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MEASUREMENT OF THERMAL CONDUCTIVITY USING A ONE-DIMENSIONAL STEADY-STATE HEAT FLUX METHOD

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Abstract

The thermal conductivity of a material is a key property in many heat transfer applications. Thermal conductivity indicates the resistance to heat being transferred through a material. A low thermal conductivity indicates a material acts more as an insulator while a high value indicates a material acts more as a conductor of heat.

The goal of the project was to create a method that would measure the thermal conductivity of various materials. The development of this method was validated using materials with known thermal conductivity properties. By developing and validating a method, it allows the characterization of thermal conductivity of new materials with unknown properties. After a literature survey and uncertainty analysis was completed, a one-dimensional, steady-state heat flux method was selected as the test method. Once the testing apparatus was constructed, the method was verified by measuring the thermal conductivity of a well known material, namely 303 stainless steel. A new material was characterized as well and compared with a value that others have obtained.

Acknowledgements

I would like to thank my parents, Daniel and Annette, and my sister, Abby, for all of their love and support throughout my life. I am also very grateful to Dr. Karen Thole for all that she has taught me and her help. I would like to thank Mike Barringer for all of his help and answering any questions I had.

I owe a huge thank you to my partner in this project, Robert Schroeder. He was extremely hard working, would answer any questions I had, very knowledgeable about heat transfer and statistics, and taught me more about Microsoft Excel than I knew was possible. Also, I am very grateful to everyone I worked with in the PSU Exccl Lab, especially Steve Lynch and Jason Ostanek. They would always take time, even when they were busy and answer questions I had and give advice to me.

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Nomenclature

k	Thermal Conductivity
α	Thermal Diffusivity
ρ	Density
c	Specific Heat of the Solid
Qdot	Power
A	Area
dT	Temperature Difference across specimen
dx	Thickness of Specimen
µ	Uncertainty
R	Resistance
h	Heat Transfer Coefficient
V	Voltage
T	Temperature

Subscripts and Superscripts

loss	Heat loss out of the system
Side	The sides of the specimen
Bottom	The bottom of the specimen
tmeasure	The measured thickness of the specimen
h	The hot side of the specimen
c	The cold side of the specimen
∞	Ambient
Spec	Specimen
Heart or ht1	Primary Heater
Guard	Guard Heater
Resistor	The voltage drop across the precise resistor
Prec	The precise resistor

Chapter 1 Introduction

1.1 Background and Motivation

In heat transfer applications, the thermal conductivity of a material must be precisely known. It indicates the material's resistance to heat flowing through it. Therefore, it is necessary to measure a material's thermal conductivity if it does not have a well established value. Knowing the thermal conductivity of a material is important in many research areas, as well, particularly those related to gas turbine heat transfer.

1.2 Goals and Approach

The project for this thesis was to develop a method and construct a device that could accurately measure the thermal conductivity of materials. The goals of the device were that it must be easy to construct and use, able to test a wide range of materials in both size and estimated conductivity, and have a low uncertainty. Furthermore, the procedure should be easy to apply such that a person can test a material's thermal conductivity in a reasonable amount of time for a reasonable cost.

The approach of the project was to first conduct a literature review on known methods and measurement standards. Once a method and device was selected, an uncertainty analysis was performed to design the device based on the thermal conductivity range of interest. Based on the uncertainty analysis, the device was to be constructed and samples were tested. The device was then validated by measuring the thermal conductivity of a well established material. Finally, unknown materials were tested.

Chapter 2 Literature Review

The thermal conductivity of a material is an important property that must be precisely known for a variety of reasons. Thermal conductivity describes if a material will insulate or allow heat to pass through easily pass. This literature review discusses the methods that can be used to measure the thermal conductivity of a material. Several of these methods are described by the American Society for Testing and Materials (ASTM). The measurement technique varies with the type of material and the range of conductivity to be measured. High thermal conductivity materials usually do not use the same tests as low thermal conductivity materials because of the inaccuracies that may occur. Although there is a wide range of laboratory tests and papers on measuring thermal conductivity, most follow an ASTM Standard. Some experiments, however, use other methods, particularly those done outside of the U.S.

2.1 Measurement Methods Using ASTM Standards

Throughout the ASTM standards, there are two main testing procedures to measure thermal conductivity. The first technique is to calculate the thermal diffusivity, α, of the test specimen and calculate the thermal conductivity from the equation:

$$k = \alpha * \rho * c \qquad [1]$$

The thermal diffusivity is found throughout a variety of methods; most notably, lasers are used to find the diffusivity. While very accurate, this measurement method is expensive and requires a large capital investment in lasers and computers. Other methods find the diffusivity by using calorimetry. Calorimetry, too, requires expensive measurement devices and computer programs to find the conductivity.

Another method promoted the ASTM uses to find thermal conductivity is to measure a temperature difference across a test specimen with constant heat flux. This method uses the equation:

$$k = \dot{Q}/(A * \frac{dT}{dx}) \qquad [2]$$

The ASTM standard ([1] ASTM Standard C177, 2004) focuses on this method. This standard uses many heaters, one primary and multiple guard heaters, to create a uniform heat flow throughout the specimen. There are two specimens in this standard on each side of the primary heater and the temperature difference across the specimen are measured using thermocouples, as shown in Figure 2.1 for the typical ASTM arrangement.

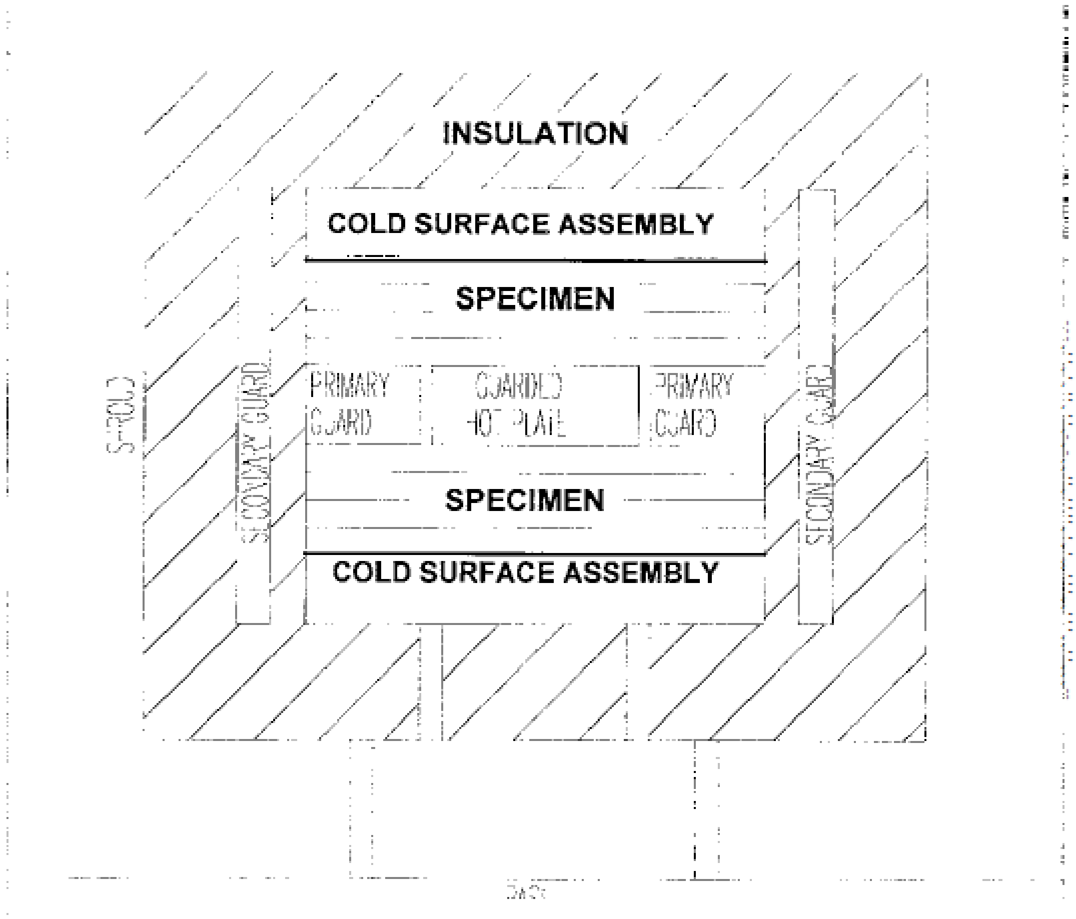


FIG.

Figure 2.1 The ASTM standard's diagram of a typical thermal conductivity test. ([1]ASTM Standard C177, 2004).

There are other ASTM Standards that use the same principal but have small differences. One standard ([2] ASTM Standard C1114, 2006) uses a single thin heater with fewer guards but still has two testing specimens. Another standard ([3] ASTM Standard C1044, 2007) uses a single thin heater and a single guard heater, but only has one test specimen; therefore, it is a one-directional test.

2.2 Comparisons of Measurement Methods Reported in the Literature

With many different types of testing procedures available from ASTM, a search of published experiments was performed to see which technique is the most feasible for this project. Initially, all types of thermal conductivity measurements were considered.

For solid materials, the most common and oldest method is the heater method similar to ASTM C177. Some experiments ([4] Pratt, 1962; [5]Somers and Cyphers, 1951) had experiments similar to the ASTM standards and were performed before 1970. They both had good testing results, which were very encouraging considering the measurement technology of today is much better with advancement in computer data acquisition systems.

A modern example of the ASTM standard ([6] Moore and Cummings, 2009) uses new technologies such as a digital acquisition system and computers to digitally resolve their measurements. They used a single heater with two test samples with thermocouples in-between, as shown in Figure 2.

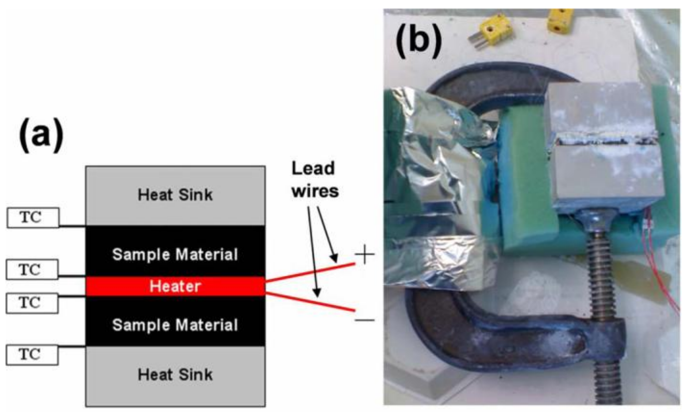


Figure 2.2 Two views on the experimental setup used by Moore and Cummings to measure thermal conductivity. ([6] Moore and Cummings, 2009).

The thermal conductivity range for this experiment was similar to the range of the epoxies to be measured. Their experiment also produced accurate results. The setup was extremely simple and had a very low cost.

Also, recent papers ([7] Campbell and Smith, 1999), ([8]Cheruparambil and Farouk, 2000) have used other methods to test for thermal conductivity, mostly involving lasers. Both experiments yielded accurate results, but the experiment setup is extremely complicated and expensive.

Chapter 3 Experimental Setup and Procedure

After researching the different types of thermal conductivity measurement methods and comparing them to the constraints of the project, mainly cost and simplicity, the one dimensional steady state heat flux method was selected. There were three ASTM Standards used for the design of the testing apparatus and procedures. Also, a list of design considerations for the testing device was created based on the needs of the project that were not included in the Standards. First, the testing rig needed to be able to measure different types of materials at different thicknesses. Second, the test rig must be easy to machine and reassemble. Next, the device needed to be kept to a low cost. Also, the device must need to be assembled and taken apart in a short amount of time. Furthermore, a maximum of 5% uncertainty would be required. Finally, heat loss out of the sides of the device must be kept to a minimum.

3.1 Uncertainty Analysis

Once the one dimensional steady state heat flux method was selected, an uncertainty analysis was performed to design the testing apparatus. This analysis was completed by Robert Schroeder and Scott Fishbone. Uncertainties were calculated as a function of sample cross-sectional areas, temperature differences across the thickness of the specimen, the heat flux through the specimen, and specimen thickness, as shown in Figure 3.1, Equations 3.1, and Appendix A.

$$\mu k = \sqrt{\left(\frac{\partial k}{\partial \dot{Q}}\mu\dot{Q}\right)^2 + \left(\frac{\partial k}{\partial \Delta x}\mu\Delta x\right)^2 + \left(\frac{\partial k}{\partial A_{spec}}\mu A_{spec}\right)^2 + \left(\frac{\partial k}{\partial \Delta T}\mu\Delta T\right)^2} \quad 3.1$$

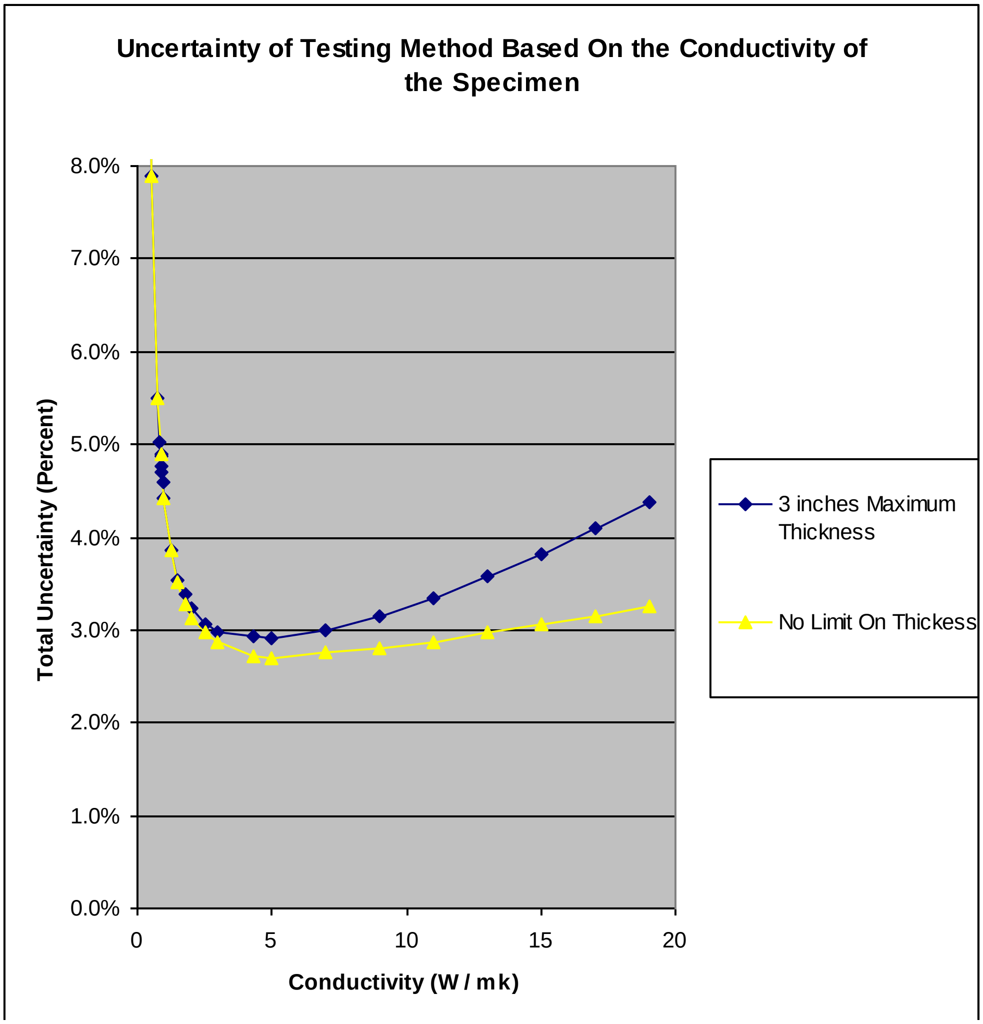


Figure 3.1 The uncertainty of the testing device plotted against thermal conductivity([9] Schroeder, 2009).

3.2 Device Setup

The testing apparatus was constructed to create a one dimensional steady state heat flux through the specimen, as shown in Figure 3.2. To do this, a 5″ x 5″ thin resistance heater was used. The resistance heaters that were selected were manufactured by Minco©. The heaters were 5 inches long by 5 inches wide and had a resistance of 106 ohms. One additional heater was used as a guard heater to reduce the heat losses from the testing apparatus and to ensure heat from the main heater primarily went through the specimen. From the uncertainty analysis, an 8 inch thick insulation was placed around the heaters with a 1inch thick layer of insulation and a 1inch thick layer of wood were placed below the guard heater. The heat loss from each test was calculated in the equations:

$$\dot{Q}_{loss} = \dot{Q}_{side} + \dot{Q}_{botom} \tag{3.2}$$

$$\dot{Q}_{side} = t_{measure} \times (2w + 2l) \times \frac{0.5 \times (T_h + T_c) - T_\infty}{R''_{side}} \tag{3.3}$$

$$R''_{side} = \frac{t_{side}}{k_{side}} + \frac{1}{h} \tag{3.4}$$

$$\dot{Q}_{bottom} = k_{bottom} \times A_{spec} \times \frac{T_{htr\ 1} - T_{guard}}{t_{bottom}} \tag{3.5}$$

The heaters are then taped to the insulation with singled sided Kapton tape at the corners of the heater, taking up as small of an area as possible.

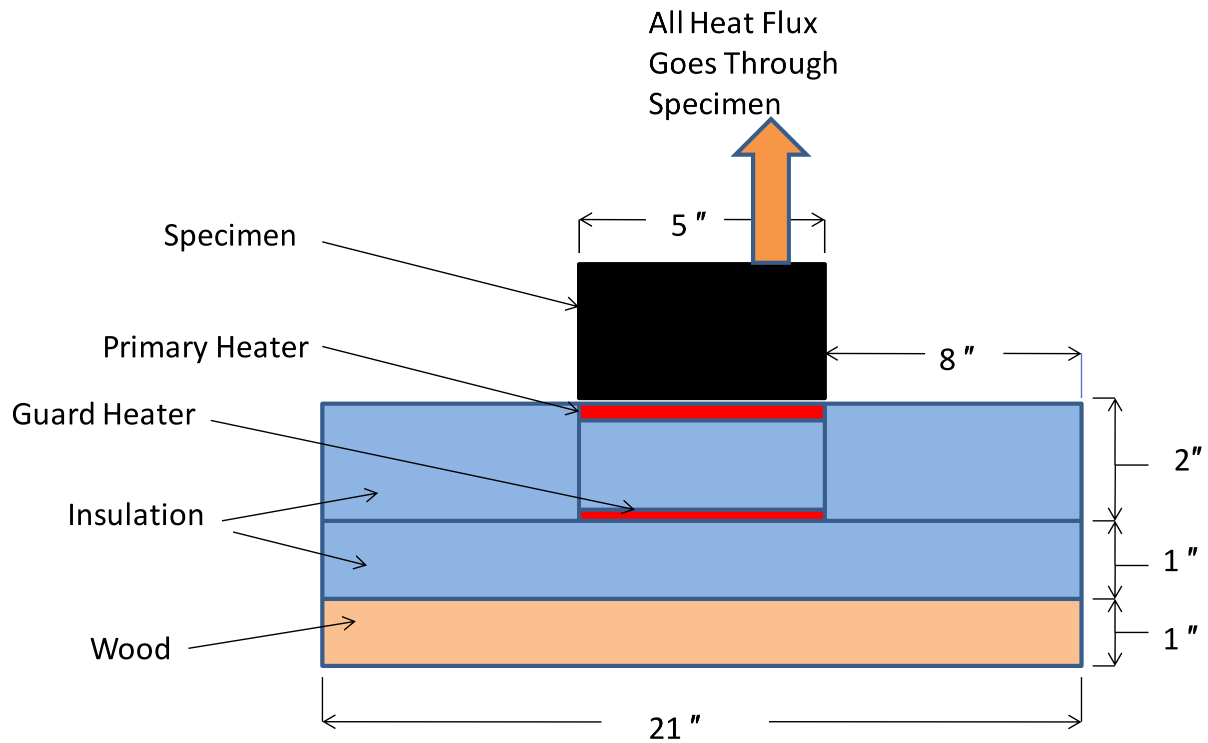


Figure 3.2. The heater and insulation setup to ensure that all the heat flux from the primary heater goes through the specimen.

