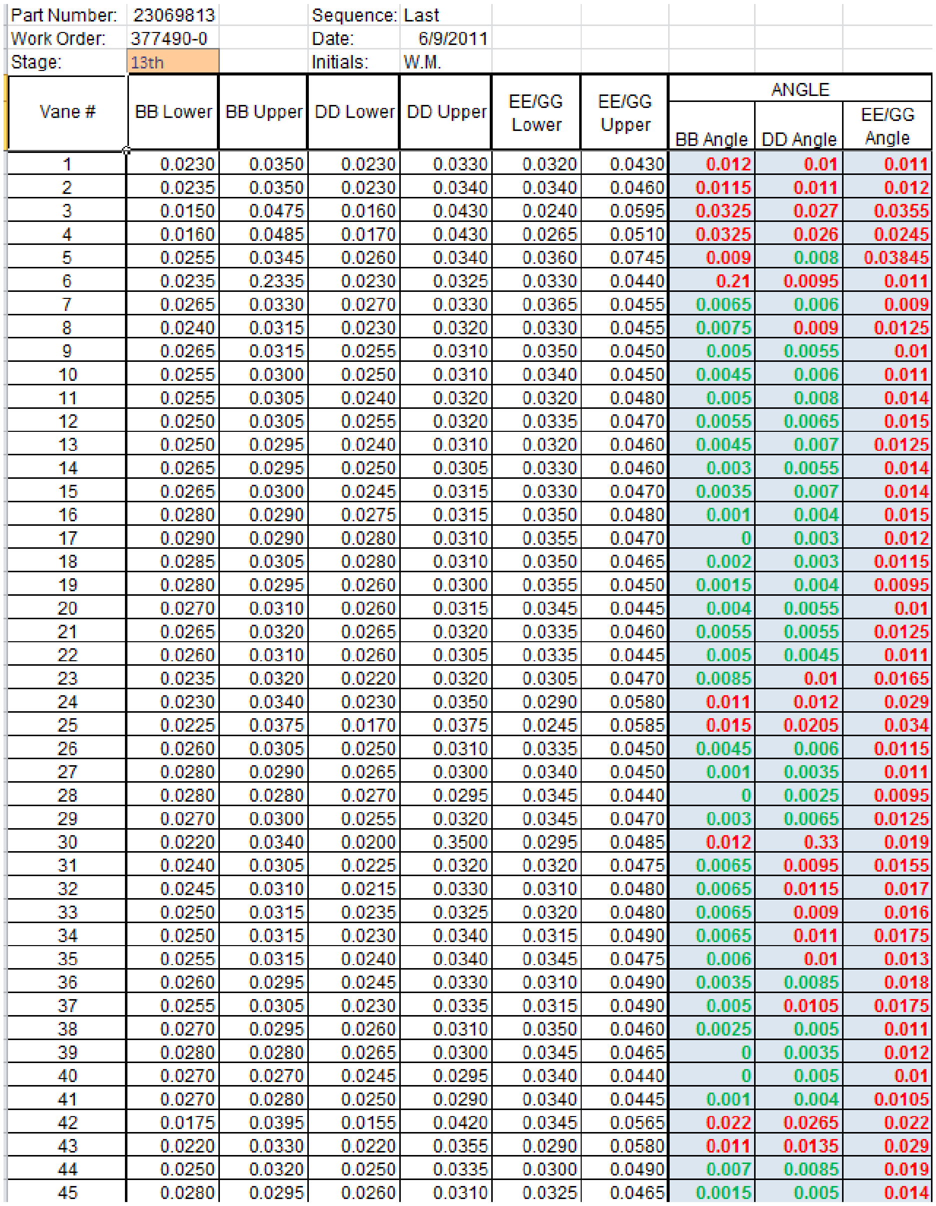


Part Number: 23074450
Work Order: 375769-0
Stage: 6th
Sequence: First
Date: 5.23.2011
Initials:

Vane #	BB Lower	BB Upper	DD Lower	DD Upper	EE/GG Lower	EE/GG Upper	ANGLE		
							BB Angle	DD Angle	EE/GG Angle
1	0.0230	0.0280	0.0240	0.0250	0.0260	0.0260	0.005	0.001	0
2	0.0250	0.0260	0.0250	0.0250	0.0210	0.0340	0.001	0	0.013
3	0.0160	0.0390	0.0130	0.0360	0.0215	0.0320	0.023	0.023	0.0105
4	0.0160	0.0320	0.0180	0.0300	0.0210	0.0310	0.016	0.012	0.01
5	0.0220	0.0250	0.0230	0.0230	0.0260	0.0250	0.003	0	0.001
6	0.0330	0.0290	0.0220	0.0290	0.0250	0.0300	0.004	0.007	0.005
7	0.0210	0.0280	0.0220	0.0270	0.0250	0.0280	0.007	0.005	0.003
8	0.0250	0.0280	0.0250	0.0270	0.0270	0.0290	0.003	0.002	0.002
9	0.0260	0.0270	0.0260	0.0260	0.0290	0.0280	0.001	0	0.001
10	0.0220	0.0230	0.0230	0.0220	0.0260	0.0240	0.001	0.001	0.002
11	0.0240	0.0280	0.0250	0.0260	0.0280	0.0290	0.004	0.001	0.003
12	0.0240	0.0270	0.0250	0.0260	0.0270	0.0280	0.003	0.001	0
13	0.0230	0.0290	0.0240	0.0280	0.0270	0.0290	0.006	0.004	0.002
14	0.0240	0.0220	0.0260	0.0220	0.0280	0.0240	0.002	0.004	0.003
15	0.0260	0.0270	0.0270	0.0270	0.0290	0.0300	0.001	0	0.002
16	0.0240	0.0230	0.0250	0.0230	0.0270	0.0250	0.001	0.002	0.004
17	0.0250	0.0250	0.0270	0.0250	0.03	0.0270	0	0.002	0
18	0.0170	0.0340	0.0190	0.0320	0.0220	0.0330	0.017	0.013	0.011
19	0.0170	0.0350	0.0200	0.0330	0.0240	0.0330	0.018	0.013	0.009
20	0.0250	0.0250	0.0250	0.0240	0.0280	0.0260	0	0.001	0.002
21	0.0250	0.0230	0.0250	0.0210	0.0280	0.0240	0.002	0.004	0.004
22	0.0270	0.0270	0.0280	0.0270	0.0300	0.0280	0	0.001	0.002
23	0.0230	0.0250	0.0250	0.0240	0.0280	0.0250	0.002	0.001	0.003
24	0.0250	0.0250	0.0270	0.0250	0.0290	0.0270	0	0.002	0.002
25	0.0250	0.0270	0.0260	0.0260	0.0290	0.0280	0.002	0	0.001
26	0.0230	0.0280	0.0240	0.0270	0.0280	0.0290	0.005	0.003	0.001
27	0.0170	0.0300	0.0180	0.0280	0.0220	0.0290	0.013	0.01	0.007
28	0.0180	0.0370	0.0200	0.0360	0.0240	0.0360	0.019	0.016	0.012
29	0.0230	0.0260	0.0240	0.0260	0.0270	0.0280	0.003	0.002	0.001
30	0.0230	0.0250	0.0240	0.0240	0.0260	0.0250	0.002	0	0.001
31	0.0250	0.0300	0.0270	0.0280	0.0300	0.0290	0.005	0.001	0.001
32	0.0230	0.0240	0.0230	0.0220	0.0260	0.0230	0.001	0.001	0.003
33	0.0250	0.0270	0.0270	0.0250	0.0280	0.0260	0.002	0.002	0.002
34	0.0190	0.0310	0.0200	0.0290	0.0240	0.0300	0.012	0.009	0.006
35	0.0210	0.0280	0.0210	0.0250	0.0240	0.0270	0.007	0.004	0.003
36	0.0240	0.0280	0.0270	0.0270	0.0300	0.0290	0.004	0	0.001
37	0.0180	0.0330	0.0200	0.0300	0.0230	0.0310	0.015	0.01	0.008
38	0.0200	0.0350	0.0220	0.0330	0.0260	0.0290	0.015	0.011	0.003
39	0.0240	0.0270	0.0270	0.0260	0.0300	0.0280	0.003	0.001	0.002
40	0.0250	0.0270	0.0250	0.0270	0.0290	0.0290	0.002	0.002	0

Figure 16: Data of 6th Stage Stator

The chart above is the data of a 6th stage stator, which has 40 vanes, measured May 23, 2011. There 10 vanes out of the 40 that have a red angle, meaning the angle is outside of specification. The Excel file is set to automatically format angles outside of the required specifications in red. This example has one of the highest percentages of correctly angles vanes out of all of the stators measured, with only 25% needing to be recambered.



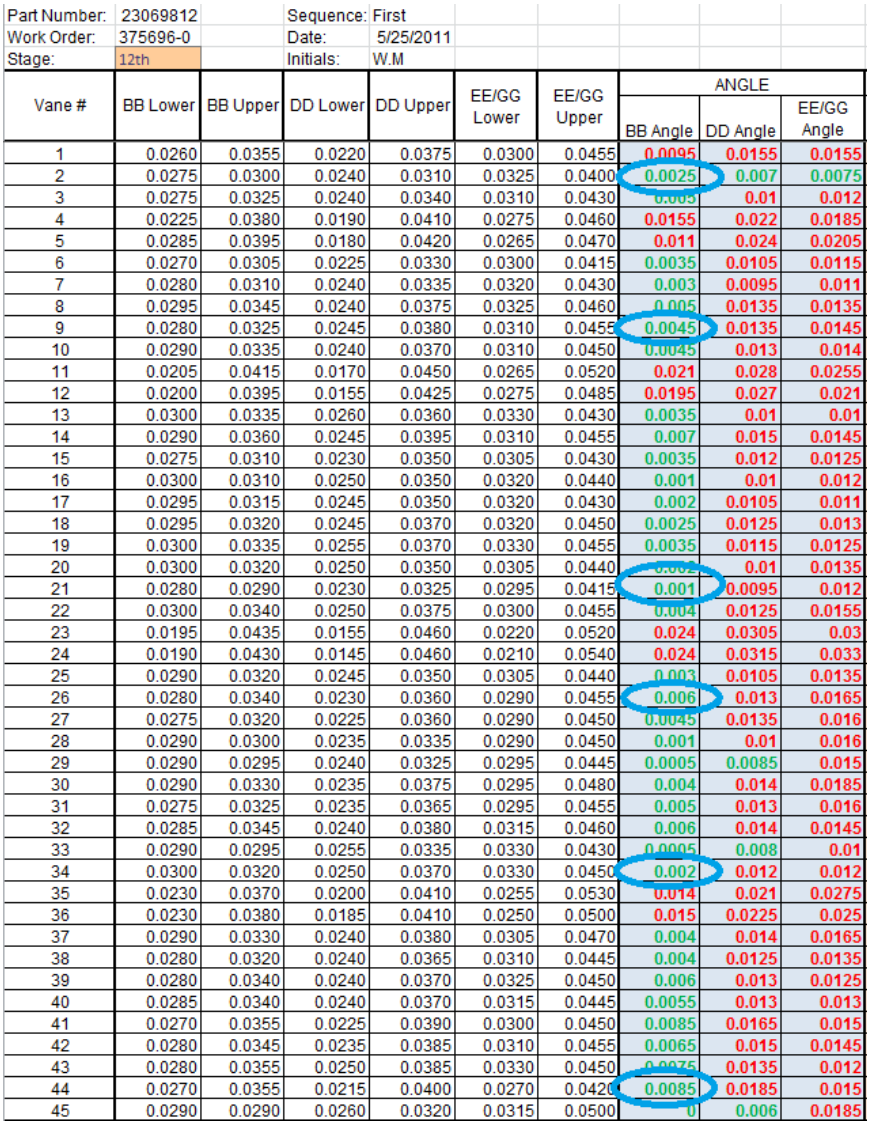
Part Number: 23069813
Work Order: 377490-0
Stage: 13th
Sequence: Last
Date: 6/9/2011
Initials: W.M.

Vane #	BB Lower	BB Upper	DD Lower	DD Upper	EE/GG Lower	EE/GG Upper	ANGLE		
							BB Angle	DD Angle	EE/GG Angle
1	0.0230	0.0350	0.0230	0.0330	0.0320	0.0430	0.012	0.01	0.011
2	0.0235	0.0350	0.0230	0.0340	0.0340	0.0460	0.0115	0.011	0.012
3	0.0150	0.0475	0.0160	0.0430	0.0240	0.0595	0.0325	0.027	0.0355
4	0.0160	0.0485	0.0170	0.0430	0.0265	0.0510	0.0325	0.026	0.0245
5	0.0255	0.0345	0.0260	0.0340	0.0360	0.0745	0.009	0.008	0.03845
6	0.0235	0.2335	0.0230	0.0325	0.0330	0.0440	0.21	0.0095	0.011
7	0.0265	0.0330	0.0270	0.0330	0.0365	0.0455	0.0065	0.006	0.009
8	0.0240	0.0315	0.0230	0.0320	0.0330	0.0455	0.0075	0.009	0.0125
9	0.0265	0.0315	0.0255	0.0310	0.0350	0.0450	0.005	0.0055	0.01
10	0.0255	0.0300	0.0250	0.0310	0.0340	0.0450	0.0045	0.006	0.011
11	0.0255	0.0305	0.0240	0.0320	0.0320	0.0480	0.005	0.008	0.014
12	0.0250	0.0305	0.0255	0.0320	0.0335	0.0470	0.0055	0.0065	0.015
13	0.0250	0.0295	0.0240	0.0310	0.0320	0.0460	0.0045	0.007	0.0125
14	0.0265	0.0295	0.0250	0.0305	0.0330	0.0460	0.003	0.0055	0.014
15	0.0265	0.0300	0.0245	0.0315	0.0330	0.0470	0.0035	0.007	0.014
16	0.0280	0.0290	0.0275	0.0315	0.0350	0.0480	0.001	0.004	0.015
17	0.0290	0.0290	0.0280	0.0310	0.0355	0.0470	0	0.003	0.012
18	0.0285	0.0305	0.0280	0.0310	0.0350	0.0465	0.002	0.003	0.0115
19	0.0280	0.0295	0.0260	0.0300	0.0355	0.0450	0.0015	0.004	0.0095
20	0.0270	0.0310	0.0260	0.0315	0.0345	0.0445	0.004	0.0055	0.01
21	0.0265	0.0320	0.0265	0.0320	0.0335	0.0460	0.0055	0.0055	0.0125
22	0.0260	0.0310	0.0260	0.0305	0.0335	0.0445	0.005	0.0045	0.011
23	0.0235	0.0320	0.0220	0.0320	0.0305	0.0470	0.0085	0.01	0.0165
24	0.0230	0.0340	0.0230	0.0350	0.0290	0.0580	0.011	0.012	0.029
25	0.0225	0.0375	0.0170	0.0375	0.0245	0.0585	0.015	0.0205	0.034
26	0.0260	0.0305	0.0250	0.0310	0.0335	0.0450	0.0045	0.006	0.0115
27	0.0280	0.0290	0.0265	0.0300	0.0340	0.0450	0.001	0.0035	0.011
28	0.0280	0.0280	0.0270	0.0295	0.0345	0.0440	0	0.0025	0.0095
29	0.0270	0.0300	0.0255	0.0320	0.0345	0.0470	0.003	0.0065	0.0125
30	0.0220	0.0340	0.0200	0.3500	0.0295	0.0485	0.012	0.33	0.019
31	0.0240	0.0305	0.0225	0.0320	0.0320	0.0475	0.0065	0.0095	0.0155
32	0.0245	0.0310	0.0215	0.0330	0.0310	0.0480	0.0065	0.0115	0.017
33	0.0250	0.0315	0.0235	0.0325	0.0320	0.0480	0.0065	0.009	0.016
34	0.0250	0.0315	0.0230	0.0340	0.0315	0.0490	0.0065	0.011	0.0175
35	0.0255	0.0315	0.0240	0.0340	0.0345	0.0475	0.006	0.01	0.013
36	0.0260	0.0295	0.0245	0.0330	0.0310	0.0490	0.0035	0.0085	0.018
37	0.0255	0.0305	0.0230	0.0335	0.0315	0.0490	0.005	0.0105	0.0175
38	0.0270	0.0295	0.0260	0.0310	0.0350	0.0460	0.0025	0.005	0.011
39	0.0280	0.0280	0.0265	0.0300	0.0345	0.0465	0	0.0035	0.012
40	0.0270	0.0270	0.0245	0.0295	0.0340	0.0440	0	0.005	0.01
41	0.0270	0.0280	0.0250	0.0290	0.0340	0.0445	0.001	0.004	0.0105
42	0.0175	0.0395	0.0155	0.0420	0.0345	0.0565	0.022	0.0265	0.022
43	0.0220	0.0330	0.0220	0.0355	0.0290	0.0580	0.011	0.0135	0.029
44	0.0250	0.0320	0.0250	0.0335	0.0300	0.0490	0.007	0.0085	0.019
45	0.0280	0.0295	0.0260	0.0310	0.0325	0.0465	0.0015	0.005	0.014

Figure 17: Data of 13th Stage Stator

The above chart is a 13th stage stator which has 45 vanes measured on June 9, 2011. All of the EE/GG angles are in red, meaning all of the vanes had to be recambered. A part like this with so many issues would take more than the average 30 minutes to be recambered because the recamber process is a very manual, guess and check process. While these are the two extremes in terms of recamber data, most stators are measured closer to the latter option as they have an average of 66% of vanes that must be recambered. As previously mentioned, recamber should be a touch up to the process not completely changing all of the angles on each part.

Overall the only angles within specifications were the ones near where the stator is mounted to the hot upset machine. This is because the clamps hold the vanes in place and allow for less torque and bending in the vanes nearest them. As the vanes further away from clamps are studied, it is very noticeable that their measurements are further away from the correct angles and tolerances. This is consistent with the suggestion of making a more stable mount for the hot upset machine which would hold all of the tangs in place while the machine sets them into place. The outer ring has already been split by the time it goes to hot upset, but the inner ring it still one piece. Occasionally the vanes on the outside of the clamps on each half are outside of the specifications. This may be because they are only attached at one side and have more room to move when compressed.



Part Number:	23069812		Sequence:	First				
Work Order:	375696-0		Date:	5/25/2011				
Stage:	12th		Initials:	W.M				

Vane #	BB Lower	BB Upper	DD Lower	DD Upper	EE/GG Lower	EE/GG Upper	ANGLE		
							BB Angle	DD Angle	EE/GG Angle
1	0.0260	0.0355	0.0220	0.0375	0.0300	0.0455	0.0095	0.0155	0.0155
2	0.0275	0.0300	0.0240	0.0310	0.0325	0.0400	0.0025	0.007	0.0075
3	0.0275	0.0325	0.0240	0.0340	0.0310	0.0430	0.005	0.01	0.012
4	0.0225	0.0380	0.0190	0.0410	0.0275	0.0460	0.0155	0.022	0.0185
5	0.0285	0.0395	0.0180	0.0420	0.0265	0.0470	0.011	0.024	0.0205
6	0.0270	0.0305	0.0225	0.0330	0.0300	0.0415	0.0035	0.0105	0.0115
7	0.0280	0.0310	0.0240	0.0335	0.0320	0.0430	0.003	0.0095	0.011
8	0.0295	0.0345	0.0240	0.0375	0.0325	0.0460	0.005	0.0135	0.0135
9	0.0280	0.0325	0.0245	0.0380	0.0310	0.0455	0.0045	0.0135	0.0145
10	0.0290	0.0335	0.0240	0.0370	0.0310	0.0450	0.0045	0.013	0.014
11	0.0205	0.0415	0.0170	0.0450	0.0265	0.0520	0.021	0.028	0.0255
12	0.0200	0.0395	0.0155	0.0425	0.0275	0.0485	0.0195	0.027	0.021
13	0.0300	0.0335	0.0260	0.0360	0.0330	0.0430	0.0035	0.01	0.01
14	0.0290	0.0360	0.0245	0.0395	0.0310	0.0455	0.007	0.015	0.0145
15	0.0275	0.0310	0.0230	0.0350	0.0305	0.0430	0.0035	0.012	0.0125
16	0.0300	0.0310	0.0250	0.0350	0.0320	0.0440	0.001	0.01	0.012
17	0.0295	0.0315	0.0245	0.0350	0.0320	0.0430	0.002	0.0105	0.011
18	0.0295	0.0320	0.0245	0.0370	0.0320	0.0450	0.0025	0.0125	0.013
19	0.0300	0.0335	0.0255	0.0370	0.0330	0.0455	0.0035	0.0115	0.0125
20	0.0300	0.0320	0.0250	0.0350	0.0305	0.0440	0.002	0.01	0.0135
21	0.0280	0.0290	0.0230	0.0325	0.0295	0.0415	0.001	0.0095	0.012
22	0.0300	0.0340	0.0250	0.0375	0.0300	0.0455	0.004	0.0125	0.0155
23	0.0195	0.0435	0.0155	0.0460	0.0220	0.0520	0.024	0.0305	0.03
24	0.0190	0.0430	0.0145	0.0460	0.0210	0.0540	0.024	0.0315	0.033
25	0.0290	0.0320	0.0245	0.0350	0.0305	0.0440	0.003	0.0105	0.0135
26	0.0280	0.0340	0.0230	0.0360	0.0290	0.0455	0.006	0.013	0.0165
27	0.0275	0.0320	0.0225	0.0360	0.0290	0.0450	0.0045	0.0135	0.016
28	0.0290	0.0300	0.0235	0.0335	0.0290	0.0450	0.001	0.01	0.016
29	0.0290	0.0295	0.0240	0.0325	0.0295	0.0445	0.0005	0.0085	0.015
30	0.0290	0.0330	0.0235	0.0375	0.0295	0.0480	0.004	0.014	0.0185
31	0.0275	0.0325	0.0235	0.0365	0.0295	0.0455	0.005	0.013	0.016
32	0.0285	0.0345	0.0240	0.0380	0.0315	0.0460	0.006	0.014	0.0145
33	0.0290	0.0295	0.0255	0.0335	0.0330	0.0430	0.0005	0.008	0.01
34	0.0300	0.0320	0.0250	0.0370	0.0330	0.0450	0.002	0.012	0.012
35	0.0230	0.0370	0.0200	0.0410	0.0255	0.0530	0.014	0.021	0.0275
36	0.0230	0.0380	0.0185	0.0410	0.0250	0.0500	0.015	0.0225	0.025
37	0.0290	0.0330	0.0240	0.0380	0.0305	0.0470	0.004	0.014	0.0165
38	0.0280	0.0320	0.0240	0.0365	0.0310	0.0445	0.004	0.0125	0.0135
39	0.0280	0.0340	0.0240	0.0370	0.0325	0.0450	0.006	0.013	0.0125
40	0.0285	0.0340	0.0240	0.0370	0.0315	0.0445	0.0055	0.013	0.013
41	0.0270	0.0355	0.0225	0.0390	0.0300	0.0450	0.0085	0.0165	0.015
42	0.0280	0.0345	0.0235	0.0385	0.0310	0.0455	0.0065	0.015	0.0145
43	0.0280	0.0355	0.0250	0.0385	0.0330	0.0450	0.0075	0.0135	0.012
44	0.0270	0.0355	0.0215	0.0400	0.0270	0.0420	0.0085	0.0185	0.015
45	0.0290	0.0290	0.0260	0.0320	0.0315	0.0500	0	0.006	0.0185

Figure 18: Vanes that are clamped during hot upset process.

The above chart has some angles circled. These are the angles with corresponding vanes that are clamped during the hot upset process. Typically the angle where the clamp is deviates very little, but one most stators as the vane is further from the clamp then the angle is further off from what it should be.

Stage	**Date**	**Total Vanes**	**Incorrect Vanes**	**% Needing Recambering**
6	6/8/2011	40	10	25%
6	5/23/2011	40	12	30%
10	6/14/2011	45	36	80%
10	6/13/2011	45	33	73%
11	5/25/2011	45	5	11%
11	5/19/2011	45	25	56%
12	5/27/2011	45	26	58%
12	5/26/2011	45	40	89%
12	5/25/2011	45	44	98%
12	5/19/2011	45	41	91%
13	6/13/2011	45	38	84%
13	6/9/2011	45	45	100%

Figure 19: Recamber Accuracy Table

Overall there is not much correlation between stage or date as to how many vanes are at the incorrect angles. The problem appears to have gotten better over time, but this is very limited sample and making an accurate conclusion based on that assumption would not be correct.

6.3 Capacity Study

6.3.1 Current Standings

Currently there are 2,000 overdue stators. This is about 1.5 million dollars in potentially revenue once these parts are produced and distributed to the customer. Most of the parts are between two and three months behind schedule. Multiple engineers at Building #3 have attested that clients call daily looking for their late parts. Keeping client satisfaction is important for a business, but that relationship is not there presently due to the fact that the cell is at capacity currently without any chances being made. The shop pays about $110 per hour for utilities. Employees on average make $16 per hour, with 30% benefits on top of that resulting in a payroll expense of $20.80 per hour per employee. Pay rates depend on skill, time at GE and type of employment.

Process	**Number of Shifts**
Assembly*	0
Hot Upset	1.5
Wash	2
Straightening	2
Lathe	2.5
Recamber	3

Figure 20: Number of Shifts Per Process

*indicates that this process is currently done by the same person during the same shift as hot upset

The above chart shows the number of shifts of the main, time consuming processes between hot upset and final inspection. Up until recently there were two shifts maximum although my processes only have someone there first shift. Throughout the project work, several other shifts were added. The chart above represents the new shifts.

Process	**Time (minutes)**
Assembly	10
Hot Upset	10
Hot Upset Mount Change	25
Wash	45
Straightening	10
Heat Treat	5760
Straightening	20
Lathe	15
Wash 2	45
FPI	2
Wash 3	45
Marking	5
Coating	10080
Lathe 2	15
Lathe 3	15
Burr	2
Wash 4	45
Wire EDM	10
Recamber	30
Mill	2
Burr 2	3
Wash 5	45
Final Inspection	5
TOTAL	16244

Figure 21: Time Per Process

Without travel time, down time or time spent sitting in queue each stator takes about 12 days to make. The graph below compares the different processing times.

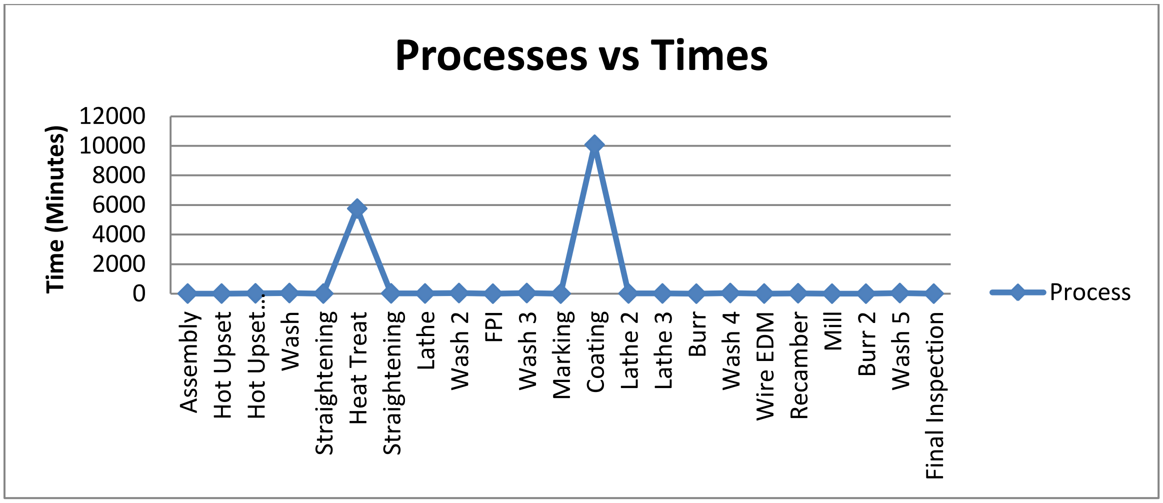


Figure 22: Processes vs. Times

The stator does spend most of its processing life outside of the company at heat treatment or at coating. This is due to shipping and processing times at other locations and is not as negotiable as the lead and queue time of processes within Building #3.

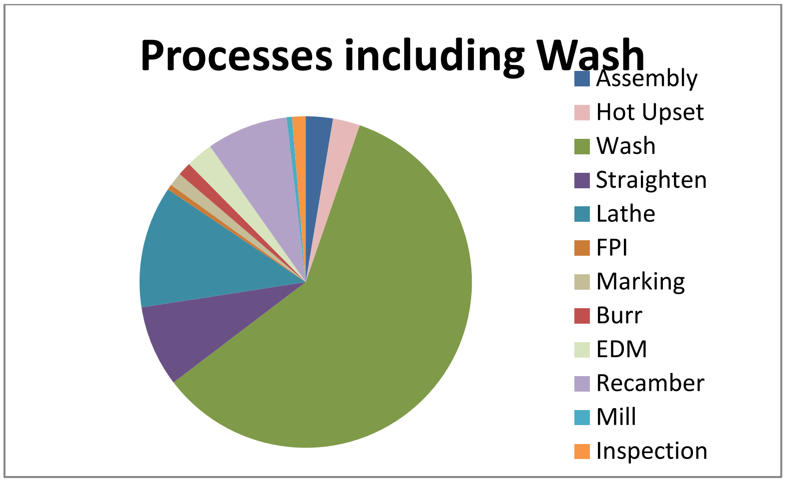


Figure 23: Processes Including Wash

The above pie chart shows all of the different phases that a 6th stage stator goes through between assembly for hot upset and final inspection. The wash process is clearly the most dominant process that occurs in building #3. Each stator goes through 5 different cycles of at 45 minute wash. The wash process currently has two shifts, but every part must go through numerous times.

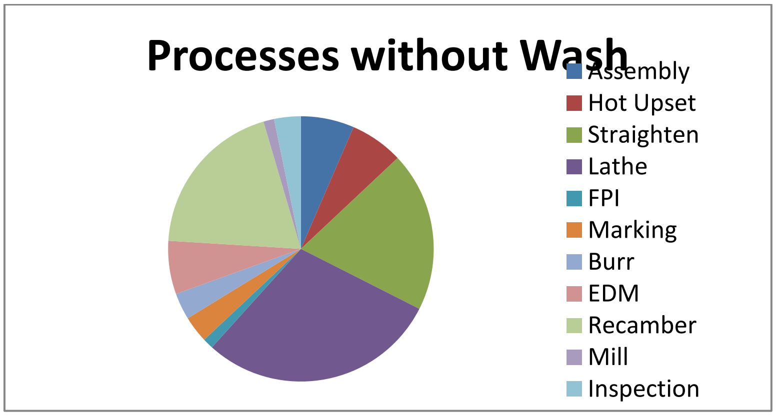


Figure 24: Processes Without Wash

The above pie chart shows the production percentages without external vendors or the wash cycle. A significant amount of time is spent at the straightening, lathe and recamber processes. Straightening occurs in two cycles. First the stator is straightened before going to heat treatment. This straightening takes roughly 10 minutes, but when it returns from heat treatment it must be straightened again which takes roughly 20 minutes. The operator who does the straightening during one shift has said that the part gets bent and/or squished during the heat treatment process and takes significantly longer to straighten after this occurs. Currently there are two shifts of straightening and three workers who are capable of doing the straightening. Wash, lathe and recamber currently have two shifts. Each lathe cycle, of which each stator has three, takes roughly 45 minutes. These high volume processes are the source of many queues or bottlenecks.

6.3.2 Proposed Changes and Effects

The team would like to purpose adding shifts to several processes. With this new schedule, straightening, wash and lathe would get a third full-time shift and hot upset would get a second full-time shift. These processes were chosen because they are large cause of queues and lead times. Adding a third shift to the cell would cost about $880 per day for utilities, which has already been added throughout the course of this project, therefore the team's suggestions would not have a significant utility cost to GE Aviation. Having four new full-time employees would cost payroll $83.20 per hour or $332.80 per day, as each employee makes $20.80 per hour each and two of the processes already have half a shift already. Monthly this would cost the company roughly $7,500 per month and $90,000 per year.

In the short term adding these shifts would allow the company to catch up on overdue orders which would help to appease the customer. It would also decrease many long standing queues and take away some stress from current workers. In an ideal situation all orders would be caught up on within three months of having these extra employees, even if no other changes were made.

Thinking future into the future with keeping these extra shifts or possibly adding more where needed, in the long term 528 more stators per month could be produced on top of what is already being made. Each day 16 more stators could get through straightening, 2 more could get through wash, 24 more could get through hot upset, and 5 more could get through lathe. This could increase the cell's capacity and increase revenue in the future. In addition to the monetary benefits all long queues and late orders would be diminished.

There are also many business continuity benefits. There would overall be more knowledgeable employees capable of doing each process. Currently if there is only one person who know how to do a process, that process may come to a halt if that individual is not there. There is no implemented plan if that one worker is sick, leaves the company or decides to take a vacation. By having standard operating procedures and more shifts, there would be no chance of the company being at a loss due to employment termination or time off. Newly created shift employees could cover the work of someone who is absent and newer employees would be able to do new jobs in a more seamless manner. GE would also be providing more jobs to the community in these rough economic times.

In conclusion creating standard operating procedures and adding shifts will prove to be very beneficial to the company as well as the client and the surrounding community. Fixing the recamber issue before it goes to recamber is the main key to success and is the quickest, short term fix to reduce lead time and give the customers their products sooner.

6.4 Reflection Essay

Using an understand and statistics of the current processes, the team worked on making improvements to the current shift design which is a key component of stator production at GE Aviation in Manchester, CT. To do this they looked at the objectives and criteria set forth by the managers, engineers and factory workers at the cell. The goal was to increase production to catch up on orders that were behind which would ultimately increase the capacity of the factory. Making these changes in the most cost effective, timely and logical way was most desired. By analyzing current data, such as shift coverage, stator processing times at each step, recamber angle data and cost data to create different solutions to the problem. A plan was then constructed and reported on in detail in previous sections.

The biggest constraint would be financial concerns. Initially these changes would cost the company a significant amount of money in order for them to catch up on back orders. After the old orders were all finished and shipped to the customer, the cell would be able to produce enough stators with this new capacity in order to make up for the previous losses due to hiring and catching up and would in fact be able to make a significant profit. If the process did not improve production results then these changes may not be sustainable. Environmentally, ethically, health-wise, politically and safety-wise the changes would not be negative or of concern. In fact, these changes would be helping the local economy by adding new jobs to the area to benefit may families. If GE Aviation Manchester, were to follow this trend with other products, they could make a significant impact on the Connecticut economy especially that of Manchester.

Implementation would be a gradual process. There would be a hiring and training phase. During this time, potential employees would submit resumes and applications while following proper GE Aviation hiring protocol. After employees were hired they would go through GE's standard training, if they have HR training for all new employees, and they would train and observe with current workers who would do the same process. These new employees should observe and work with the current operators and should also be observed by the current operators periodically to ensure the same high quality standards. The results of the shift additions could be evaluated by the production results and evaluating customer satisfaction. The production schedule is very behind currently and evaluating how many new stators are produced compared to predicted results would analyze if the changes to the current design were effective.

7. Concluding Remarks

The team working on Issues #1 and #2 was able to fulfill their original project methodology by completing the following. We successfully performed preliminary problem analysis by examining copper removal and recamber lead time and identifying characteristics of stators with excess copper and recamber issues, respectively. Several areas were chosen for further experimentation and analysis of the assembly processes, including straightening, piercing, hot upset, and inspection using the shadowgraph, as well as the effects of trumpeting and tang size. After collecting data from all experiments, it was analyzed for variation that could cause excess copper brazing or recamber issues. Variation was found in almost all of the areas, especially piercing and tang size. Because of this, we were able to offer recommendations to correct or eliminate the variation by purchasing new piercing dies and developing a part to hold angles in place during hot upset. We also agreed that the vane and tang manufacturing process should be analyzed to reduce variation and lower the average mean closer to the midpoint of the accepted tolerances.