To power the two heaters, two AC to DC power supplies were used. See Figure 3.3 for the electrical diagram of the heaters. The current provided to the heaters from the power supplies was one of the variables needed to calculate the heat flux, as shown in Equation 3.1; therefore, a precise value was needed. To obtain this measurement of current, a precision resistor with a resistance of 1 ± 0.01 ohm was connected to the wires connecting the heater and the power supply and the voltage drop across the resistor was measured with a voltmeter. The power to the guard heater was determined by measuring the temperature of the primary heater and then adjusting the power of the guard heater so its temperature matched the primary heater.

$$\dot{Q} = V_{Heater} * \frac{V_{resistor}}{R_{prec}} \tag{3.6}$$

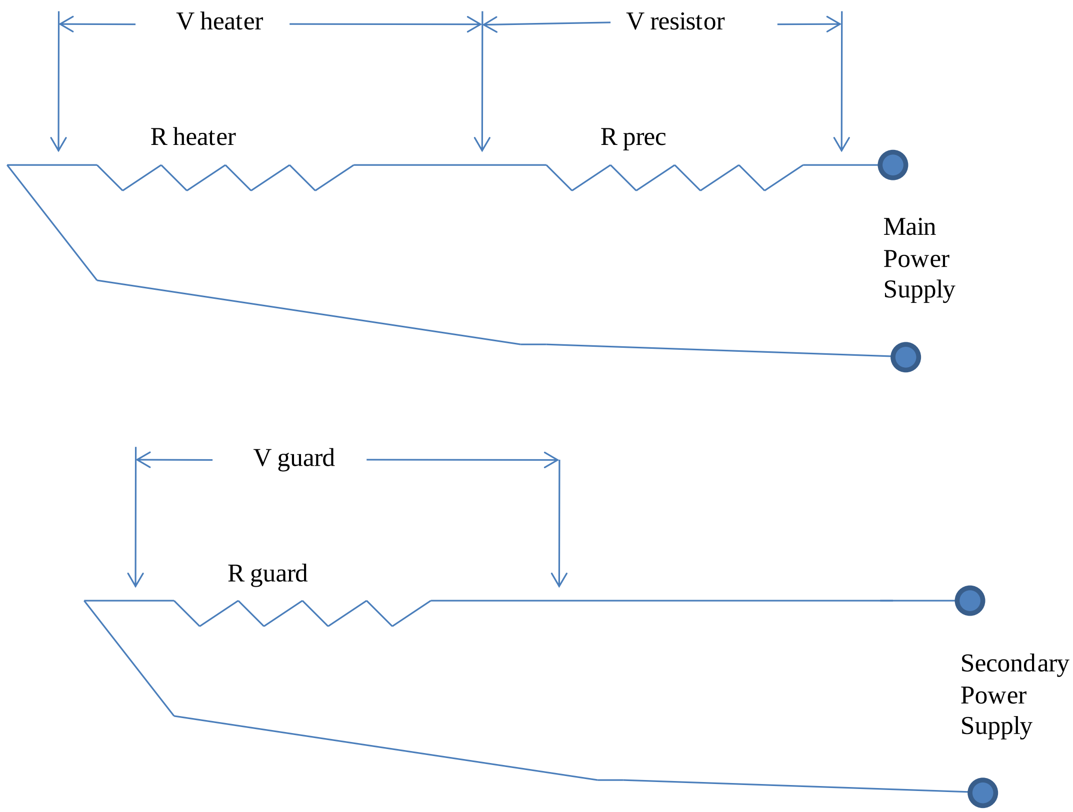
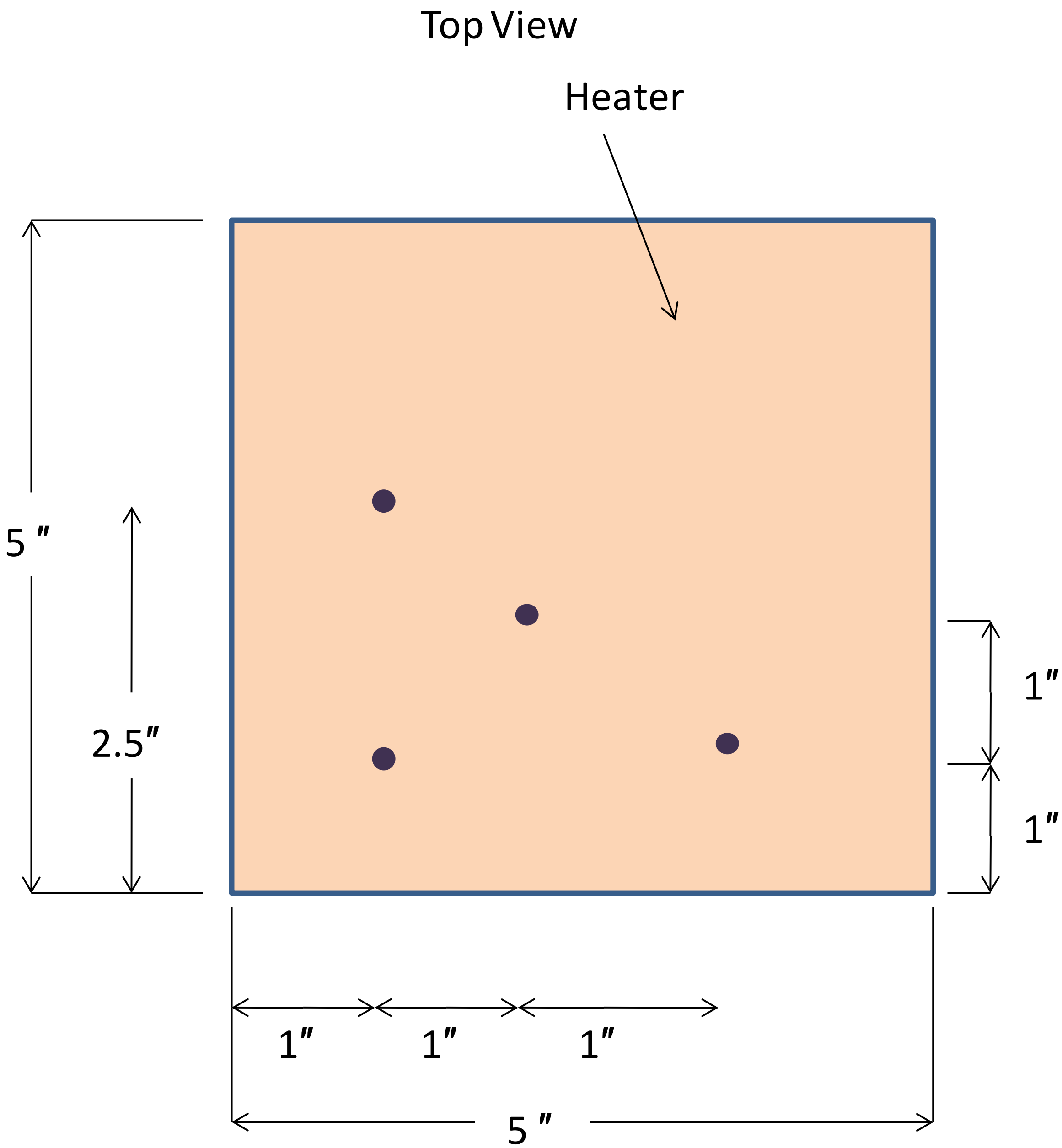


Figure 3.3 The electrical diagram for the primary and guard heater with the precision resistor included.

To measure the temperature of the heaters and specimen, Type E thermocouples were used. For all materials, four thermocouples were placed on each of the heaters at various locations, as shown in Figure 3.4. The number of thermocouples on a certain material depends on the uncertainly analysis for that material. The thermocouples were produced as short as possible and were connected to extension wires. The extension wires were inserted into two National Instruments© SCXI™ -1303 32-Channel Isothermal Terminal Block with the pullup and bias resistors in place. The blocks were connected to National Instruments© SCXI™ 1102 Modules in a National Instruments© SCXI™ 1000 and then a computer. A National Instruments Lab VIEW program was written to record the temperatures at a rate of 2 Hertz every 3 hours.


Top View
Heater
5 ″
2.5″
1″
1″
1″
1″
1″
5 ″

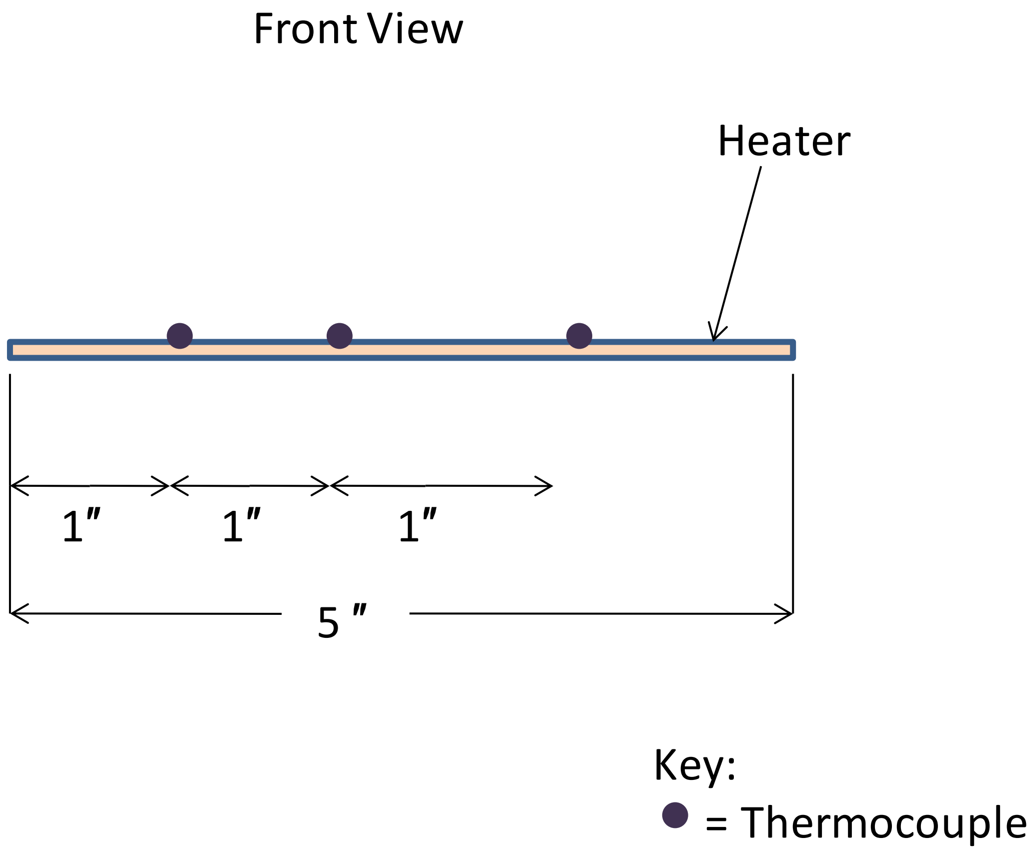


Figure 3.4 The thermocouple locations on the guard and primary heater.

3.3 Specimen preparation

Three materials with a wide range of thermal conductivities were selected to be tested in this project, as shown in Table 3.1

Table 3.1 The materials to be tested in the project based on given information from the manufacturer for the epoxies and the ASM Metals Handbook for the stainless steel. The thickness of each material was selected based on the uncertainty analysis ([9] Schroeder, 2009) as viewed in Figure 3.5.

Material	Thermal Conductivity from Reference (W/m*K)	Thickness of Material (inches)	Predicted Uncertainty
303 Stainless Steel	13-16.5[10]	2.5	11%
Polycast© PC159	0.87 [11]	1.9	4%
Polycast© PC287	4.33 [12]	3	5%

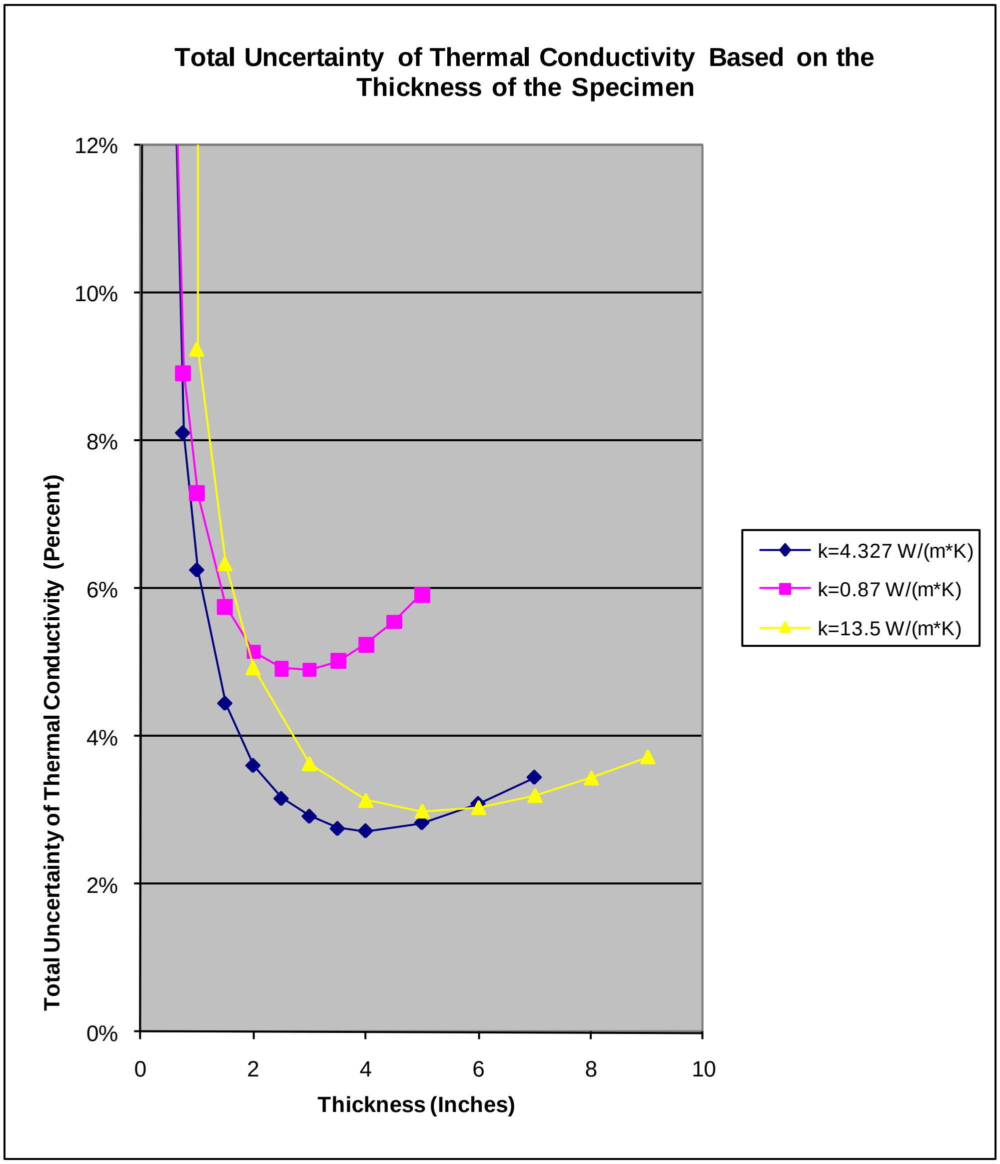


Figure 3.5 The uncertainty in the measured thermal conductivity value versus the thickness of each material. A thickness near the minimum of each curve was selected for the test.

The 303 stainless steel was selected to as the material for validation of the method developed. This choice was made because its thermal conductivity has been measured many times and is well known. The conductivity of the 303 stainless steel ranges from 13 W/ mK to 16.5 W/ mK for 20°C to 200°C ([10]ASM International, 2004). This 303 stainless steel was selected because of its relatively low thermal conductivity compared to other well known materials, like copper, whose thermal conductivity is 400 W/ m *k ([13] Incropera and Dewitt, 2006).

To prepare the steel to be tested, a rectangular bar was cut into pieces that were 2.5″ x 5″ x 0.50″ in dimension. This was done so that an overall testing specimen of 2.5″ x 5″ x 5″ could be constructed, as seen in Figure 3.6. A single piece with the overall dimensions of 2.5″ x 5″ x 5″ was not used because it would be extremely expensive. To minimize error, high thermal conductivity grease was placed in-between the slices and all of the slices were clamped together, as shown in figure 3.7.

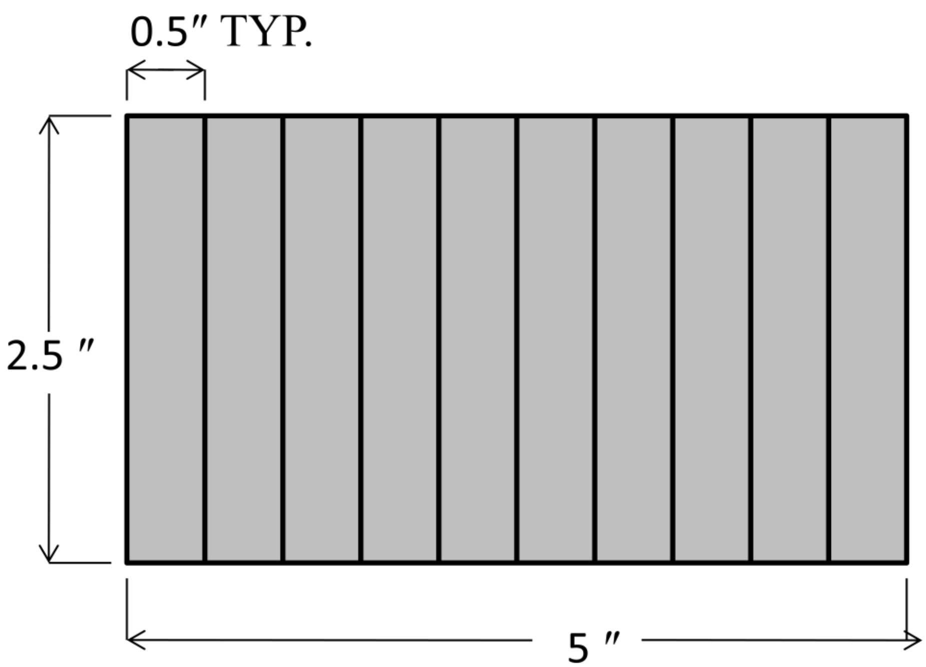


Figure 3.6 Side view of the arrangement of individual pieces of steel was used create a larger slab for testing.

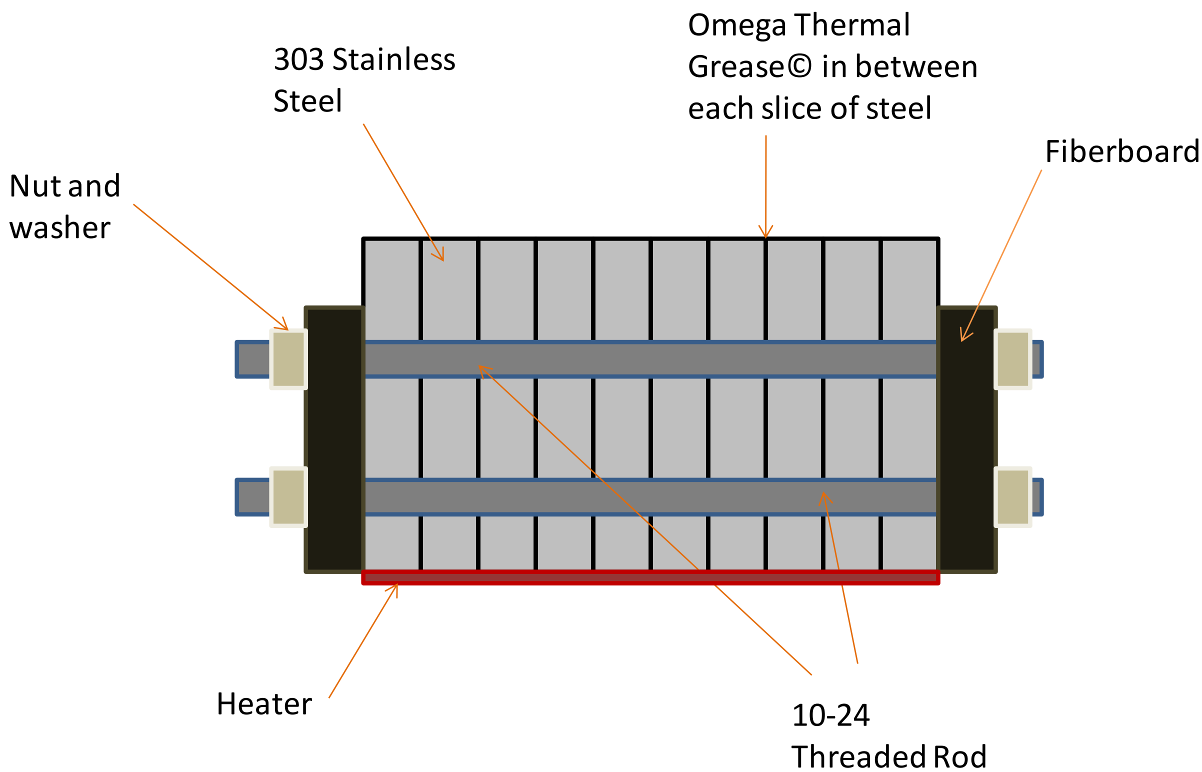


Figure 3.7 A side view of the setup of slices of steel that were clamped together with thermal grease placed between them.

The number of thermocouples needed for each of the hot and cold sides of the stainless steel from the uncertainty analysis was 12. If thermocouples were to be placed on the flat surface, they would form bumps with air pockets around the thermocouple, destroying the contact needed between the heater and the steel. To solve this problem, grooves were cut into the stainless steel so the thermocouple can fit inside of them, as shown in Figure 3.8. To prevent the thermocouple bead from touching the steel and to keep the thermocouple in the groove, the thermocouples were coated with Duralco high thermal conductivity cement.

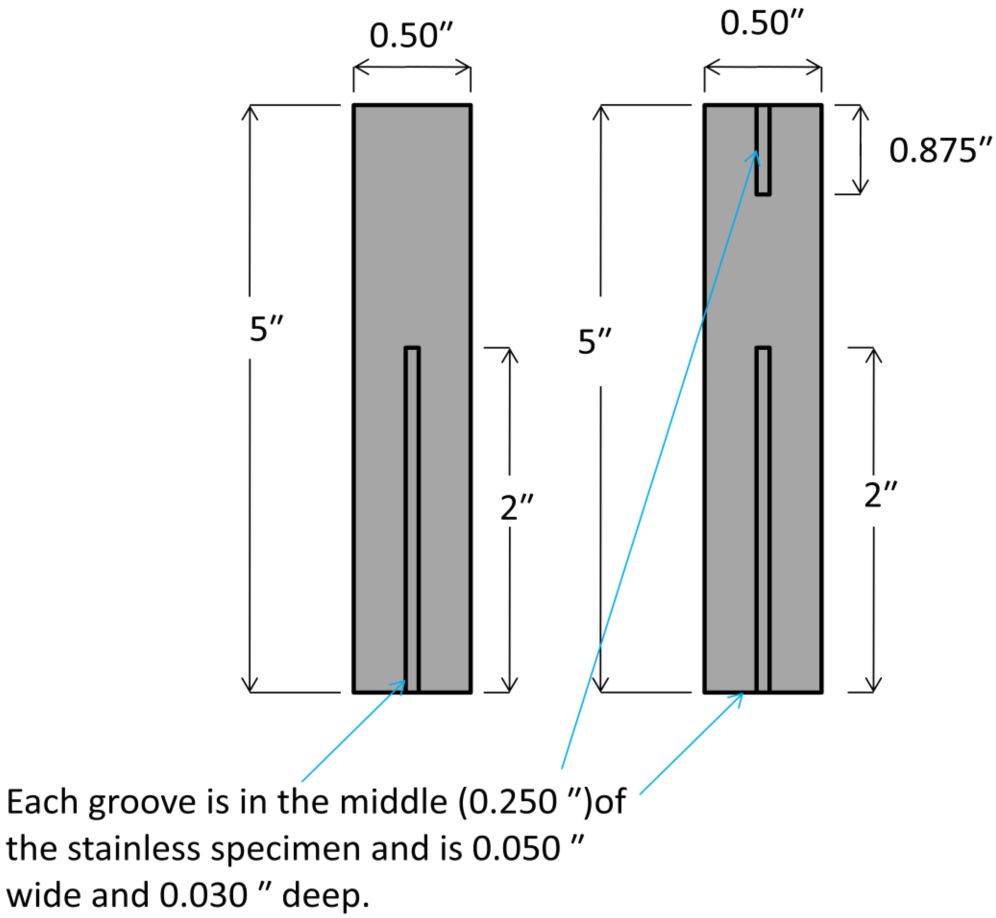


Figure 3.8 A single groove was cut into eight stainless steel pieces and two groves were cut into two pieces for the thermocouples to fit inside.

The two Polycast© epoxies were selected because of their high thermal conductivities compared to other epoxies and their ability to be molded into any shape. Because of these properties, the Polycast PC 287 epoxy is a material of interest to be used in gas turbine studies at the Penn State Experimental and Computational Convection Lab. For the conductivity tests, the ASTM standards state that each material must be square; therefore, square molds were created for each of the epoxies.

To make the molds to the dimensions from the uncertainty analysis of each epoxy, MDF was machined to be square and have a tolerance of ±0.005″ of each. Teflon© tape was placed on the inner surfaces of the mold so that the hardened epoxy would not stick to the MDF. The epoxies were measured to the weight ratio specifications from the manufacture, mixed together thoroughly, and poured into the molds to cure.

Great care was taken to avoid air bubbles forming in the hardened epoxy. One of the methods used to reduce air bubbles was to pour the mixture of liquid epoxy into the mold very slowly. Another was to create a mold that had raisers at the top of the container so that excess material and bubble could flow out of the mold, as viewed in Figure 3.9. Also, once the mold was full of epoxy, it would be tapped against the ground to promote air bubbles to move out of the mixture. Finally, (only done for the PC-287) after the mold was poured, the mixture was heated in a kiln to 50ºC so that any remaining air bubbles would rise out of the epoxy.

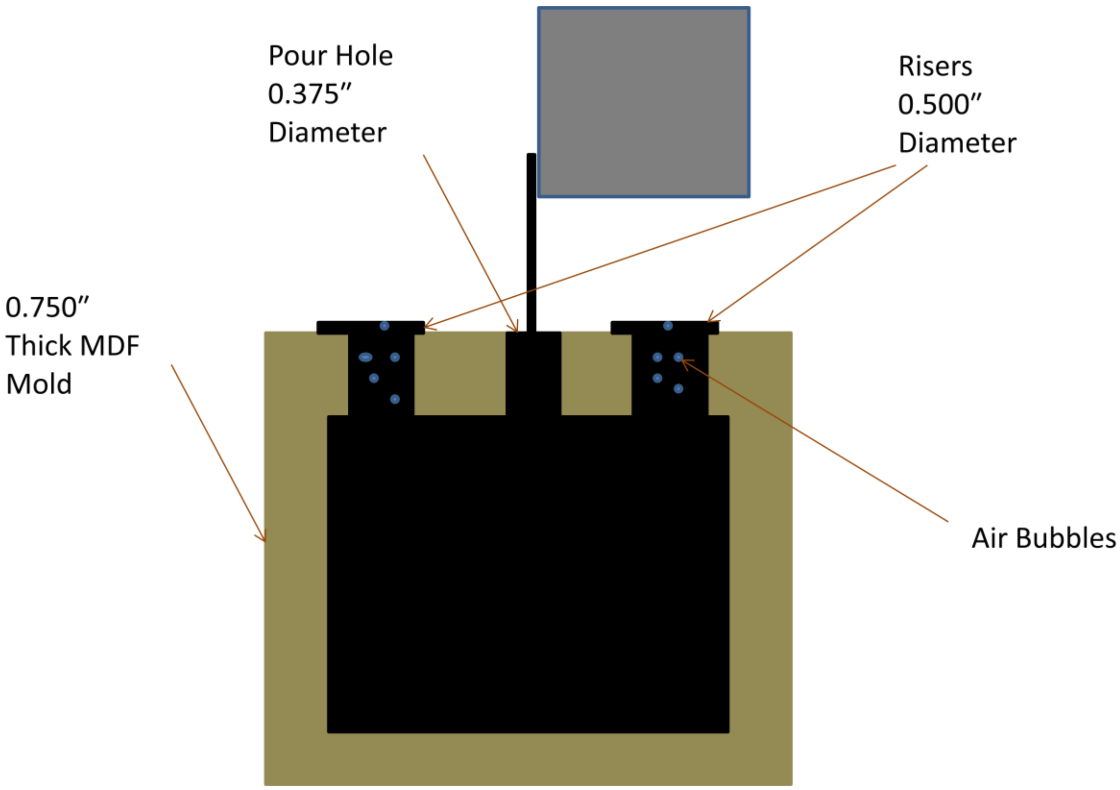


Figure 3.9 Risers were drilled into the top of the mold so that air bubbles could move out of the epoxy mixture.

The surfaces of both epoxies had grooves cut into them just like the stainless steel to place the thermocouples. The pattern of the grooves was different than the stainless steel in that their positions varied greatly over the surfaces, as viewed in Figure 3.10. This was done because the epoxies were each a single piece compared to the ten pieces of steel and they could be easily machined compared to the steel.

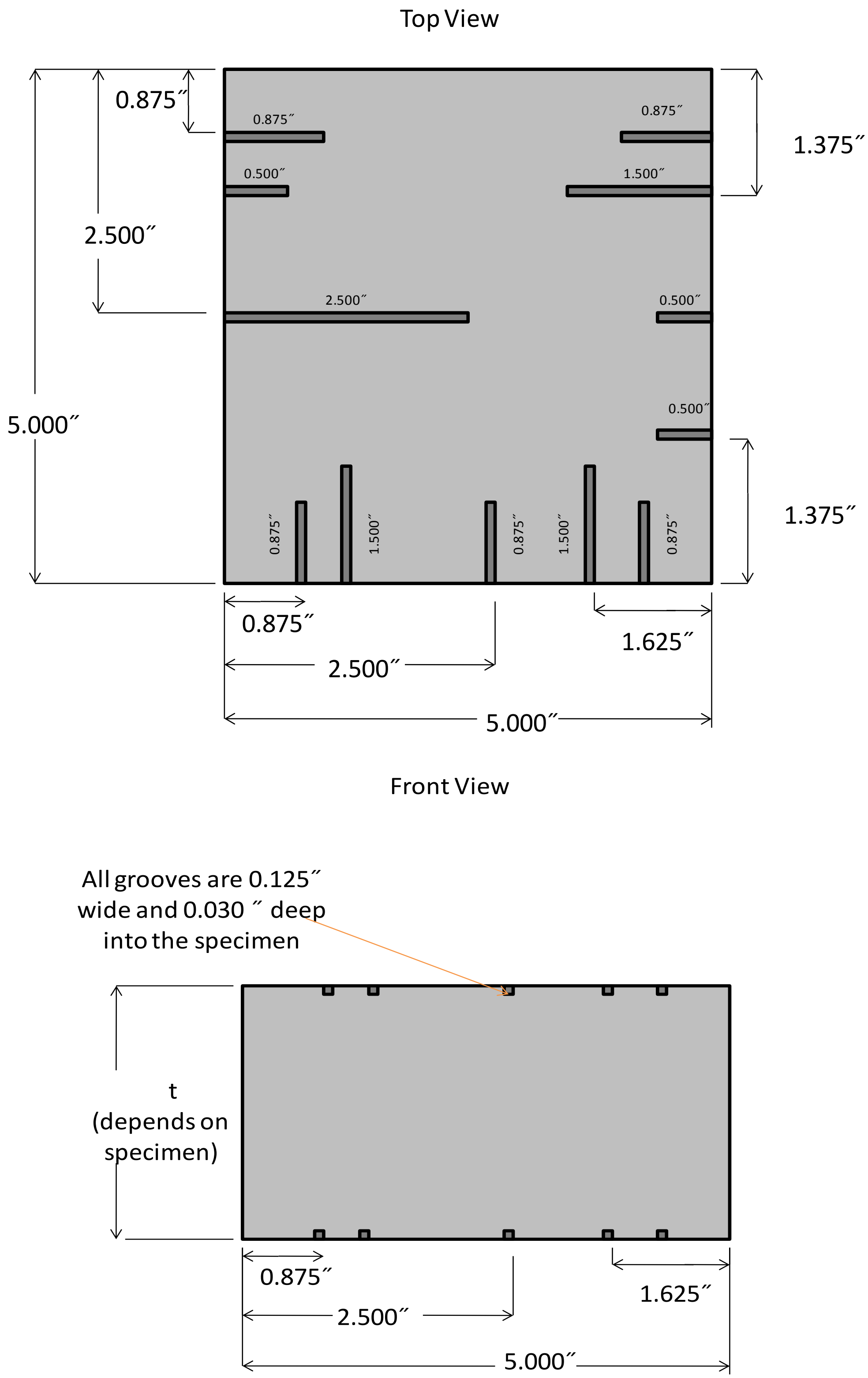


Figure 3.10 The hot and cold surfaces of both PC159 and PC287 epoxies had a different thermocouple groove pattern than the stainless steel.

3.4 Thermocouple Calibration

Thermocouples were used to measure the temperatures of heaters and materials. Omega© Type E thermocouples were used because of their low uncertainty and are rated for use in the temperature range used in the testing. To lower the uncertainty of the thermocouples' temperature readings, an ice bath calibration was performed. To do this, all of the thermocouples were bundled together and placed in a well insulated bath of mostly crushed ice and water, as seen in Figures 3.11 through 3.13.

Figure 3.11 Thermocouples were bundled together to be put in the ice bath to minimize the influence of spatial temperature differences in the water.

Figure 3.12 The ice bath was inside of a cooler with insulation surrounding it to ensure a temperature as close as possible to 0˚C.

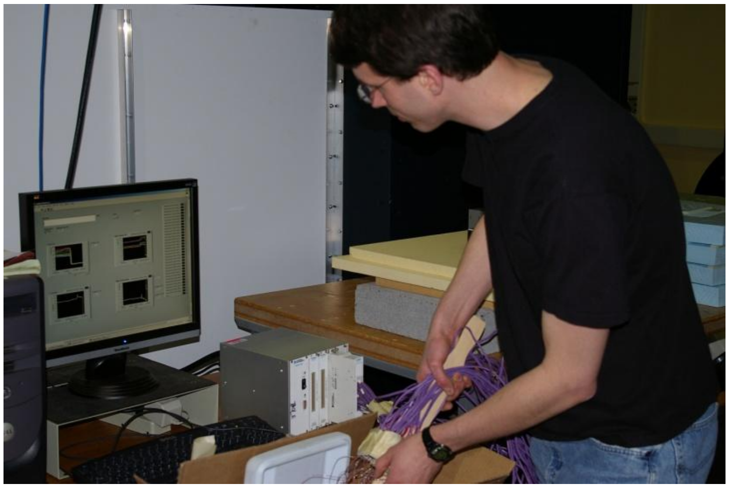


Figure 3.13 The bundle of thermocouples were inserted to the ice bath multiple times for two to three minutes to allow for equilibrium.

The ice bath calibration was performed many times due to issues involving errors found in the data acquisition system. To solve these errors, two separate buses were used with a combination of channels to create the lowest uncertainty. With the final configuration, a thermocouple uncertainty was found to be ±0.30 ˚C, as shown in Figure 3.14.

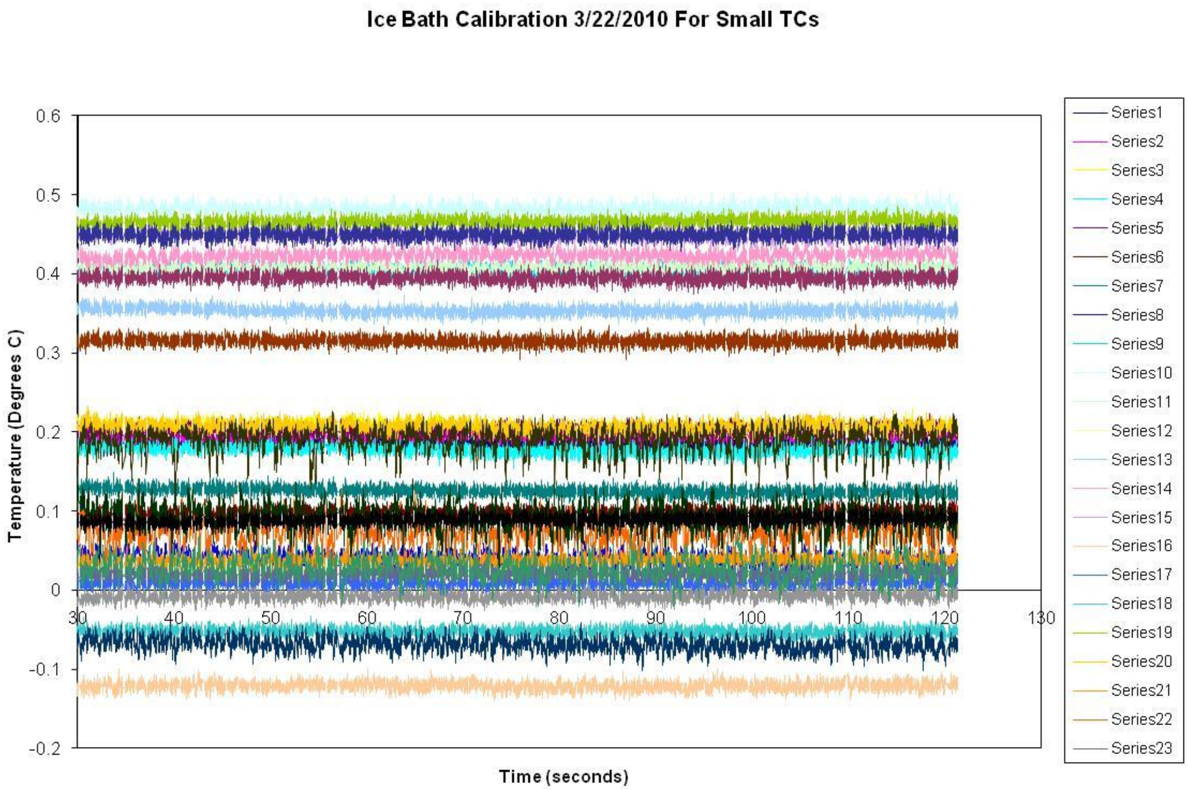


Figure 3.14 The ice calibration of the thermocouples was calculated by using the maximum and minimum readings from this graph to obtain a value of ±0.30°C.