For Issue #3 the goal was to identify the root causes of the discoloration issue and improve the manufacturability of the assemblies. While we were unable to specifically pinpoint exactly what was causing the issue, a number of key factors were identified. We spoke with stakeholders, industry professionals, and materials experts to determine what can be contributing to the issue and what can be done to prevent this. We quantifiably analyzed the issue using a Scanning Electron Microscope to evaluate the elemental composition of the surface layers. It was determined that through alternative brazing processes the operating costs for the heat treatment vendor and the overall lead time for GE can be significantly decreased.

Bibliography

A Brief History of Lean. 2009. 6 October 2011 <http://www.lean.org/WhatsLean/History.cfm>.

AirCav: Compressors. January 2008. 9 October 2011 <http://www.aircav.com/gencompr.html>.

Akinlawon, A. O. Thinking of Lean Manufacturing Systems. 2011. September 2011 <http://www.sae.org/manufacturing/lean/column/leandec01.htm>.

Boeing 502-6 Turboshaft Engine. 2009. 9 October 2011 <http://www.boeing502.com/specs.shtml>.

Clarke, David and Steve Bold. Aerospace Materials, Materials development in aeroengine gas turbines. London: Institute of Physics Publishing, 2001.

GE Aviation. Jet Engines 101. 2011. 1 October 2011 <http://www.geaviation.com/education/engines101/>.

—. Jet Engins 101. 2011. 1 October 2011 <http://www.geaviation.com/education/engines101/>.

Heppenheimer, T.A. Jet Engines. 9 October 2011 <http://www.centennialofflight.gov/essay/Evolution_of_Technology/jet_engines/Tech24.htm>.

Hi TecMetal Group, Inc. Copper Brazing. 2010. September 2011 <http://www.copperbrazing.info/>.

Institute Of Industrial Engineers. Six Sigma Green Belt. n/a, 2011.

Kay, Dan. Vac Aero International Inc. 2010. 12 October 2010 <http://vacaero.com/Vacuum-Brazing-with-Dan-Kay/Vacuum-Brazing-with-Dan-Kay/honeycomb-brazing-essentials-for-successful-use-as-turbine-seals.html>.

Krajewski, Lee J. Operations Management. Prentice Hall, 2010.

Principles of Lean. 2009. 7 October 2011 <http://www.lean.org/WhatsLean/Principles.cfm>.

Rolls Royce. "Gas Turbine Technology." Informational Document. 2007.

—. Rolls-Royce Education. 2011. 12 October 2011 <http://www.rolls-royce.com/about/education/resources/12_19_year_olds/index.jsp>.

Sawyer, John Wesley. Sawyer's Gas Turbine Engineering Handbook Volume 1. Gas Trubine Publications, Inc., 1972.

Thai Technics. Engine Construction. 2001. 12 October 2011 <http://www.thaitechnics.com/engine/engine_construction.html>.

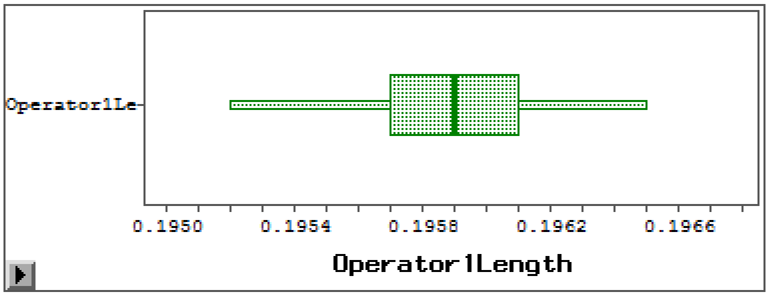
Appendices

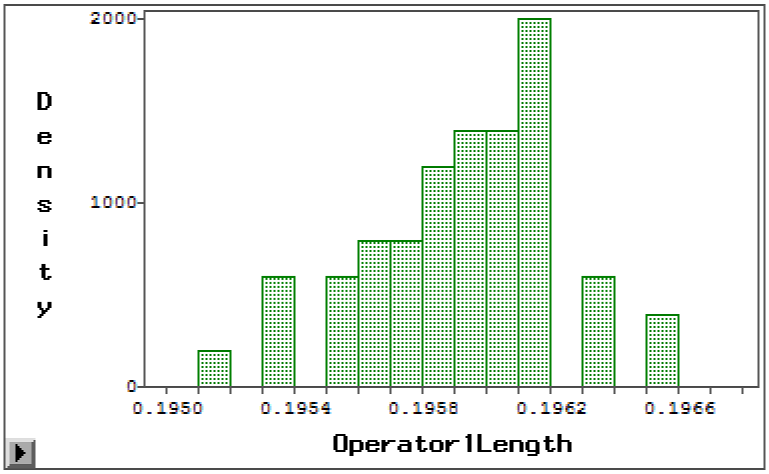
Appendix A: Tang Size Analysis (Chpt. 4)

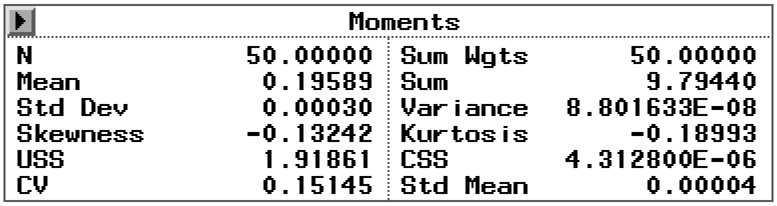
Fixed Tang Length Measurements by Operator

Operator 1

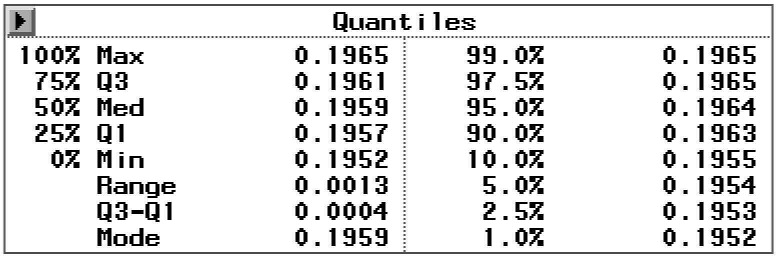
Operator1Length







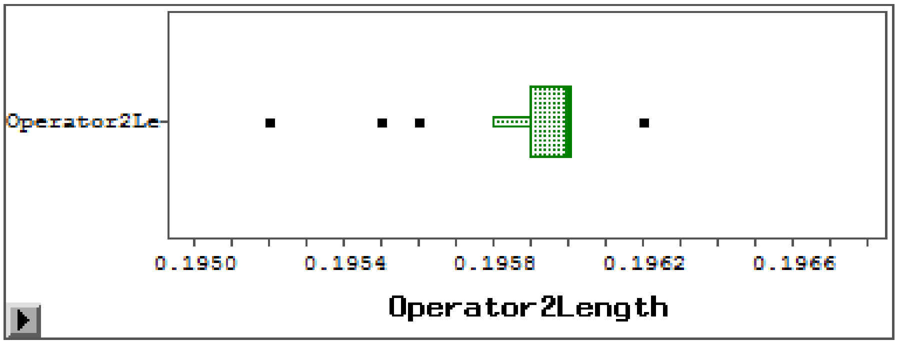
```
                              Moments
N                 50.00000 | Sum Wgts         50.00000
Mean               0.19589 | Sum               9.79440
Std Dev            0.00030 | Variance     8.801633E-08
Skewness          -0.13242 | Kurtosis         -0.18993
USS                1.91861 | CSS          4.312800E-06
CV                 0.15145 | Std Mean          0.00004
```

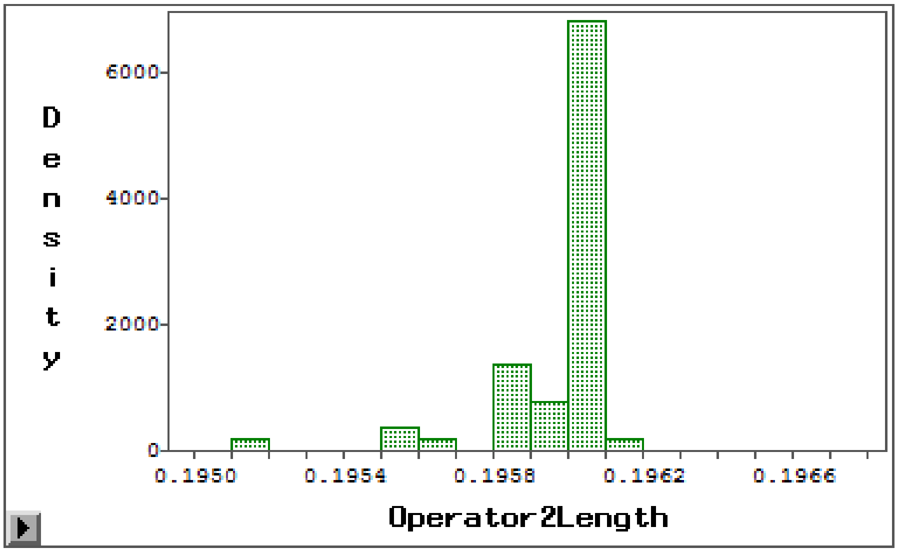


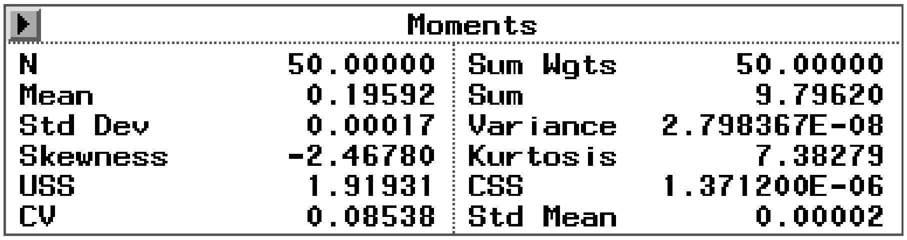
```
                             Quantiles
100% Max             0.1965 |  99.0%             0.1965
 75% Q3              0.1961 |  97.5%             0.1965
 50% Med             0.1959 |  95.0%             0.1964
 25% Q1              0.1957 |  90.0%             0.1963
  0% Min             0.1952 |  10.0%             0.1955
     Range           0.0013 |   5.0%             0.1954
     Q3-Q1           0.0004 |   2.5%             0.1953
     Mode            0.1959 |   1.0%             0.1952
```

Operator 2

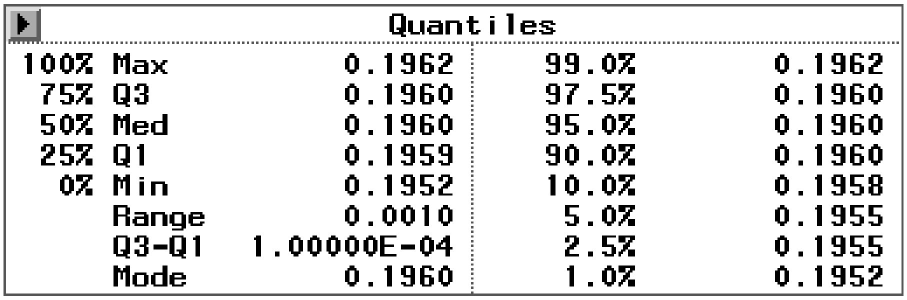
Operator2Length







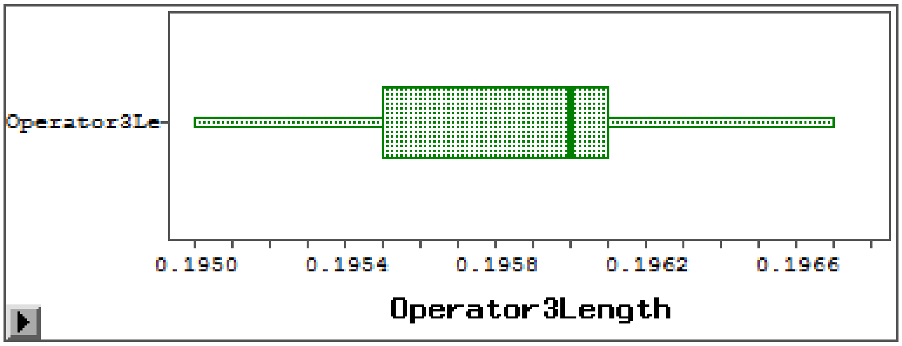
```
                          Moments
N              50.00000 | Sum Wgts          50.00000
Mean            0.19592 | Sum                9.79620
Std Dev         0.00017 | Variance    2.798367E-08
Skewness       -2.46780 | Kurtosis           7.38279
USS             1.91931 | CSS         1.371200E-06
CV              0.08538 | Std Mean           0.00002
```

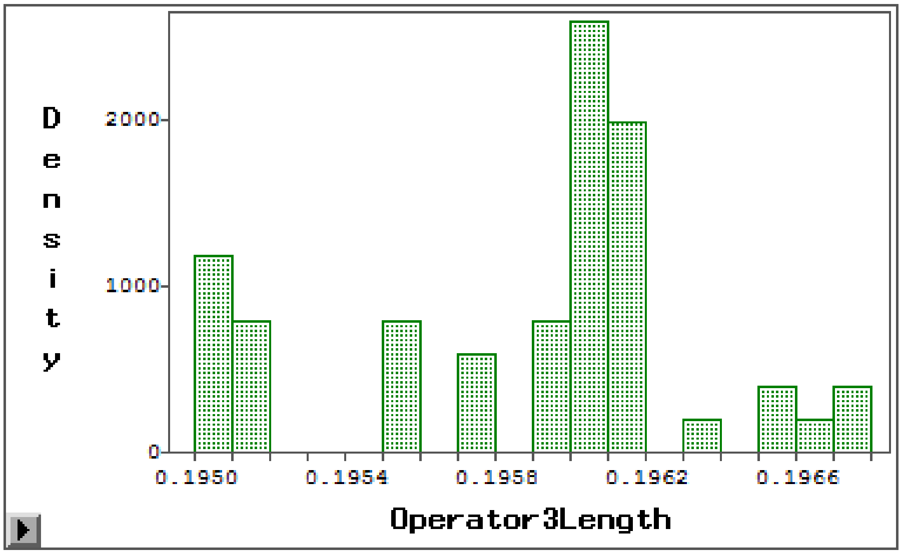


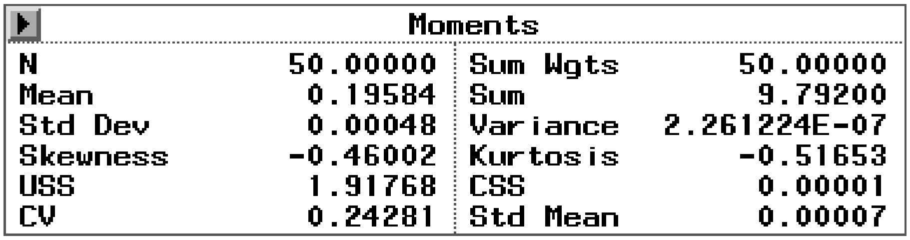
```
                          Quantiles
100% Max            0.1962 |   99.0%          0.1962
 75% Q3             0.1960 |   97.5%          0.1960
 50% Med            0.1960 |   95.0%          0.1960
 25% Q1             0.1959 |   90.0%          0.1960
  0% Min            0.1952 |   10.0%          0.1958
     Range          0.0010 |    5.0%          0.1955
     Q3-Q1    1.00000E-04  |    2.5%          0.1955
     Mode           0.1960 |    1.0%          0.1952
```

Operator 3

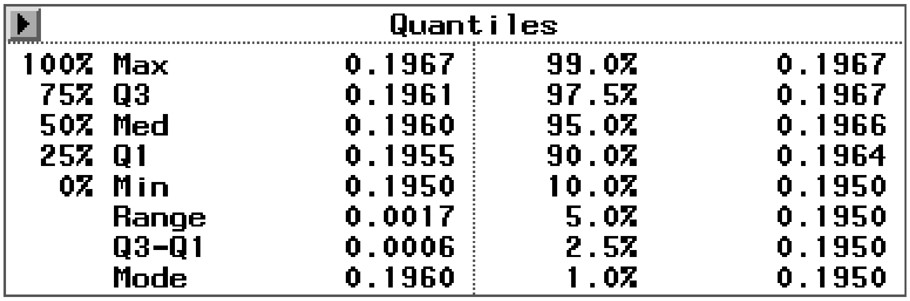
Operator3Length







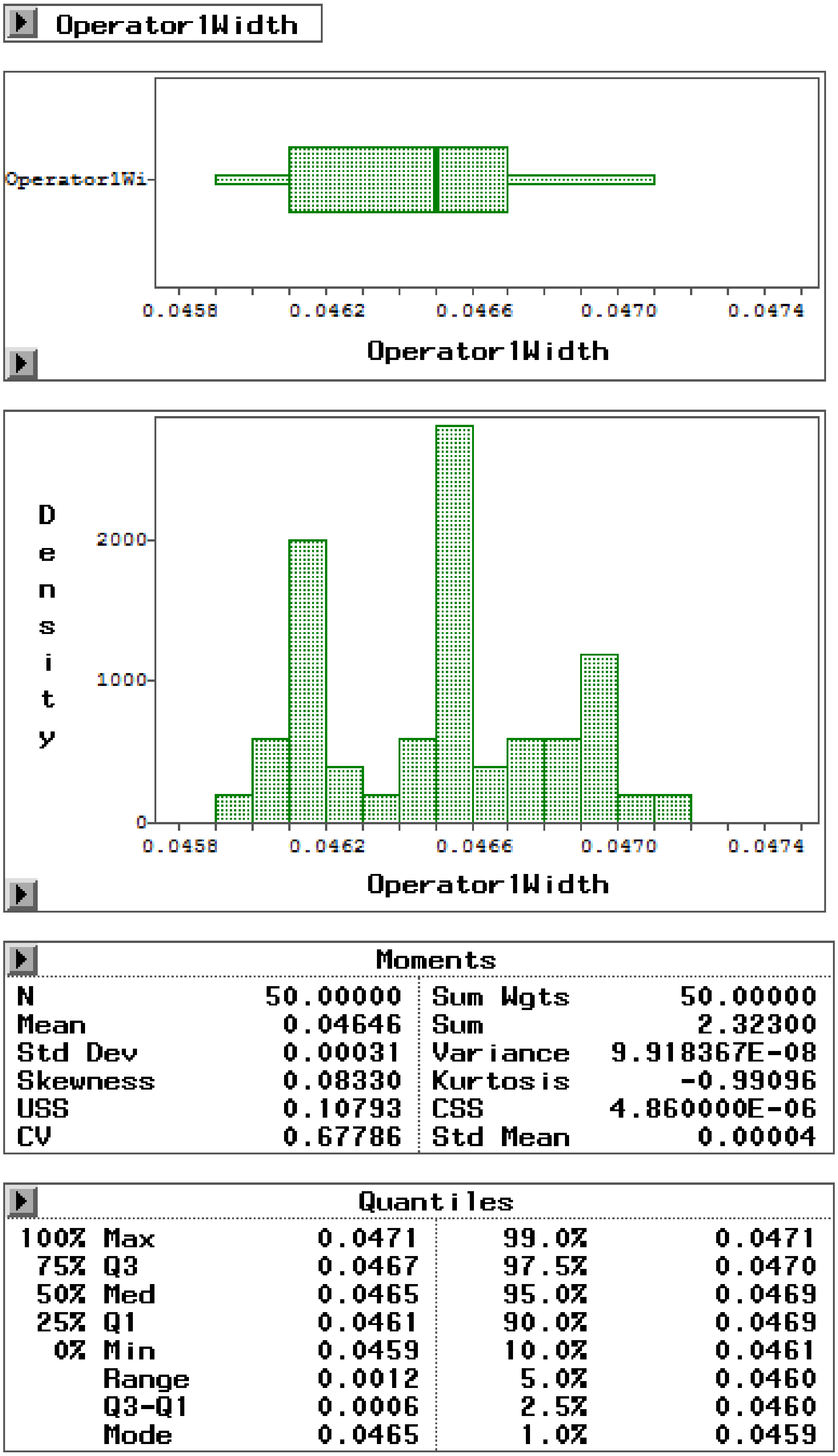
```
                          Moments
N               50.00000   Sum Wgts          50.00000
Mean             0.19584   Sum                9.79200
Std Dev          0.00048   Variance      2.261224E-07
Skewness        -0.46002   Kurtosis          -0.51653
USS              1.91768   CSS                0.00001
CV               0.24281   Std Mean           0.00007
```



```
                        Quantiles
100% Max          0.1967      99.0%          0.1967
 75% Q3           0.1961      97.5%          0.1967
 50% Med          0.1960      95.0%          0.1966
 25% Q1           0.1955      90.0%          0.1964
  0% Min          0.1950      10.0%          0.1950
     Range        0.0017       5.0%          0.1950
     Q3-Q1        0.0006       2.5%          0.1950
     Mode         0.1960       1.0%          0.1950
```

Fixed Tang Width Measurements by Operator

Operator 1

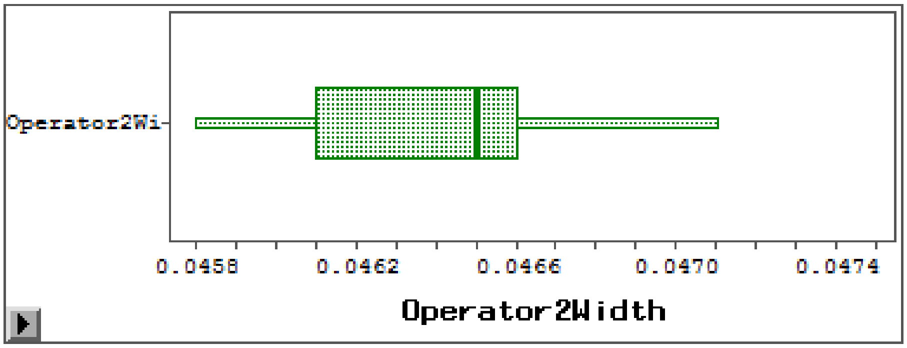


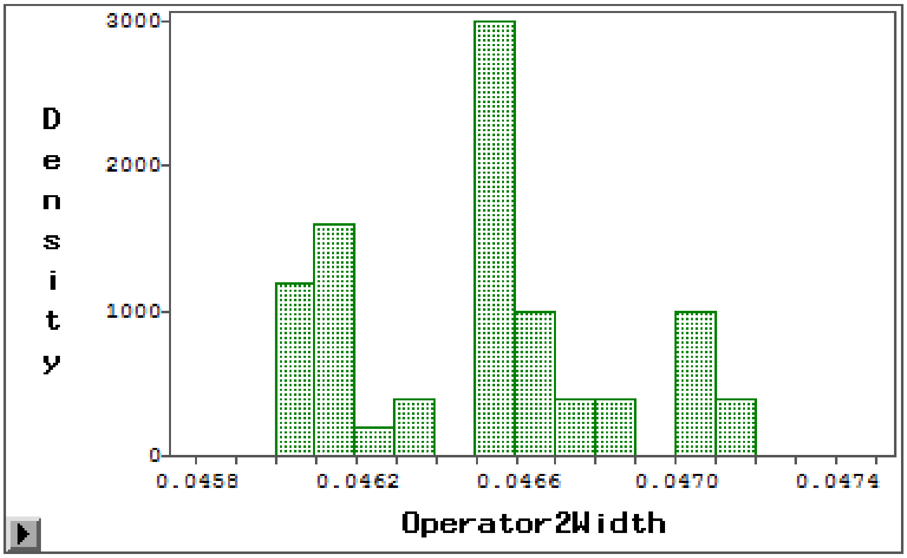
```
                         Moments
N                 50.00000  Sum Wgts          50.00000
Mean               0.04646  Sum                2.32300
Std Dev            0.00031  Variance      9.918367E-08
Skewness           0.08330  Kurtosis          -0.99096
USS                0.10793  CSS           4.860000E-06
CV                 0.67786  Std Mean           0.00004
```

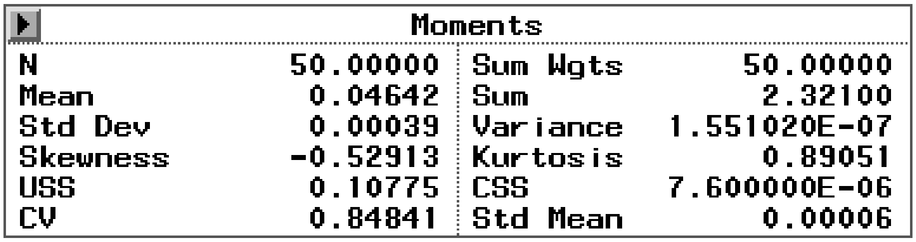
```
                        Quantiles
100% Max           0.0471       99.0%          0.0471
 75% Q3            0.0467       97.5%          0.0470
 50% Med           0.0465       95.0%          0.0469
 25% Q1            0.0461       90.0%          0.0469
  0% Min           0.0459       10.0%          0.0461
     Range         0.0012        5.0%          0.0460
     Q3-Q1         0.0006        2.5%          0.0460
     Mode          0.0465        1.0%          0.0459
```

Operator 2

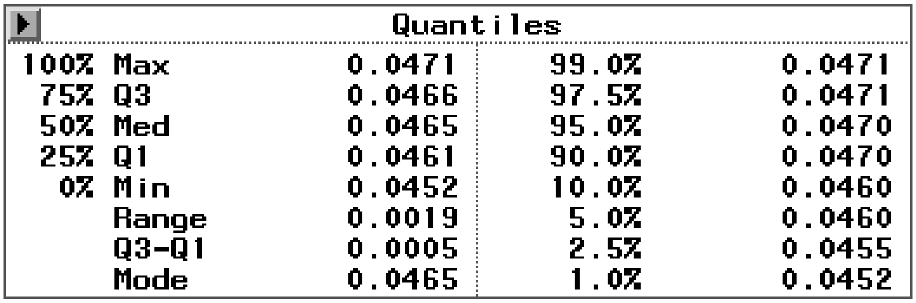
Operator2Width





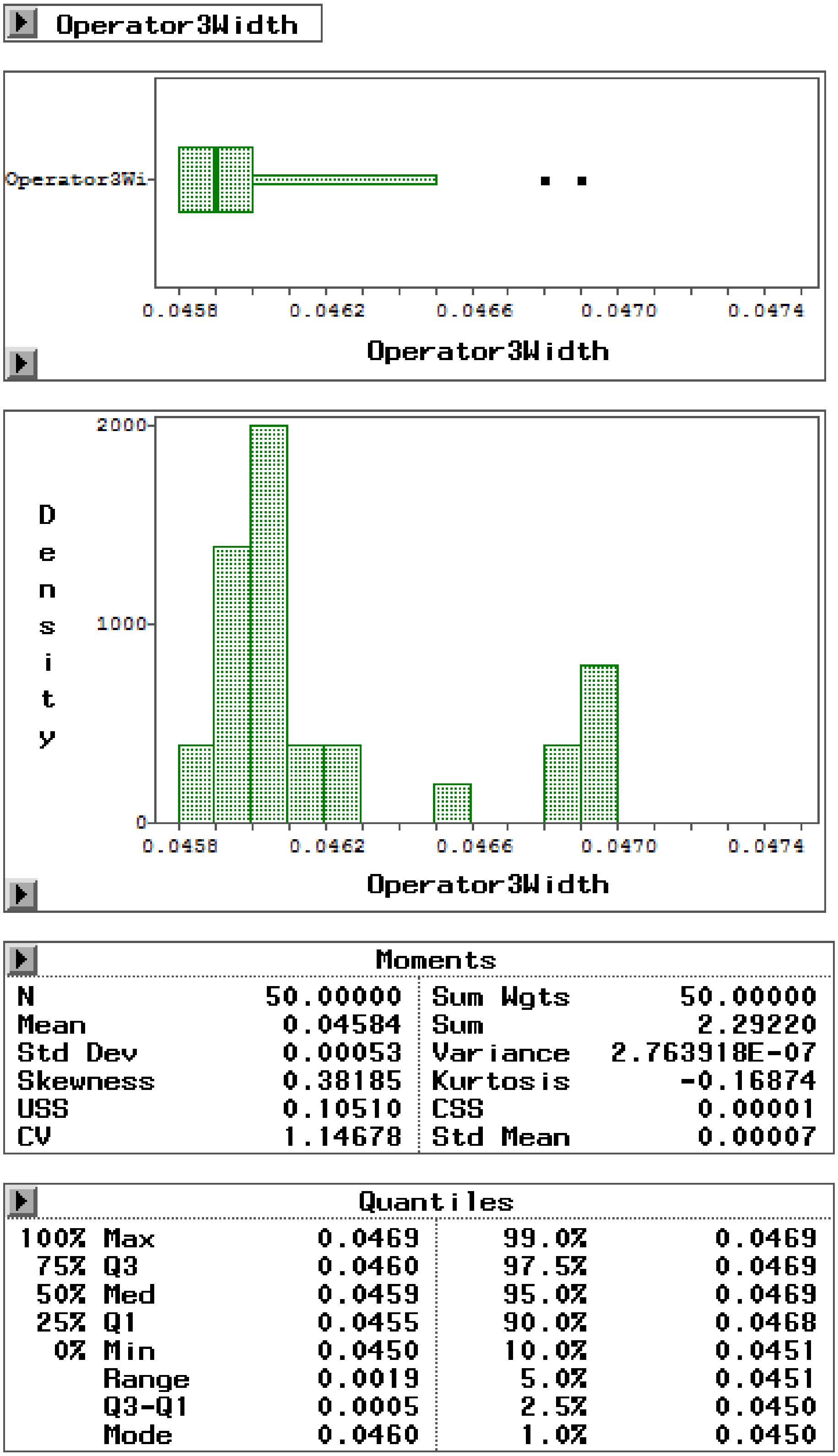


```
                              Moments
N                   50.00000 | Sum Wgts        50.00000
Mean                 0.04642 | Sum              2.32100
Std Dev              0.00039 | Variance    1.551020E-07
Skewness            -0.52913 | Kurtosis         0.89051
USS                  0.10775 | CSS         7.600000E-06
CV                   0.84841 | Std Mean         0.00006
```



```
                             Quantiles
100% Max              0.0471 |   99.0%           0.0471
 75% Q3               0.0466 |   97.5%           0.0471
 50% Med              0.0465 |   95.0%           0.0470
 25% Q1               0.0461 |   90.0%           0.0470
  0% Min              0.0452 |   10.0%           0.0460
     Range            0.0019 |    5.0%           0.0460
     Q3-Q1            0.0005 |    2.5%           0.0455
     Mode             0.0465 |    1.0%           0.0452
```

Operator 3



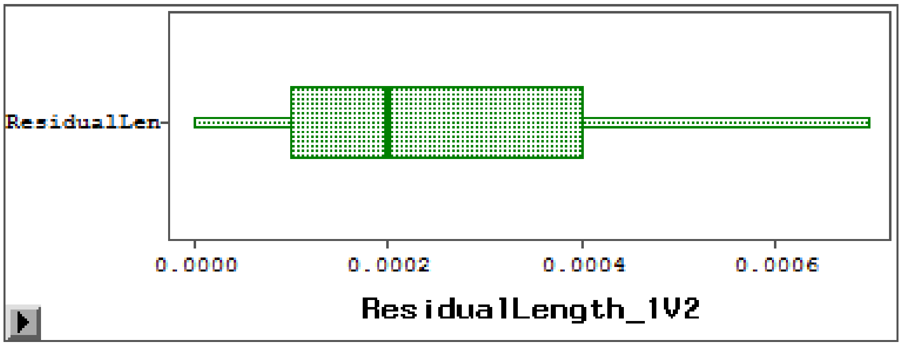
```
                          Moments
N                50.00000   Sum Wgts          50.00000
Mean              0.04584   Sum                2.29220
Std Dev           0.00053   Variance      2.763918E-07
Skewness          0.38185   Kurtosis          -0.16874
USS               0.10510   CSS                0.00001
CV                1.14678   Std Mean           0.00007
```

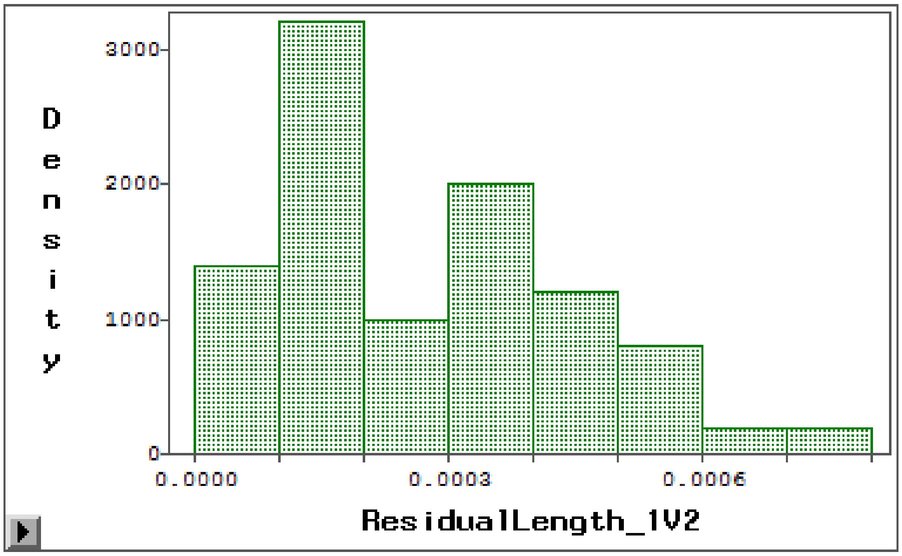
```
                         Quantiles
100% Max           0.0469      99.0%            0.0469
 75% Q3            0.0460      97.5%            0.0469
 50% Med           0.0459      95.0%            0.0469
 25% Q1            0.0455      90.0%            0.0468
  0% Min           0.0450      10.0%            0.0451
     Range         0.0019       5.0%            0.0451
     Q3-Q1         0.0005       2.5%            0.0450
     Mode          0.0460       1.0%            0.0450
```

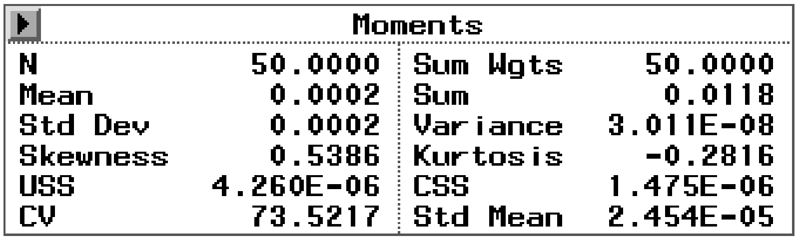
Fixed Tang Length Residuals

Operator 1 vs. 2

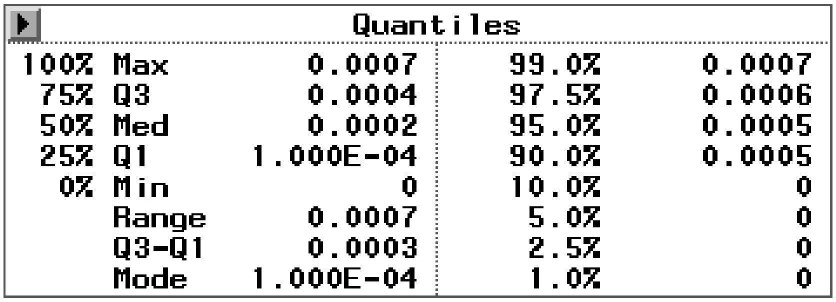
ResidualLength_1V2







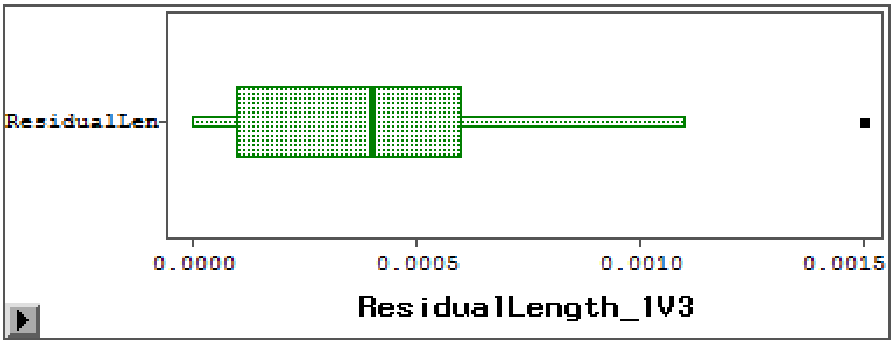
```
                         Moments
N                50.0000  Sum Wgts       50.0000
Mean              0.0002  Sum             0.0118
Std Dev           0.0002  Variance     3.011E-08
Skewness          0.5386  Kurtosis       -0.2816
USS            4.260E-06  CSS          1.475E-06
CV               73.5217  Std Mean     2.454E-05
```