3.5 Overall Testing Procedure

The basic testing procedure for each material was dictated by the ASTM standard. First, twenty cross sectional area and thickness measurements of each specimen were taken with a digital caliper and recorded. Next, the specimen was placed on top of the heater with the thermocouples in the material's grooves. A piece of aluminum was then placed on the other side of the specimen to act as a heat sink since its thermal conductivity of 170 W/ mK ([13] Incropera and Dewitt, 2006) is an order of magnitude greater than any material tested. Insulation was placed around the specimen and clamps we placed tightened down on the assembly to help create thermal contact. A diagram of the final setup can be viewed in Figure 3.15. A cardboard box was placed around the assembly to help prevent temperature fluctuations in the surroundings from affecting the test.

Once the system was assembled, the guard heater and primary heater were turned on. The power value that the primary heater was set to minimized the uncertainty of the test ([9]

Schroeder, 2010). The data collection software was then opened and started to collect temperature measurements. Measurements were recorded at a rate of two Hertz for three hours to determine if the system had reached steady-state conditions. Steady-state conditions of the system were found by plotting every thermocouple's time-averaged value over sequential three hour periods and observing if two criterions were met. First, the data must be monotonic, not having a linear trend. Second, the maximum random temperature fluctuations over the testing period must not exceed 0.5°C. If the two conditions were not met, another three hour run was taken and the process was repeated until steady state conditions were reached, as viewed in Figure 3.16.

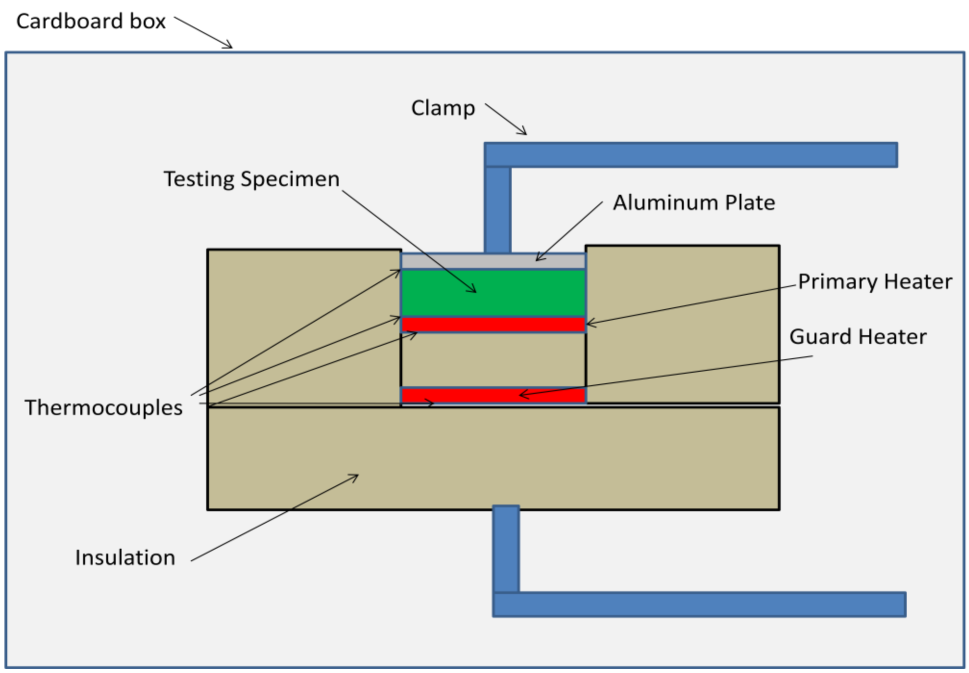


Figure 3.15 The basic test setup for all the materials to be tested was given by the ASTM standard.

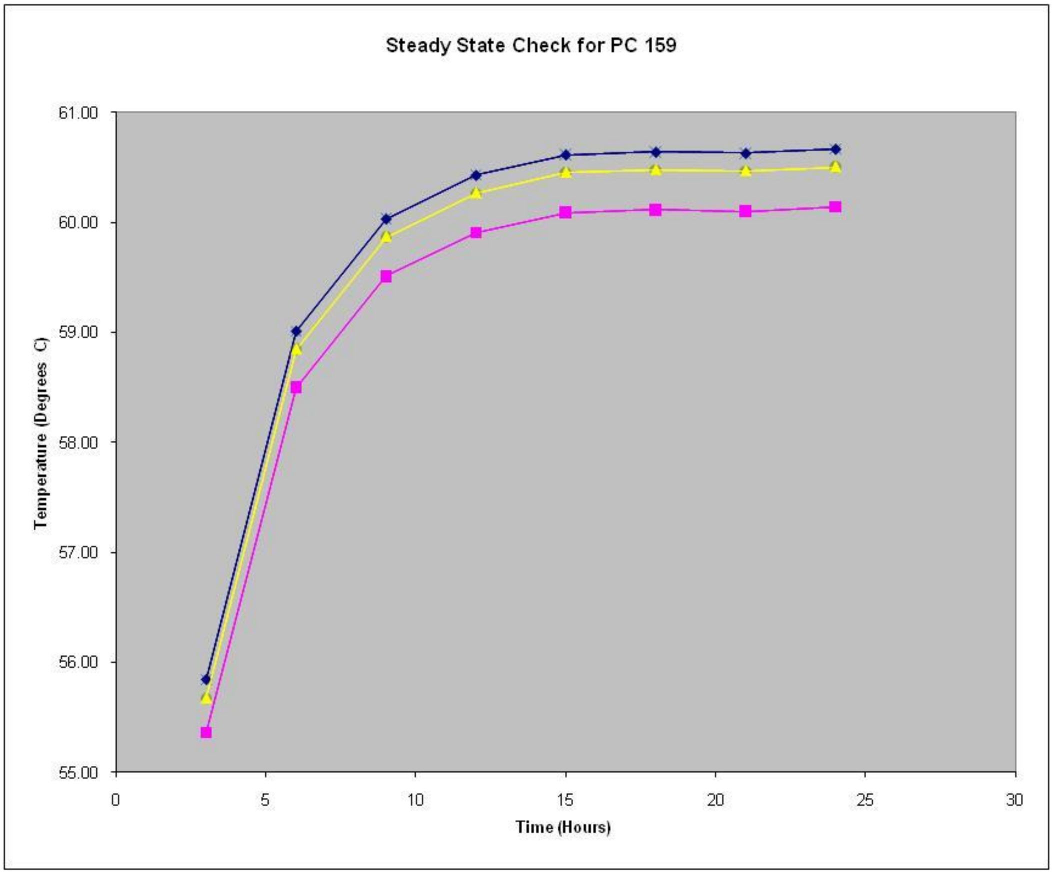


Figure 3.16 A plot of the average temperatures of the hot and cold surfaces along with the averages of the primary heater was used to see if steady state conditions were reached.

Once steady state was reached, data was collected for three time constants. One time constant was defined as the time it took the system to move 63% from its initial temperatures toward its final, steady-state temperatures.

After all of the data was collected, the thermal conductivity was calculated. The average and standard deviation were calculated for the guard heater, primary heater, cold and hot surfaces, as viewed in Appendix C. The averages and standard deviations were inserted into a spreadsheet that calculated the thermal conductivity and uncertainty for that temperature on the hot surface. The entire process was repeated three to four times to ensure the results were repeatable.

3.6 Testing Procedure Differences

The overall testing procedure from Section 3.5 was repeated for each material; however, each time a test was performed, small changes were made in the procedure. The changes were caused by various reasons, including reducing uncertainty, safety concerns and material challenges. A table listing all the changes for each test can be found in Appendix B.

The first material to be tested was the Polycast© PC159. This material was chosen first because it was the easiest to machine and the cheapest material in the project. Therefore, if errors were made in testing, it would not be as costly as the stainless steel or PC287 epoxy. For the Polycast PC 159 material, changes were made to reduce uncertainty. Some of the major modifications were to fill the thermocouple grooves with thermal grease, attach the heater to the epoxy with two-sided Kapton tape and to attach the aluminum plate to the specimen with two-sided Kapton tape.

The 303 alloy of stainless steel was the next material to be tested. Reducing uncertainty and safety were the main reasons for modifications for this material. The first major change was to coat the thermocouple with Duralco© Cement to prevent the thermocouple bead itself to be in electrical contact with the steel, which would cause the thermocouple to read temperatures incorrectly. Also, the grooves were filled with the same cement and the heater was attached to the hot surface of the steel with this cement. The cement was added to provide better contact with the stainless steel. On the cold surface, only one-sided Kapton tape was used because the two-sided Kapton tape would not adhere to the steel. Furthermore, insulation was placed in between the clamp and the aluminum plate. Without the insulation, the heat would flow through the aluminum plate and into the clamp, which was metal, and the clamp would act like a large fin. This caused the temperature distribution across the cold surface to differ greatly and no longer simulate one-dimensional heat transfer. Finally, the steel was tested at temperatures up to 170°C. Those high temperatures caused the original foam insulation to melt and created unpleasant odors. Fiberglass insulation was installed around the specimen, while the wood fiberboard was placed under the sample and between the heaters to prevent any more safety issues.

The final material tested was the Polycast© PC287 epoxy. It used all of the previous changes except the grooves were filled with the thermal grease instead of the cement.

Chapter 4 Results and Conclusions

4.1 Epoxy PC 159 Results

As previously mentioned, the first material tested was Polycast PC 159 epoxy. The manufacturer claimed an estimated thermal conductivity of 0.87 W/(m*K) with no uncertainty given. Tests were performed at five different temperatures, as can be viewed in Table 4.1. The results of the tests, see Appendix C for calculations, can be viewed in Figure 4.1.

Table 4.1 The temperatures of the hot surface of the PC 159 epoxy for the thermal conductivity test.

Measured Thermal Conductivity	% Uncertainty	Hot Surface Temperature
(W/(mK)	(percent)	(ºC)
0.87 Manufacturer's Value[11]	Not Given	N/A
0.754	6.18%	78.43
0.754	7.33%	57.97
0.754	6.67%	70.63
0.748	6.16%	88.45

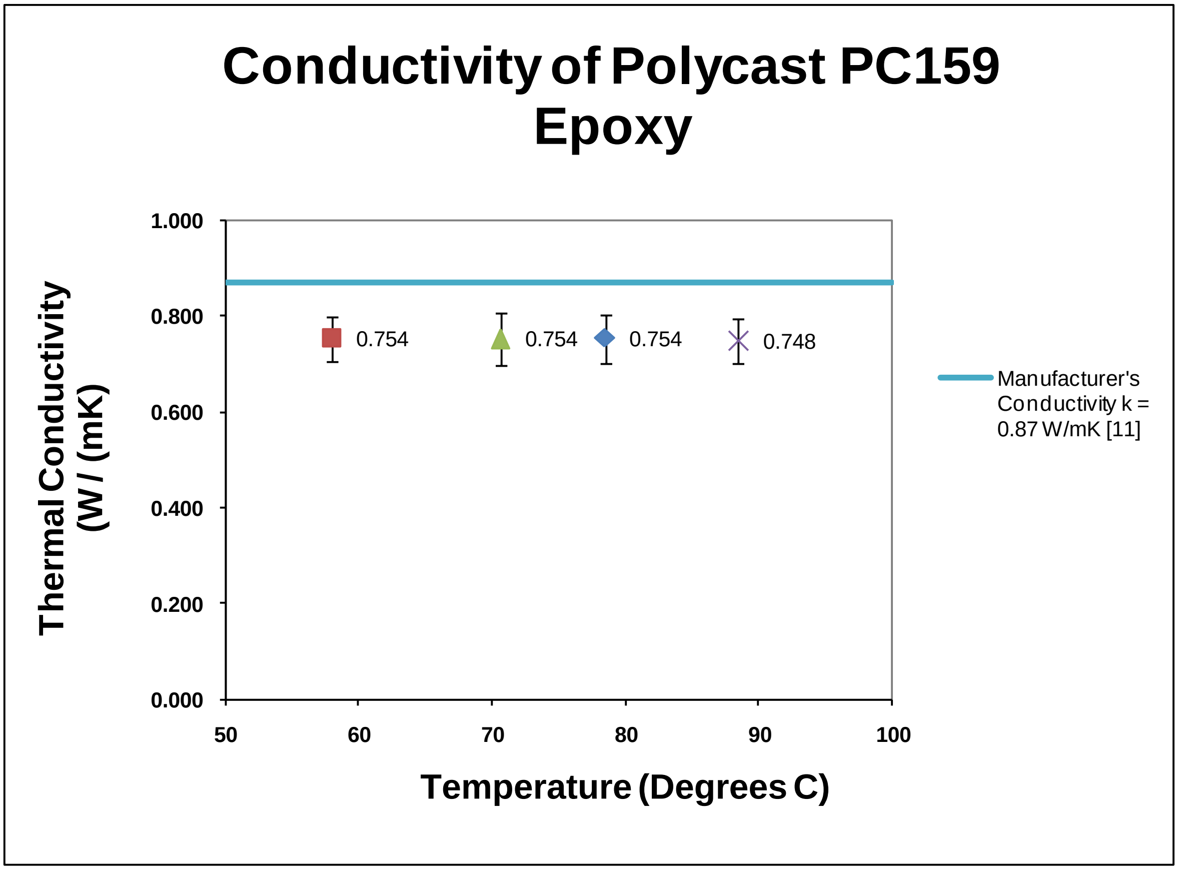


Figure 4.1 The results of the thermal conductivity tests performed on epoxy PC159.

The conductivity average calculated by the test was 0.750 W / (m*K). The measured average value was 14.2% off of the 0.87 W/(m*K) given by the manufacturer[11].

4.2 303 Stainless Steel Results

The device was validated by measuring the conductivity 303 stainless steel. The steel was tested at three temperatures as listed in Table 4.2

Table 4.2 The temperatures of the hot side of the 303 stainless steel that were selected for the thermal conductivity test along with the ASM Handbook's Thermal Conductivity Values for 303 Stainless Steel.

Hot Surface Temperature (°C)	Measured Thermal Conductivity (W/ (m*K)	% Uncertainty
70-200	**13-16.5 [10]**	
120	12.95	15
140	13.50	12.9
170	16.18	16.7

The high temperatures of testing were needed so that the largest temperature change across the material could occur to lower the uncertainty. The results of the tests can be viewed in Figure 4.2

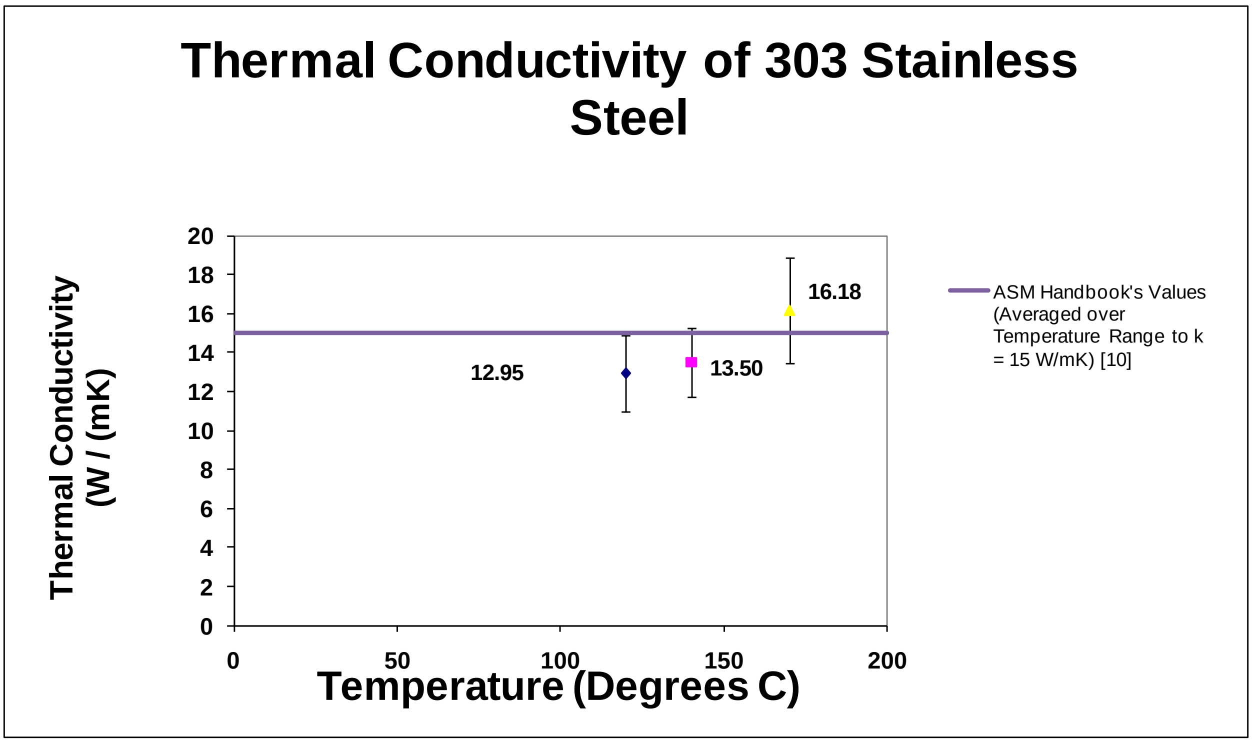


Figure 4.2 The measured thermal conductivities of 303 stainless steel were close to the values in the ASM Handbook.

4.3 Epoxy PC 287 Results

The last specimen to be tested was Polycast PC287 Epoxy. The hot surface temperatures that the specimen was tested at can be viewed in Table 4.3

Table 4.3 The results and testing conditions for Polycast PC287 epoxy along with previously measure values.

Hot Surface Temperature (°C)	Measured Thermal Conductivity (W/ (mK)	% Uncertainty
N/A	4.33 [12]	N/A
N/A	1.08 [14]	6
95	2.13	11.4
105	2.23	15.4

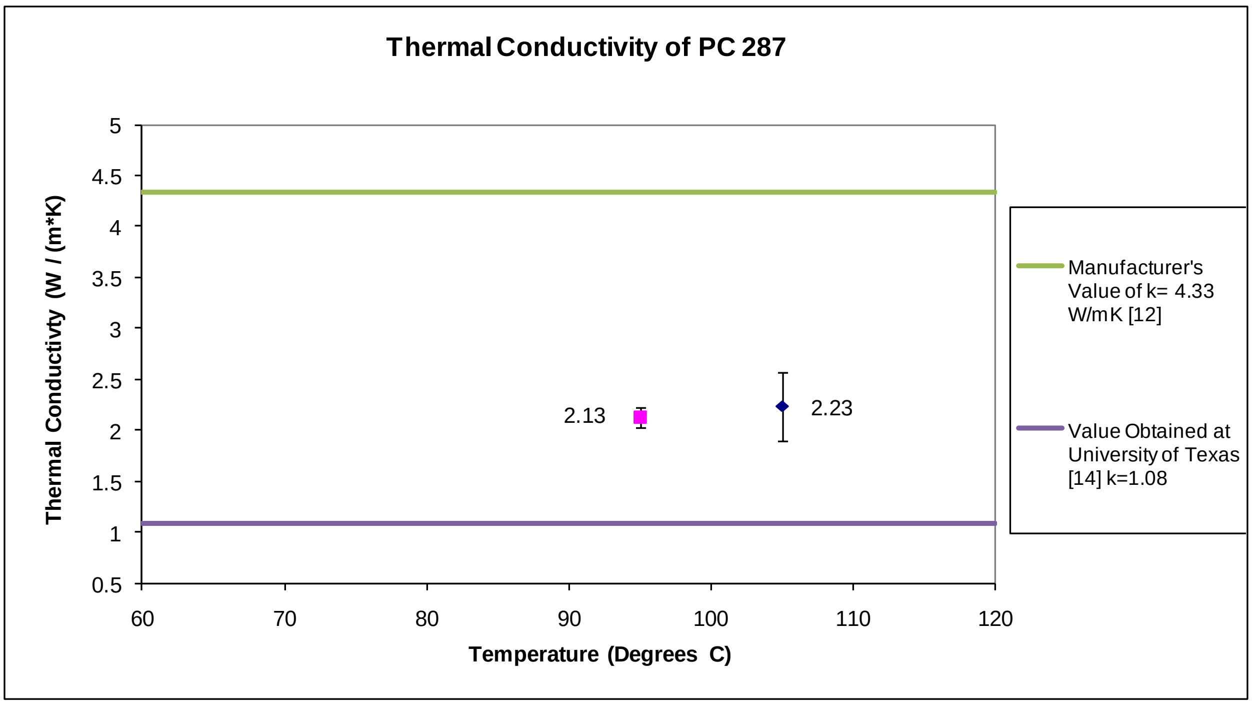


Figure 4.3 Polycast PC 287 Epoxy measured conductivity was different than previous tests.

The manufacturer claimed an estimated thermal conductivity of 4.33 W/ (m*K), which our results differed from by 58%. . However, a graduate student at the University of Texas at Austin also measured PC 287 ([14] Dobrowolski, 2009). Her measured conductivity was 1.04 W/m*K +/-6%, which is much closer to our 92 degree test.

4.4 Conclusions

After completing all of the tests, a few conclusions can be made. First, the measurement method was validated for measuring the thermal conductivity of materials. The correct measurement of the 303 stainless steel's thermal conductivity indicated the testing procedure and measurement method were correct. Second, larger uncertainties did occur during tested than were initially predicted, which was caused by the non-isothermal conditions on the hot and cold measurement surfaces. Also, the conductivity tests were measured over several temperatures for each material while achieving the same measured thermal conductivity, which implies that the testing method produced repeatable results. Furthermore, the testing method was extremely easy to set up, taking less than 2 hours to setup at test. The cost of the testing device was also small, with most of the cost going to the heaters and power supplies. Finally, the method created can be used for future conductivity tests for almost any material and give valid results.

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[1] ASTM Standard C177, 2004, " Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus," ASTM International, West Conshohocken, PA, 2003, DOI: 10.1520/C0033-03, www.astm.org.

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diamond films using a modified thermal comparator method." Transactions of the ASME. Journal of Heat Transfer **122**(Copyright 2001, IEE): 808-816.

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[11] "Adhesives for Electronics | Epoxies for Electronics | Silicones and Urethanes." Conductive Adhesives | Conductive Epoxy | Epoxies for Encapsulation. Web. 15 Jan. 2010. <http://www.epoxies-by-polycast.com/products.aspx?cat=2969&pageId=6&parent=2969>.

[12]"Adhesives for Electronics | Epoxies for Electronics | Silicones and Urethanes." Conductive Adhesives | Conductive Epoxy | Epoxies for Encapsulation. Web. 16 Jan. 2010. <http://www.epoxies-by-polycast.com/products.aspx?cat=2868&pageId=6&parent=2868>.

[13] Incropera, Frank P., and David P. DeWitt. Fundamentals of Heat and Mass Transfer. New York: J. Wiley, 2006. Print.

[14] Dobrowolski, Laurene D. Numerical Simulation of a Film Cooled Turbine Blade Leading Edge Including Heat Transfer Effects. Thesis. The University of Texas at Austin, 2009. Print.

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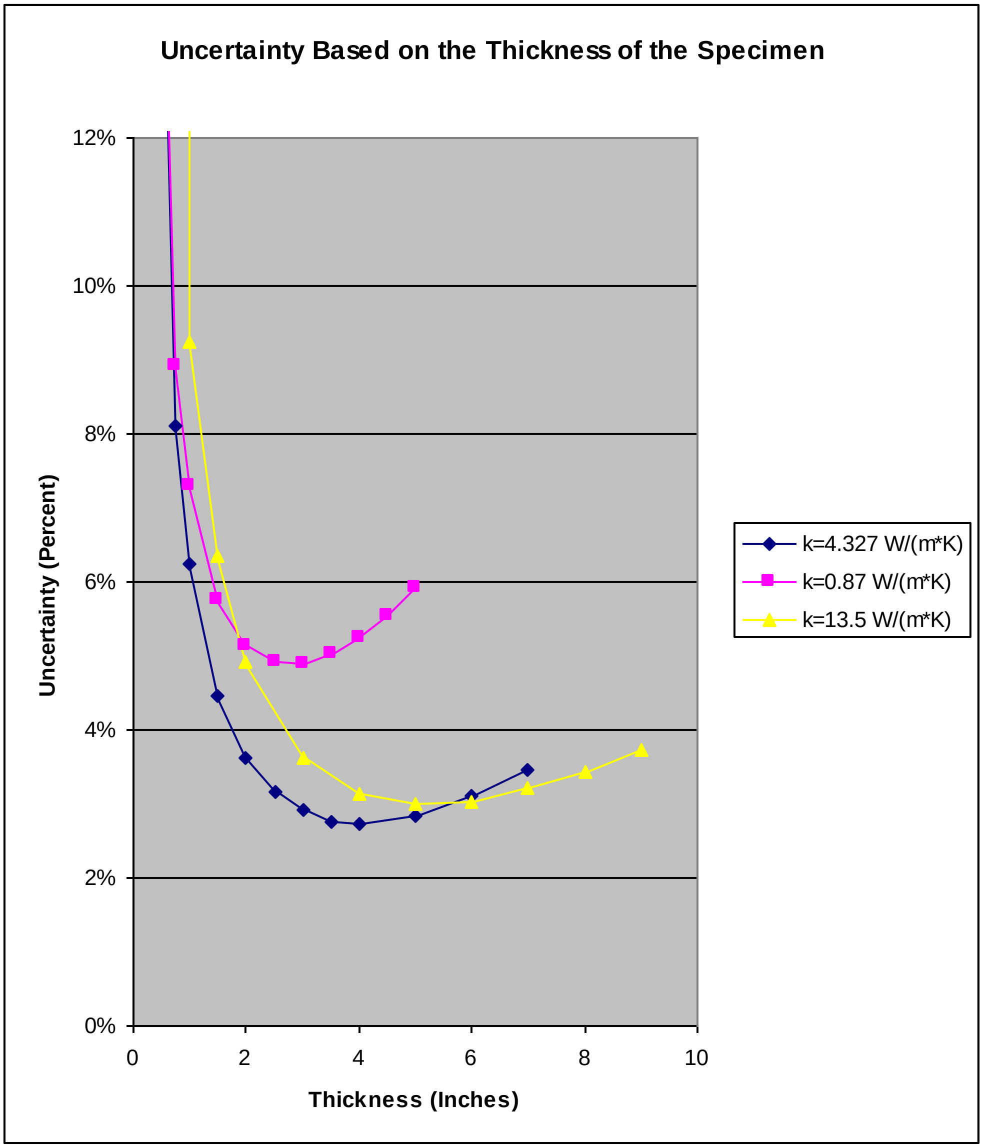
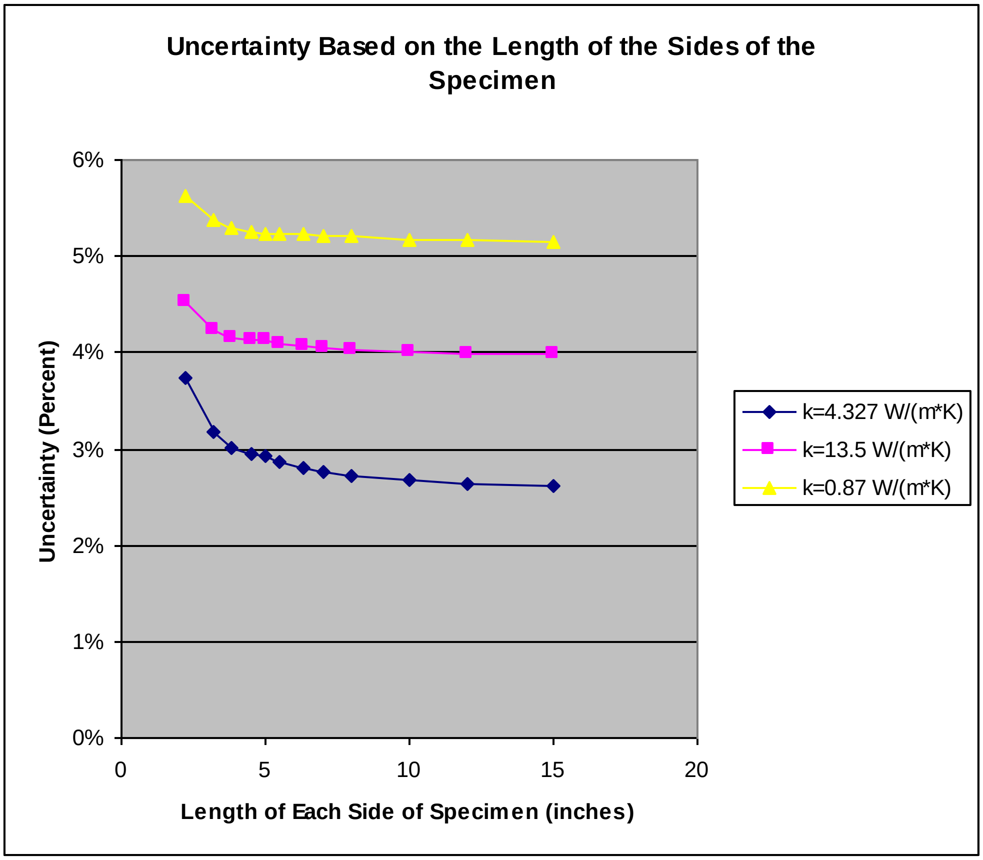
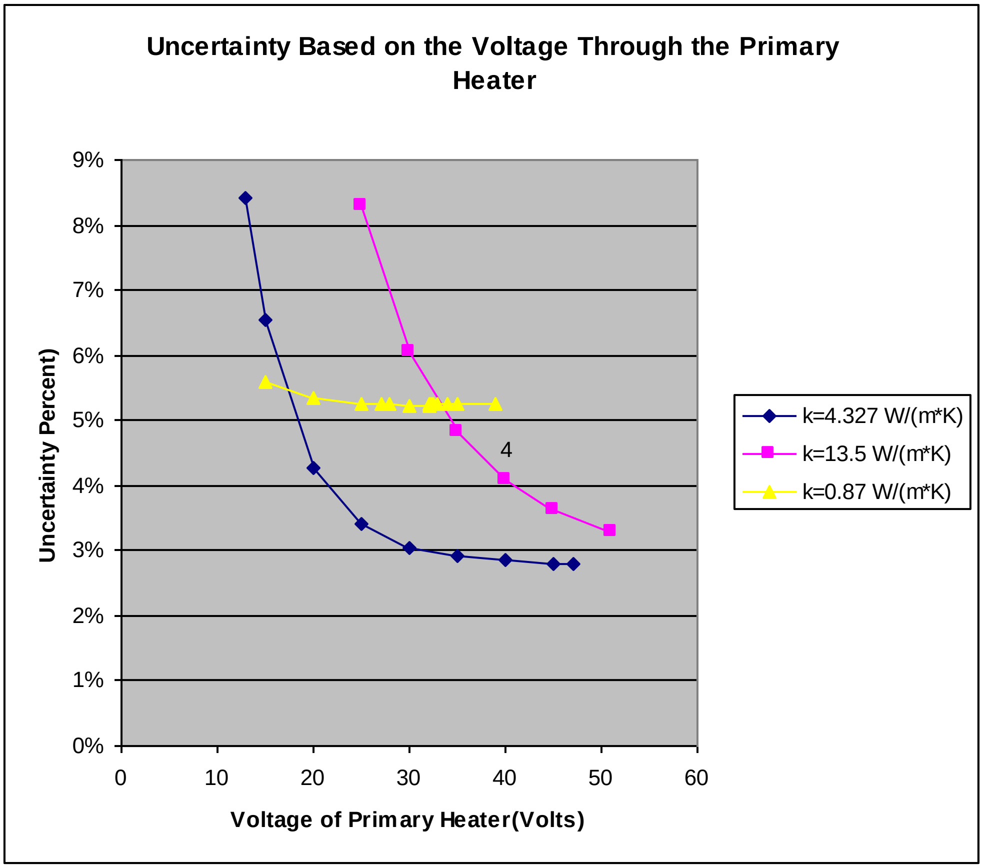
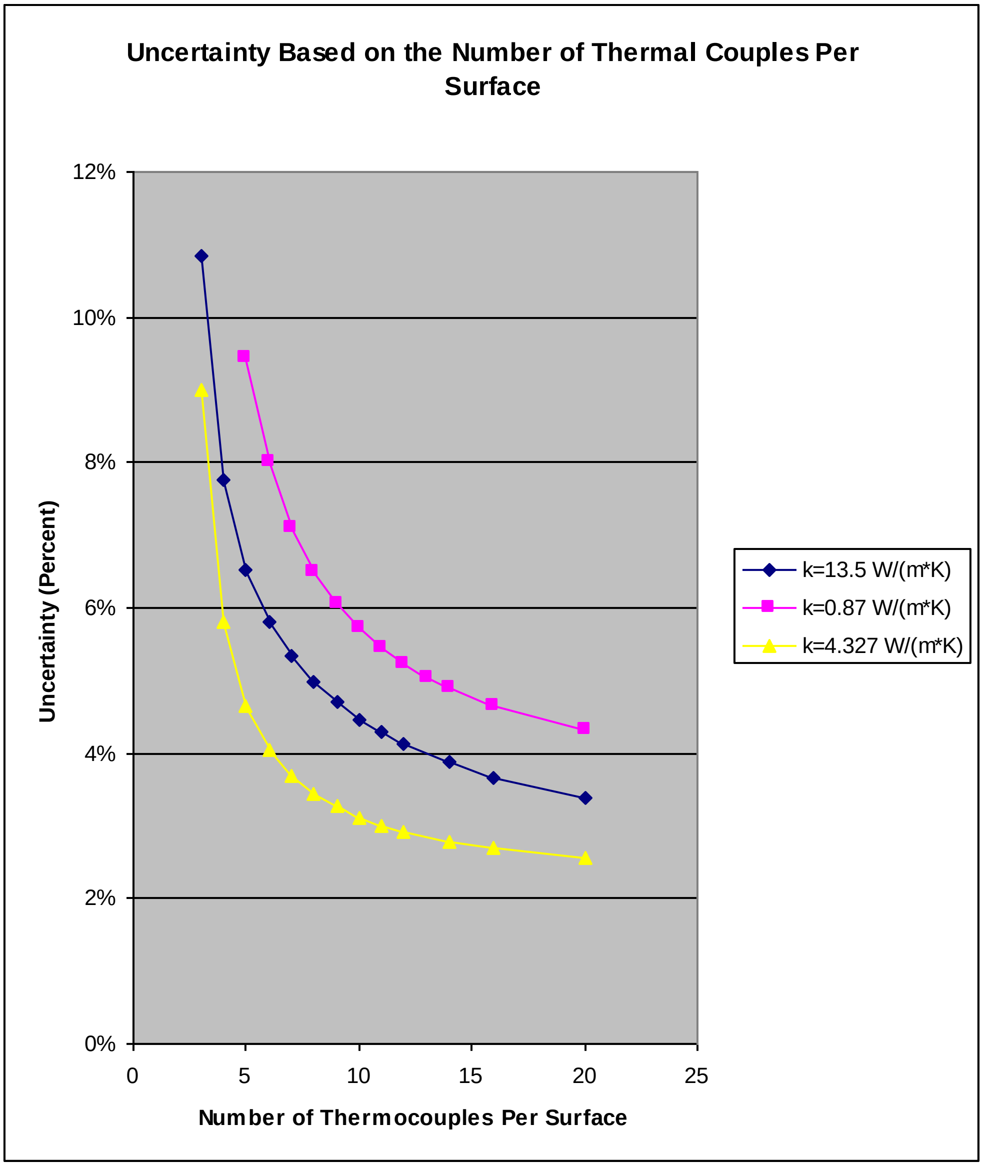
Appendix A: Uncertainty Analysis Graphs




Uncertainty Based on the Length of the Sides of the Specimen
6%
5%
4%
3%
2%
1%
0%
Uncertainty (Percent)
0
5
10
15
20
Length of Each Side of Specimen (inches)
k=4.327 W/(m*K)
k=13.5 W/(m*K)
k=0.87 W/(m*K)


Uncertainty Based on the Voltage Through the Primary Heater
9%
8%
7%
6%
5%
4%
3%
2%
1%
0%
Uncertainty Percent)
0
10
20
30
40
50
60
Voltage of Primary Heater(Volts)
4
k=4.327 W/(m*K)
k=13.5 W/(m*K)
k=0.87 W/(m*K)