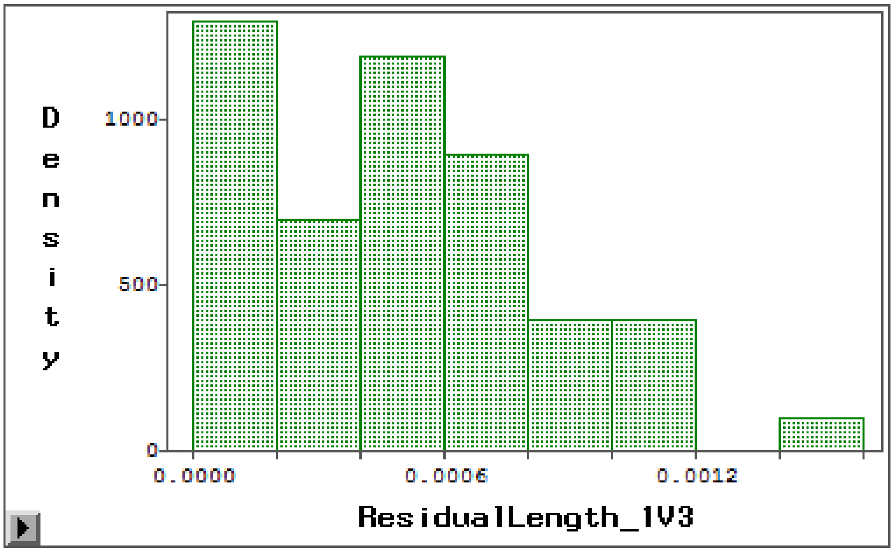


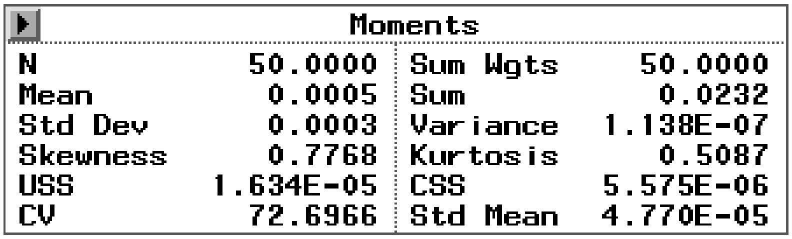
```
                         Quantiles
100% Max         0.0007     99.0%         0.0007
 75% Q3          0.0004     97.5%         0.0006
 50% Med         0.0002     95.0%         0.0005
 25% Q1       1.000E-04     90.0%         0.0005
  0% Min              0     10.0%              0
     Range       0.0007      5.0%              0
     Q3-Q1       0.0003      2.5%              0
     Mode     1.000E-04      1.0%              0
```

Operator 1 vs. 3

ResidualLength_1V3

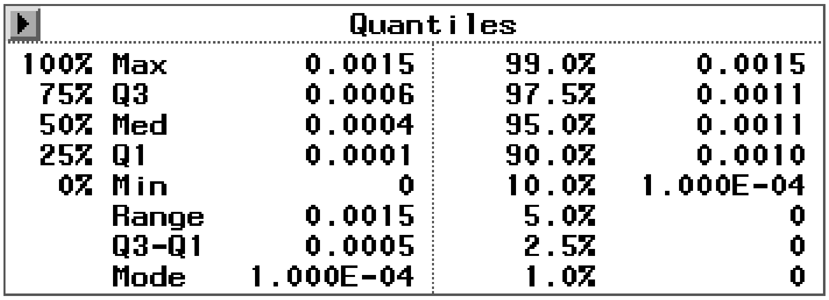






Moments

N	50.0000	Sum Wgts	50.0000
Mean	0.0005	Sum	0.0232
Std Dev	0.0003	Variance	1.138E-07
Skewness	0.7768	Kurtosis	0.5087
USS	1.634E-05	CSS	5.575E-06
CV	72.6966	Std Mean	4.770E-05

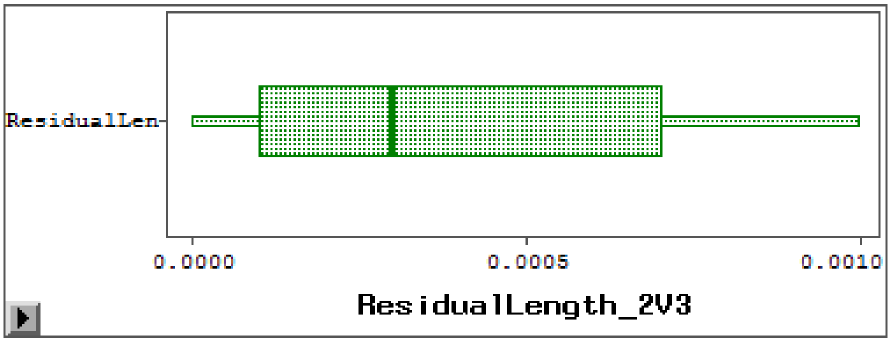


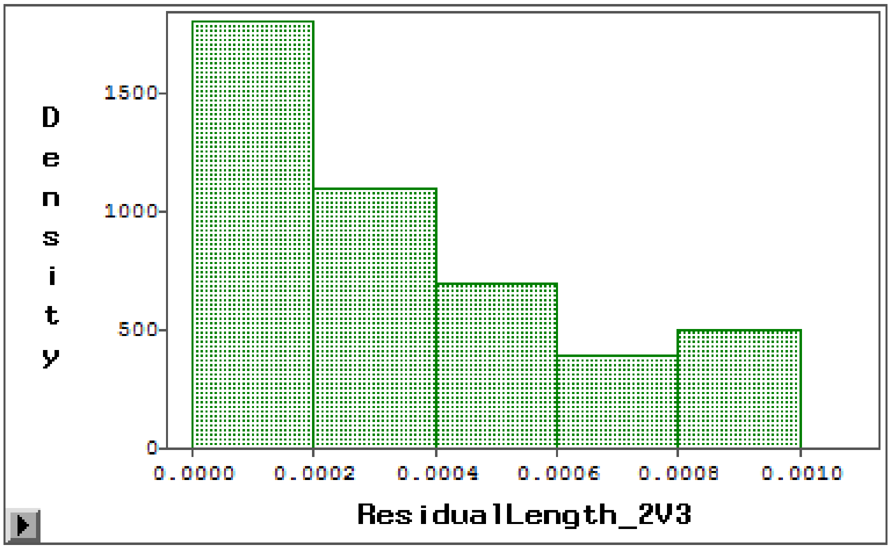
Quantiles

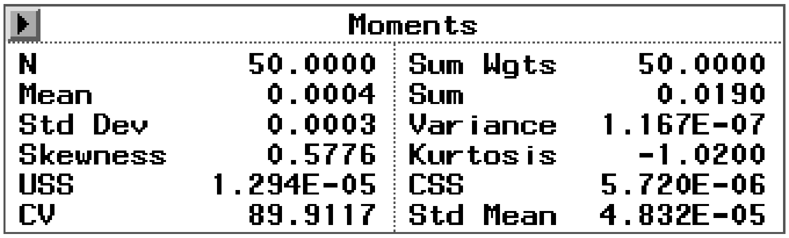
100% Max	0.0015	99.0%	0.0015
75% Q3	0.0006	97.5%	0.0011
50% Med	0.0004	95.0%	0.0011
25% Q1	0.0001	90.0%	0.0010
0% Min	0	10.0%	1.000E-04
Range	0.0015	5.0%	0
Q3-Q1	0.0005	2.5%	0
Mode	1.000E-04	1.0%	0

Operator 2 vs. 3

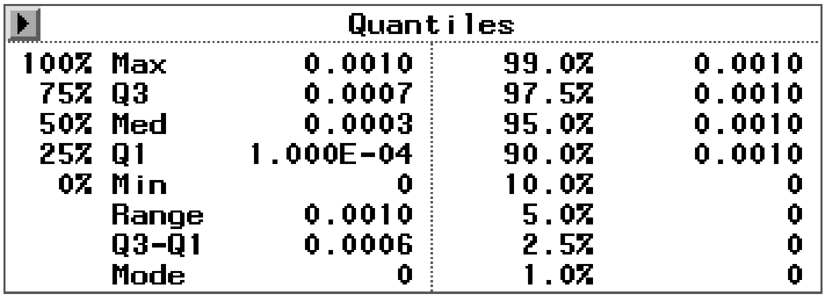
ResidualLength_2V3







```
                          Moments
N               50.0000   Sum Wgts      50.0000
Mean             0.0004   Sum            0.0190
Std Dev          0.0003   Variance    1.167E-07
Skewness         0.5776   Kurtosis      -1.0200
USS           1.294E-05   CSS         5.720E-06
CV              89.9117   Std Mean    4.832E-05
```

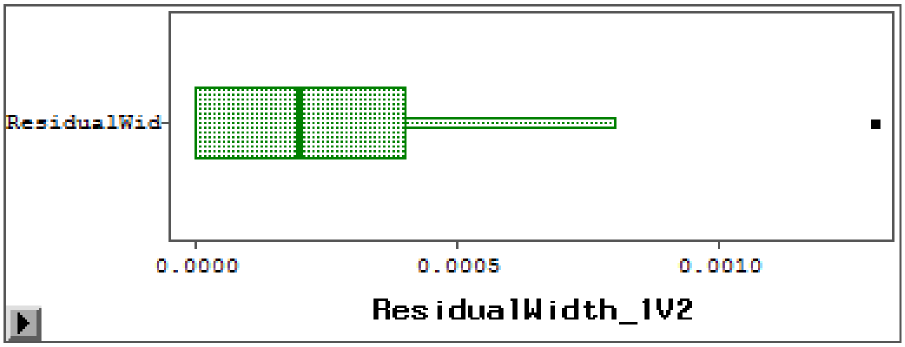


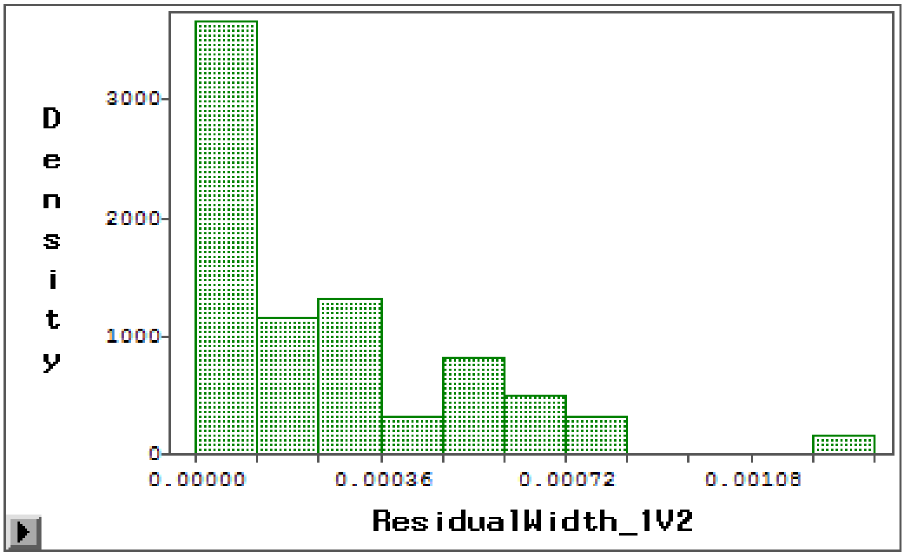
```
                        Quantiles
100% Max         0.0010    99.0%         0.0010
 75% Q3          0.0007    97.5%         0.0010
 50% Med         0.0003    95.0%         0.0010
 25% Q1       1.000E-04    90.0%         0.0010
  0% Min              0    10.0%              0
     Range       0.0010     5.0%              0
     Q3-Q1       0.0006     2.5%              0
     Mode             0     1.0%              0
```

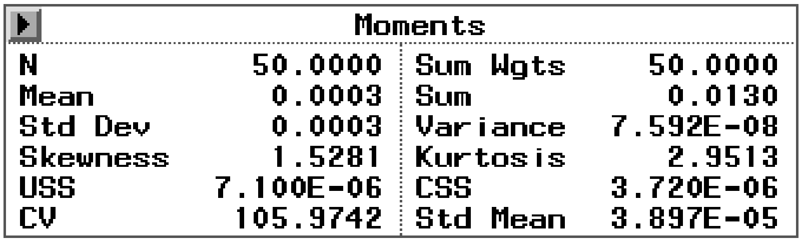
Fixed Tang Width Residuals

Operator 1 vs. 2

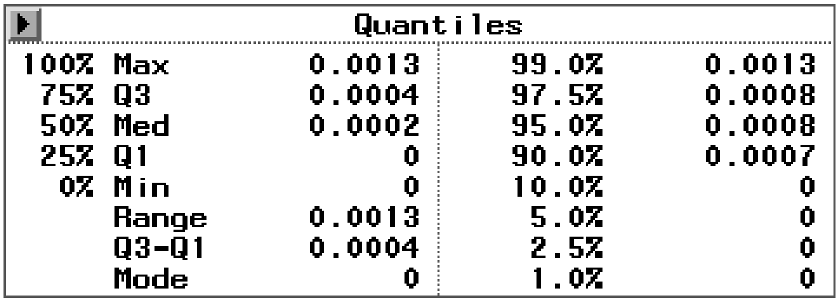
ResidualWidth_1V2







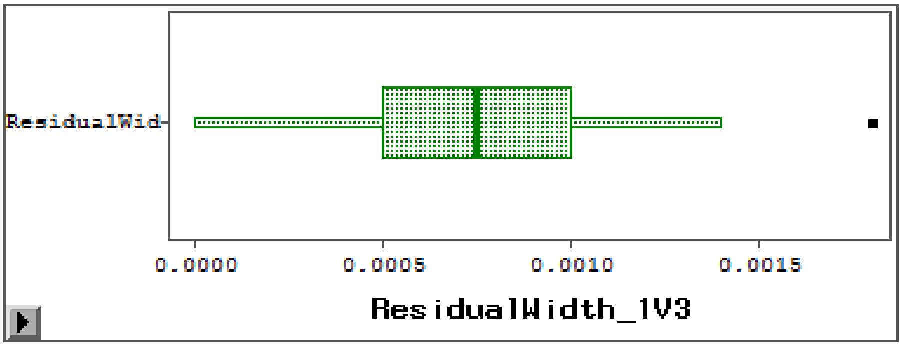
```
                         Moments
N               50.0000   Sum Wgts      50.0000
Mean             0.0003   Sum            0.0130
Std Dev          0.0003   Variance    7.592E-08
Skewness         1.5281   Kurtosis       2.9513
USS           7.100E-06   CSS         3.720E-06
CV             105.9742   Std Mean    3.897E-05
```

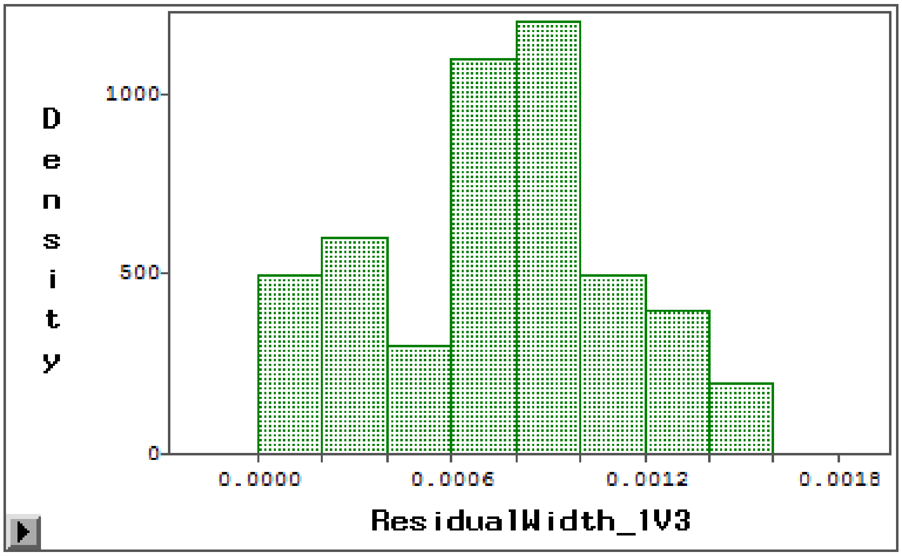


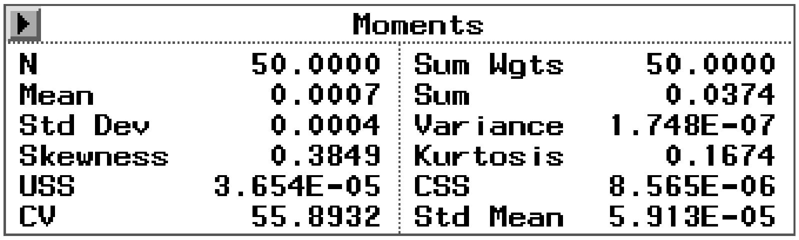
```
                         Quantiles
100% Max       0.0013       99.0%       0.0013
 75% Q3        0.0004       97.5%       0.0008
 50% Med       0.0002       95.0%       0.0008
 25% Q1             0       90.0%       0.0007
  0% Min            0       10.0%            0
     Range     0.0013        5.0%            0
     Q3-Q1     0.0004        2.5%            0
     Mode           0        1.0%            0
```

Operator 1 vs. 3

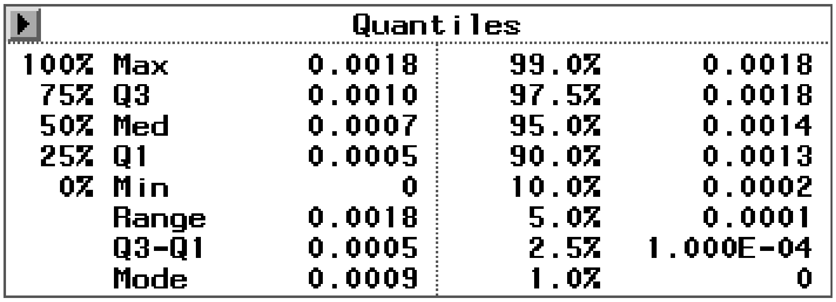
ResidualWidth_1V3







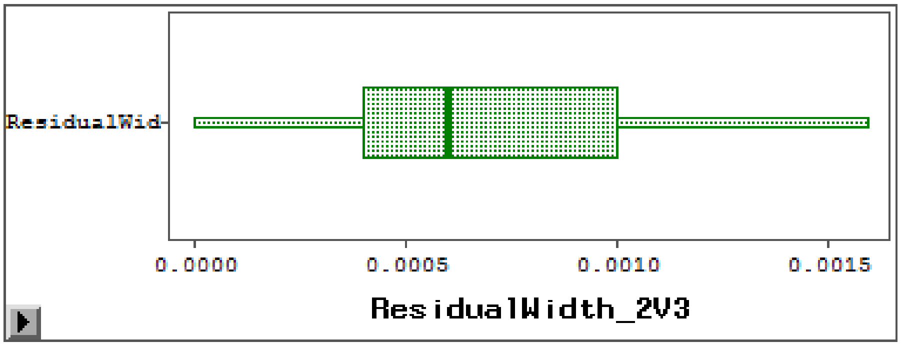
```
                          Moments
N                50.0000   Sum Wgts        50.0000
Mean              0.0007   Sum              0.0374
Std Dev           0.0004   Variance      1.748E-07
Skewness          0.3849   Kurtosis         0.1674
USS            3.654E-05   CSS           8.565E-06
CV               55.8932   Std Mean      5.913E-05
```

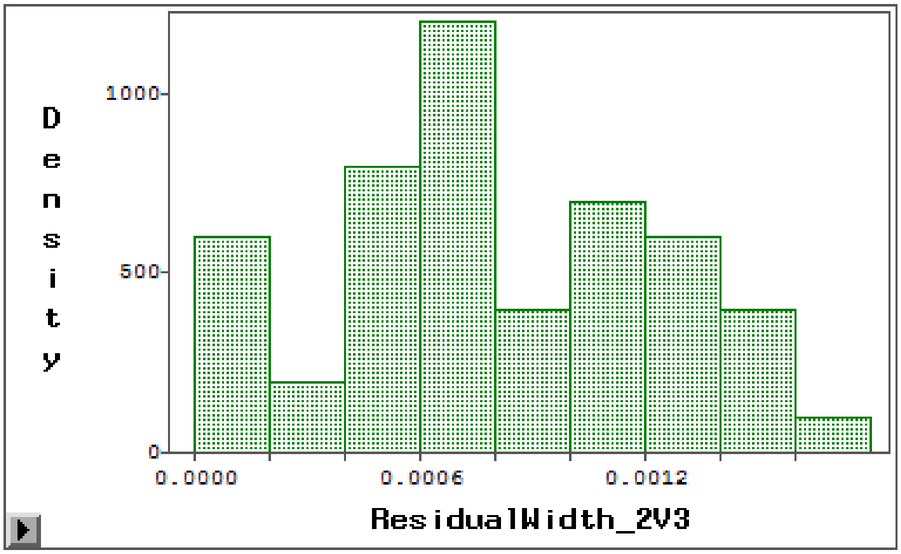


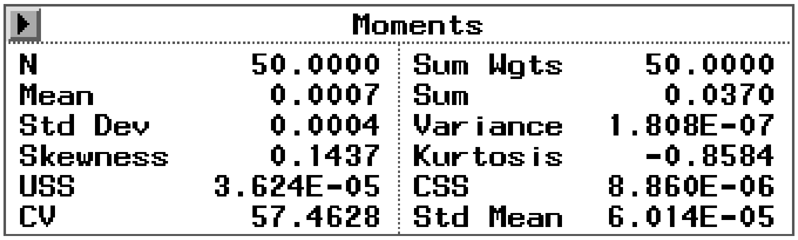
```
                          Quantiles
100% Max          0.0018        99.0%          0.0018
 75% Q3           0.0010        97.5%          0.0018
 50% Med          0.0007        95.0%          0.0014
 25% Q1           0.0005        90.0%          0.0013
  0% Min               0        10.0%          0.0002
     Range        0.0018         5.0%          0.0001
     Q3-Q1        0.0005         2.5%       1.000E-04
     Mode         0.0009         1.0%               0
```

Operator 2 vs. 3

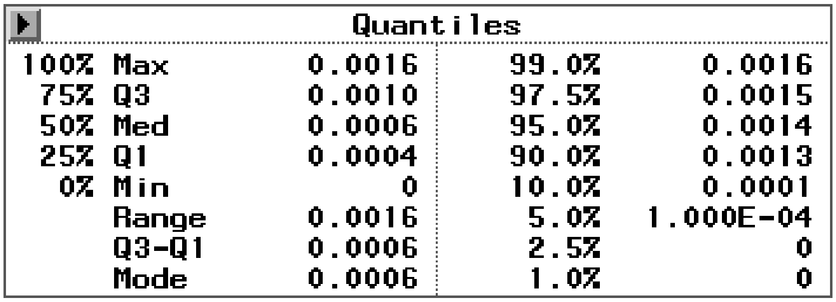
ResidualWidth_2V3







```
                      Moments
N             50.0000   Sum Wgts      50.0000
Mean           0.0007   Sum            0.0370
Std Dev        0.0004   Variance    1.808E-07
Skewness       0.1437   Kurtosis      -0.8584
USS         3.624E-05   CSS         8.860E-06
CV            57.4628   Std Mean    6.014E-05
```

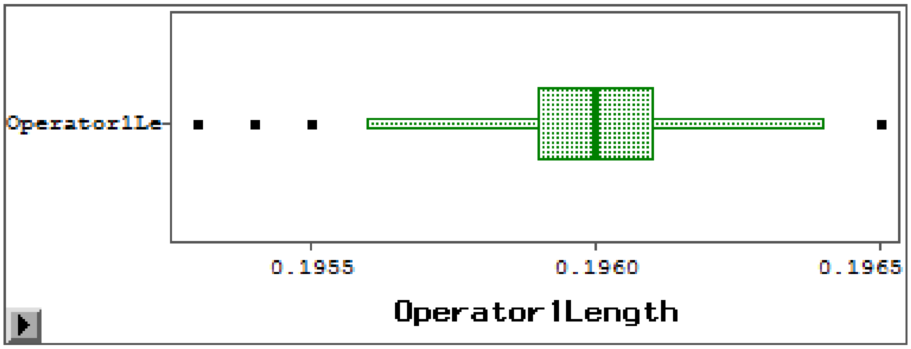


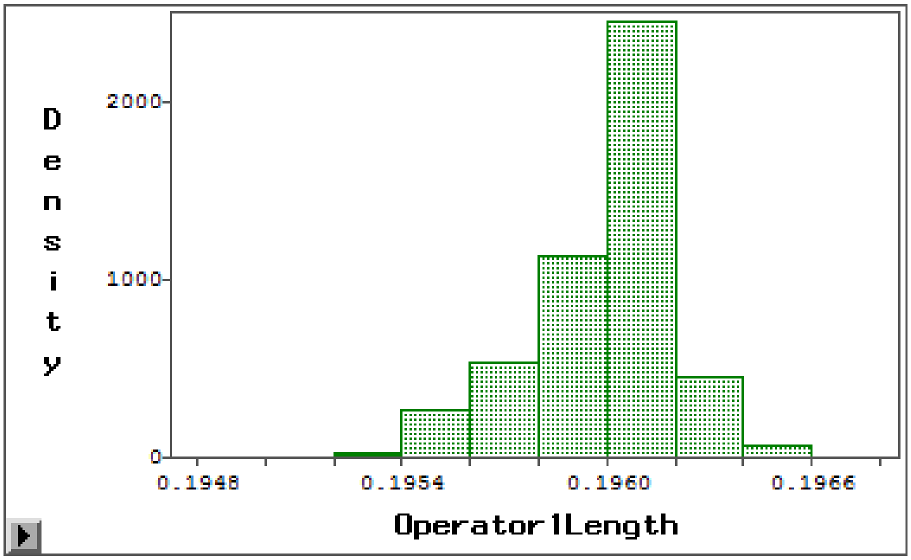
```
                        Quantiles
100% Max            0.0016     99.0%        0.0016
 75% Q3             0.0010     97.5%        0.0015
 50% Med            0.0006     95.0%        0.0014
 25% Q1             0.0004     90.0%        0.0013
  0% Min                 0     10.0%        0.0001
     Range          0.0016      5.0%     1.000E-04
     Q3-Q1          0.0006      2.5%             0
     Mode           0.0006      1.0%             0
```

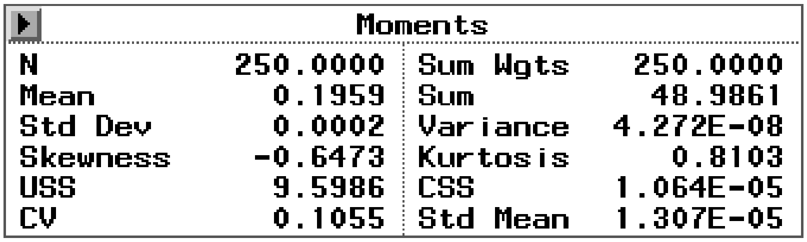
Random Tang Length Measurements by Operator

Operator 1

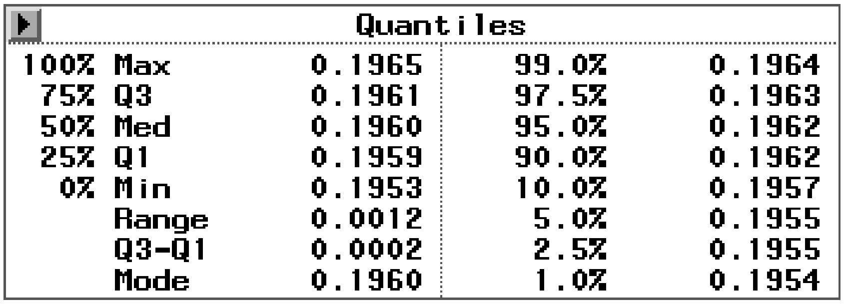
Operator1Length







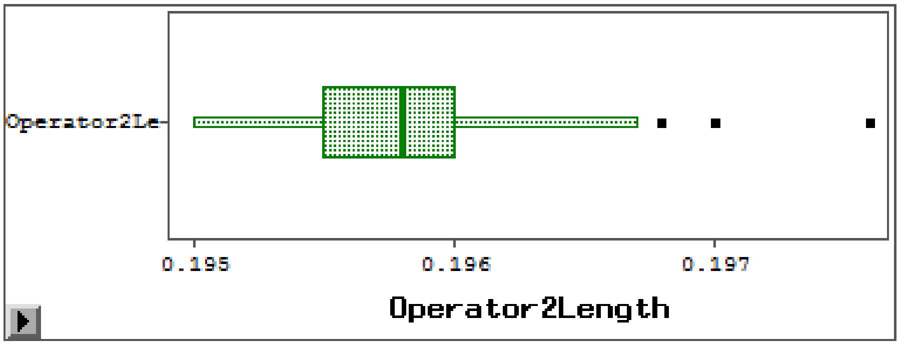
```
                          Moments
N              250.0000   Sum Wgts      250.0000
Mean             0.1959   Sum            48.9861
Std Dev          0.0002   Variance     4.272E-08
Skewness        -0.6473   Kurtosis        0.8103
USS              9.5986   CSS          1.064E-05
CV               0.1055   Std Mean     1.307E-05
```

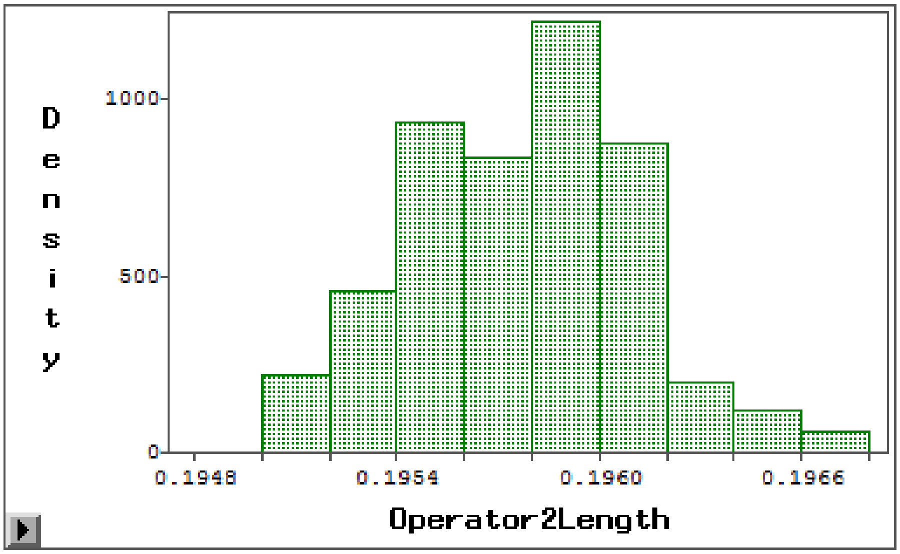


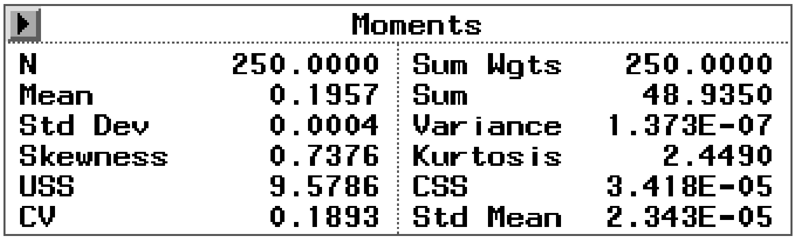
```
                          Quantiles
100% Max          0.1965      99.0%         0.1964
 75% Q3           0.1961      97.5%         0.1963
 50% Med          0.1960      95.0%         0.1962
 25% Q1           0.1959      90.0%         0.1962
  0% Min          0.1953      10.0%         0.1957
     Range        0.0012       5.0%         0.1955
     Q3-Q1        0.0002       2.5%         0.1955
     Mode         0.1960       1.0%         0.1954
```

Operator 2

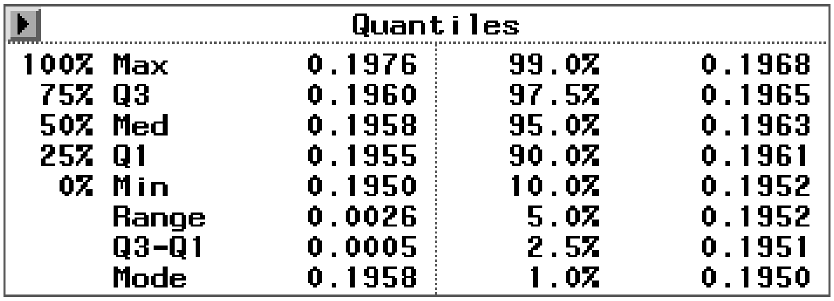
Operator2Length







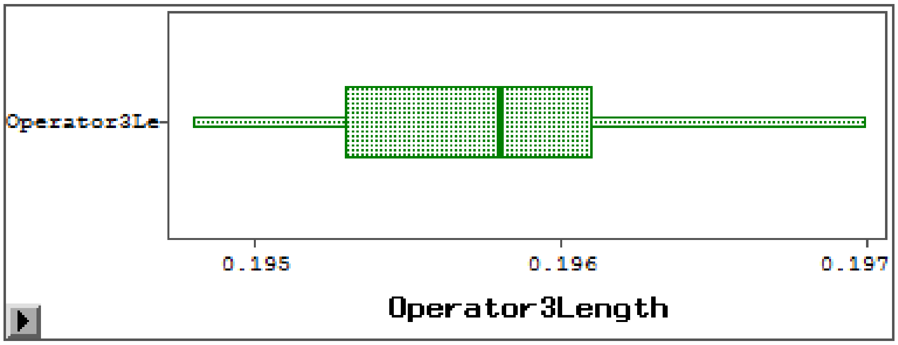
```
                    Moments
N           250.0000   Sum Wgts     250.0000
Mean          0.1957   Sum           48.9350
Std Dev       0.0004   Variance    1.373E-07
Skewness      0.7376   Kurtosis       2.4490
USS           9.5786   CSS         3.418E-05
CV            0.1893   Std Mean    2.343E-05
```