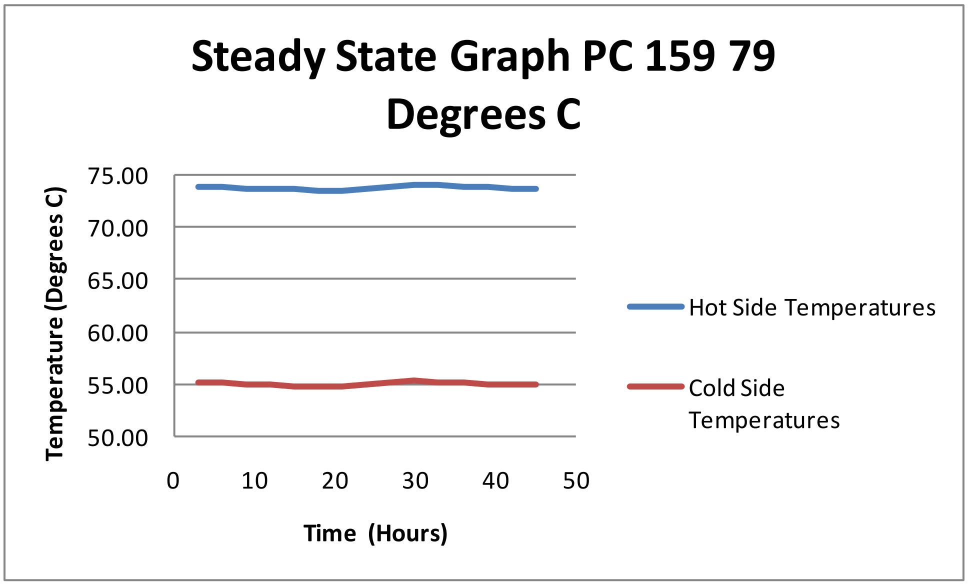


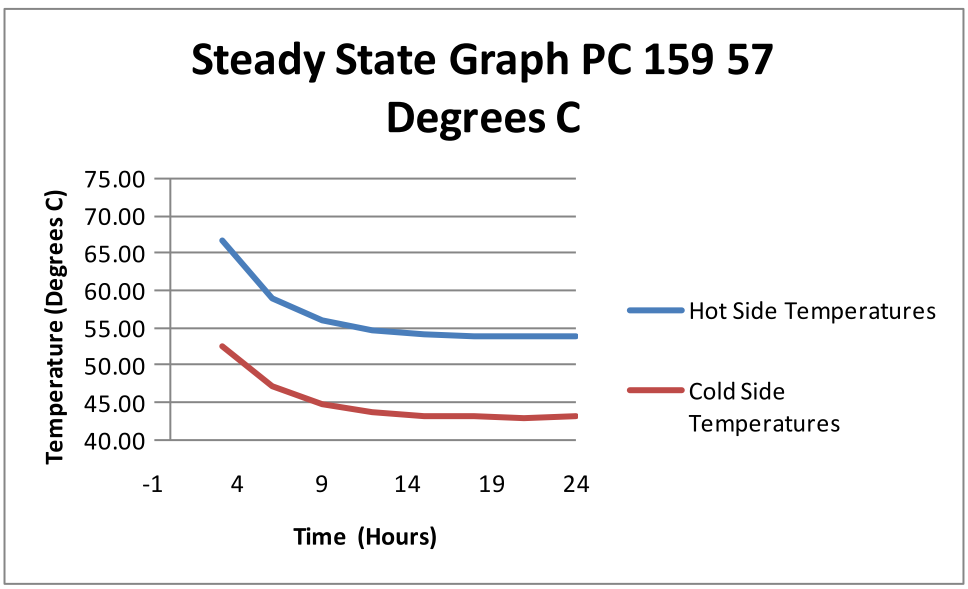
Uncertainty Based on the Number of Thermal Couples Per Surface
12%
10%
8%
6%
4%
2%
0%
Uncertainty (Percent)
0
5
10
15
20
25
Number of Thermocouples Per Surface
k=13.5 W/(m*K)
k=0.87 W/(m*K)
k=4.327 W/(m*K)

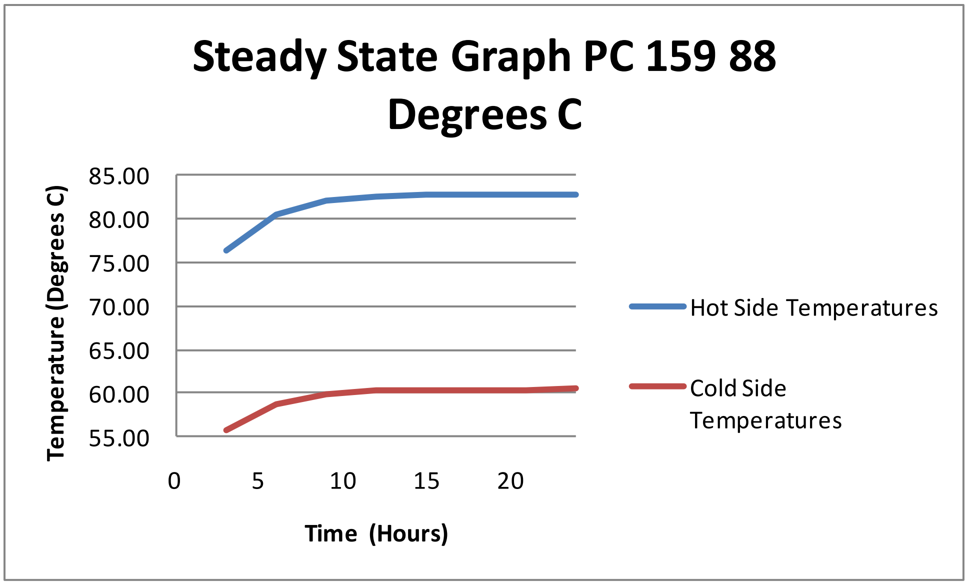
Appendix B: Table of Changes Throughout Project

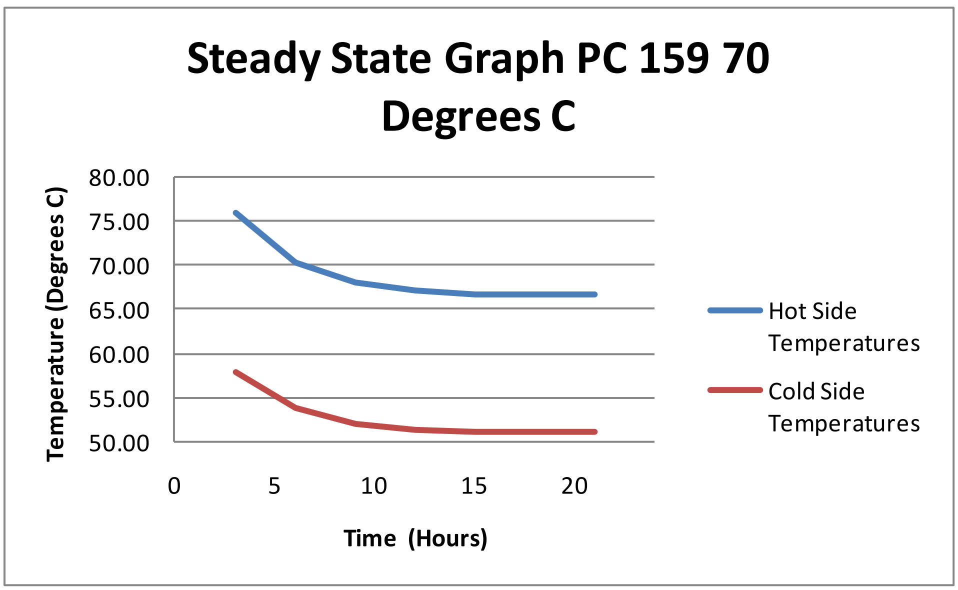
Type Of Material	Temperature of Hot Side of Specimen	LabVIEW Run Numbers	Date Range of Tests	Type of Insulation Around Specimen	Type Of Insulation Betweem Heaters	Thermal filer in grooves for Heater (Hot) Side	Thermal filer in grooves for Cold Side	Groove Width	Number of Thermocou (Hot,Cold,Primary, and (
PC 159 Epoxy	Various	273-327	2/12/2010-2/17/2010	Solid Blue Polystyrene	Yellow Last-A-Foam Insulation	2 sided Kapton Tape with thermal grease in grooves	2 sided Kapton Tape with thermal grease in grooves	0.125 inches	Hot surface-12, Cold Sur Primary and Guard Hea
303 Stainless Steel	120°C	436-441	4/2/2010-4/3/2010	Yellow Last-A-Foam Insulation	Yellow Last-A-Foam Insulation	Thermcouple Beads were cemented then cemented into grooves and then the heater was	Thermocouple Beads were cemented, then were taped into their grooves with 1-sided Kapton	0.050 inches	Hot surface-12, Cold Surf Primary and Guard Hea
303 Stainless Steel	140°C	442-457	4/3/2010-4/5/2010	Yellow Last-A-Foam Insulation	Yellow Last-A-Foam Insulation	Thermcouple Beads were cemented then cemented into grooves and then the heater was	Thermocouple Beads were cemented, then were taped into their grooves with 1-sided Kapton	0.050 inches	Hot surface-12, Cold Surf Primary and Guard Hea
303 Stainless Steel	230°C and above	458-470	4/5/2010-4/6/2010	Ownes-Corning© Fiberglass	0.75 inch thick wood fiber board	Thermcouple Beads were cemented then cemented into grooves and then the heater was	Thermocouple Beads were cemented, then were taped into their grooves with 1-sided Kapton	0.050 inches	Hot surface-12, Cold Surf Primary and Guard Hea
303 Stainless Steel	170°C	471-484	4/6/2010-4/8/2010	Johns Manville© Fiberglass	0.75 inch thick wood fiber board	Thermcouple Beads were cemented then cemented into grooves; after drying thermal	Thermocouple Beads were cemented, then were taped into their grooves with 1-sided Kapton	0.050 inches	Hot surface-12, Cold Surf Primary and Guard Hea
303 Stainless Steel	170°C	485-496	4/8/2010-4/10/2010	Johns Manville© Fiberglass Also inbetween clamp and aluminum plate*	0.75 inch thick wood fiber board	Thermcouple Beads were cemented then cemented into grooves; after drying thermal	Thermocouple Beads were cemented, then were taped into their grooves with 1-sided Kapton	0.125 inches	Hot surface-12, Cold Surf Primary and Guard Hea
PC287 Epoxy	Various	497-517	4/10/2010-4/12/2010	Johns Manville© Fiberglass Also inbetween clamp and aluminum plate*	0.75 inch thick wood fiber board	Grooves were filled with thermal grease, then specimen was placed on top of the heater and	Grooves were filled with thermal grease, then 1 sided Kapton tape covered the surface of the	0.125 inches	Hot surface-12, Cold Surf Primary and Guard Hea

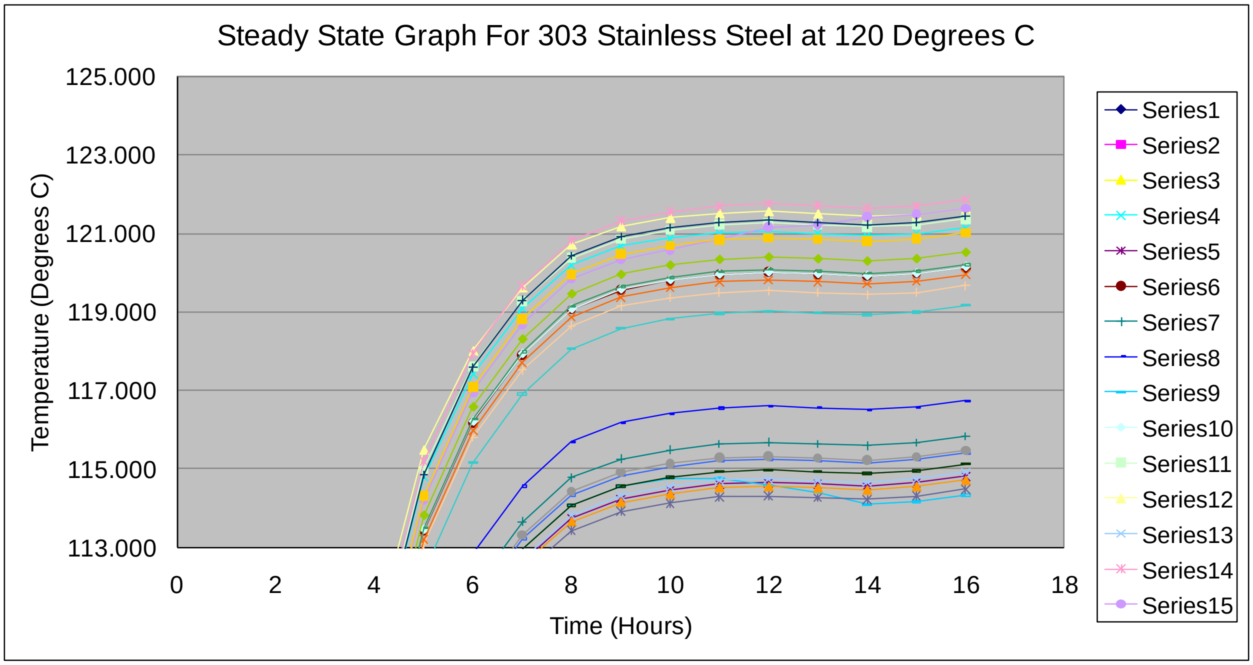
Appendix C Steady State Graphs

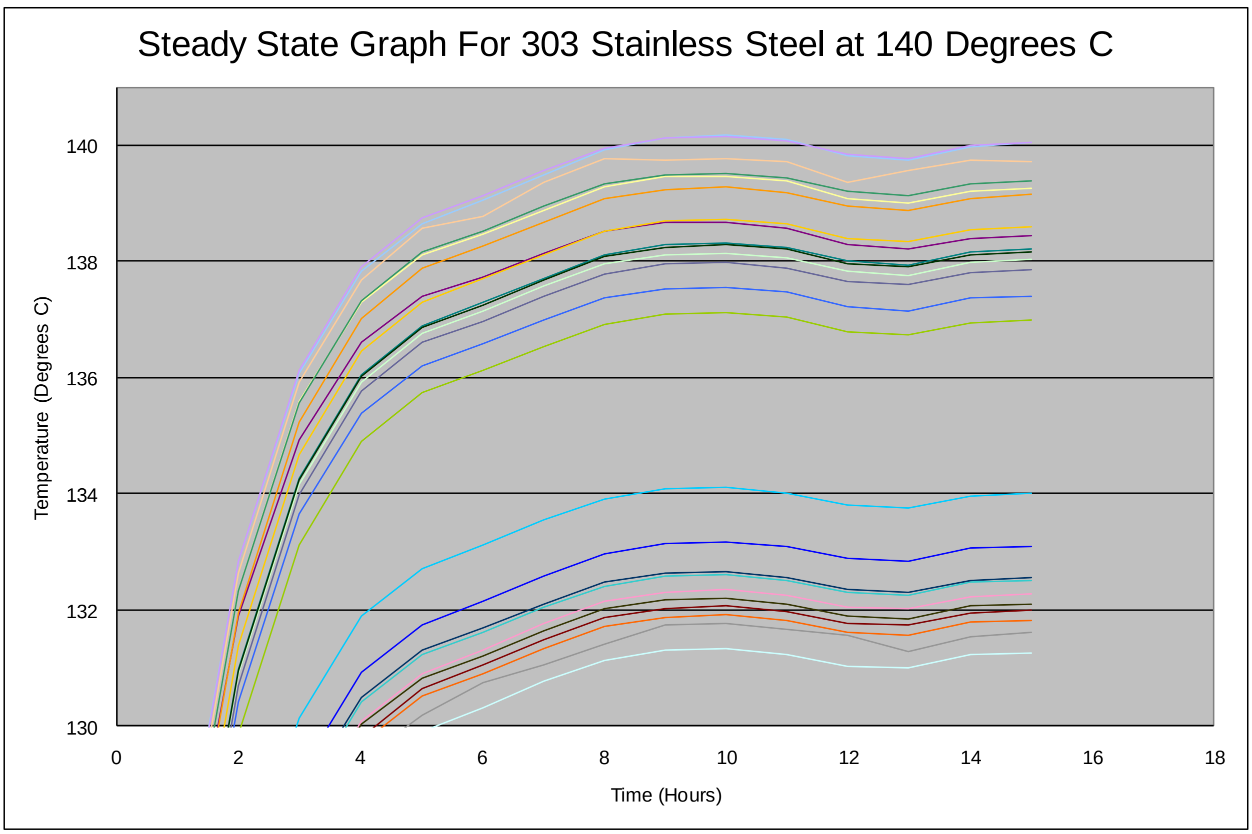


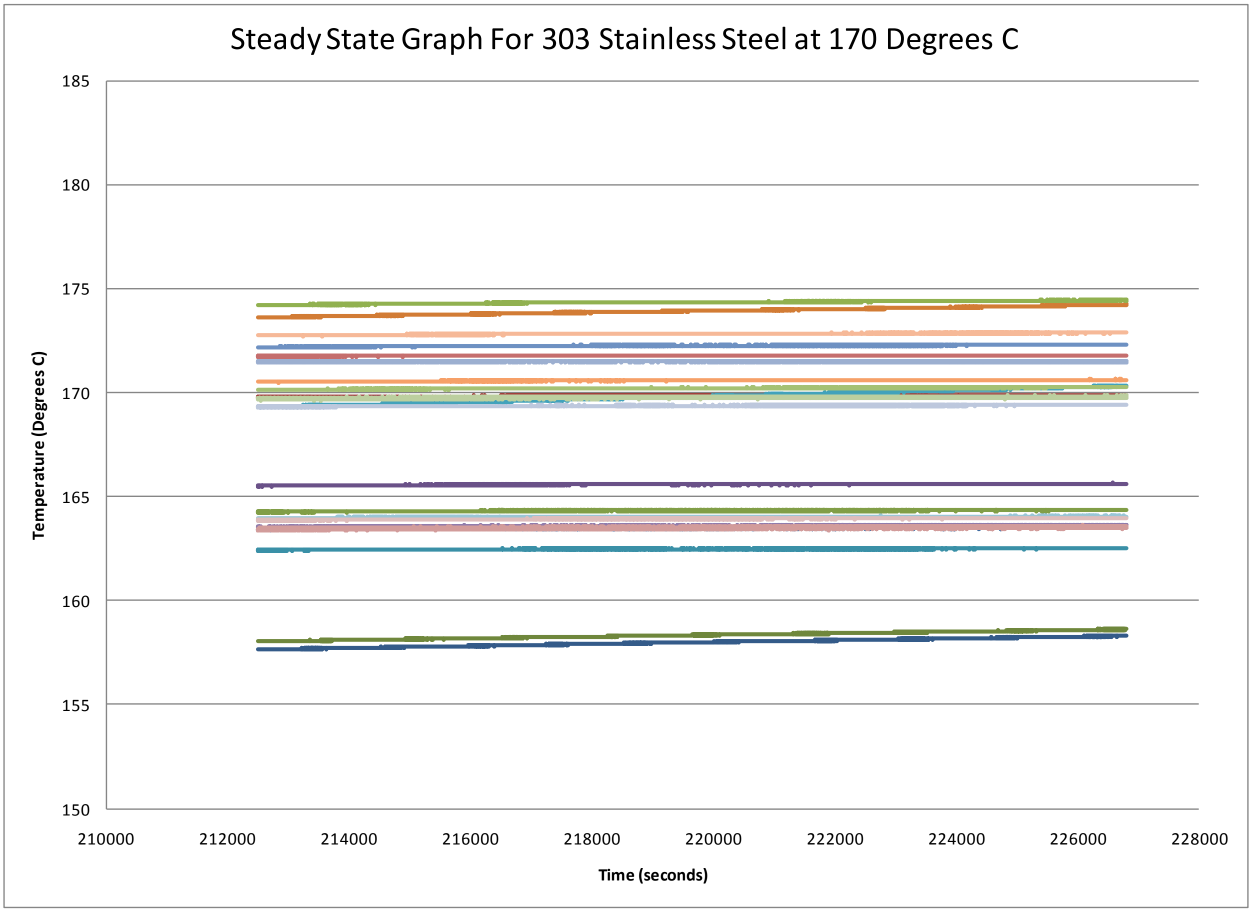


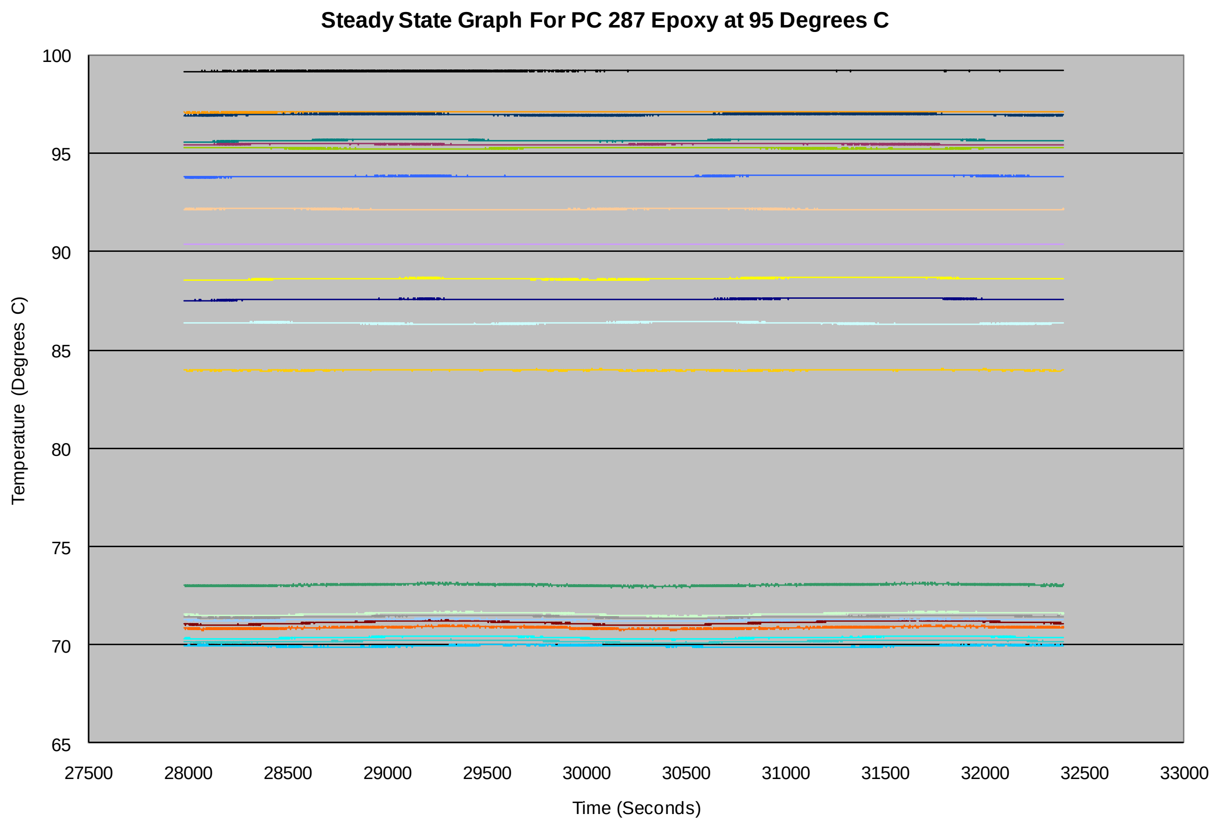

Steady State Graph PC 159 88 Degrees C
85.00
80.00
75.00
70.00
65.00
60.00
55.00
Temperature (Degrees C)
0
5
10
15
20
Time (Hours)
Hot Side Temperatures
Cold Side Temperatures

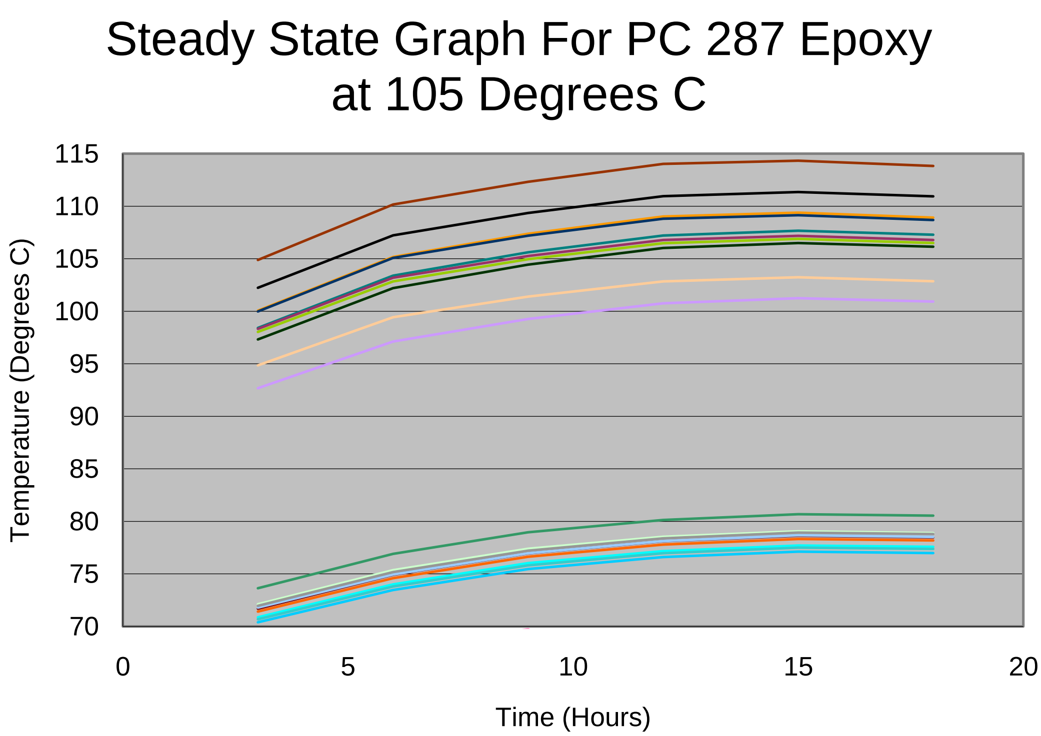

Steady State Graph PC 159 70 Degrees C
80.00
75.00
70.00
65.00
60.00
55.00
50.00
Temperature (Degrees C)
0
5
10
15
20
Time (Hours)
Hot Side Temperatures
Cold Side Temperatures


Steady State Graph For 303 Stainless Steel at 120 Degrees C
125.000
123.000
121.000
119.000
117.000
115.000
113.000
Temperature (Degrees C)
0
2
4
6
8
10
12
14
16
18
Time (Hours)
Series1
Series2
Series3
Series4
Series5
Series6
Series7
Series8
Series9
Series10
Series11
Series12
Series13
Series14
Series15


Steady State Graph For 303 Stainless Steel at 140 Degrees C
140
138
136
134
132
130
Temperature (Degrees C)
0
2
4
6
8
10
12
14
16
18
Time (Hours)


Steady State Graph For 303 Stainless Steel at 170 Degrees C
185
180
175
170
165
160
155
150
Temperature (Degrees C)
210000
212000
214000
216000
218000
220000
222000
224000
226000
228000
Time (seconds)


Steady State Graph For PC 287 Epoxy at 95 Degrees C
Temperature (Degrees C)
100
95
90
85
80
75
70
65
27500
28000
28500
29000
29500
30000
30500
31000
31500
32000
32500
33000
Time (Seconds)


Steady State Graph For PC 287 Epoxy at 105 Degrees C
Temperature (Degrees C)
115
110
105
100
95
90
85
80
75
70
0
5
10
15
20
Time (Hours)

Appendix D Calculations

The calculations were performed by a spreadsheet with data imported to it from the LabVIEW program. This spreadsheet was created by Robert Schroeder [10]. See below for an example of the calculations for thermal conductivity from a 303 Stainless Steel Test.

					Nth						
		thermal conductivity	(W / (m*K))	16.1798	2.7024	16.7%					
	LEVEL		units	nominal	# pts	stud t	stdev	PRECISION	BIAS	OTHER	Nth
	1	Qdot	(W)	28.753							1.1730
	2	V_htr	(volts)	60.4	NA	NA	NA	0.005	0.2812	NA	0.2812
	2	V_resistor	(volts)	0.515	NA	NA	NA	0.0005	0.002545	NA	0.0026
	2	R_prec	(ohms)	1	NA	NA	NA	NA	0.01	NA	0.0100
	2	Qdot_side	(W)	0.861							0.3039
	3	balancing factor	(unitless)	1	NA	NA	NA	NA	NA	0.25	0.25
	3	T_hot	(ºC)	170.8							0.8720
	3	T_cool	(ºC)	163.87							0.7012
	3	T_infi	(ºC)	25.4	NA	NA	NA	NA	1	NA	1.0000
	3	A_side	(in^2)	49.649							0.3329
		A_side	(m^2)	0.032							0.000215
	3	R"_side	(m^2 *K/W)	5.280							1.315
	4	t_side	(in)	8	NA	NA	NA	NA	0.5	NA	0.5000
2.886640162	4	t_side	(m)	0.2032							0.0127
	4	k_side	(W / (m*K))	0.04	NA	NA	NA	NA	0.01	NA	0.0100
	4	h	(W / (m^2*K))	5	NA	NA	NA	NA	3	NA	3.0000
	5	t_meas	(in)	2.49							0.0157
	5	width	(in)	4.9876							0.0159
	5	length	(in)	4.982							0.0165
	2	Qdot_bottom	(W)	1.492							1.0683
	3	k_bottom	(W / (m*K))	0.09	NA	NA	NA	NA	0.01	NA	0.0100
1.618811709	3	A_spec	(m^2)	0.0160							0.000074
1.721906332	3	t_bottom	(in)	0.72	NA	NA	NA	NA	0.125	NA	0.1250
		t_bottom	(m)	0.018							0.003
1.435720066	3	T_htr1	(ºC)	174.180	43200	1.960	0.2099	0.002	0.2121	2.3753	2.3847
	4	T_htr1 non-isc	(ºC)	NA	2	12.706	0.2644	2.375	NA	NA	2.3753
	3	T_guard	(ºC)	155.272	64800	1.960	4.191	0.032	0.1732	12.7453	12.7465
4.413898074	4	T_guard non-i:	(ºC)	NA	3	4.303	5.1307	12.745	NA	NA	12.7453
	1	ΔT	(ºC)	6.93							1.1189
6.92660917608006	2	ΔT disturb bias	(ºC)	NA	NA	NA	NA	NA	negligible	NA	0.0000
	2	T_hot	(ºC)	170.792	216000	1.960	1.1496	0.005	0.0949	0.8668	0.8720
	3	T_hot non-isothe	(ºC)	NA	10	2.262	1.2117	0.867	NA	NA	0.8668
	2	T_cool	(ºC)	163.87	172800	1.960	0.8861	0.004	0.1061	0.6931	0.7012
	3	T_cool non-isotl	(ºC)	NA	8	2.365	0.8291	0.693	NA	NA	0.6931
	1	Δx	(in)	2.4600							0.0264
		Δx	(m)	0.062							0.001
	2	t_meas	(in)	2.4900	20	2.093	0.00	0.001	0.015625	NA	0.0157
	2	1/2 t_groove	(in)	0.0150	NA	NA	NA	NA	0.0150	NA	0.0150
	2	1/2 t_groove	(in)	0.0150	NA	NA	NA	NA	0.0150	NA	0.0150
	1	A_spec	(in^2)	24.8482232							0.1140
		A_spec	(m^2)	0.0160							0.000074
	2	width	(in)	4.988	20	2.093	0.01	0.003	0.015625	NA	0.0159
	2	length	(in)	4.982	20	2.093	0.01	0.005	0.015625	NA	0.0165

$$\dot{Q} = V_{Heater} * \frac{V_{resistor}}{R_{prec}} - \dot{Q}_{loss} = V_{Heater} * \frac{V_{resistor}}{R_{prec}} - \dot{Q}_{side} - \dot{Q}_{botom}$$

$$= 60.4 \text{ Volts} \times \frac{0.505 \text{ Volts}}{1 \text{ Ohm}} - 0.861\text{Watts} - 1.492 \text{ Watts} = 28.753 \text{ Watts}$$

$$k = \frac{\dot{Q}}{A * \frac{dT}{dx}} = \frac{28.753 \text{ Watts}}{0.0160\text{m}^2 \times \frac{6.93℃}{0.062\text{m}}} = 16.1798 \text{ W/mK}$$

The following were the all of the spreadsheets used to calculate all of the thermal conductivity values of Polycast PC 159 Epoxy.

				Nth						
	thermal conductivity	(W / (m*K))	0.7541	0.0466	6.2%					
LEVEL		**units**	**nominal**	**# pts**	**stud t**	**stdev**	**PRECISION**	**BIAS**	**OTHER**	**Nth**
1	Qdot	(W)	6.048							0.2287
2	V_htr	(volts)	26.72	NA	NA	NA	0.005	0.09016	NA	0.0903
2	V_prec	(volts)	0.24	NA	NA	NA	0.0005	0.000814	NA	0.0010
2	R_prec	(ohms)	1	NA	NA	NA	NA	0.01	NA	0.0100
2	Qdot_side	(W)	0.147							0.0625
3	balancing factor	(unitless)	1	NA	NA	NA	NA	NA	0.25	0.25
3	T_hot	(ºC)	78.4							0.8847
3	T_cool	(ºC)	54.92							0.6373
3	T_infi	(ºC)	22.8	NA	NA	NA	NA	1	NA	1.0000
3	A_side	(in^2)	37.647							0.3466
	A_side	(m^2)	0.024							0.000224
3	R"_side	(m^2 *K/W)	7.244							2.484
4	t_side	(in)	8	NA	NA	NA	NA	0.5	NA	0.5000
4	t_side	(m)	0.2032							0.0127
4	k_side	(W / (m*K))	0.0288468	NA	NA	NA	NA	0.01	NA	0.0100
4	h	(W / (m^2*K))	5	NA	NA	NA	NA	3	NA	3.0000
5	t_meas	(in)	1.88370833							0.0168
5	width	(in)	5.005975							0.0162
5	length	(in)	4.986775							0.0157
2	Qdot_bottom	(W)	0.164							0.2079
3	k_bottom	(W / (m*K))	0.03721237	NA	NA	NA	NA	0.01	NA	0.0100
3	A_spec	(m^2)	0.0161							0.000073
3	t_bottom	(in)	0.96	NA	NA	NA	NA	0.125	NA	0.1250
	t_bottom	(m)	0.024							0.003
3	T_htr1	(ºC)	79.2527656	86400	1.960	1.573	0.010	0.1000	2.8901	2.8919
4	T_htr1 non-isc	(ºC)	NA	4	3.182	1.8163	2.890	NA	NA	2.8901
3	T_guard	(ºC)	72.5765624	86400	1.960	4.1886	0.028	0.1000	7.6960	7.6967
4	T_guard non-is	(ºC)	NA	4	3.182	4.8365	7.696	NA	NA	7.6960
1	ΔT	(ºC)	23.46							1.0903
2	ΔT disturb bias	(ºC)	NA	NA	NA	NA	NA	negligible	NA	0.0000
2	T_hot	(ºC)	78.38	259200	1.960	1.3304	0.005	0.0577	0.8828	0.8847
3	T_hot non-isothe	(ºC)	NA	12	2.201	1.3894	0.883	NA	NA	0.8828
2	T_cool	(ºC)	54.92	64800	1.960	0.2064	0.002	0.1155	0.6267	0.6373
3	T_cool non-isoth	(ºC)	NA	3	4.303	0.2523	0.627	NA	NA	0.6267
1	Δx	(in)	1.8550							0.0264
	Δx	(m)	0.047							0.001
2	t_meas	(in)	1.8837	12	2.201	0.01	0.006	0.015625	NA	0.0168
2	1/2 t_groove	(in)	0.0144	NA	NA	NA	NA	0.0144	NA	0.0144
2	1/2 t_groove	(in)	0.0144	NA	NA	NA	NA	0.0144	NA	0.0144
1	A_spec	(in^2)	24.963671							0.1125
	A_spec	(m^2)	0.0161							0.000073
2	width	(in)	5.006	20	2.093	0.01	0.004	0.015625	NA	0.0162
2	length	(in)	4.986775	20	2.093	0.00	0.001	0.015625	NA	0.0157

				Nth						
	thermal conductivity	(W / (m*K))	0.7543	0.0552	7.3%					
LEVEL		**units**	**nominal**	**# pts**	**stud t**	**stdev**	**PRECISION**	**BIAS**	**OTHER**	**Nth**
1	Qdot	(W)	3.492							0.1670
2	V_htr	(volts)	19.79	NA	NA	NA	0.005	0.06937	NA	0.0695
2	V_prec	(volts)	0.18	NA	NA	NA	0.0005	0.000631	NA	0.0008
2	R_prec	(ohms)	1	NA	NA	NA	NA	0.01	NA	0.0100
2	Qdot_side	(W)	0.091							0.0389
3	balancing factor	(unitless)	1	NA	NA	NA	NA	NA	0.25	0.25
3	T_hot	(ºC)	56.6							0.5347
3	T_cool	(ºC)	43.04							0.4864
3	T_infi	(ºC)	22.6	NA	NA	NA	NA	1	NA	1.0000
3	A_side	(in^2)	37.647							0.3466
	A_side	(m^2)	0.024							0.000224
3	R"_side	(m^2 *K/W)	7.244							2.484
4	t_side	(in)	8	NA	NA	NA	NA	0.5	NA	0.5000
4	t_side	(m)	0.2032							0.0127
4	k_side	(W / (m*K))	0.0288468	NA	NA	NA	NA	0.01	NA	0.0100
4	h	(W / (m^2*K))	5	NA	NA	NA	NA	3	NA	3.0000
5	t_meas	(in)	1.88370833							0.0168
5	width	(in)	5.005975							0.0162
5	length	(in)	4.986775							0.0157
2	Qdot_bottom	(W)	-0.081							0.1573
3	k_bottom	(W / (m*K))	0.03721237	NA	NA	NA	NA	0.01	NA	0.0100
3	A_spec	(m^2)	0.0161							0.000073
3	t_bottom	(in)	0.96	NA	NA	NA	NA	0.125	NA	0.1250
	t_bottom	(m)	0.024							0.003
3	T_htr1	(ºC)	57.0677947	86400	1.960	0.9318	0.006	0.1000	1.7098	1.7128
4	T_htr1 non-isc	(ºC)	NA	4	3.182	1.0745	1.710	NA	NA	1.7098
3	T_guard	(ºC)	60.3460411	86400	1.960	3.3126	0.022	0.1000	6.0861	6.0869
4	T_guard non-is	(ºC)	NA	4	3.182	3.8248	6.086	NA	NA	6.0861
1	ΔT	(ºC)	13.54							0.7228
2	ΔT disturb bias	(ºC)	NA	NA	NA	NA	NA	negligible	NA	0.0000
2	T_hot	(ºC)	56.58	259200	1.960	0.8024	0.003	0.0577	0.5316	0.5347
3	T_hot non-isothe	(ºC)	NA	12	2.201	0.8367	0.532	NA	NA	0.5316
2	T_cool	(ºC)	43.04	64800	1.960	0.1593	0.001	0.1155	0.4725	0.4864
3	T_cool non-isoth	(ºC)	NA	3	4.303	0.1902	0.472	NA	NA	0.4725
1	Δx	(in)	1.8550							0.0264
	Δx	(m)	0.047							0.001
2	t_meas	(in)	1.8837	12	2.201	0.01	0.006	0.015625	NA	0.0168
2	1/2 t_groove	(in)	0.0144	NA	NA	NA	NA	0.0144	NA	0.0144
2	1/2 t_groove	(in)	0.0144	NA	NA	NA	NA	0.0144	NA	0.0144
1	A_spec	(in^2)	24.963671							0.1125
	A_spec	(m^2)	0.0161							0.000073
2	width	(in)	5.006	20	2.093	0.01	0.004	0.015625	NA	0.0162
2	length	(in)	4.986775	20	2.093	0.00	0.001	0.015625	NA	0.0157