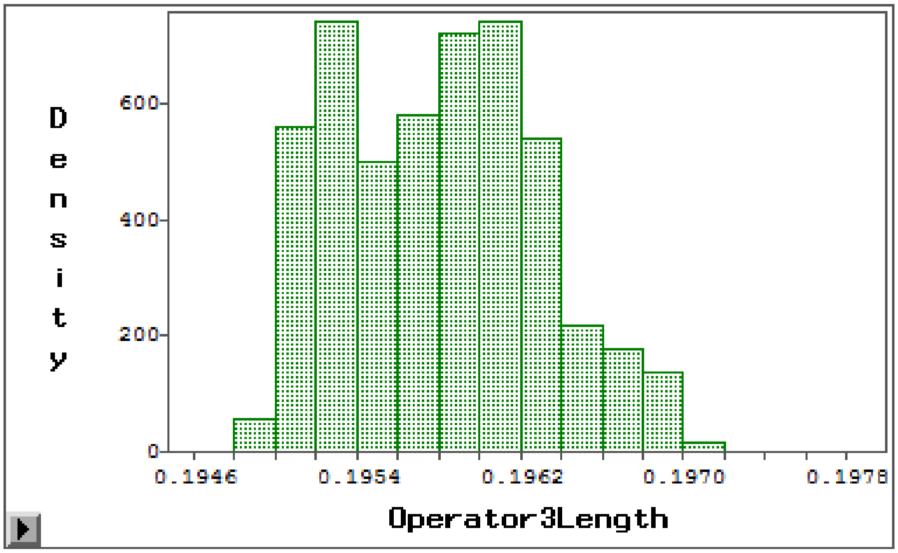


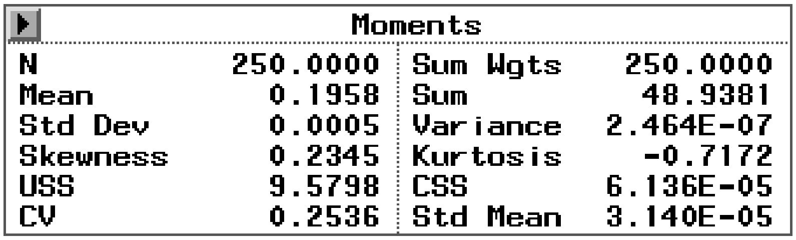
```
                       Quantiles
100% Max          0.1976      99.0%        0.1968
 75% Q3           0.1960      97.5%        0.1965
 50% Med          0.1958      95.0%        0.1963
 25% Q1           0.1955      90.0%        0.1961
  0% Min          0.1950      10.0%        0.1952
     Range        0.0026       5.0%        0.1952
     Q3-Q1        0.0005       2.5%        0.1951
     Mode         0.1958       1.0%        0.1950
```

Operator 3

Operator3Length

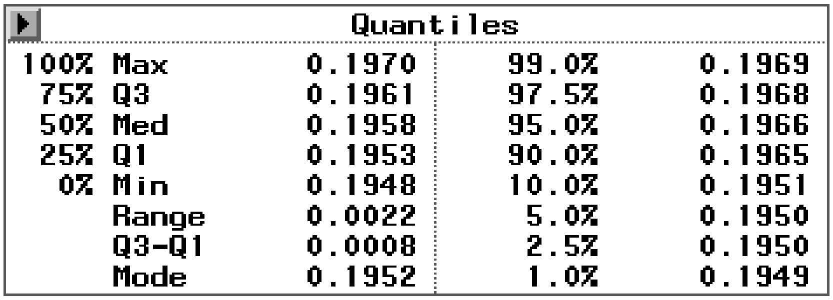






Moments

N	250.0000	Sum Wgts	250.0000
Mean	0.1958	Sum	48.9381
Std Dev	0.0005	Variance	2.464E-07
Skewness	0.2345	Kurtosis	-0.7172
USS	9.5798	CSS	6.136E-05
CV	0.2536	Std Mean	3.140E-05



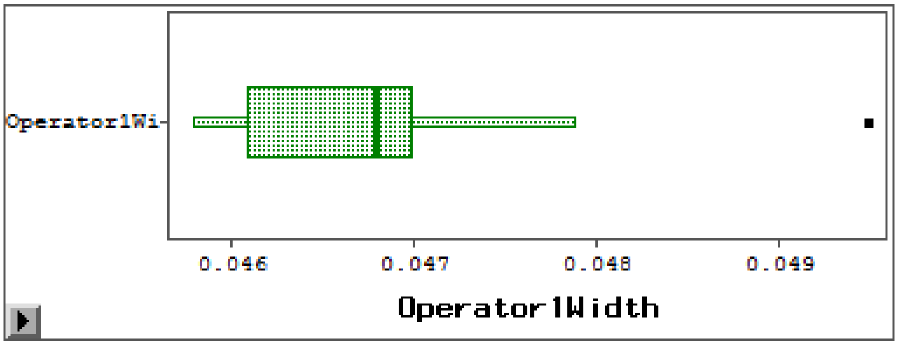
Quantiles

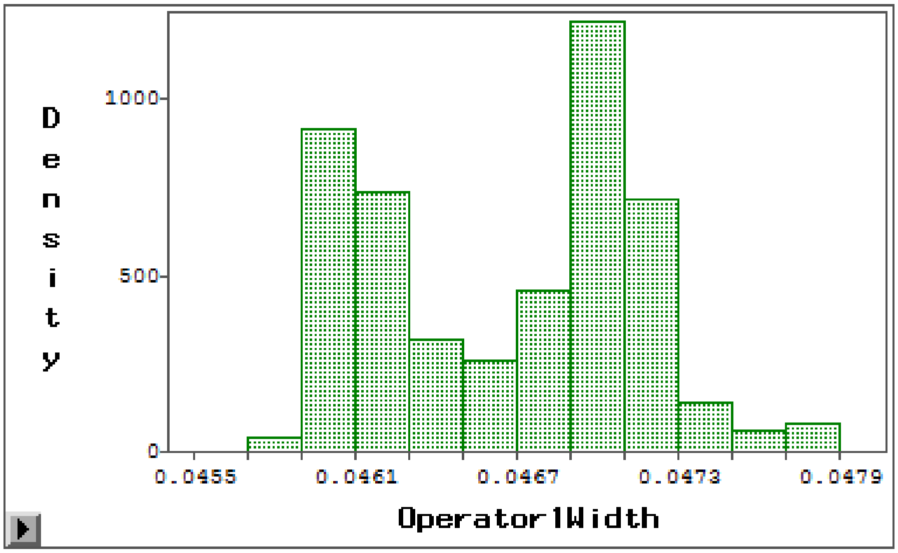
100%	Max	0.1970	99.0%	0.1969
75%	Q3	0.1961	97.5%	0.1968
50%	Med	0.1958	95.0%	0.1966
25%	Q1	0.1953	90.0%	0.1965
0%	Min	0.1948	10.0%	0.1951
	Range	0.0022	5.0%	0.1950
	Q3-Q1	0.0008	2.5%	0.1950
	Mode	0.1952	1.0%	0.1949

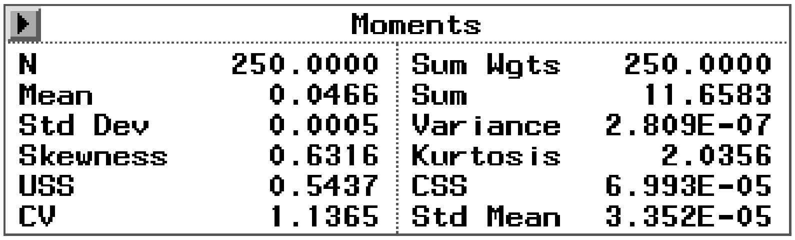
Random Tang Width Measurements by Operator

Operator 1

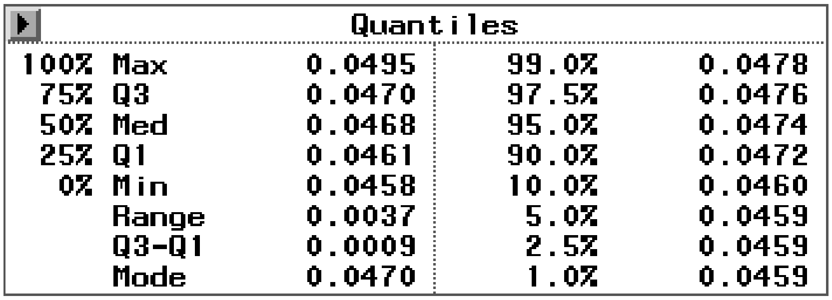
Operator1Width







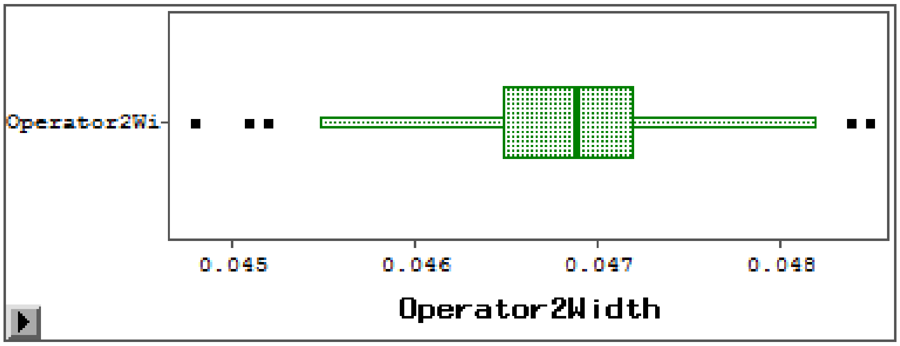
```
                      Moments
N             250.0000   Sum Wgts     250.0000
Mean            0.0466   Sum           11.6583
Std Dev         0.0005   Variance    2.809E-07
Skewness        0.6316   Kurtosis       2.0356
USS             0.5437   CSS         6.993E-05
CV              1.1365   Std Mean    3.352E-05
```

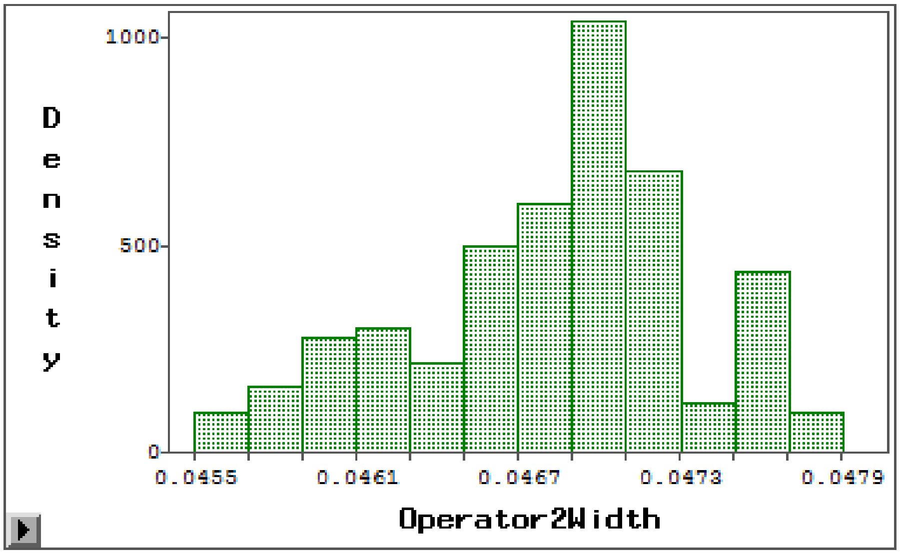


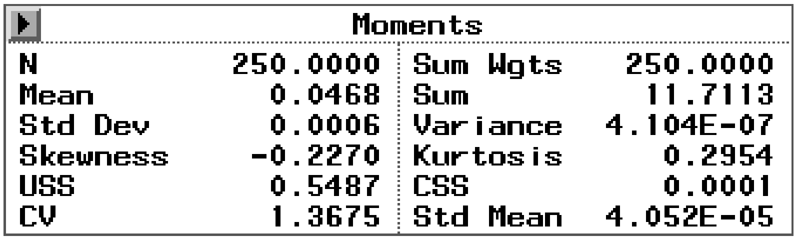
```
                       Quantiles
100% Max        0.0495      99.0%        0.0478
 75% Q3         0.0470      97.5%        0.0476
 50% Med        0.0468      95.0%        0.0474
 25% Q1         0.0461      90.0%        0.0472
  0% Min        0.0458      10.0%        0.0460
     Range      0.0037       5.0%        0.0459
     Q3-Q1      0.0009       2.5%        0.0459
     Mode       0.0470       1.0%        0.0459
```

Operator 2

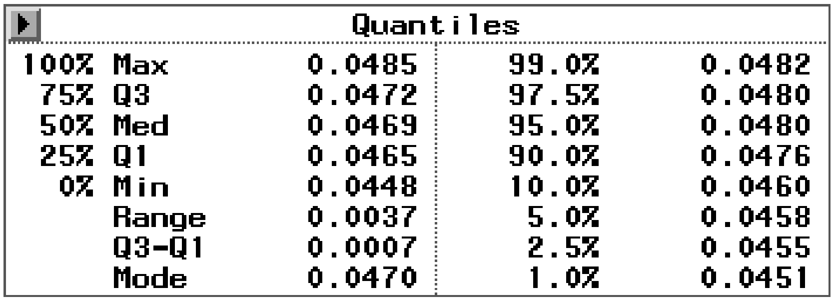
Operator2Width







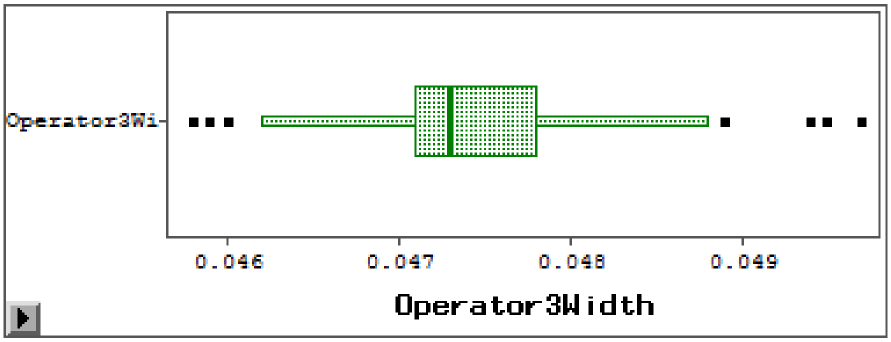
```
                      Moments
N           250.0000  Sum Wgts    250.0000
Mean          0.0468  Sum          11.7113
Std Dev       0.0006  Variance   4.104E-07
Skewness     -0.2270  Kurtosis      0.2954
USS           0.5487  CSS           0.0001
CV            1.3675  Std Mean   4.052E-05
```

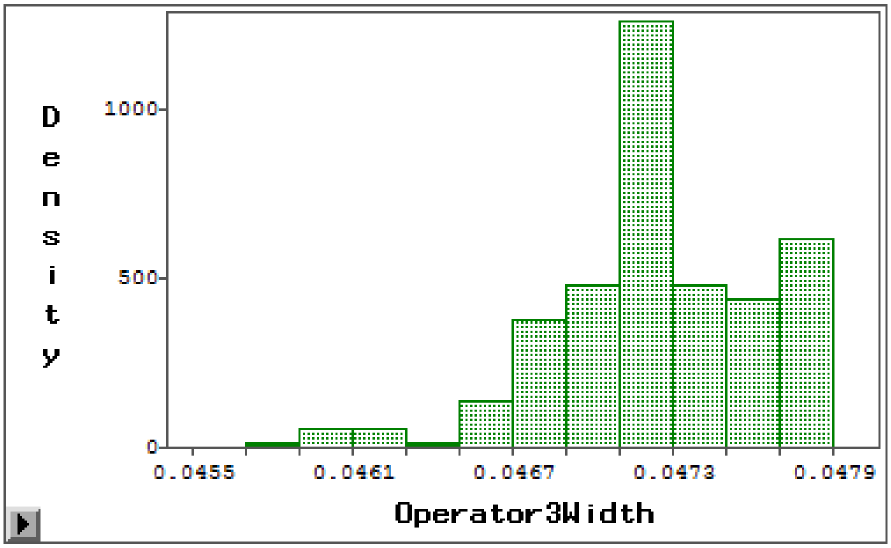


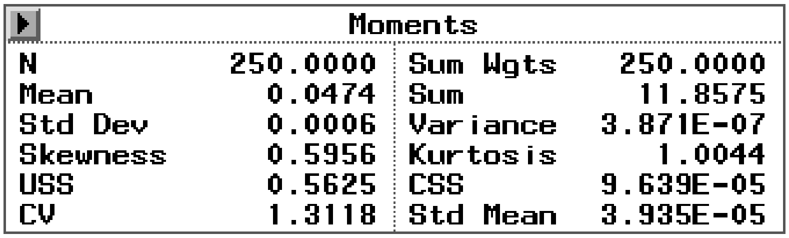
```
                      Quantiles
100% Max        0.0485      99.0%        0.0482
 75% Q3         0.0472      97.5%        0.0480
 50% Med        0.0469      95.0%        0.0480
 25% Q1         0.0465      90.0%        0.0476
  0% Min        0.0448      10.0%        0.0460
     Range      0.0037       5.0%        0.0458
     Q3-Q1      0.0007       2.5%        0.0455
     Mode       0.0470       1.0%        0.0451
```

Operator 3

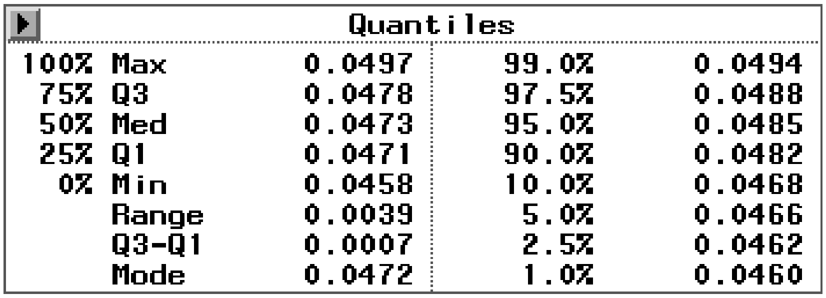
Operator3Width







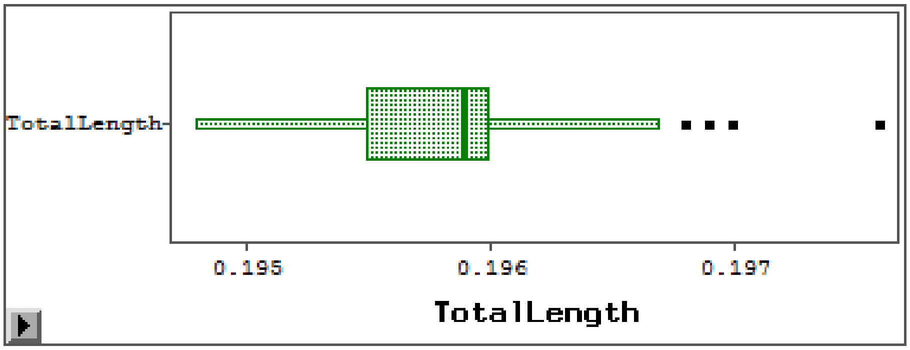
```
                     Moments
N              250.0000   Sum Wgts     250.0000
Mean             0.0474   Sum           11.8575
Std Dev          0.0006   Variance    3.871E-07
Skewness         0.5956   Kurtosis       1.0044
USS              0.5625   CSS         9.639E-05
CV               1.3118   Std Mean    3.935E-05
```

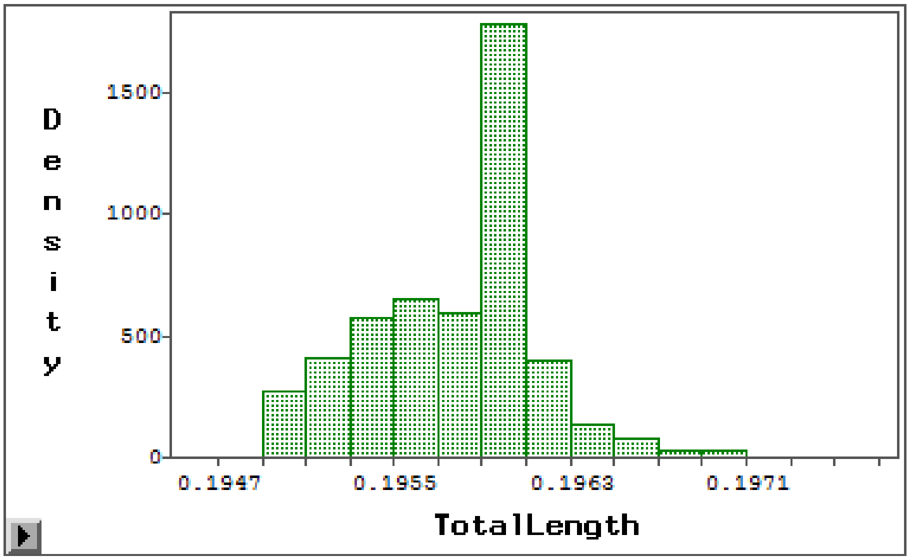


```
                      Quantiles
100% Max          0.0497     99.0%        0.0494
 75% Q3           0.0478     97.5%        0.0488
 50% Med          0.0473     95.0%        0.0485
 25% Q1           0.0471     90.0%        0.0482
  0% Min          0.0458     10.0%        0.0468
     Range        0.0039      5.0%        0.0466
     Q3-Q1        0.0007      2.5%        0.0462
     Mode         0.0472      1.0%        0.0460
```

Overall Tang Length Measurements

TotalLength



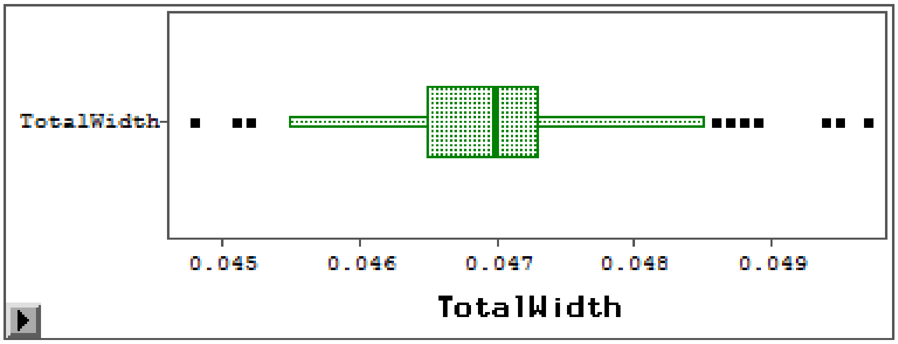


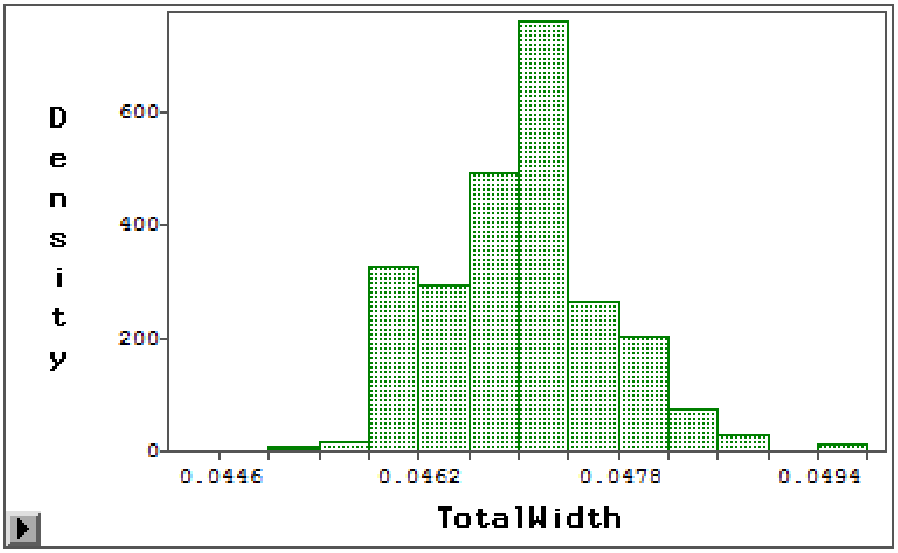
```
                      Moments
N                750.0000 | Sum Wgts     750.0000
Mean               0.1958 | Sum          146.8592
Std Dev            0.0004 | Variance    1.505E-07
Skewness           0.0265 | Kurtosis       0.5237
USS               28.7569 | CSS            0.0001
CV                 0.1981 | Std Mean    1.417E-05
```

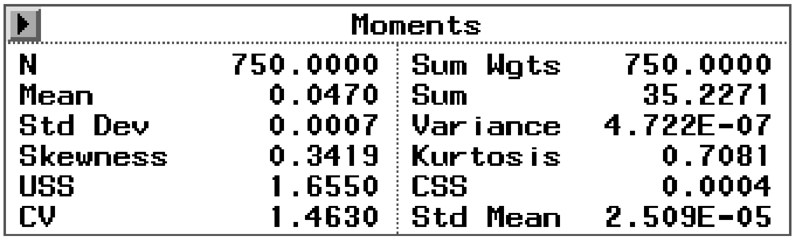
```
                      Quantiles
100% Max           0.1976 |   99.0%         0.1968
 75% Q3            0.1960 |   97.5%         0.1966
 50% Med           0.1959 |   95.0%         0.1965
 25% Q1            0.1955 |   90.0%         0.1962
  0% Min           0.1948 |   10.0%         0.1952
     Range         0.0028 |    5.0%         0.1951
     Q3-Q1         0.0005 |    2.5%         0.1950
     Mode          0.1960 |    1.0%         0.1950
```

Overall Tang Width Measurements

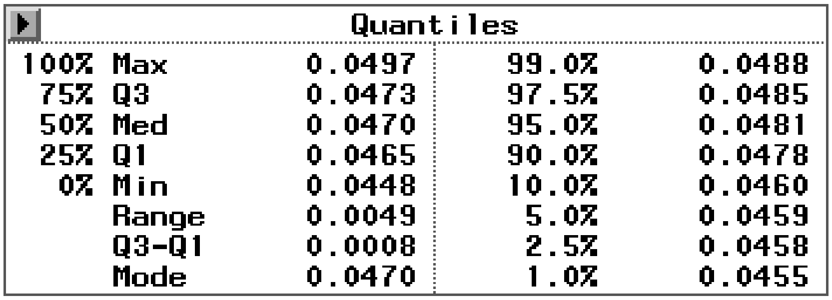
TotalWidth







```
                           Moments
N             750.0000   Sum Wgts      750.0000
Mean            0.0470   Sum            35.2271
Std Dev         0.0007   Variance     4.722E-07
Skewness        0.3419   Kurtosis        0.7081
USS             1.6550   CSS             0.0004
CV              1.4630   Std Mean     2.509E-05
```

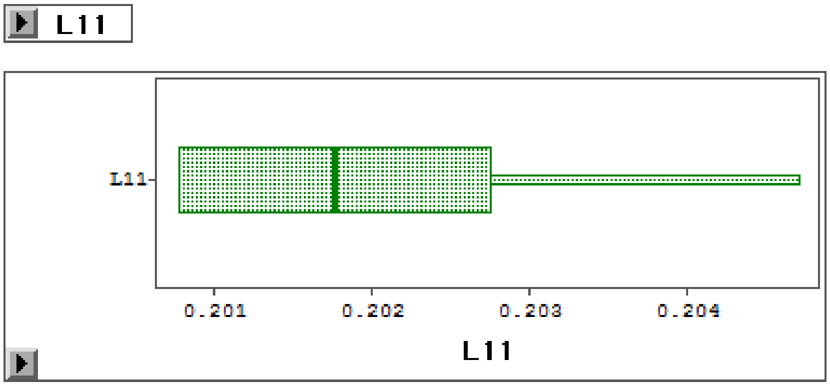


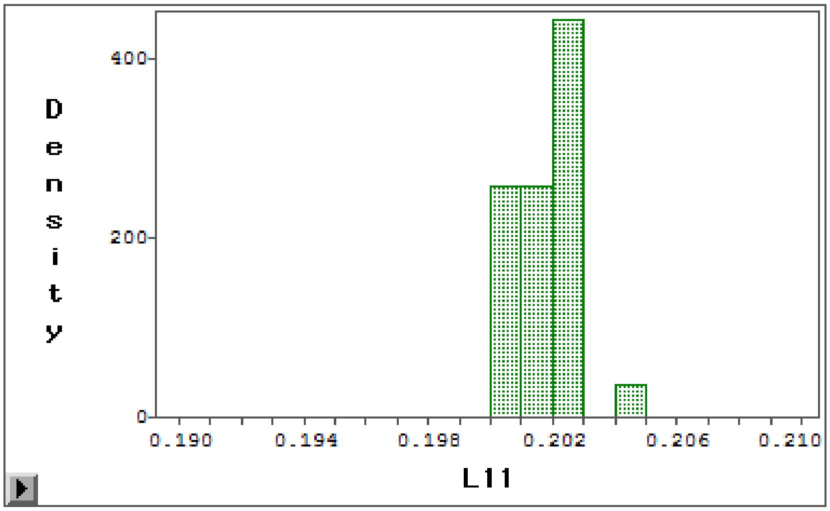
```
                           Quantiles
100% Max           0.0497      99.0%          0.0488
 75% Q3            0.0473      97.5%          0.0485
 50% Med           0.0470      95.0%          0.0481
 25% Q1            0.0465      90.0%          0.0478
  0% Min           0.0448      10.0%          0.0460
     Range         0.0049       5.0%          0.0459
     Q3-Q1         0.0008       2.5%          0.0458
     Mode          0.0470       1.0%          0.0455
```

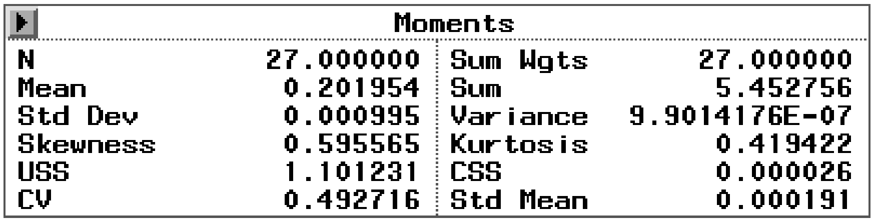
Appendix B: Slot Size Analysis (Chpt. 4)

Lot 1

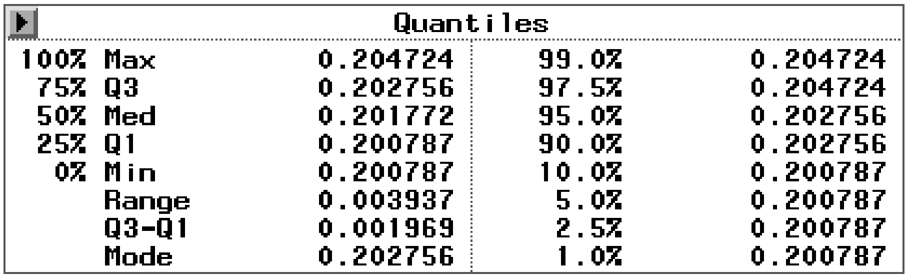
Lot 1: Length







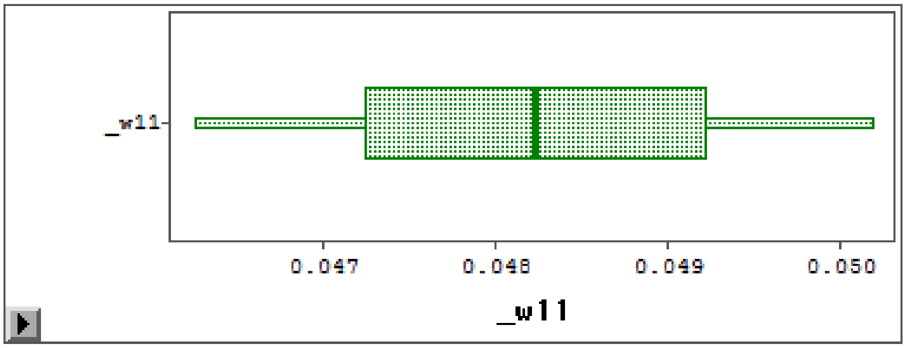
```
                          Moments
N                27.000000  Sum Wgts       27.000000
Mean              0.201954  Sum             5.452756
Std Dev           0.000995  Variance   9.9014176E-07
Skewness          0.595565  Kurtosis        0.419422
USS               1.101231  CSS             0.000026
CV                0.492716  Std Mean        0.000191
```

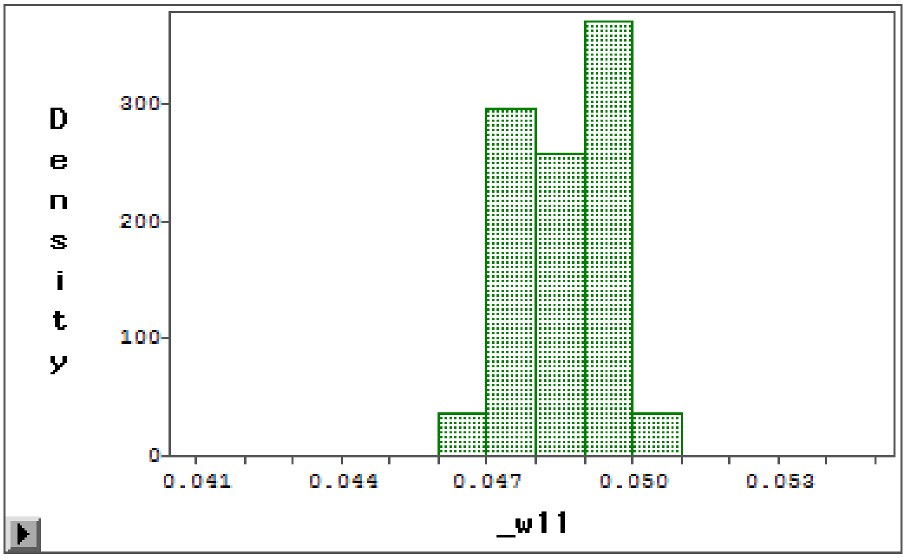


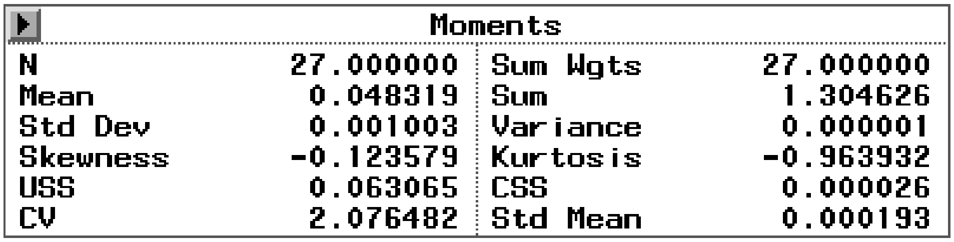
```
                          Quantiles
100% Max           0.204724      99.0%          0.204724
 75% Q3            0.202756      97.5%          0.204724
 50% Med           0.201772      95.0%          0.202756
 25% Q1            0.200787      90.0%          0.202756
  0% Min           0.200787      10.0%          0.200787
     Range         0.003937       5.0%          0.200787
     Q3-Q1         0.001969       2.5%          0.200787
     Mode          0.202756       1.0%          0.200787
```

Lot 1: Width 1

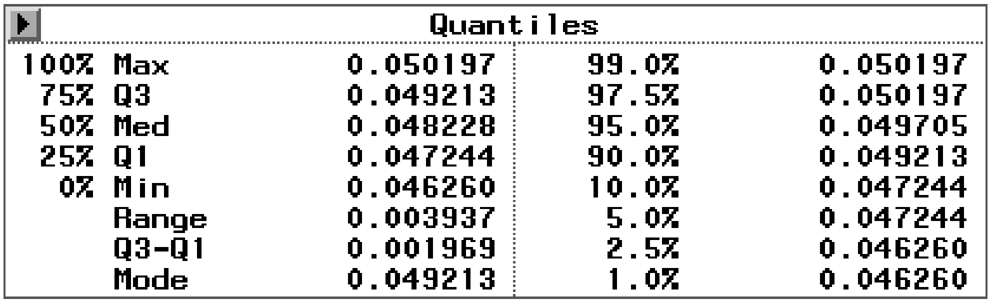
_w11





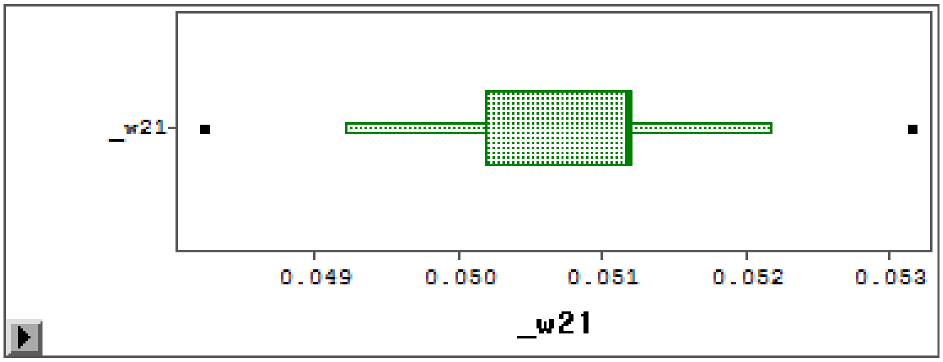


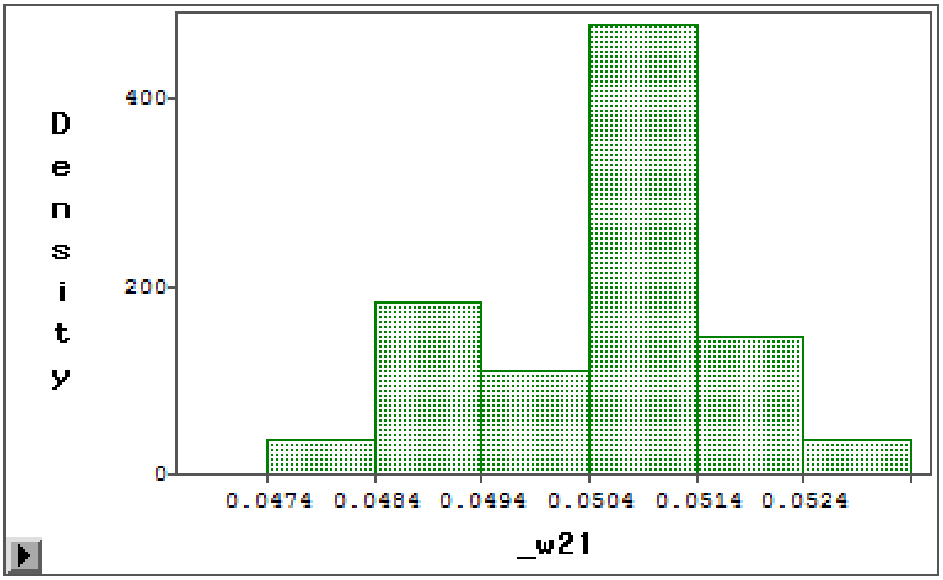
```
                          Moments
N               27.000000 | Sum Wgts        27.000000
Mean             0.048319 | Sum              1.304626
Std Dev          0.001003 | Variance         0.000001
Skewness        -0.123579 | Kurtosis        -0.963932
USS              0.063065 | CSS              0.000026
CV               2.076482 | Std Mean         0.000193
```

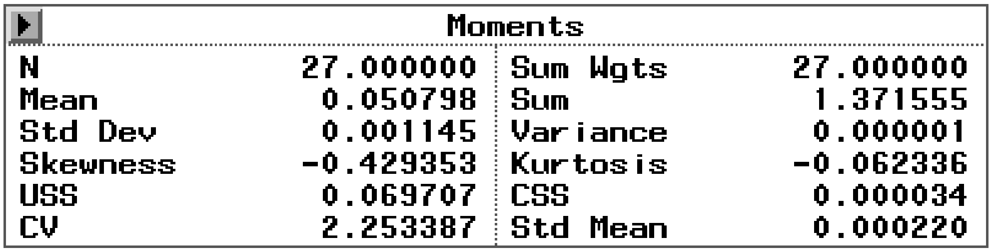


```
                           Quantiles
100% Max             0.050197 |   99.0%            0.050197
 75% Q3              0.049213 |   97.5%            0.050197
 50% Med             0.048228 |   95.0%            0.049705
 25% Q1              0.047244 |   90.0%            0.049213
  0% Min             0.046260 |   10.0%            0.047244
     Range           0.003937 |    5.0%            0.047244
     Q3-Q1           0.001969 |    2.5%            0.046260
     Mode            0.049213 |    1.0%            0.046260
```

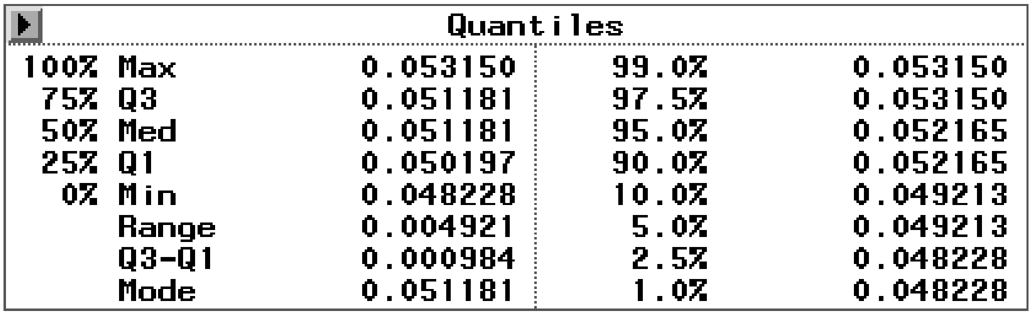
Lot 1: Width 2







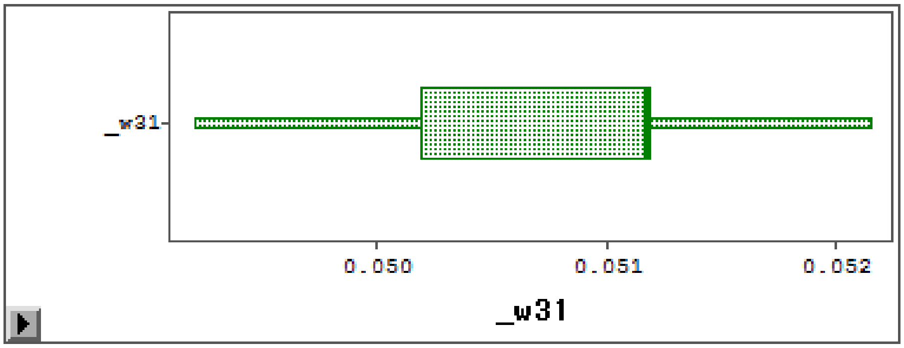
```
                          Moments
N              27.000000   Sum Wgts      27.000000
Mean            0.050798   Sum            1.371555
Std Dev         0.001145   Variance       0.000001
Skewness       -0.429353   Kurtosis      -0.062336
USS             0.069707   CSS            0.000034
CV              2.253387   Std Mean       0.000220
```

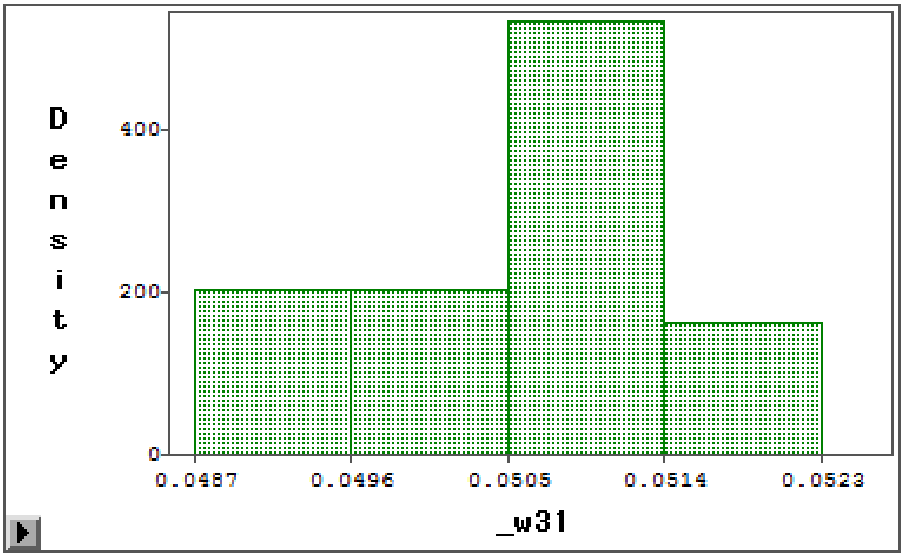


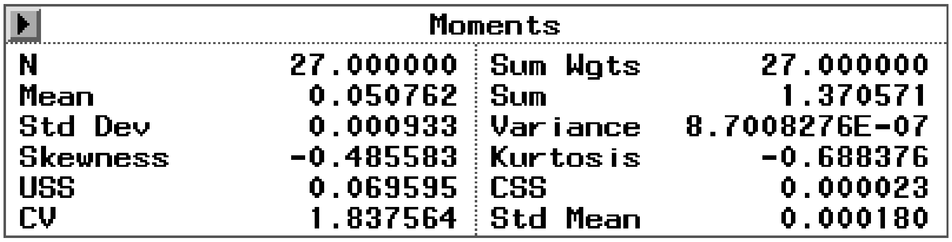
```
                          Quantiles
100% Max        0.053150        99.0%       0.053150
 75% Q3         0.051181        97.5%       0.053150
 50% Med        0.051181        95.0%       0.052165
 25% Q1         0.050197        90.0%       0.052165
  0% Min        0.048228        10.0%       0.049213
     Range      0.004921         5.0%       0.049213
     Q3-Q1      0.000984         2.5%       0.048228
     Mode       0.051181         1.0%       0.048228
```

Lot 1: Width 3

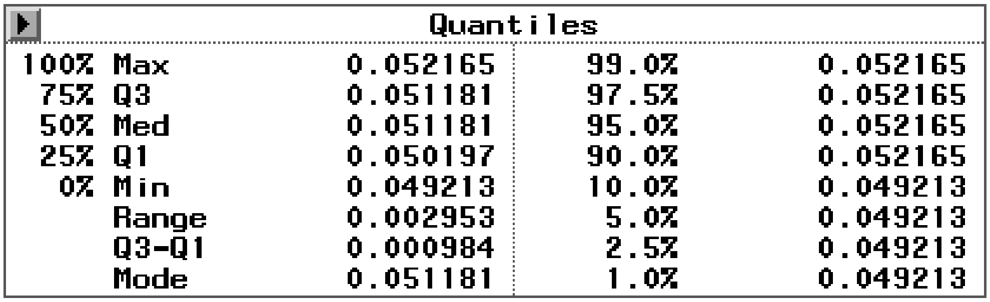
_w31







```
                              Moments
N                     27.000000  Sum Wgts          27.000000
Mean                   0.050762  Sum                1.370571
Std Dev                0.000933  Variance      8.7008276E-07
Skewness              -0.485583  Kurtosis          -0.688376
USS                    0.069595  CSS                0.000023
CV                     1.837564  Std Mean           0.000180
```

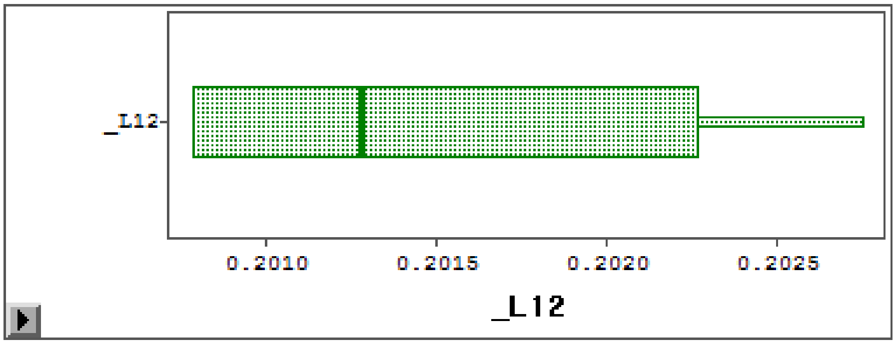


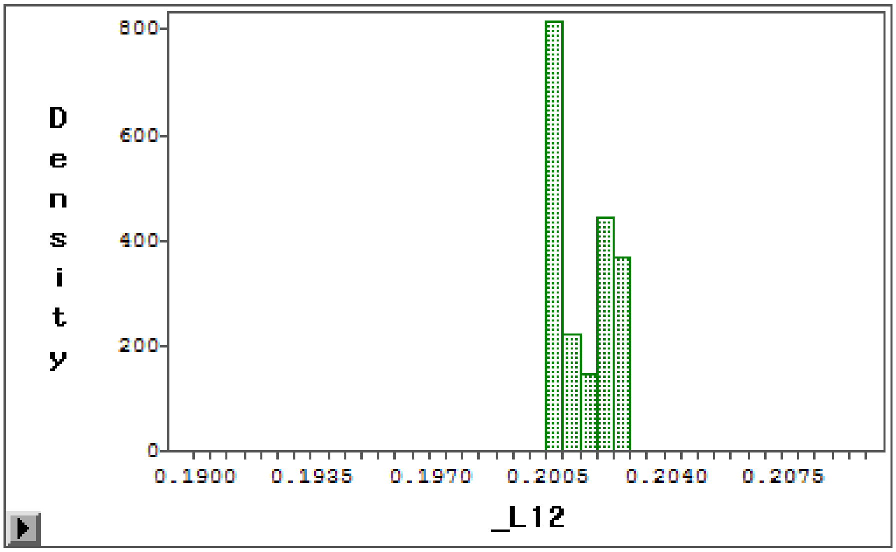
```
                              Quantiles
100% Max               0.052165       99.0%           0.052165
 75% Q3                0.051181       97.5%           0.052165
 50% Med               0.051181       95.0%           0.052165
 25% Q1                0.050197       90.0%           0.052165
  0% Min               0.049213       10.0%           0.049213
     Range             0.002953        5.0%           0.049213
     Q3-Q1             0.000984        2.5%           0.049213
     Mode              0.051181        1.0%           0.049213
```

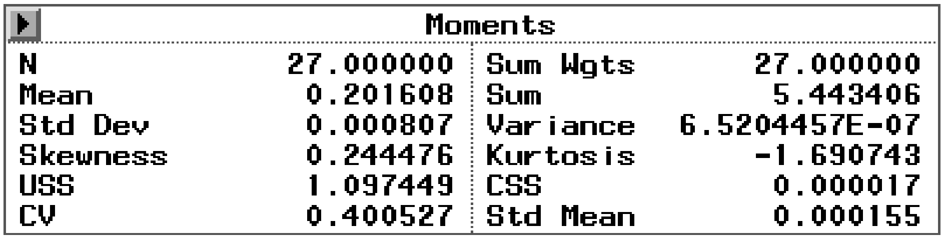
Lot 2

Lot 2: Length

_L12

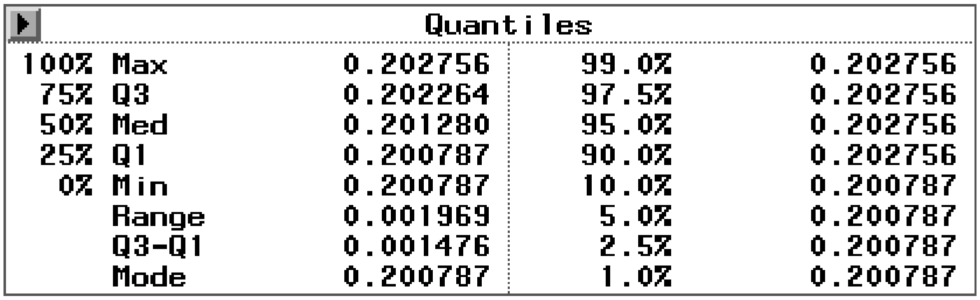






Moments

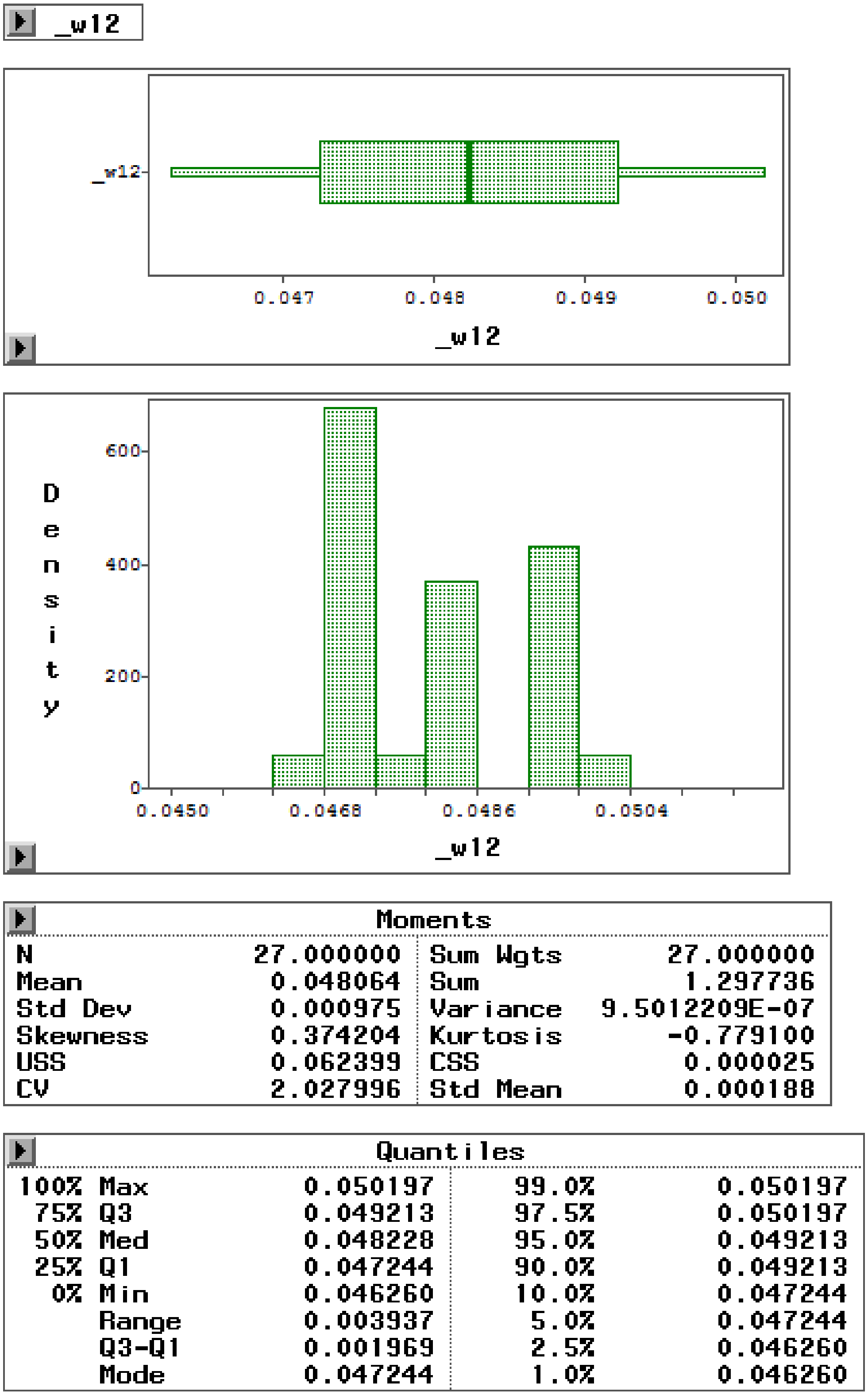
N	27.000000	Sum Wgts	27.000000
Mean	0.201608	Sum	5.443406
Std Dev	0.000807	Variance	6.5204457E-07
Skewness	0.244476	Kurtosis	-1.690743
USS	1.097449	CSS	0.000017
CV	0.400527	Std Mean	0.000155



Quantiles

100%	Max	0.202756	99.0%	0.202756
75%	Q3	0.202264	97.5%	0.202756
50%	Med	0.201280	95.0%	0.202756
25%	Q1	0.200787	90.0%	0.202756
0%	Min	0.200787	10.0%	0.200787
	Range	0.001969	5.0%	0.200787
	Q3-Q1	0.001476	2.5%	0.200787
	Mode	0.200787	1.0%	0.200787

Lot 2: Width 1

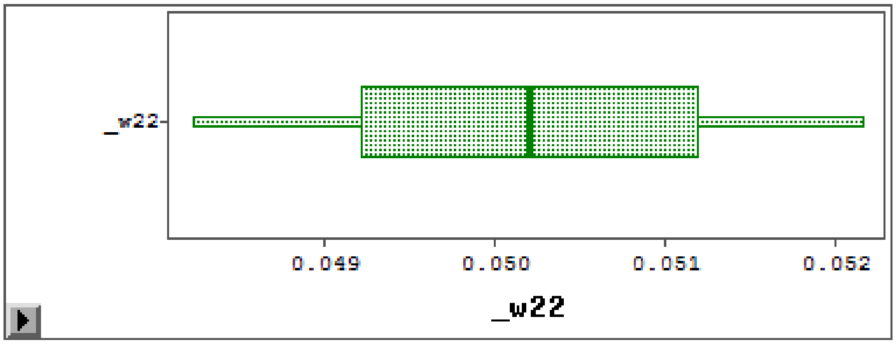


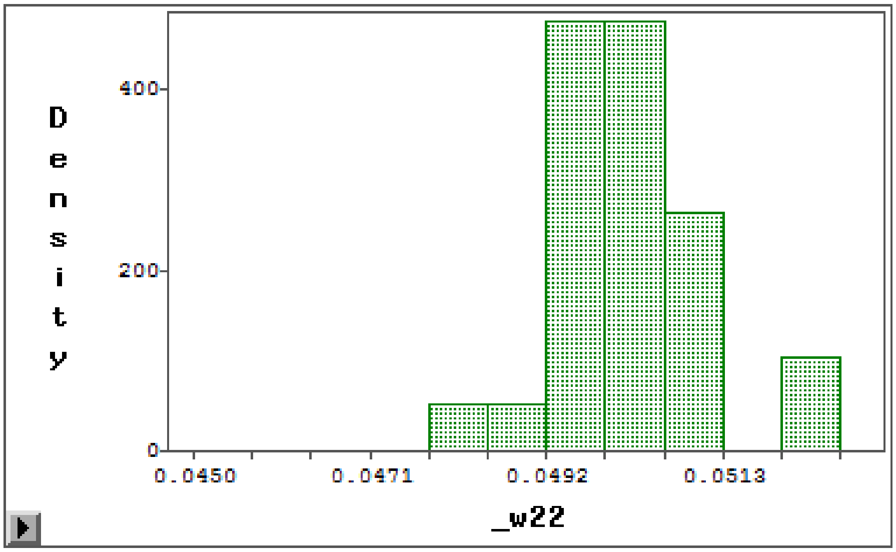
```
                          Moments
N                  27.000000  Sum Wgts        27.000000
Mean                0.048064  Sum              1.297736
Std Dev             0.000975  Variance   9.5012209E-07
Skewness            0.374204  Kurtosis        -0.779100
USS                 0.062399  CSS              0.000025
CV                  2.027996  Std Mean         0.000188
```

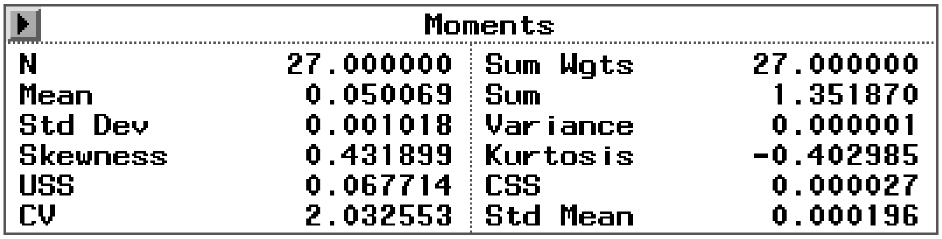
```
                          Quantiles
100% Max          0.050197      99.0%          0.050197
 75% Q3           0.049213      97.5%          0.050197
 50% Med          0.048228      95.0%          0.049213
 25% Q1           0.047244      90.0%          0.049213
  0% Min          0.046260      10.0%          0.047244
     Range        0.003937       5.0%          0.047244
     Q3-Q1        0.001969       2.5%          0.046260
     Mode         0.047244       1.0%          0.046260
```

Lot 2: Width 2

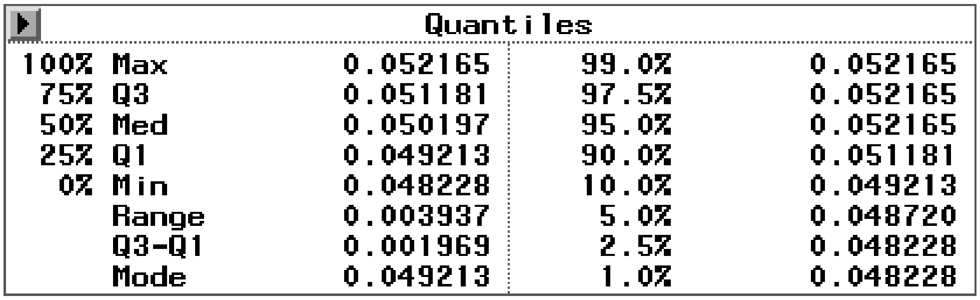
_w22







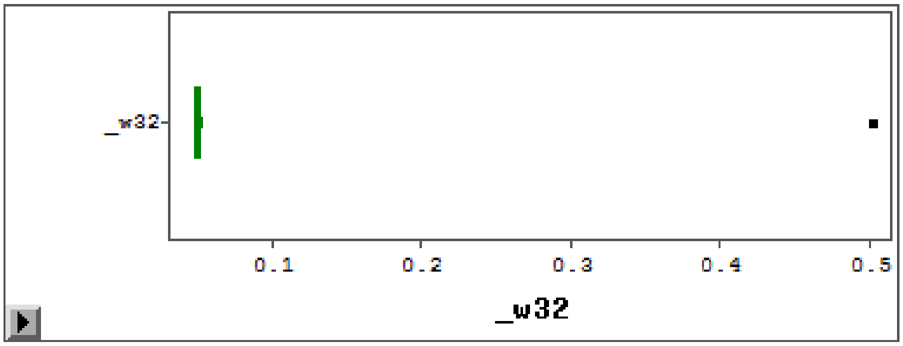
```
                              Moments
N                 27.000000 | Sum Wgts          27.000000
Mean               0.050069 | Sum                1.351870
Std Dev            0.001018 | Variance           0.000001
Skewness           0.431899 | Kurtosis          -0.402985
USS                0.067714 | CSS                0.000027
CV                 2.032553 | Std Mean           0.000196
```

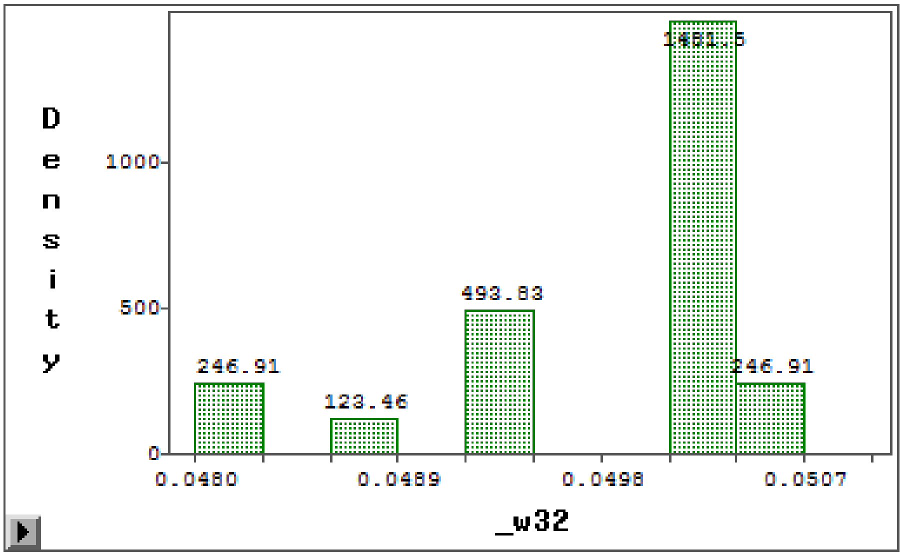


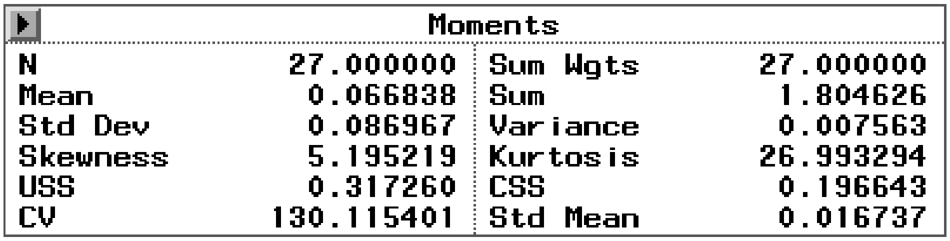
```
                              Quantiles
100% Max           0.052165 |  99.0%             0.052165
 75% Q3            0.051181 |  97.5%             0.052165
 50% Med           0.050197 |  95.0%             0.052165
 25% Q1            0.049213 |  90.0%             0.051181
  0% Min           0.048228 |  10.0%             0.049213
     Range         0.003937 |   5.0%             0.048720
     Q3-Q1         0.001969 |   2.5%             0.048228
     Mode          0.049213 |   1.0%             0.048228
```

Lot 2: Width 3

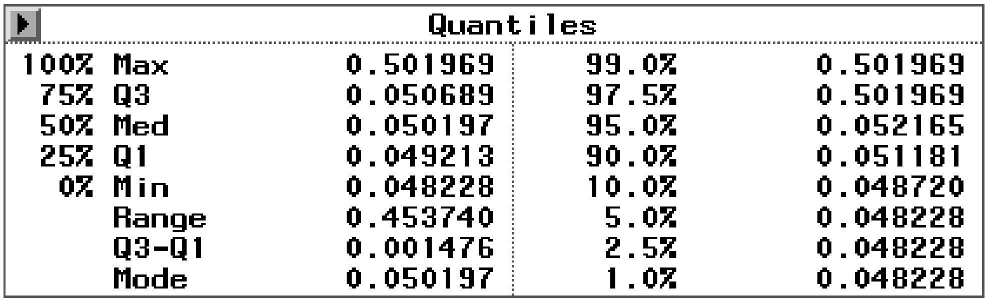
_w32







```
                           Moments
N                 27.000000   Sum Wgts          27.000000
Mean               0.066838   Sum                1.804626
Std Dev            0.086967   Variance           0.007563
Skewness           5.195219   Kurtosis          26.993294
USS                0.317260   CSS                0.196643
CV               130.115401   Std Mean           0.016737
```

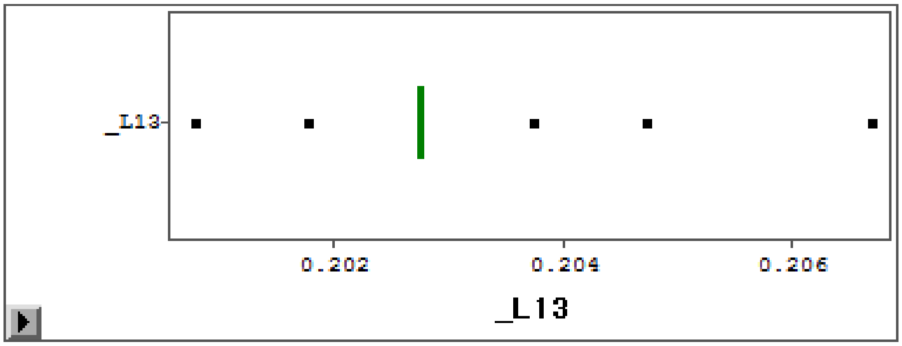


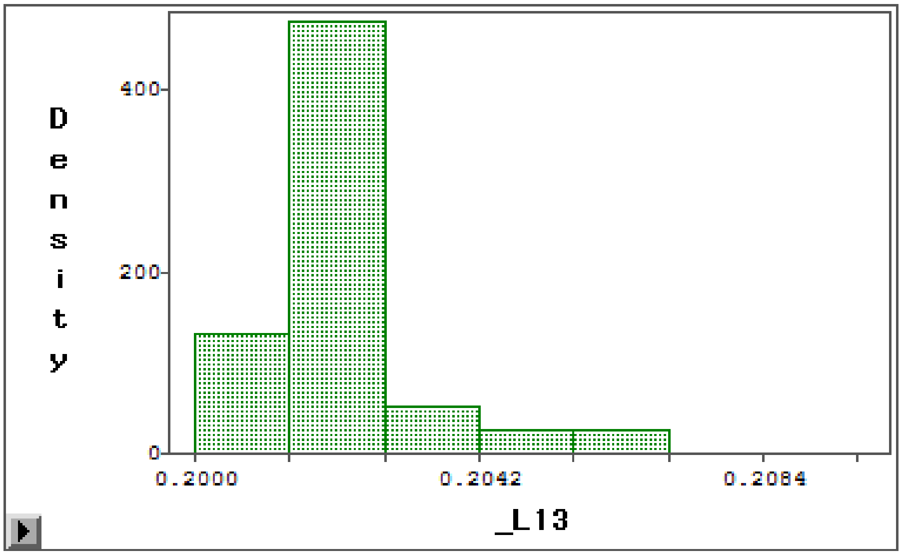
```
                           Quantiles
100% Max          0.501969      99.0%          0.501969
 75% Q3           0.050689      97.5%          0.501969
 50% Med          0.050197      95.0%          0.052165
 25% Q1           0.049213      90.0%          0.051181
  0% Min          0.048228      10.0%          0.048720
     Range        0.453740       5.0%          0.048228
     Q3-Q1        0.001476       2.5%          0.048228
     Mode         0.050197       1.0%          0.048228
```

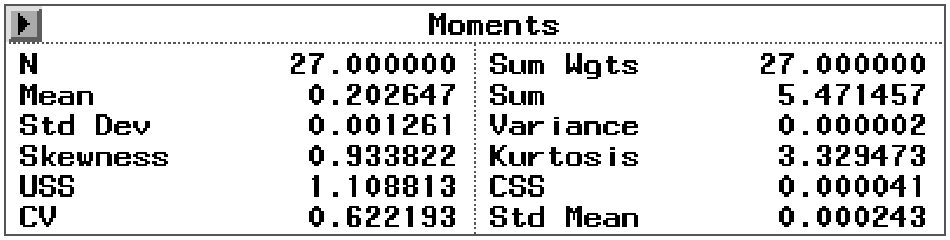
Lot 3

Lot 3: Length

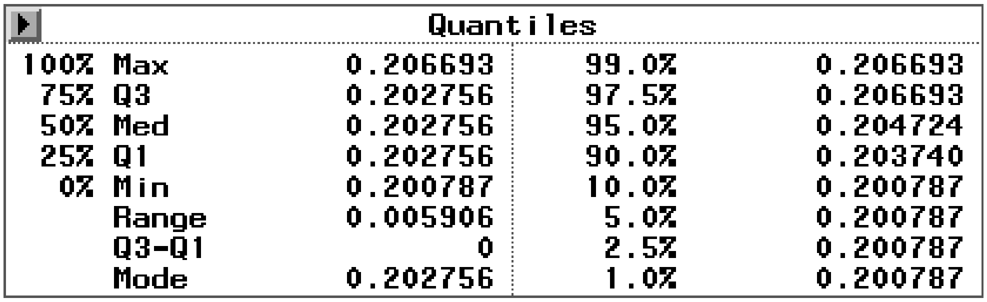
_L13







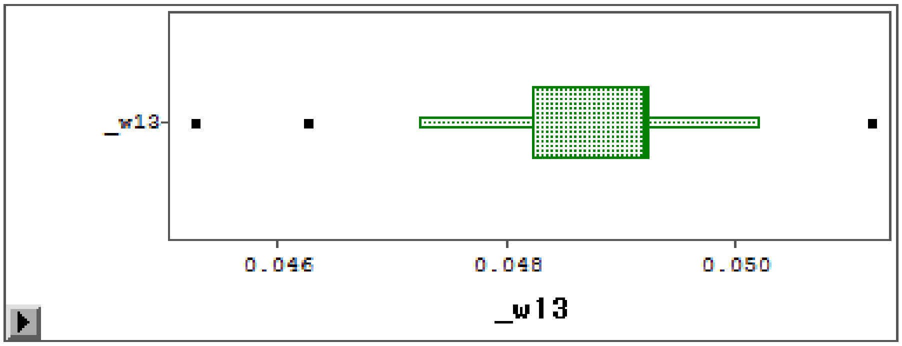
```
                          Moments
N                27.000000 | Sum Wgts       27.000000
Mean              0.202647 | Sum             5.471457
Std Dev           0.001261 | Variance        0.000002
Skewness          0.933822 | Kurtosis        3.329473
USS               1.108813 | CSS             0.000041
CV                0.622193 | Std Mean        0.000243
```

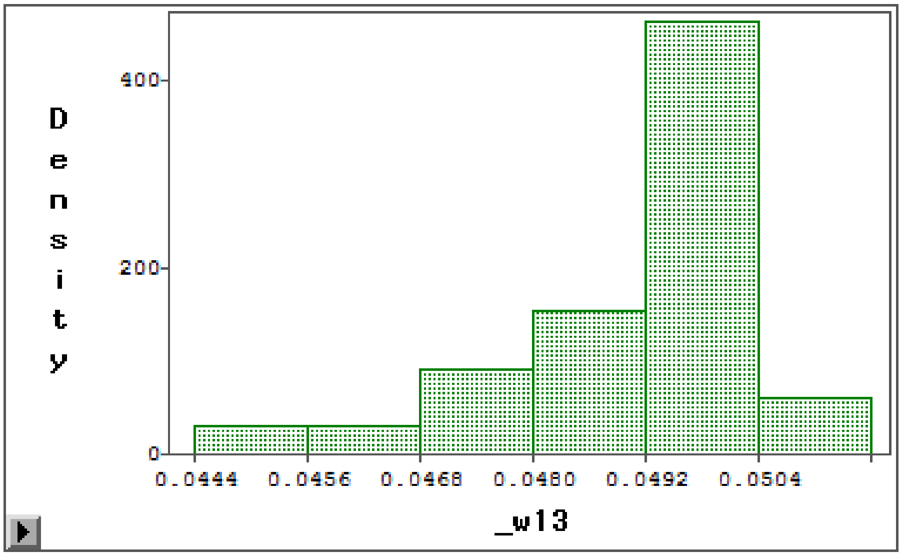


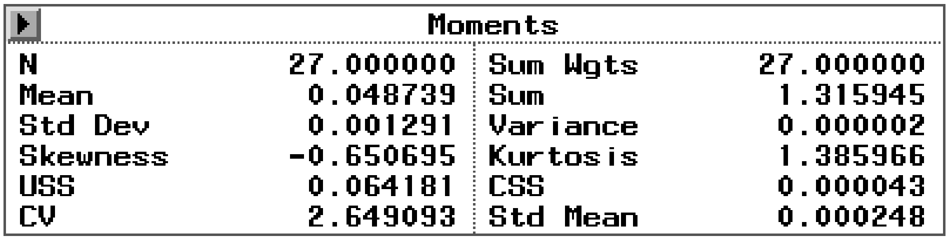
```
                          Quantiles
100% Max           0.206693 |   99.0%          0.206693
 75% Q3            0.202756 |   97.5%          0.206693
 50% Med           0.202756 |   95.0%          0.204724
 25% Q1            0.202756 |   90.0%          0.203740
  0% Min           0.200787 |   10.0%          0.200787
     Range         0.005906 |    5.0%          0.200787
     Q3-Q1                0 |    2.5%          0.200787
     Mode          0.202756 |    1.0%          0.200787
```

Lot 3: Width 1

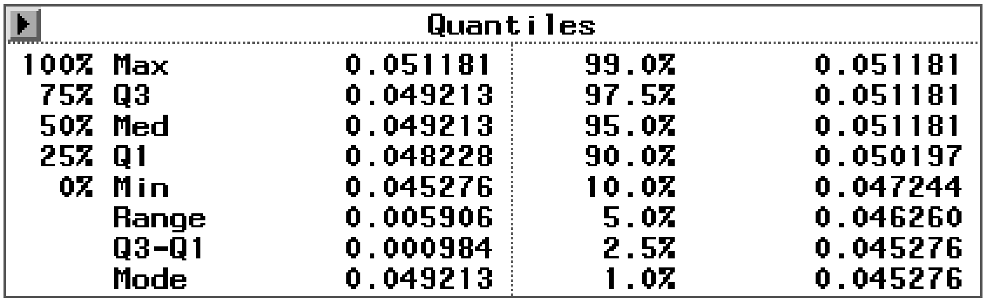
_w13





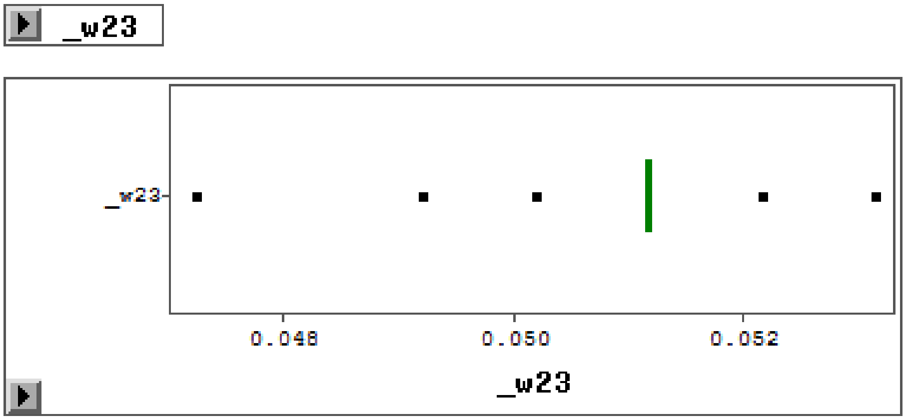


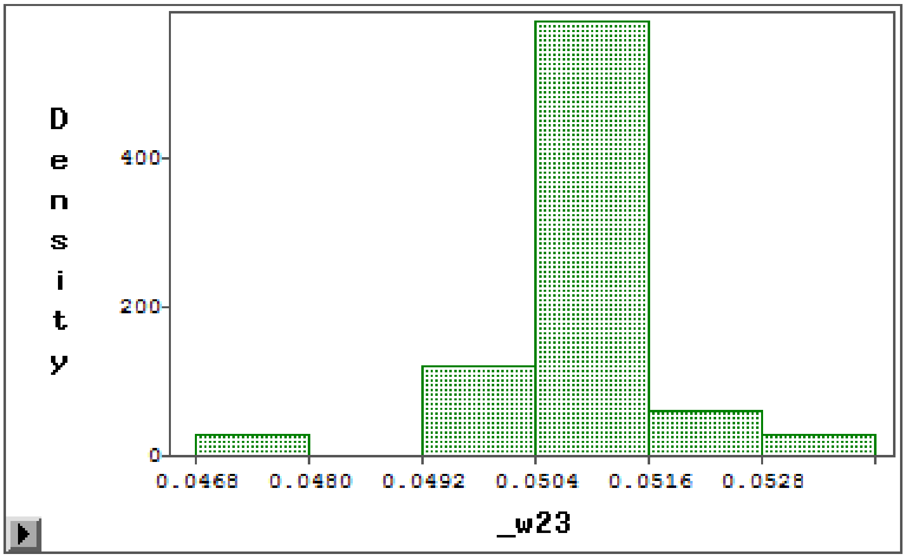
```
                              Moments
N                27.000000 | Sum Wgts        27.000000
Mean              0.048739 | Sum              1.315945
Std Dev           0.001291 | Variance         0.000002
Skewness         -0.650695 | Kurtosis         1.385966
USS               0.064181 | CSS              0.000043
CV                2.649093 | Std Mean         0.000248
```

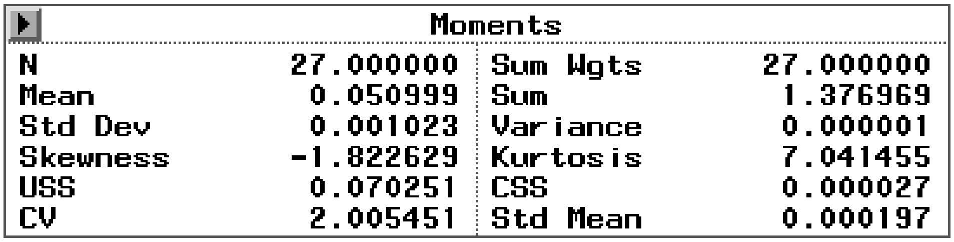


```
                              Quantiles
100% Max            0.051181 |   99.0%          0.051181
 75% Q3             0.049213 |   97.5%          0.051181
 50% Med            0.049213 |   95.0%          0.051181
 25% Q1             0.048228 |   90.0%          0.050197
  0% Min            0.045276 |   10.0%          0.047244
     Range          0.005906 |    5.0%          0.046260
     Q3-Q1          0.000984 |    2.5%          0.045276
     Mode           0.049213 |    1.0%          0.045276
```

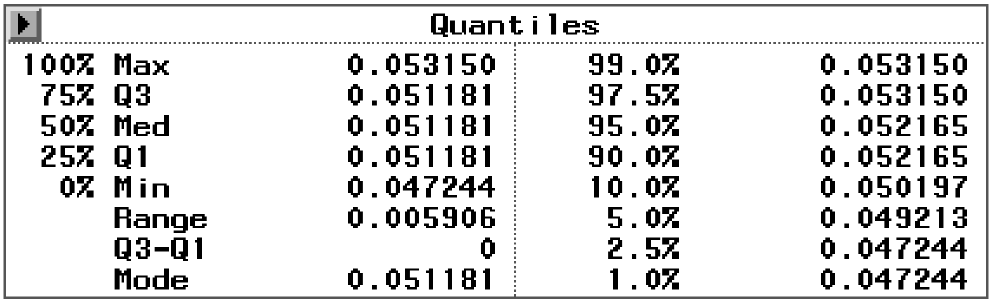
Lot 3: Width 2







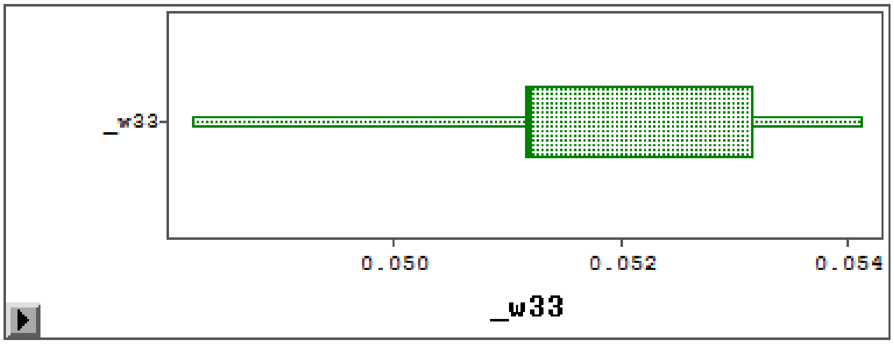
```
                              Moments
N                  27.000000 | Sum Wgts           27.000000
Mean                0.050999 | Sum                 1.376969
Std Dev             0.001023 | Variance            0.000001
Skewness           -1.822629 | Kurtosis            7.041455
USS                 0.070251 | CSS                 0.000027
CV                  2.005451 | Std Mean            0.000197
```

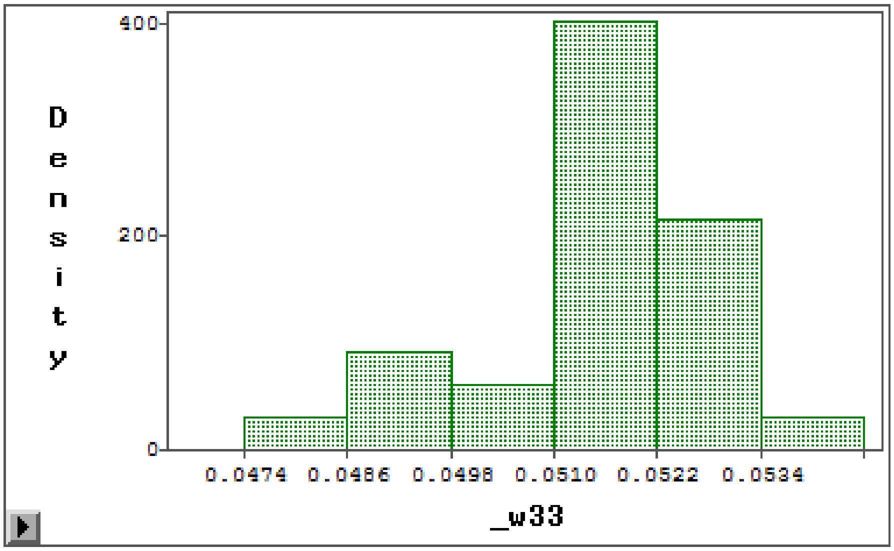


```
                              Quantiles
100% Max            0.053150 |   99.0%             0.053150
 75% Q3             0.051181 |   97.5%             0.053150
 50% Med            0.051181 |   95.0%             0.052165
 25% Q1             0.051181 |   90.0%             0.052165
  0% Min            0.047244 |   10.0%             0.050197
     Range          0.005906 |    5.0%             0.049213
     Q3-Q1                 0 |    2.5%             0.047244
     Mode           0.051181 |    1.0%             0.047244
```

Lot 3: Width 3

_w33



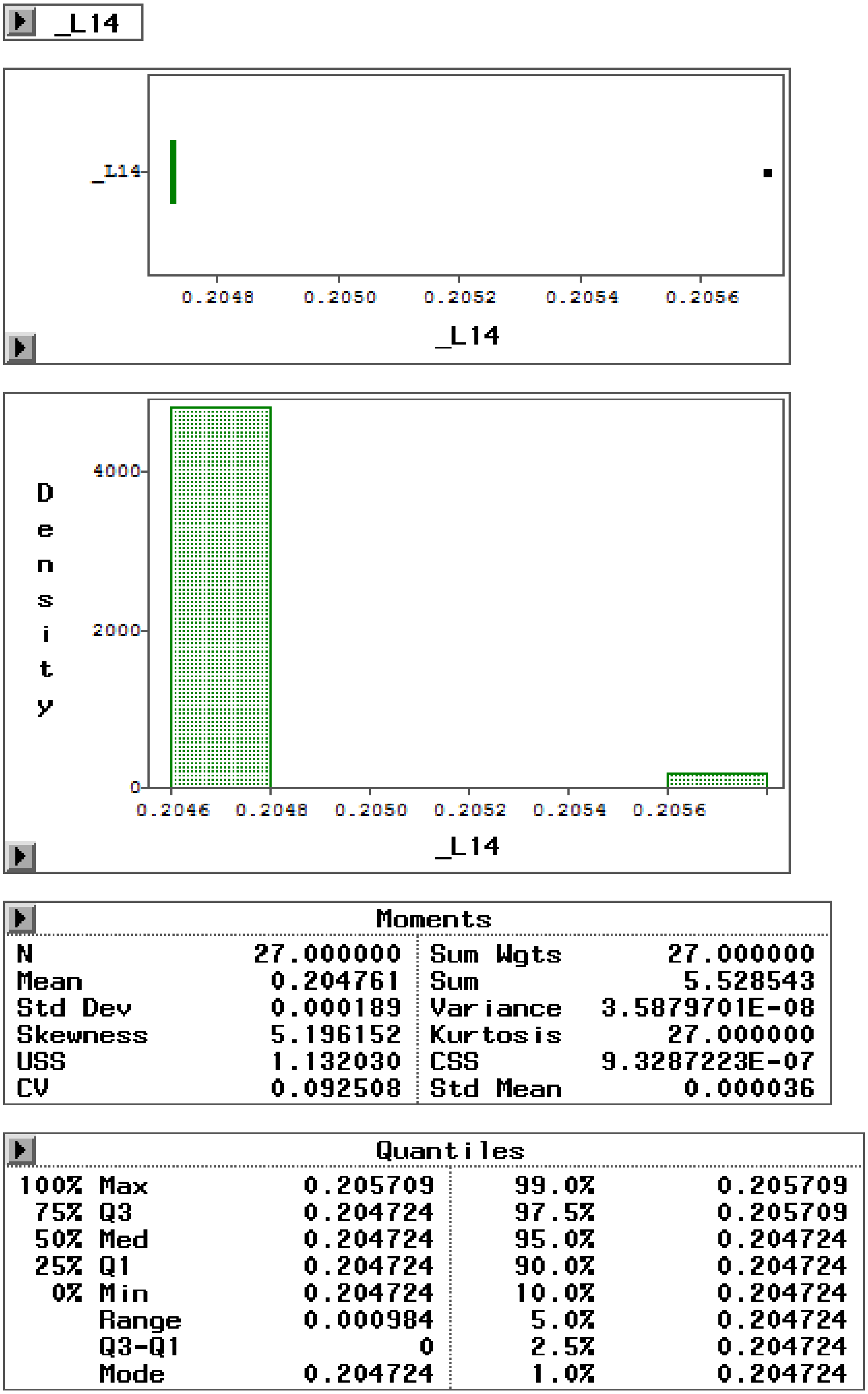


```
                              Moments
N                27.000000 | Sum Wgts       27.000000
Mean              0.051582 | Sum             1.392717
Std Dev           0.001502 | Variance        0.000002
Skewness         -0.477158 | Kurtosis       -0.388310
USS               0.071898 | CSS             0.000059
CV                2.911151 | Std Mean        0.000289
```

```
                              Quantiles
100% Max            0.054134 |   99.0%        0.054134
 75% Q3             0.053150 |   97.5%        0.054134
 50% Med            0.051181 |   95.0%        0.053150
 25% Q1             0.051181 |   90.0%        0.053150
  0% Min            0.048228 |   10.0%        0.049213
     Range          0.005906 |    5.0%        0.049213
     Q3-Q1          0.001969 |    2.5%        0.048228
     Mode           0.051181 |    1.0%        0.048228
```

Lot 4

Lot 4: Length

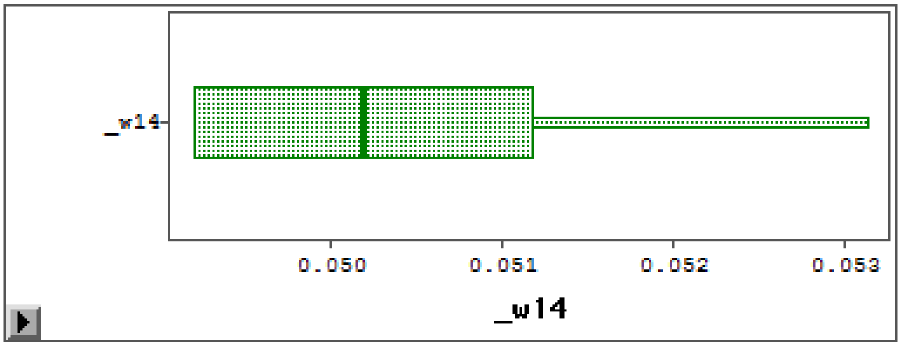


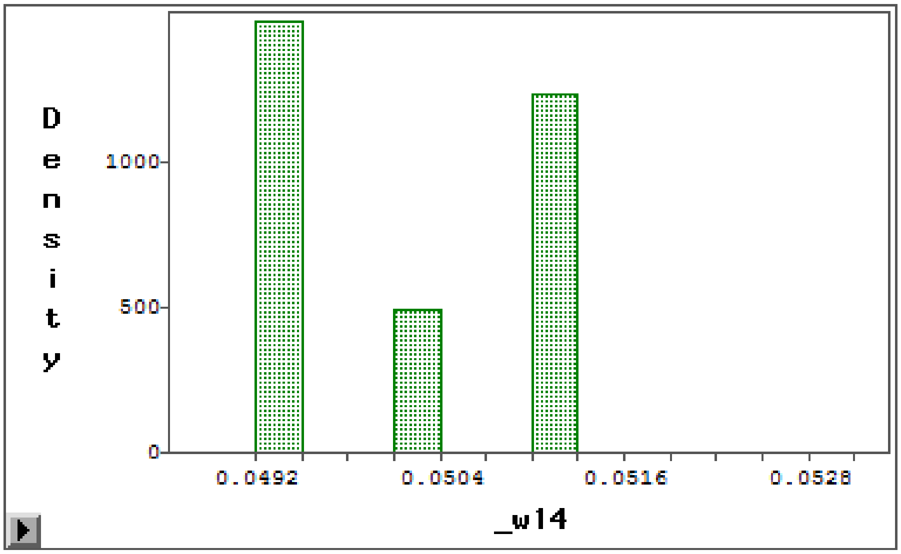
```
                         Moments
N              27.000000  Sum Wgts        27.000000
Mean            0.204761  Sum              5.528543
Std Dev         0.000189  Variance     3.5879701E-08
Skewness        5.196152  Kurtosis        27.000000
USS             1.132030  CSS          9.3287223E-07
CV              0.092508  Std Mean         0.000036
```

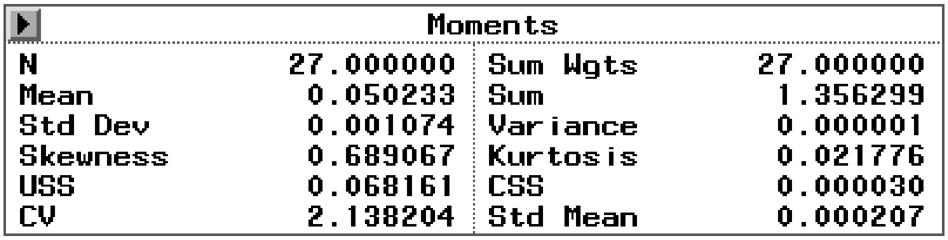
```
                         Quantiles
100% Max         0.205709    99.0%           0.205709
 75% Q3          0.204724    97.5%           0.205709
 50% Med         0.204724    95.0%           0.204724
 25% Q1          0.204724    90.0%           0.204724
  0% Min         0.204724    10.0%           0.204724
     Range       0.000984     5.0%           0.204724
     Q3-Q1              0     2.5%           0.204724
     Mode        0.204724     1.0%           0.204724
```

Lot 4: Width 1

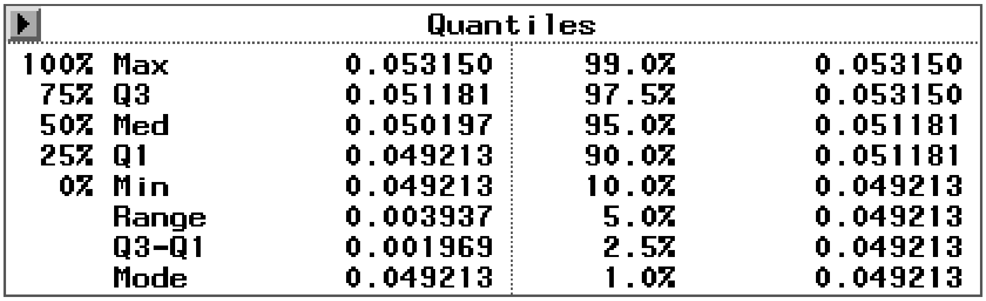
_w14





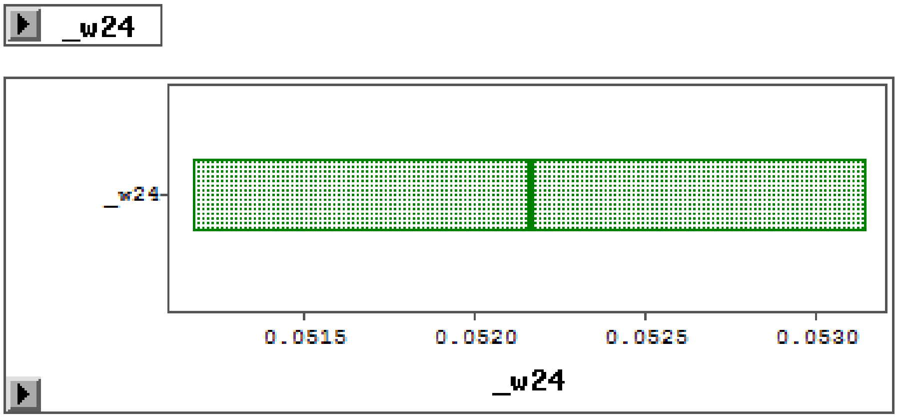


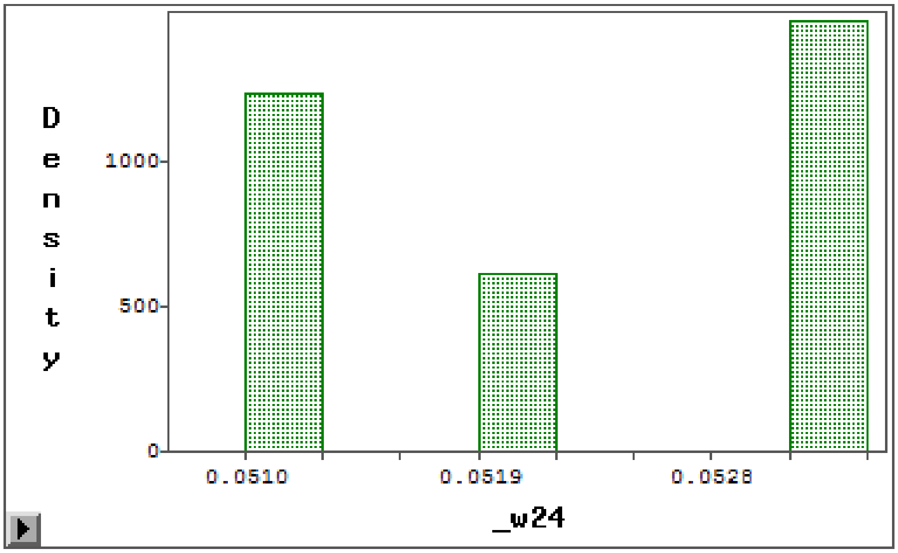
```
                        Moments
N              27.000000   Sum Wgts      27.000000
Mean            0.050233   Sum            1.356299
Std Dev         0.001074   Variance       0.000001
Skewness        0.689067   Kurtosis       0.021776
USS             0.068161   CSS            0.000030
CV              2.138204   Std Mean       0.000207
```

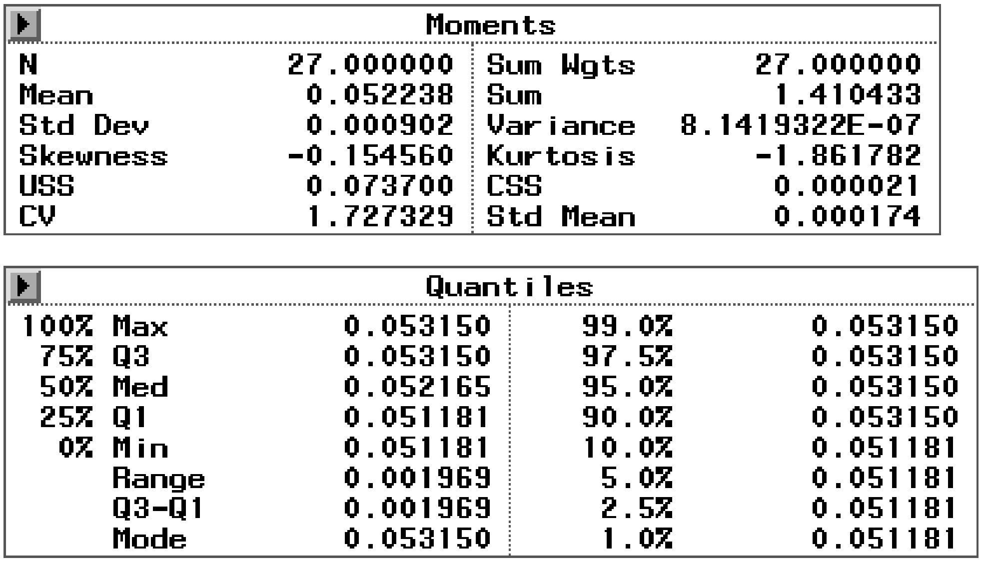


```
                        Quantiles
100% Max         0.053150        99.0%          0.053150
 75% Q3          0.051181        97.5%          0.053150
 50% Med         0.050197        95.0%          0.051181
 25% Q1          0.049213        90.0%          0.051181
  0% Min         0.049213        10.0%          0.049213
     Range       0.003937         5.0%          0.049213
     Q3-Q1       0.001969         2.5%          0.049213
     Mode        0.049213         1.0%          0.049213
```

Lot 4: Width 2





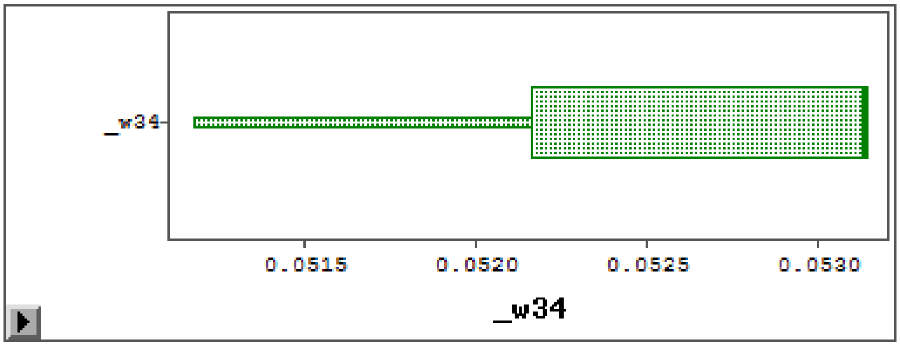


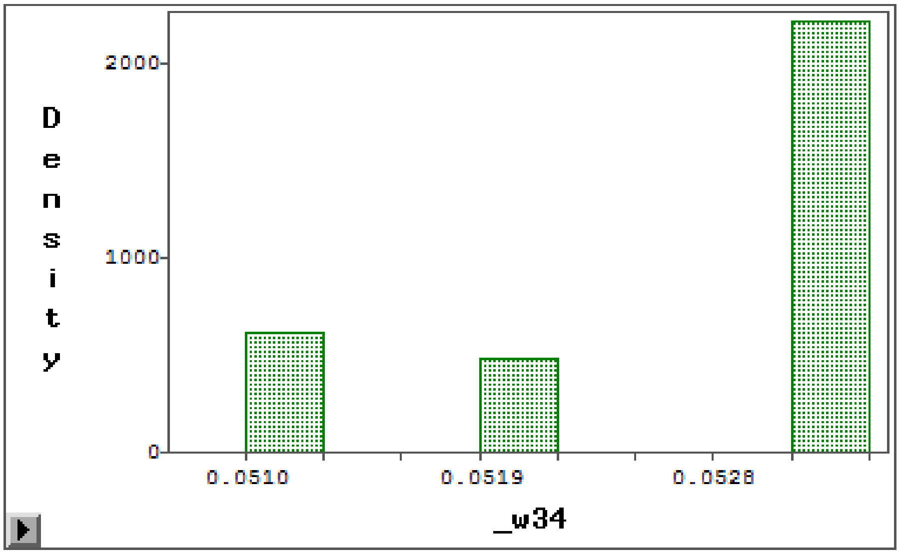
```
                          Moments
N             27.000000 | Sum Wgts         27.000000
Mean           0.052238 | Sum               1.410433
Std Dev        0.000902 | Variance    8.1419322E-07
Skewness      -0.154560 | Kurtosis         -1.861782
USS            0.073700 | CSS               0.000021
CV             1.727329 | Std Mean          0.000174
```

```
                          Quantiles
100% Max          0.053150 |  99.0%         0.053150
 75% Q3           0.053150 |  97.5%         0.053150
 50% Med          0.052165 |  95.0%         0.053150
 25% Q1           0.051181 |  90.0%         0.053150
  0% Min          0.051181 |  10.0%         0.051181
     Range        0.001969 |   5.0%         0.051181
     Q3-Q1        0.001969 |   2.5%         0.051181
     Mode         0.053150 |   1.0%         0.051181
```

Lot 4: Width 3

_w34



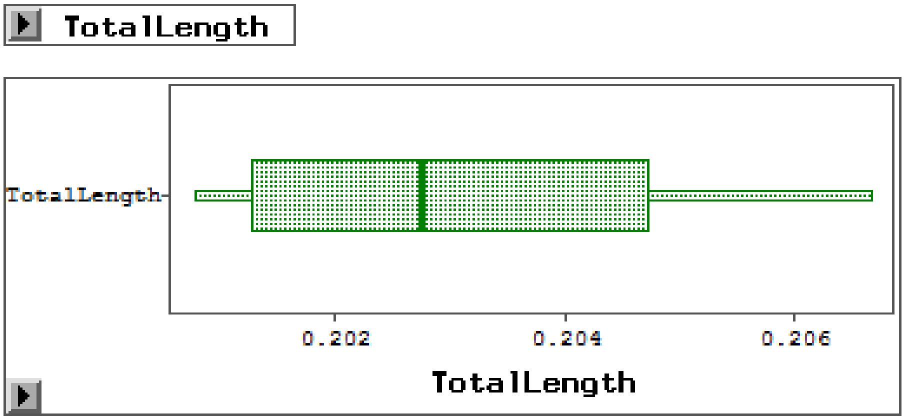


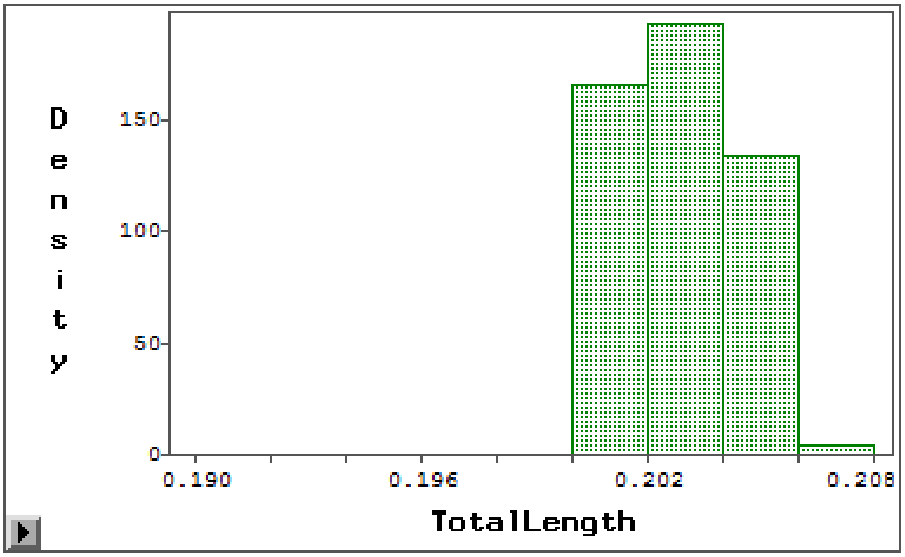
```
                              Moments
N                   27.000000 │ Sum Wgts           27.000000
Mean                 0.052639 │ Sum                 1.421260
Std Dev              0.000790 │ Variance      6.2375481E-07
Skewness            -1.141241 │ Kurtosis           -0.387312
USS                  0.074830 │ CSS                 0.000016
CV                   1.500366 │ Std Mean            0.000152
```

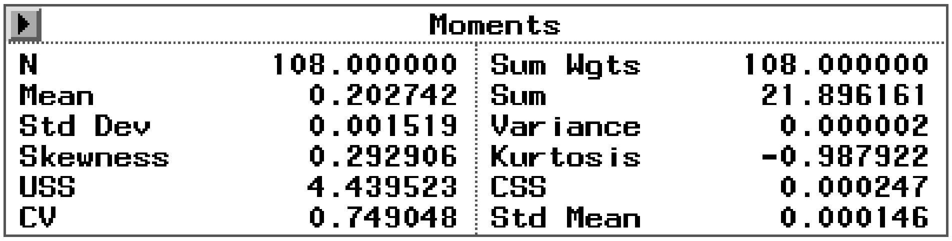
```
                              Quantiles
100% Max              0.053150 │    99.0%             0.053150
 75% Q3               0.053150 │    97.5%             0.053150
 50% Med              0.053150 │    95.0%             0.053150
 25% Q1               0.052165 │    90.0%             0.053150
  0% Min              0.051181 │    10.0%             0.051181
     Range            0.001969 │     5.0%             0.051181
     Q3-Q1            0.000984 │     2.5%             0.051181
     Mode             0.053150 │     1.0%             0.051181
```

Total Length and Widths

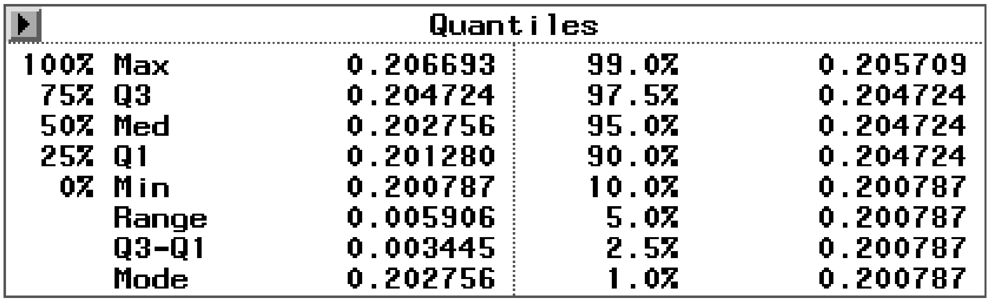
Total Length





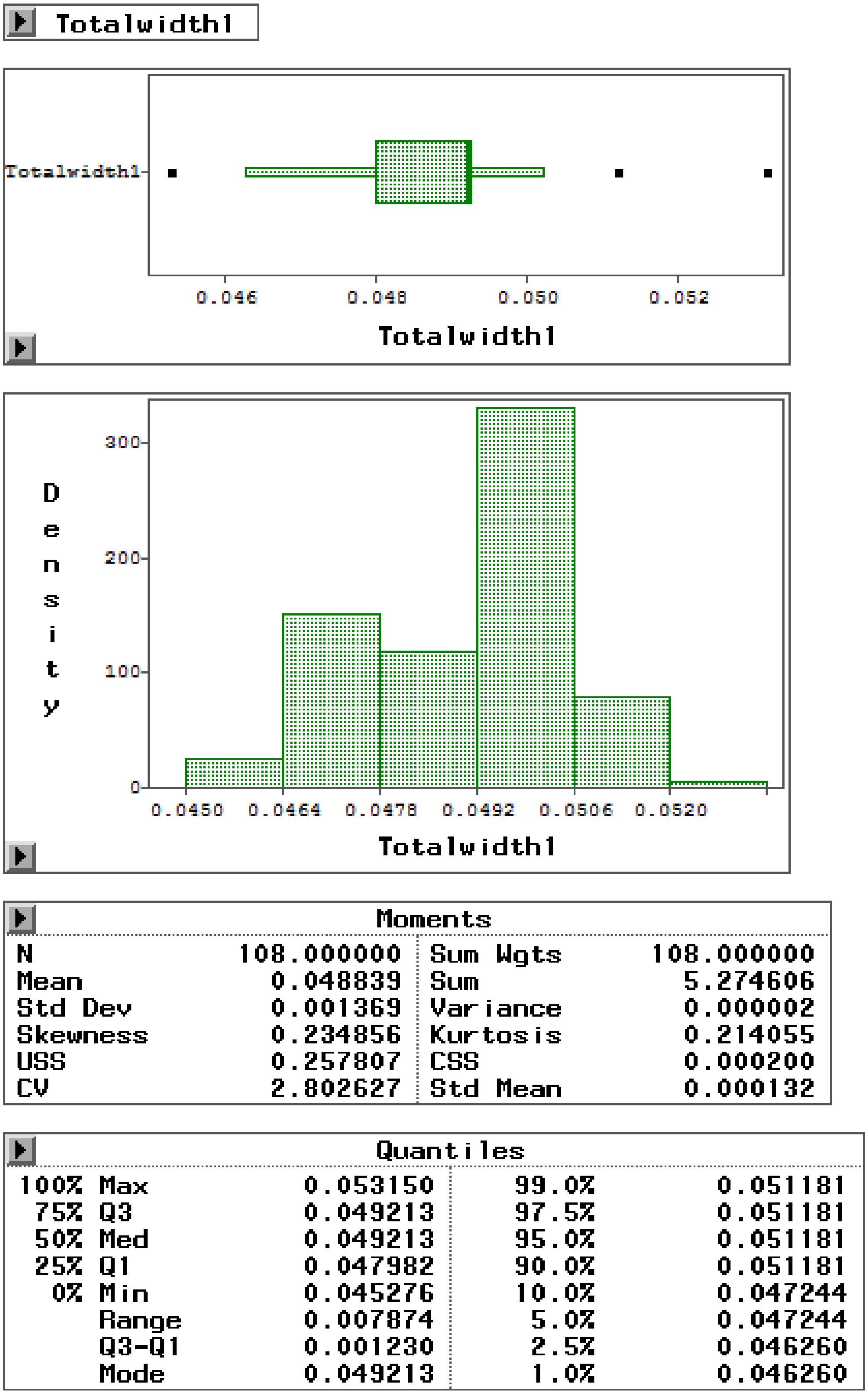


```
                              Moments
N                108.000000 | Sum Wgts      108.000000
Mean               0.202742 | Sum            21.896161
Std Dev            0.001519 | Variance        0.000002
Skewness           0.292906 | Kurtosis       -0.987922
USS                4.439523 | CSS             0.000247
CV                 0.749048 | Std Mean        0.000146
```



```
                              Quantiles
100% Max            0.206693 |  99.0%         0.205709
 75% Q3             0.204724 |  97.5%         0.204724
 50% Med            0.202756 |  95.0%         0.204724
 25% Q1             0.201280 |  90.0%         0.204724
  0% Min            0.200787 |  10.0%         0.200787
     Range          0.005906 |   5.0%         0.200787
     Q3-Q1          0.003445 |   2.5%         0.200787
     Mode           0.202756 |   1.0%         0.200787
```

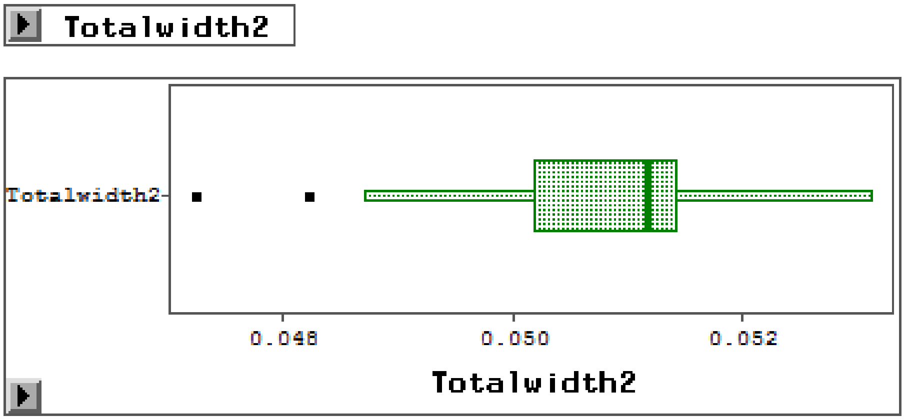
Total Width 1

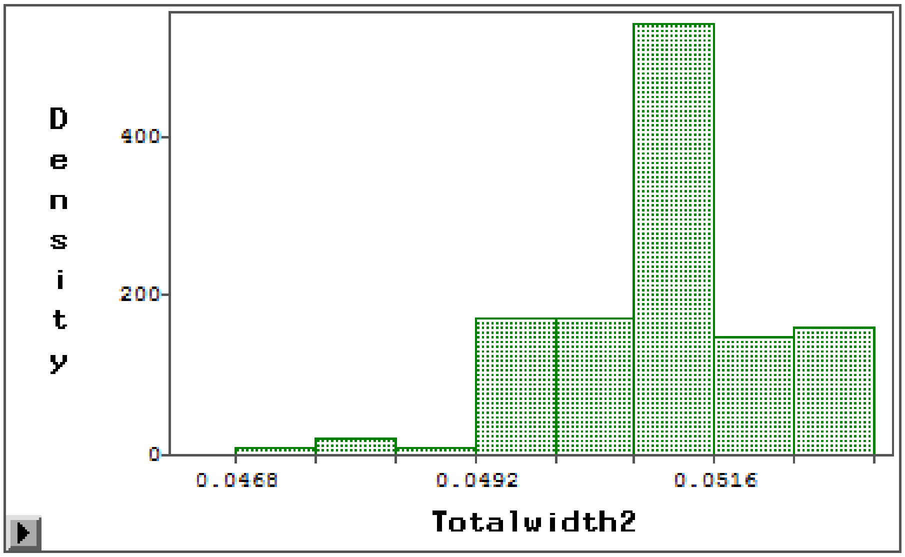


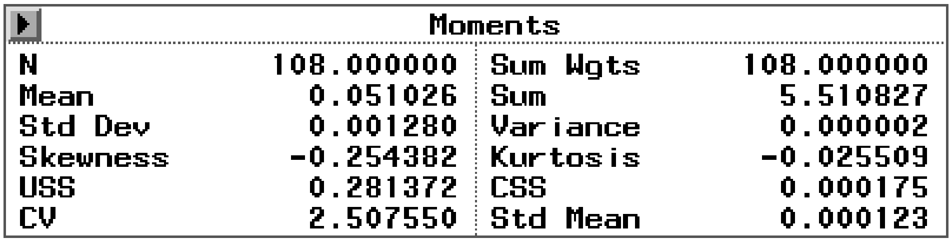
```
                         Moments
N              108.000000 | Sum Wgts      108.000000
Mean             0.048839 | Sum             5.274606
Std Dev          0.001369 | Variance        0.000002
Skewness         0.234856 | Kurtosis        0.214055
USS              0.257807 | CSS             0.000200
CV               2.802627 | Std Mean        0.000132
```

```
                         Quantiles
100% Max            0.053150 |   99.0%          0.051181
 75% Q3             0.049213 |   97.5%          0.051181
 50% Med            0.049213 |   95.0%          0.051181
 25% Q1             0.047982 |   90.0%          0.051181
  0% Min            0.045276 |   10.0%          0.047244
     Range          0.007874 |    5.0%          0.047244
     Q3-Q1          0.001230 |    2.5%          0.046260
     Mode           0.049213 |    1.0%          0.046260
```

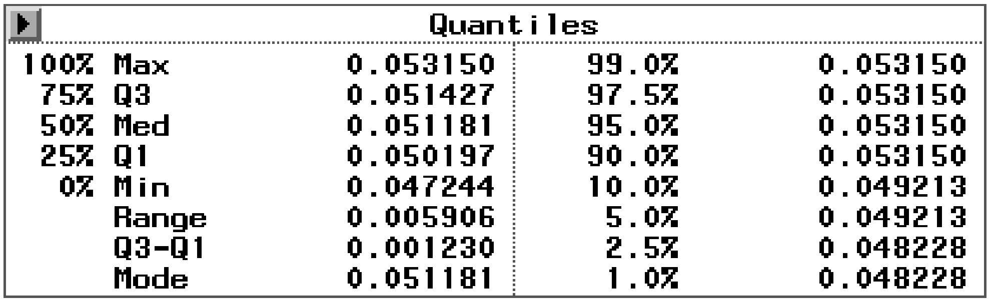
Total Width 2





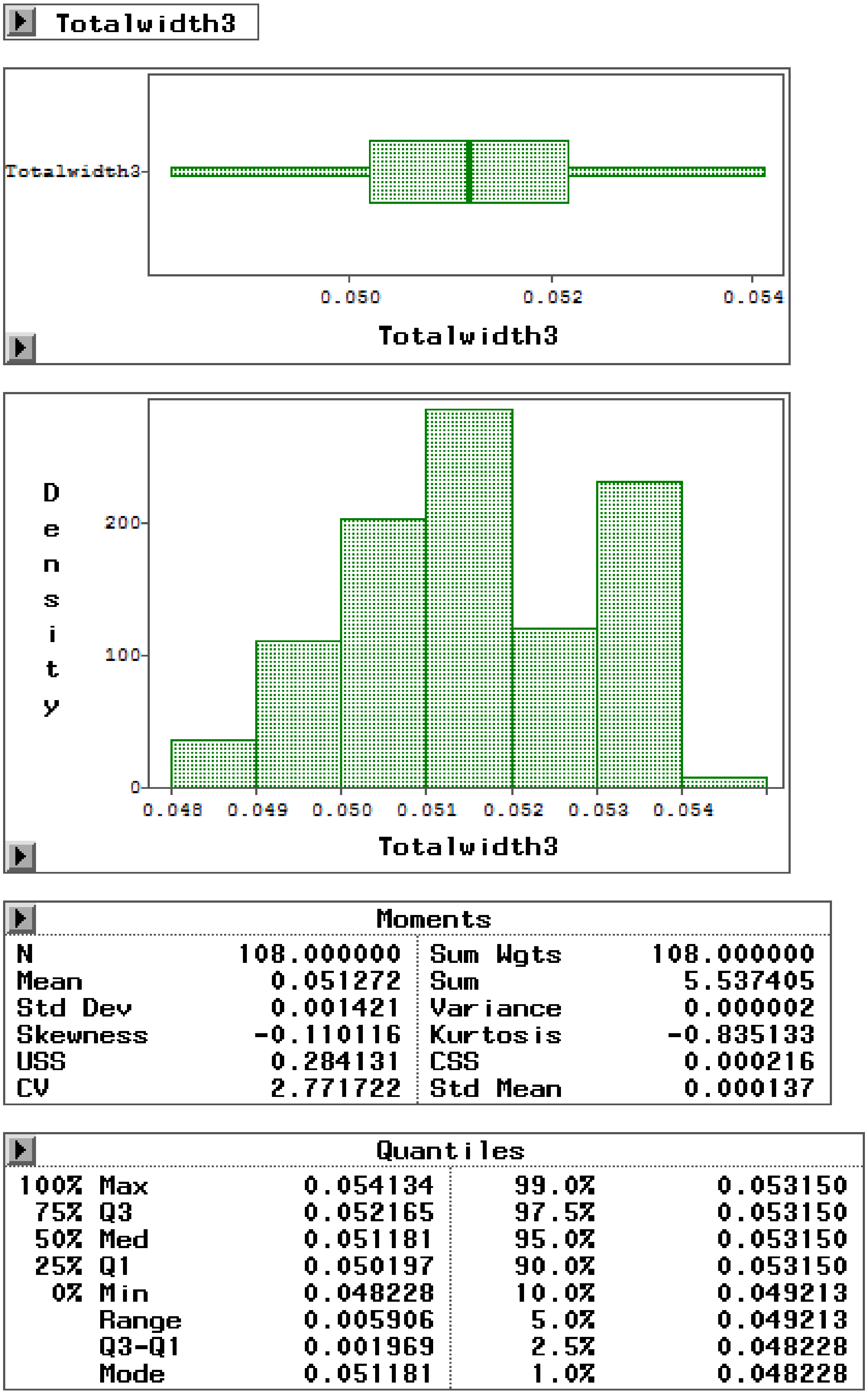


```
                              Moments
N              108.000000 │ Sum Wgts      108.000000
Mean             0.051026 │ Sum             5.510827
Std Dev          0.001280 │ Variance        0.000002
Skewness        -0.254382 │ Kurtosis       -0.025509
USS              0.281372 │ CSS             0.000175
CV               2.507550 │ Std Mean        0.000123
```



```
                              Quantiles
100% Max             0.053150 │    99.0%          0.053150
 75% Q3              0.051427 │    97.5%          0.053150
 50% Med             0.051181 │    95.0%          0.053150
 25% Q1              0.050197 │    90.0%          0.053150
  0% Min             0.047244 │    10.0%          0.049213
     Range           0.005906 │     5.0%          0.049213
     Q3-Q1           0.001230 │     2.5%          0.048228
     Mode            0.051181 │     1.0%          0.048228
```

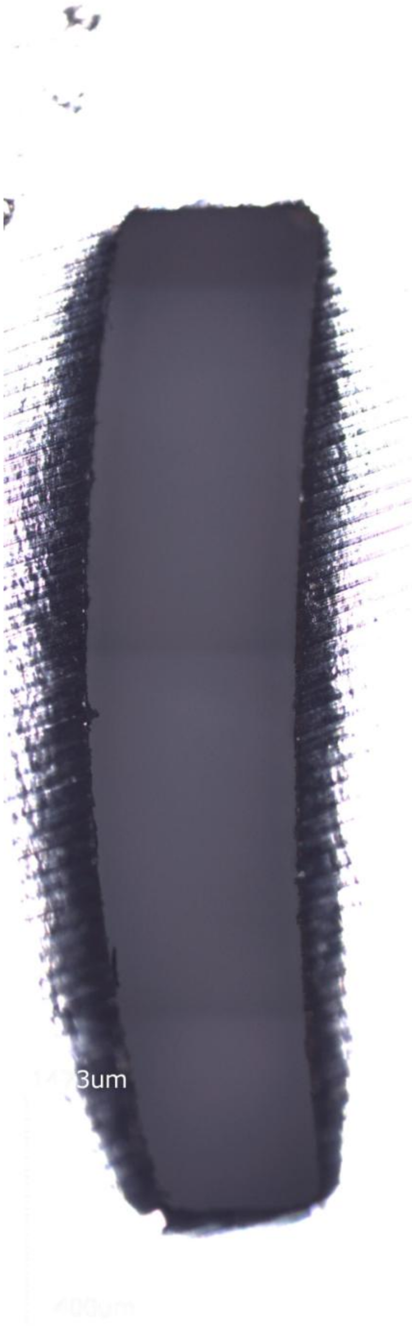
Total Width 3

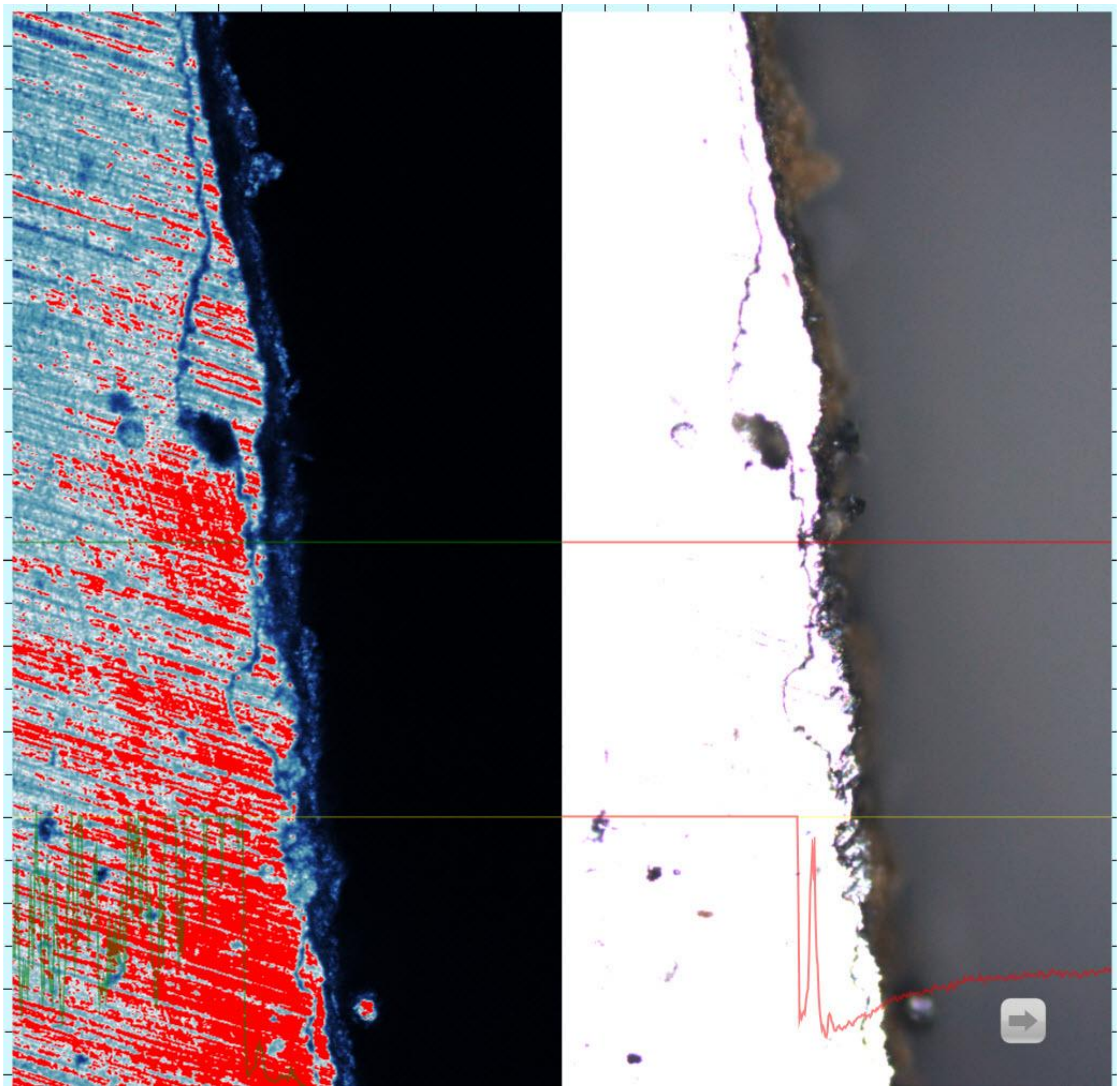


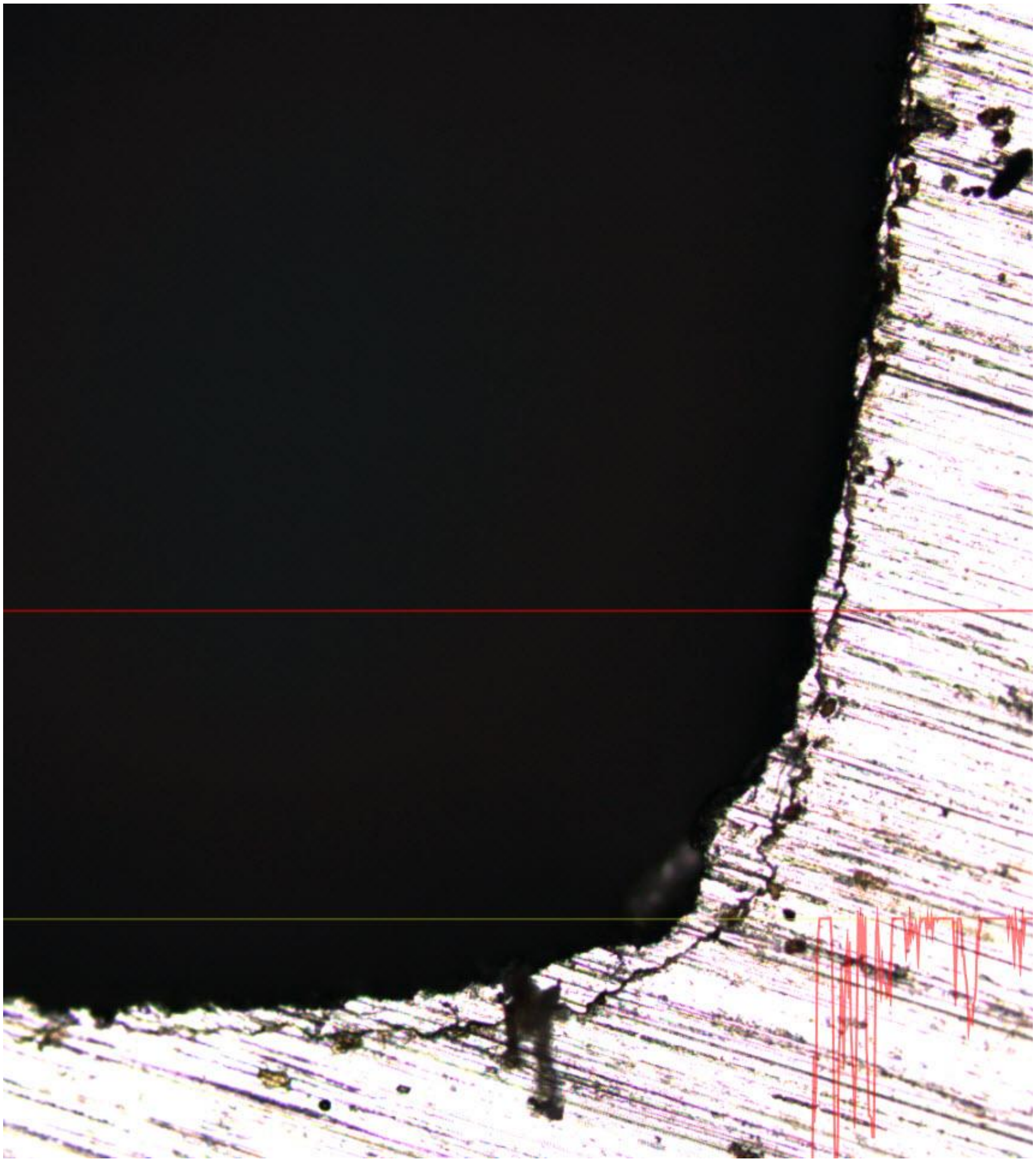
```
                          Moments
N            108.000000 | Sum Wgts      108.000000
Mean           0.051272 | Sum             5.537405
Std Dev        0.001421 | Variance        0.000002
Skewness      -0.110116 | Kurtosis       -0.835133
USS            0.284131 | CSS             0.000216
CV             2.771722 | Std Mean        0.000137
```

```
                          Quantiles
100% Max        0.054134 |    99.0%          0.053150
 75% Q3         0.052165 |    97.5%          0.053150
 50% Med        0.051181 |    95.0%          0.053150
 25% Q1         0.050197 |    90.0%          0.053150
  0% Min        0.048228 |    10.0%          0.049213
     Range      0.005906 |     5.0%          0.049213
     Q3-Q1      0.001969 |     2.5%          0.048228
     Mode       0.051181 |     1.0%          0.048228
```

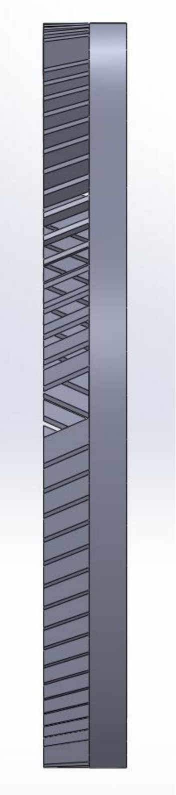
Appendix C: Trumpeting Result (Chpt. 4)

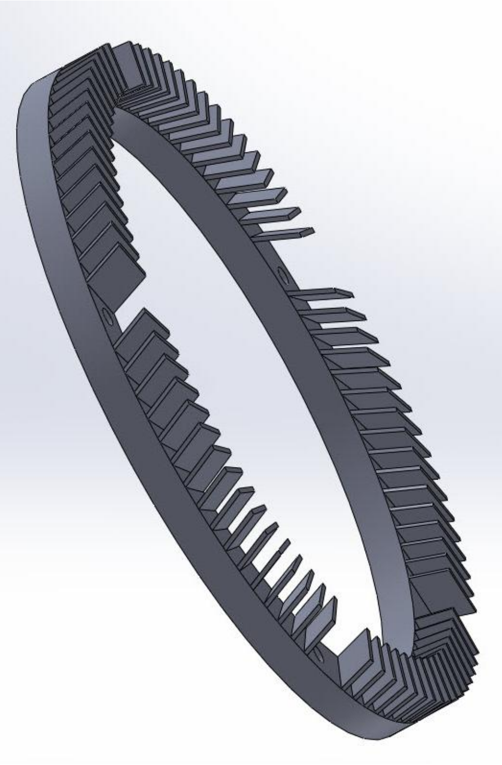






Appendix D – Hot Upset Fixture (Chpt. 4)

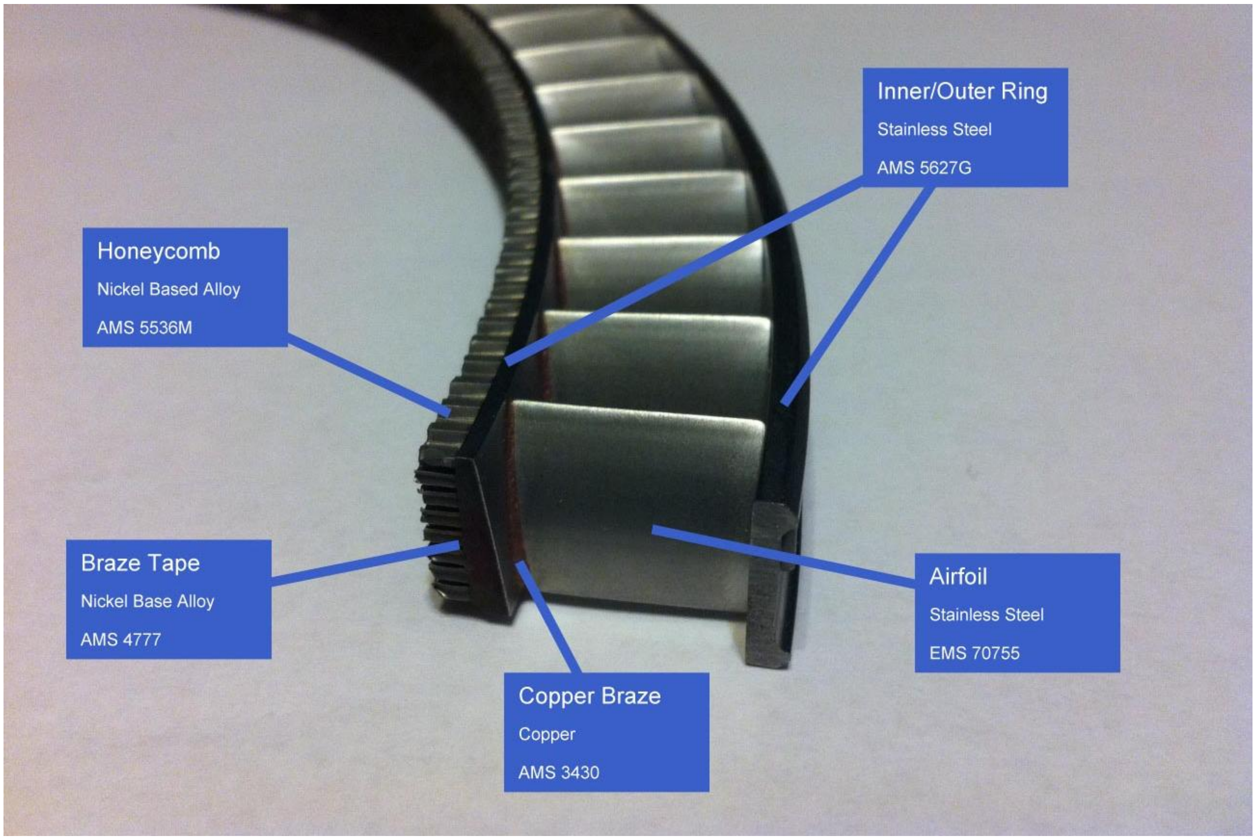




Not drawn to scale.

Appendix E – Stator Materials (Chpt. 5)

The following section details the materials which comprise the stator and the information on the alloys used.



Honeycomb Material Composition

AMS 5536M – Nickel Based Alloy

Element	Min %	Max %
Carbon	0.05	0.15
Manganese	--	1.00
Silicon	--	1.00
Phosphorus	--	0.040
Sulfur	--	0.030
Chromium	20.50	23.00
Cobalt	0.50	2.50
Molybdenum	8.00	10.00
Tungsten	0.20	1.00
Iron	17.00	20.00
Aluminum	--	0.50
Titanium	--	0.15
Boron	--	0.010
Copper	--	0.50
Nickel	Remainder	Remainder

Braze Tape Material Composition

AMS 4777 – Nickel Based Alloy

Element	Min %	Max %
Chromium	--	7.0
Silicon	--	4.1
Iron	--	3.0
Boron	--	3.0
Nickel	Remainder	Remainder

Copper Braze Material Composition

AMS 3430 – Copper

Element	Min %	Max %
Solvent Agents	--	--
Copper	Remainder	Remainder

Airfoil Material Composition

EMS 70755 – Stainless Steel

Element	**Min %**	**Max %**
Carbon	--	0.05
Manganese	--	1.00
Silicon	--	1.00
Phosphorus	--	0.025
Sulfur	--	0.015
Chromium	14.00	16.00
Nickel	6.00	7.00
Molybdenum	0.50	1.00
Columbium + Tantalum	8 x C	--
Copper	1.25	1.75

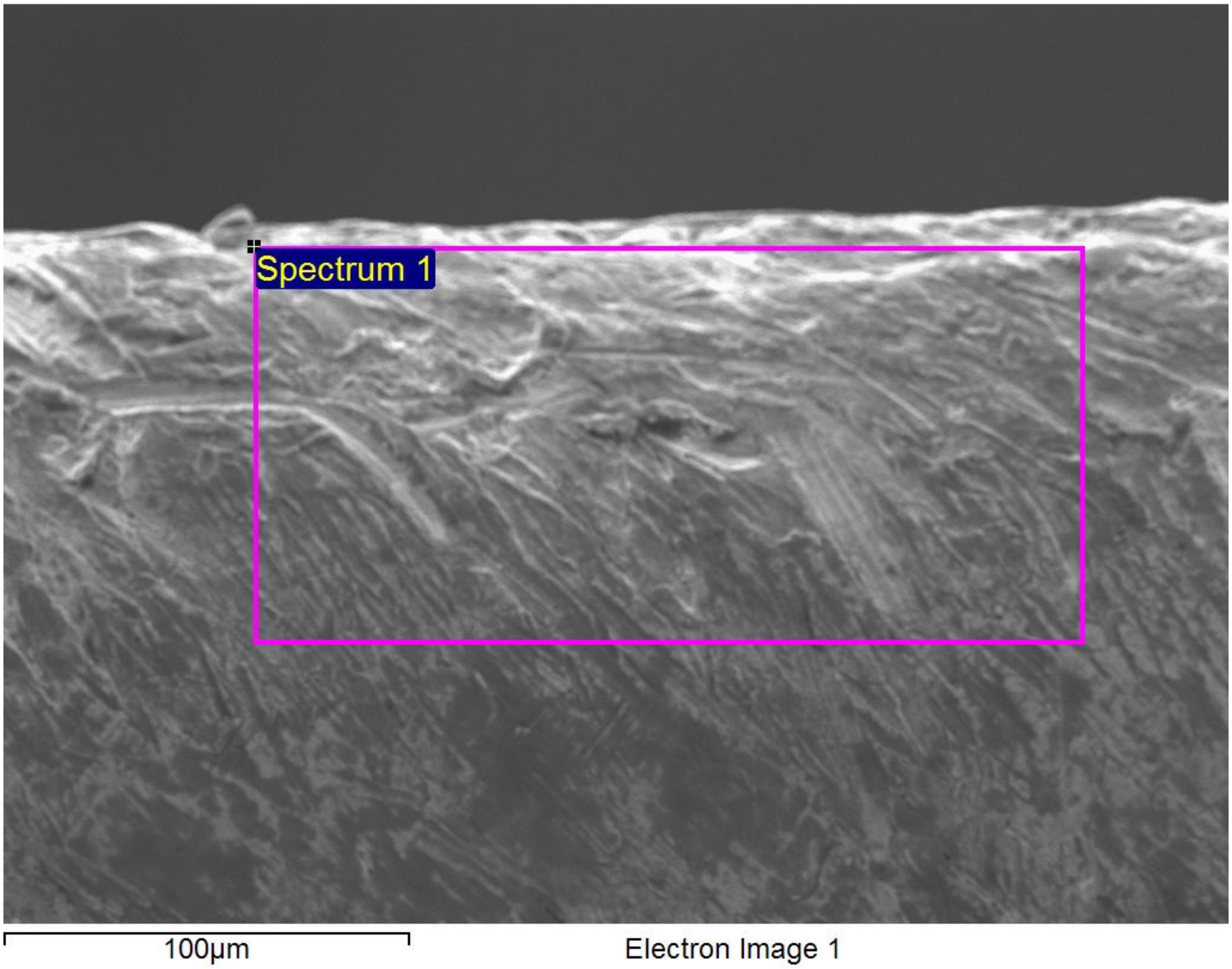
Inner/Outer Ring Material Composition

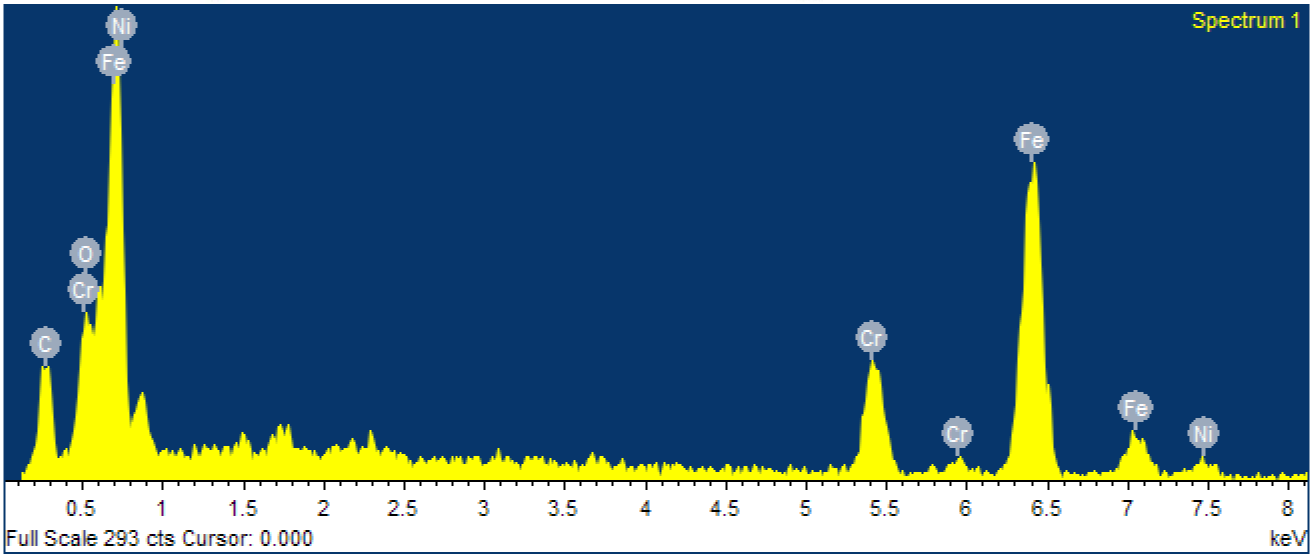
AMS 5627G – Stainless Steel

Element	**Min %**	**Max %**
Carbon	--	0.12
Manganese	--	1.00
Silicon	--	1.00
Phosphorus	--	0.040
Sulfur	--	0.030
Chromium	16.00	18.00
Nickel	--	0.75
Molybdenum	--	0.50
Copper	--	0.50
Aluminum	--	0.05
Tin	--	0.05

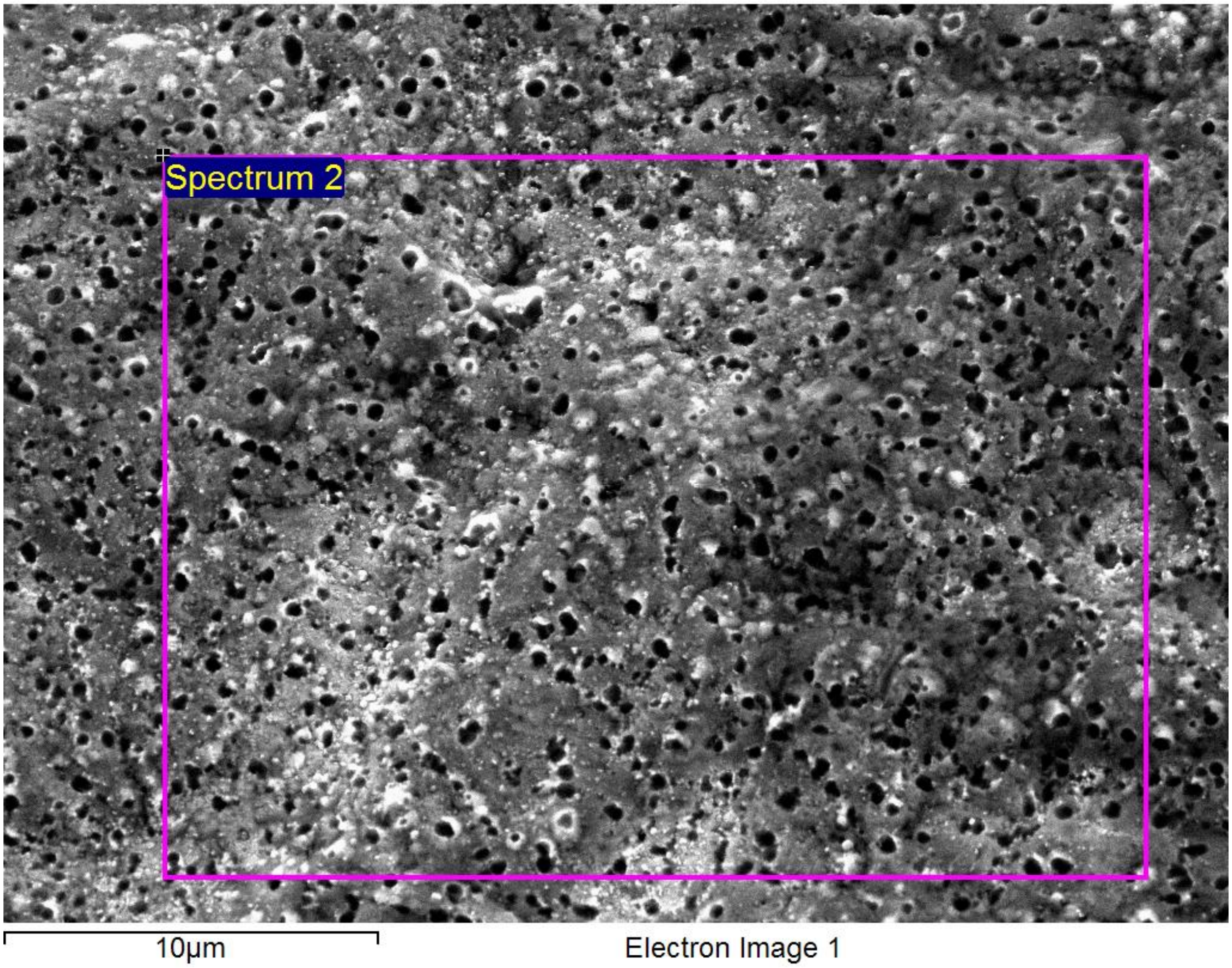
Appendix F – SEM Results (Chpt. 5)

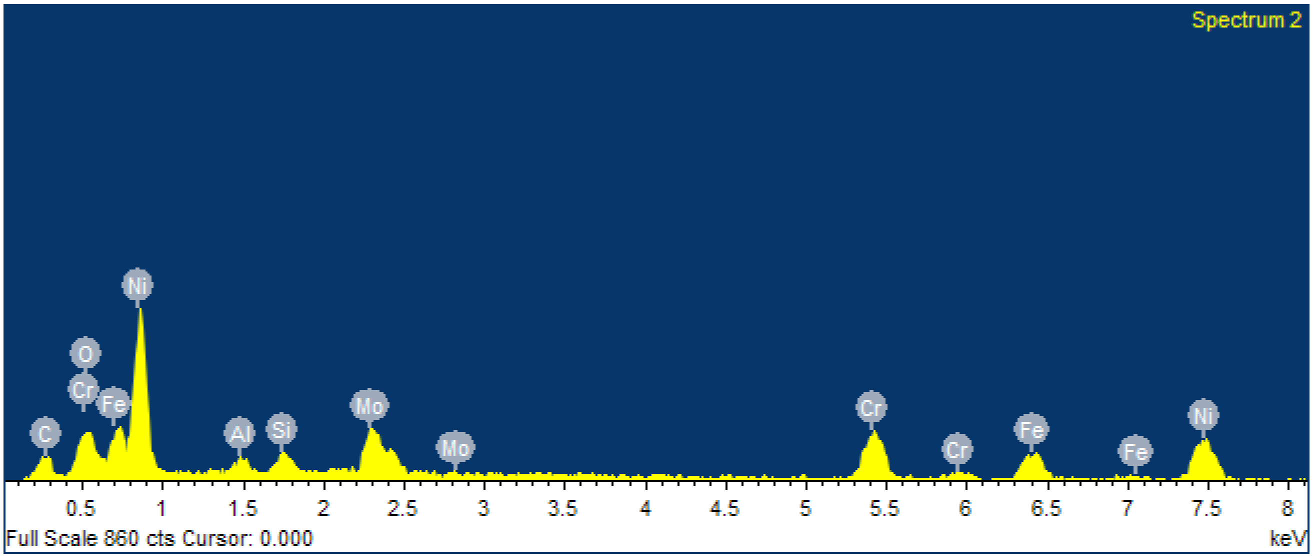
Site 1 (Airfoil) – Spectrum 1



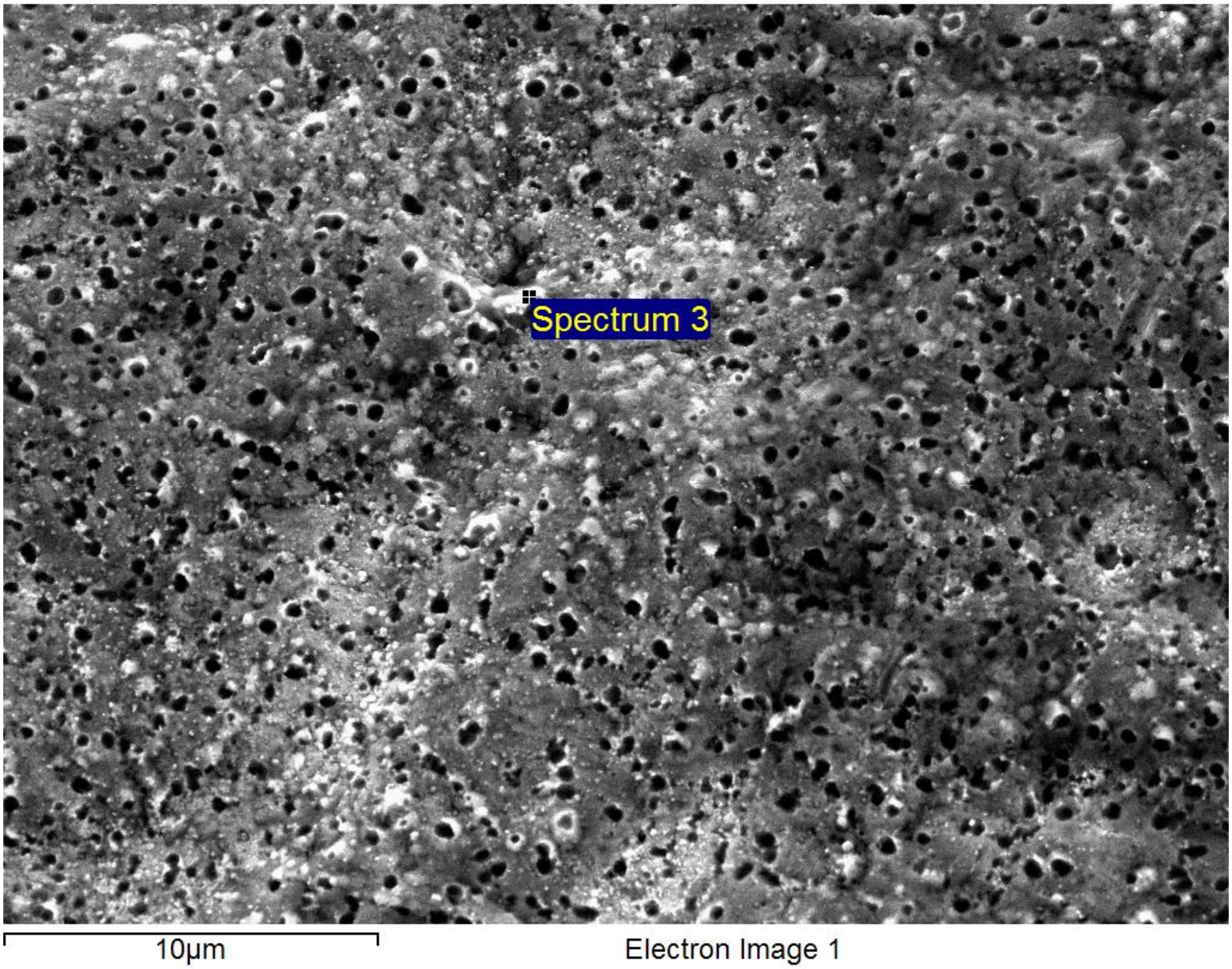


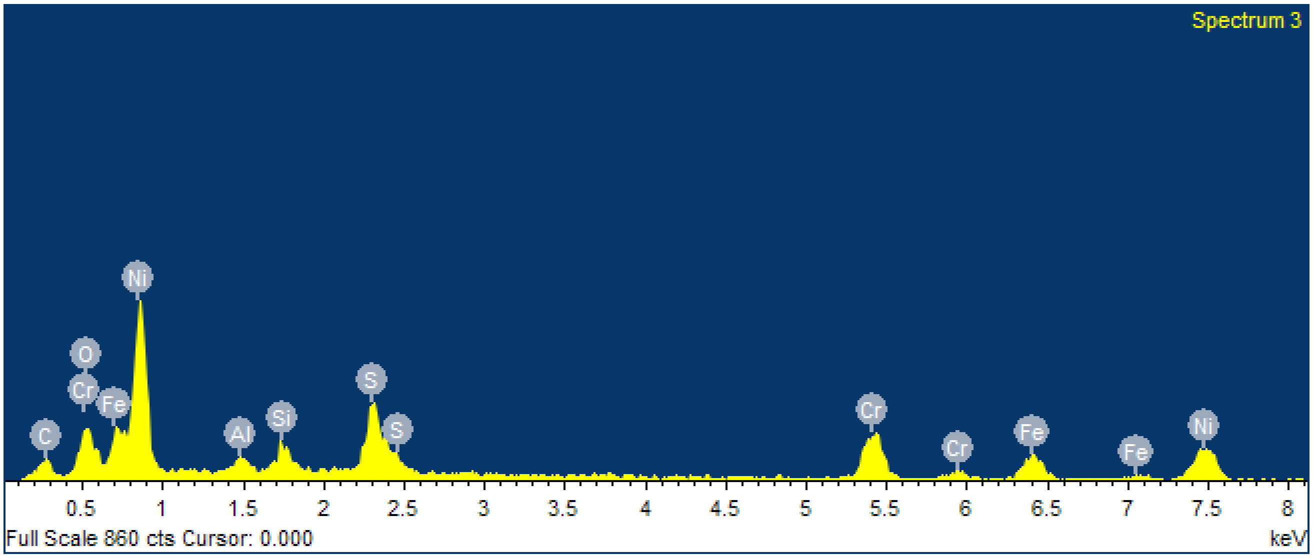
Site 2 (Honeycomb) – Spectrum 1



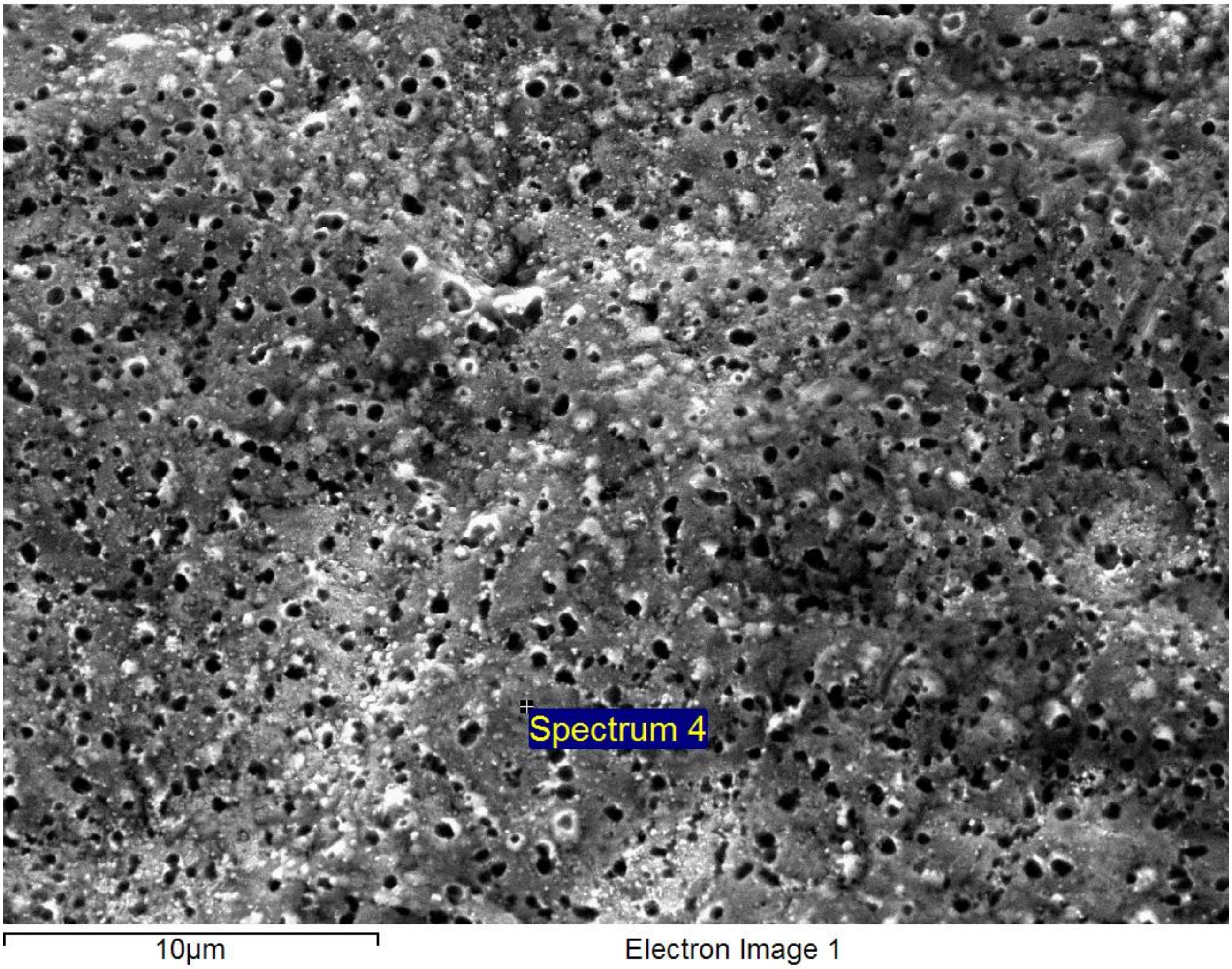


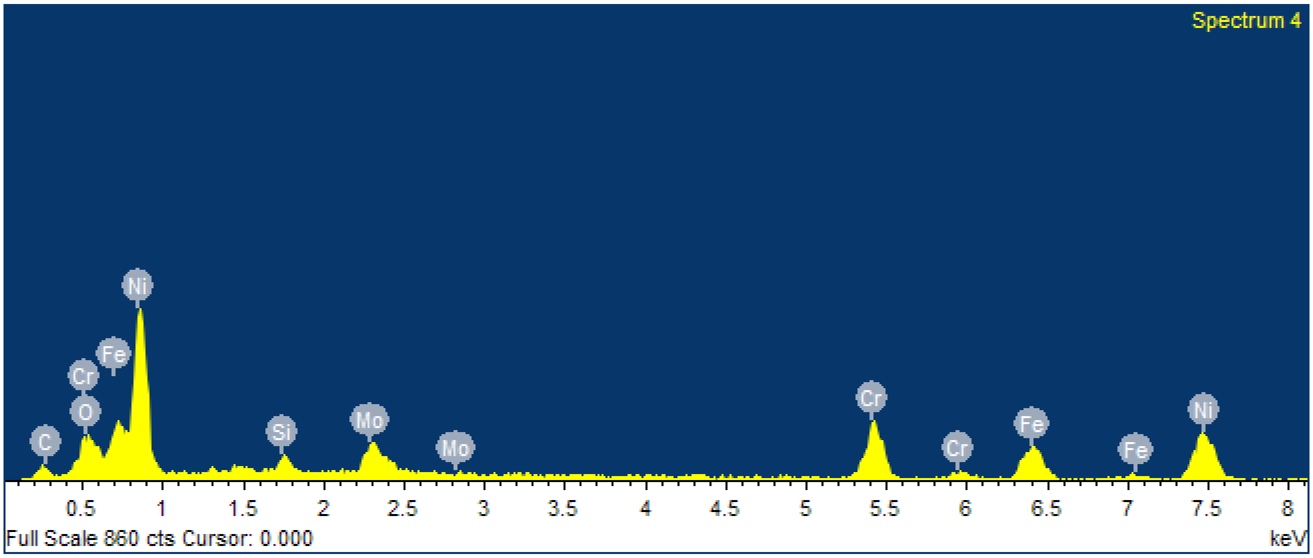
Site 2 (Honeycomb) – Spectrum 2



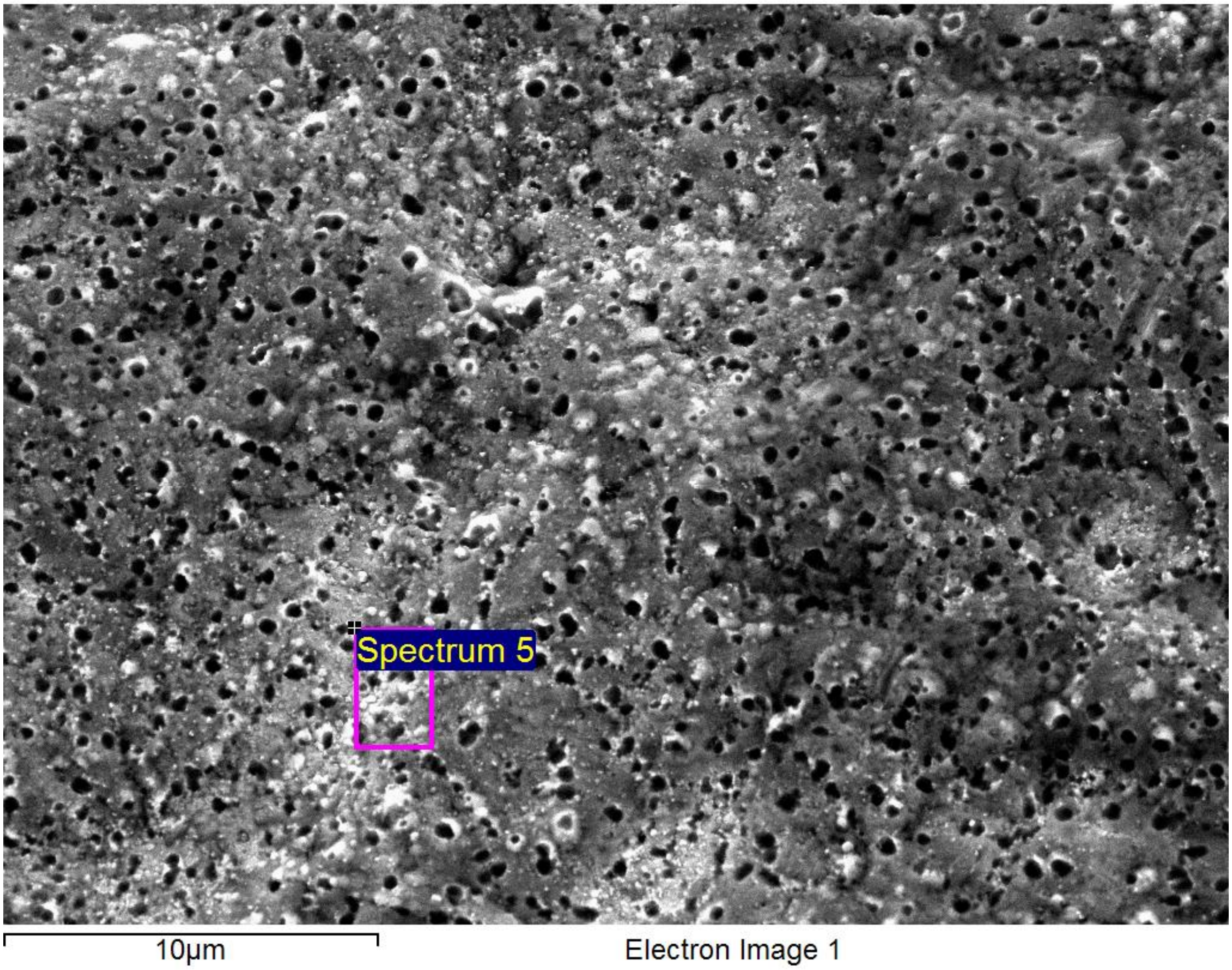


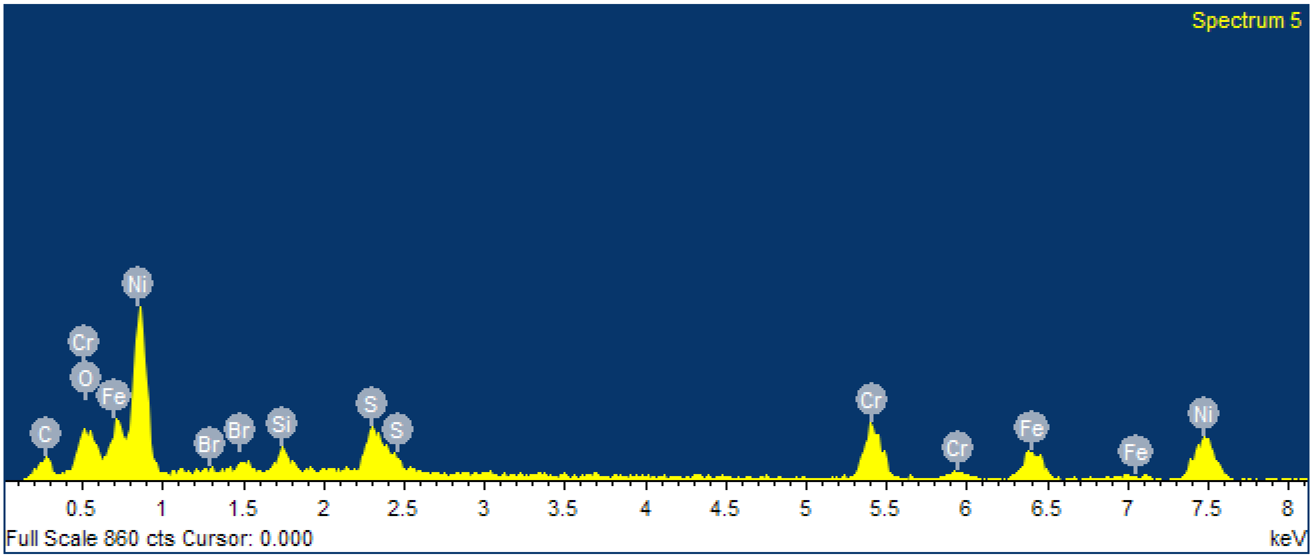
Site 2 (Honeycomb) – Spectrum 3



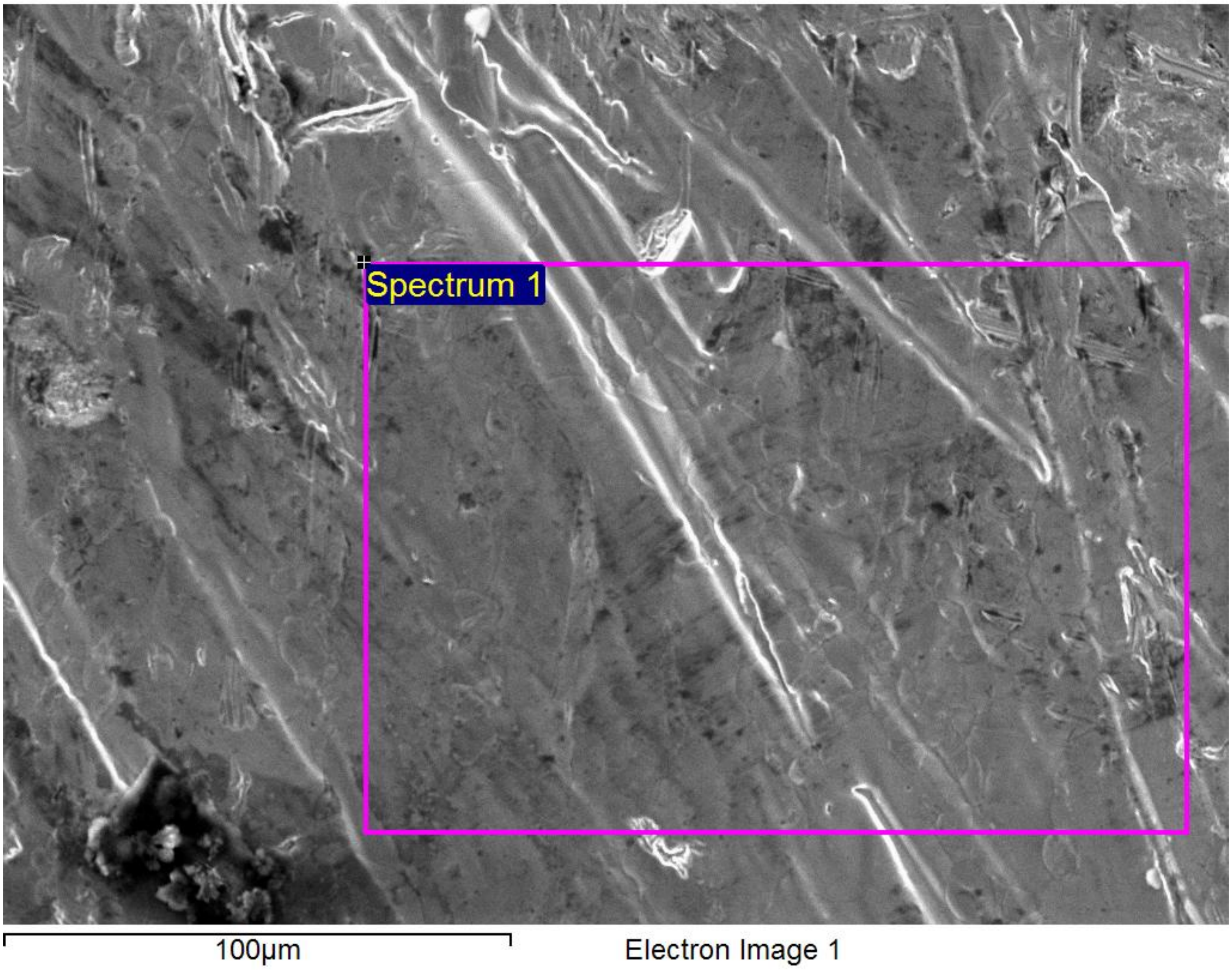


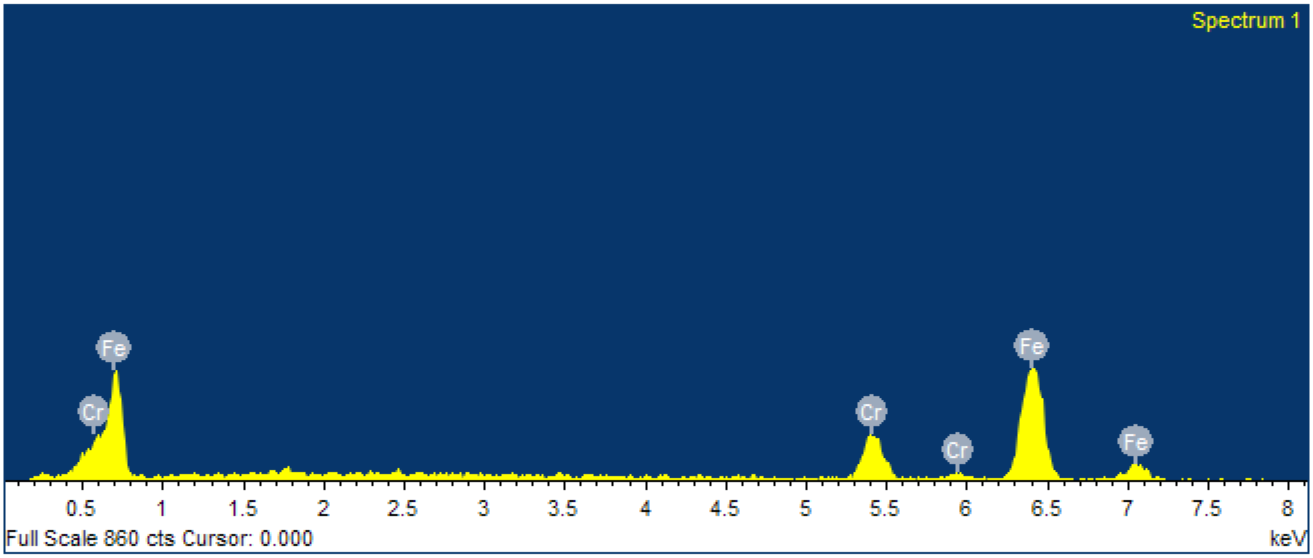
Site 2 (Honeycomb) – Spectrum 4



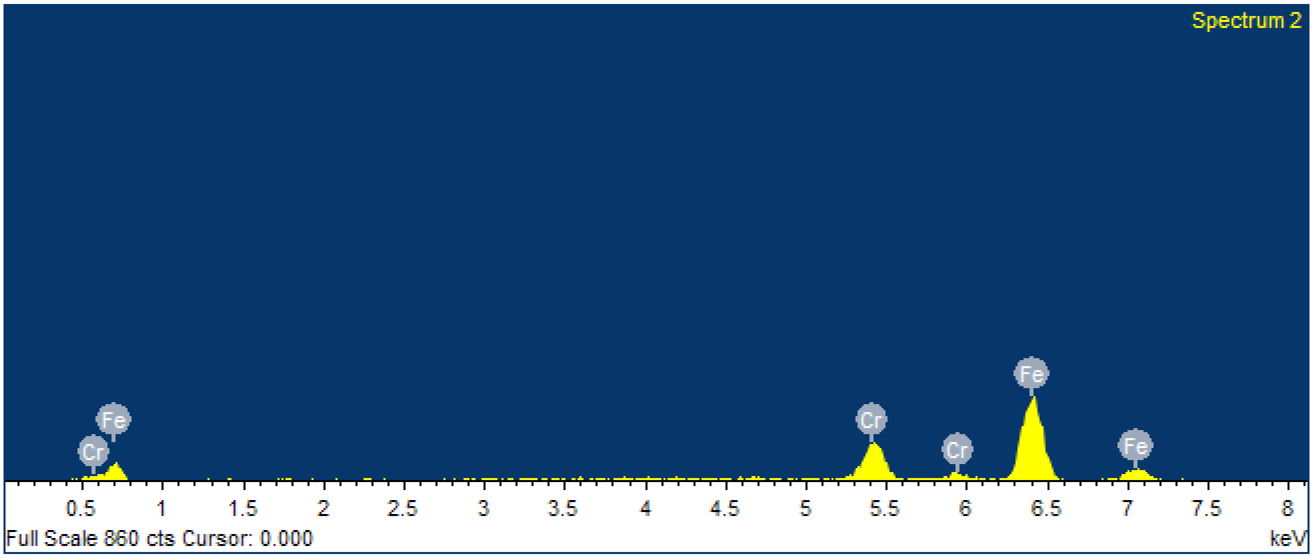


<u>Site 3 (Outer Ring) – Spectrum 1</u>





Site 3 (Outer Ring) – Spectrum 2



Site 3 (Outer Ring) – Spectrum 3