				Nth						
	thermal conductivity	(W / (m*K))	0.7478	0.0462	6.2%					
LEVEL		**units**	**nominal**	**# pts**	**stud t**	**stdev**	**PRECISION**	**BIAS**	**OTHER**	**Nth**
1	Qdot	(W)	7.160							0.2815
2	V_htr	(volts)	28.91	NA	NA	NA	0.005	0.09673	NA	0.0969
2	V_prec	(volts)	0.26	NA	NA	NA	0.0005	0.000871	NA	0.0010
2	R_prec	(ohms)	1	NA	NA	NA	NA	0.01	NA	0.0100
2	Qdot_side	(W)	0.172							0.0732
3	balancing factor	(unitless)	1	NA	NA	NA	NA	NA	0.25	0.25
3	T_hot	(ºC)	88.4							1.0688
3	T_cool	(ºC)	60.44							0.6802
3	T_infi	(ºC)	23.1	NA	NA	NA	NA	1	NA	1.0000
3	A_side	(in^2)	37.647							0.3466
	A_side	(m^2)	0.024							0.000224
3	R"_side	(m^2 *K/W)	7.244							2.484
4	t_side	(in)	8	NA	NA	NA	NA	0.5	NA	0.5000
4	t_side	(m)	0.2032							0.0127
4	k_side	(W / (m*K))	0.0288468	NA	NA	NA	NA	0.01	NA	0.0100
4	h	(W / (m^2*K))	5	NA	NA	NA	NA	3	NA	3.0000
5	t_meas	(in)	1.88370833							0.0168
5	width	(in)	5.005975							0.0162
5	length	(in)	4.986775							0.0157
2	Qdot_bottom	(W)	0.098							0.2586
3	k_bottom	(W / (m*K))	0.03721237	NA	NA	NA	NA	0.01	NA	0.0100
3	A_spec	(m^2)	0.0161							0.000073
3	t_bottom	(in)	0.96	NA	NA	NA	NA	0.125	NA	0.1250
	t_bottom	(m)	0.024							0.003
3	T_htr1	(ºC)	89.5668371	86400	1.960	1.9237	0.013	0.1000	3.5345	3.5359
4	T_htr1 non-isc	(ºC)	NA	4	3.182	2.2212	3.534	NA	NA	3.5345
3	T_guard	(ºC)	85.5826615	86400	1.960	5.3549	0.036	0.1000	9.8388	9.8394
4	T_guard non-is	(ºC)	NA	4	3.182	6.1832	9.839	NA	NA	9.8388
1	ΔT	(ºC)	28.01							1.2669
2	ΔT disturb bias	(ºC)	NA	NA	NA	NA	NA	negligible	NA	0.0000
2	T_hot	(ºC)	88.45	259200	1.960	1.6082	0.006	0.0577	1.0672	1.0688
3	T_hot non-isothe	(ºC)	NA	12	2.201	1.6797	1.067	NA	NA	1.0672
2	T_cool	(ºC)	60.44	64800	1.960	0.2207	0.002	0.1155	0.6703	0.6802
3	T_cool non-isoth	(ºC)	NA	3	4.303	0.2698	0.670	NA	NA	0.6703
1	Δx	(in)	1.8550							0.0264
	Δx	(m)	0.047							0.001
2	t_meas	(in)	1.8837	12	2.201	0.01	0.006	0.015625	NA	0.0168
2	1/2 t_groove	(in)	0.0144	NA	NA	NA	NA	0.0144	NA	0.0144
2	1/2 t_groove	(in)	0.0144	NA	NA	NA	NA	0.0144	NA	0.0144
1	A_spec	(in^2)	24.963671							0.1125
	A_spec	(m^2)	0.0161							0.000073
2	width	(in)	5.006	20	2.093	0.01	0.004	0.015625	NA	0.0162
2	length	(in)	4.986775	20	2.093	0.00	0.001	0.015625	NA	0.0157

				Nth						
	thermal conductivity	(W / (m*K))	0.7564	0.0503	6.6%					
LEVEL		**units**	**nominal**	**# pts**	**stud t**	**stdev**	**PRECISION**	**BIAS**	**OTHER**	**Nth**
1	Qdot	(W)	5.038							0.2156
2	V_htr	(volts)	24.05	NA	NA	NA	0.005	0.08215	NA	0.0823
2	V_prec	(volts)	0.21	NA	NA	NA	0.0005	0.000742	NA	0.0009
2	R_prec	(ohms)	1	NA	NA	NA	NA	0.01	NA	0.0100
2	Qdot_side	(W)	0.125							0.0534
3	balancing factor	(unitless)	1	NA	NA	NA	NA	NA	0.25	0.25
3	T_hot	(ºC)	70.6							0.7553
3	T_cool	(ºC)	51.16							0.5713
3	T_infi	(ºC)	23.5	NA	NA	NA	NA	1	NA	1.0000
3	A_side	(in^2)	37.647							0.3466
	A_side	(m^2)	0.024							0.000224
3	R"_side	(m^2 *K/W)	7.244							2.484
4	t_side	(in)	8	NA	NA	NA	NA	0.5	NA	0.5000
4	t_side	(m)	0.2032							0.0127
4	k_side	(W / (m*K))	0.0288468	NA	NA	NA	NA	0.01	NA	0.0100
4	h	(W / (m^2*K))	5	NA	NA	NA	NA	3	NA	3.0000
5	t_meas	(in)	1.88370833							0.0168
5	width	(in)	5.005975							0.0162
5	length	(in)	4.986775							0.0157
2	Qdot_bottom	(W)	-0.017							0.2005
3	k_bottom	(W / (m*K))	0.03721237	NA	NA	NA	NA	0.01	NA	0.0100
3	A_spec	(m^2)	0.0161							0.000073
3	t_bottom	(in)	0.96	NA	NA	NA	NA	0.125	NA	0.1250
	t_bottom	(m)	0.024							0.003
3	T_htr1	(ºC)	71.4012482	86400	1.960	1.3433	0.009	0.1000	2.4669	2.4689
4	T_htr1 non-isc	(ºC)	NA	4	3.182	1.5503	2.467	NA	NA	2.4669
3	T_guard	(ºC)	72.0945438	86400	1.960	4.2298	0.028	0.1000	7.7715	7.7722
4	T_guard non-is	(ºC)	NA	4	3.182	4.884	7.771	NA	NA	7.7715
1	ΔT	(ºC)	19.49							0.9470
2	ΔT disturb bias	(ºC)	NA	NA	NA	NA	NA	negligible	NA	0.0000
2	T_hot	(ºC)	70.65	259200	1.960	1.1356	0.004	0.0577	0.7530	0.7553
3	T_hot non-isothe	(ºC)	NA	12	2.201	1.1852	0.753	NA	NA	0.7530
2	T_cool	(ºC)	51.16	64800	1.960	0.191	0.001	0.1155	0.5595	0.5713
3	T_cool non-isoth	(ºC)	NA	3	4.303	0.2252	0.559	NA	NA	0.5595
1	Δx	(in)	1.8550							0.0264
	Δx	(m)	0.047							0.001
2	t_meas	(in)	1.8837	12	2.201	0.01	0.006	0.015625	NA	0.0168
2	1/2 t_groove	(in)	0.0144	NA	NA	NA	NA	0.0144	NA	0.0144
2	1/2 t_groove	(in)	0.0144	NA	NA	NA	NA	0.0144	NA	0.0144
1	A_spec	(in^2)	24.963671							0.1125
	A_spec	(m^2)	0.0161							0.000073
2	width	(in)	5.006	20	2.093	0.01	0.004	0.015625	NA	0.0162
2	length	(in)	4.986775	20	2.093	0.00	0.001	0.015625	NA	0.0157

The following are the spreadsheets used to calculated the thermal conductivity of 303 stainless steel.

				Nth						
	thermal conductivity	(W / (m*K))	12.9509	1.9461	15.0%					
LEVEL		**units**	**nominal**	**# pts**	**stud t**	**stdev**	**PRECISION**	**BIAS**	**OTHER**	**Nth**
1	Qdot	(W)	17.758							0.5196
2	V_htr	(volts)	47.0	NA	NA	NA	0.005	0.241	NA	0.2411
2	V_prec	(volts)	0.399	NA	NA	NA	0.0005	0.002197	NA	0.0023
2	R_prec	(ohms)	1	NA	NA	NA	NA	0.01	NA	0.0100
2	Qdot_side	(W)	0.533							0.1950
3	balancing factor	(unitless)	1	NA	NA	NA	NA	NA	0.25	0.25
3	T_hot	(ºC)	120.5							0.5873
3	T_cool	(ºC)	115.18							0.5213
3	T_infi	(ºC)	23.7	NA	NA	NA	NA	1	NA	1.0000
3	A_side	(in^2)	49.649							0.3329
	A_side	(m^2)	0.032							0.000215
3	R''_side	(m^2 *K/W)	5.661							1.511
4	t_side	(in)	8	NA	NA	NA	NA	0.5	NA	0.5000
4	t_side	(m)	0.2032							0.0127
4	k_side	(W / (m*K))	0.03721237	NA	NA	NA	NA	0.01	NA	0.0100
4	h	(W / (m^2*K))	5	NA	NA	NA	NA	3	NA	3.0000
5	t_meas	(in)	2.49							0.0157
5	width	(in)	4.9876							0.0159
5	length	(in)	4.982							0.0165
2	Qdot_bottom	(W)	0.463							0.4200
3	k_bottom	(W / (m*K))	0.03721237	NA	NA	NA	NA	0.01	NA	0.0100
3	A_spec	(m^2)	0.0160							0.000074
3	t_bottom	(in)	0.96	NA	NA	NA	NA	0.125	NA	0.1250
	t_bottom	(m)	0.024							0.003
3	T_htr1	(ºC)	121.383	64800	1.960	0.2071	0.002	0.1732	0.6119	0.6360
4	T_htr1 non-isc	(ºC)	NA	3	4.303	0.2463	0.612	NA	NA	0.6119
3	T_guard	(ºC)	102.474	64800	1.960	5.3241	0.041	0.1732	16.1964	16.1974
4	T_guard non-is	(ºC)	NA	3	4.303	6.5199	16.196	NA	NA	16.1964
1	ΔT	(ºC)	5.34							0.7852
2	ΔT disturb bias	(ºC)	NA	NA	NA	NA	NA	negligible	NA	0.0000
2	T_hot	(ºC)	120.524	237600	1.960	0.825	0.003	0.0905	0.5803	0.5873
3	T_hot non-isothe	(ºC)	NA	11	2.228	0.8637	0.580	NA	NA	0.5803
2	T_cool	(ºC)	115.18	216000	1.960	0.6826	0.003	0.0949	0.5125	0.5213
3	T_cool non-isoth	(ºC)	NA	10	2.262	0.7165	0.513	NA	NA	0.5125
1	Δx	(in)	2.4600							0.0264
	Δx	(m)	0.062							0.001
2	t_meas	(in)	2.4900	20	2.093	0.00	0.001	0.015625	NA	0.0157
2	1/2 t_groove	(in)	0.0150	NA	NA	NA	NA	0.0150	NA	0.0150
2	1/2 t_groove	(in)	0.0150	NA	NA	NA	NA	0.0150	NA	0.0150
1	A_spec	(in^2)	24.8482232							0.1140
	A_spec	(m^2)	0.0160							0.000074
2	width	(in)	4.988	20	2.093	0.01	0.003	0.015625	NA	0.0159
2	length	(in)	4.982	20	2.093	0.01	0.005	0.015625	NA	0.0165

				Nth						
	thermal conductivity	(W / (m*K))	13.5109	1.7570	13.0%					
LEVEL		**units**	**nominal**	**# pts**	**stud t**	**stdev**	**PRECISION**	**BIAS**	**OTHER**	**Nth**
1	Qdot	(W)	21.449							0.5549
2	V_htr	(volts)	51.6	NA	NA	NA	0.005	0.2548	NA	0.2548
2	V_prec	(volts)	0.437	NA	NA	NA	0.0005	0.002311	NA	0.0024
2	R_prec	(ohms)	1	NA	NA	NA	NA	0.01	NA	0.0100
2	Qdot_side	(W)	0.625							0.2286
3	balancing factor	(unitless)	1	NA	NA	NA	NA	NA	0.25	0.25
3	T_hot	(ºC)	138.5							0.5873
3	T_cool	(ºC)	132.32							0.5213
3	T_infi	(ºC)	25	NA	NA	NA	NA	1	NA	1.0000
3	A_side	(in^2)	49.649							0.3329
	A_side	(m^2)	0.032							0.000215
3	R"_side	(m^2 *K/W)	5.661							1.511
4	t_side	(in)	8	NA	NA	NA	NA	0.5	NA	0.5000
4	t_side	(m)	0.2032							0.0127
4	k_side	(W / (m*K))	0.03721237	NA	NA	NA	NA	0.01	NA	0.0100
4	h	(W / (m^2*K))	5	NA	NA	NA	NA	3	NA	3.0000
5	t_meas	(in)	2.49							0.0157
5	width	(in)	4.9876							0.0159
5	length	(in)	4.982							0.0165
2	Qdot_bottom	(W)	0.476							0.4213
3	k_bottom	(W / (m*K))	0.03721237	NA	NA	NA	NA	0.01	NA	0.0100
3	A_spec	(m^2)	0.0160							0.000074
3	t_bottom	(in)	0.96	NA	NA	NA	NA	0.125	NA	0.1250
	t_bottom	(m)	0.024							0.003
3	T_htr1	(ºC)	139.251	64800	1.960	0.8067	0.006	0.1732	0.6119	0.6360
4	T_htr1 non-isc	(ºC)	NA	3	4.303	0.2463	0.612	NA	NA	0.6119
3	T_guard	(ºC)	119.806	64800	1.960	7.3041	0.056	0.1732	16.1964	16.1974
4	T_guard non-is	(ºC)	NA	3	4.303	6.5199	16.196	NA	NA	16.1964
1	ΔT	(ºC)	6.19							0.7852
2	ΔT disturb bias	(ºC)	NA	NA	NA	NA	NA	negligible	NA	0.0000
2	T_hot	(ºC)	138.507	237600	1.960	0.9708	0.004	0.0905	0.5803	0.5873
3	T_hot non-isothe	(ºC)	NA	11	2.228	0.8637	0.580	NA	NA	0.5803
2	T_cool	(ºC)	132.32	216000	1.960	0.7865	0.003	0.0949	0.5125	0.5213
3	T_cool non-isoth	(ºC)	NA	10	2.262	0.7165	0.513	NA	NA	0.5125
1	Δx	(in)	2.4600							0.0264
	Δx	(m)	0.062							0.001
2	t_meas	(in)	2.4900	20	2.093	0.00	0.001	0.015625	NA	0.0157
2	1/2 t_groove	(in)	0.0150	NA	NA	NA	NA	0.0150	NA	0.0150
2	1/2 t_groove	(in)	0.0150	NA	NA	NA	NA	0.0150	NA	0.0150
1	A_spec	(in^2)	24.8482232							0.1140
	A_spec	(m^2)	0.0160							0.000074
2	width	(in)	4.988	20	2.093	0.01	0.003	0.015625	NA	0.0159
2	length	(in)	4.982	20	2.093	0.01	0.005	0.015625	NA	0.0165

				Nth						
	thermal conductivity	(W / (m*K))	16.1798	2.7024	16.7%					
LEVEL		**units**	**nominal**	**# pts**	**stud t**	**stdev**	**PRECISION**	**BIAS**	**OTHER**	**Nth**
1	Qdot	(W)	28.753							1.1730
2	V_htr	(volts)	60.4	NA	NA	NA	0.005	0.2812	NA	0.2812
2	V_prec	(volts)	0.515	NA	NA	NA	0.0005	0.002545	NA	0.0026
2	R_prec	(ohms)	1	NA	NA	NA	NA	0.01	NA	0.0100
2	Qdot_side	(W)	0.861							0.3039
3	balancing factor	(unitless)	1	NA	NA	NA	NA	NA	0.25	0.25
3	T_hot	(ºC)	170.8							0.8720
3	T_cool	(ºC)	163.87							0.7012
3	T_infi	(ºC)	25.4	NA	NA	NA	NA	1	NA	1.0000
3	A_side	(in^2)	49.649							0.3329
	A_side	(m^2)	0.032							0.000215
3	R"_side	(m^2 *K/W)	5.280							1.315
4	t_side	(in)	8	NA	NA	NA	NA	0.5	NA	0.5000
4	t_side	(m)	0.2032							0.0127
4	k_side	(W / (m*K))	0.04	NA	NA	NA	NA	0.01	NA	0.0100
4	h	(W / (m^2*K))	5	NA	NA	NA	NA	3	NA	3.0000
5	t_meas	(in)	2.49							0.0157
5	width	(in)	4.9876							0.0159
5	length	(in)	4.982							0.0165
2	Qdot_bottom	(W)	1.492							1.0683
3	k_bottom	(W / (m*K))	0.09	NA	NA	NA	NA	0.01	NA	0.0100
3	A_spec	(m^2)	0.0160							0.000074
3	t_bottom	(in)	0.72	NA	NA	NA	NA	0.125	NA	0.1250
	t_bottom	(m)	0.018							0.003
3	T_htr1	(ºC)	174.180	43200	1.960	0.2099	0.002	0.2121	2.3753	2.3847
4	T_htr1 non-isc	(ºC)	NA	2	12.706	0.2644	2.375	NA	NA	2.3753
3	T_guard	(ºC)	155.272	64800	1.960	4.191	0.032	0.1732	12.7453	12.7465
4	T_guard non-i	(ºC)	NA	3	4.303	5.1307	12.745	NA	NA	12.7453
1	ΔT	(ºC)	6.93							1.1189
2	ΔT disturb bias	(ºC)	NA	NA	NA	NA	NA	negligible	NA	0.0000
2	T_hot	(ºC)	170.792	216000	1.960	1.1496	0.005	0.0949	0.8668	0.8720
3	T_hot non-isothe	(ºC)	NA	10	2.262	1.2117	0.867	NA	NA	0.8668
2	T_cool	(ºC)	163.87	172800	1.960	0.8861	0.004	0.1061	0.6931	0.7012
3	T_cool non-isoth	(ºC)	NA	8	2.365	0.8291	0.693	NA	NA	0.6931
1	Δx	(in)	2.4600							0.0264
	Δx	(m)	0.062							0.001
2	t_meas	(in)	2.4900	20	2.093	0.00	0.001	0.015625	NA	0.0157
2	1/2 t_groove	(in)	0.0150	NA	NA	NA	NA	0.0150	NA	0.0150
2	1/2 t_groove	(in)	0.0150	NA	NA	NA	NA	0.0150	NA	0.0150
1	A_spec	(in^2)	24.8482232							0.1140
	A_spec	(m^2)	0.0160							0.000074
2	width	(in)	4.988	20	2.093	0.01	0.003	0.015625	NA	0.0159
2	length	(in)	4.982	20	2.093	0.01	0.005	0.015625	NA	0.0165

The following are the spreadsheets used to calculate the thermal conductivity of Polycast PC 287 Epoxy.

				Nth						
	thermal conductivity	(W / (m*K))	2.1306	0.2425	11.4%					
LEVEL		**units**	**nominal**	**# pts**	**stud t**	**stdev**	**PRECISION**	**BIAS**	**OTHER**	**Nth**
1	Qdot	(W)	10.765							0.7295
2	V_htr	(volts)	37.1	NA	NA	NA	0.005	0.2113	NA	0.2114
2	V_prec	(volts)	0.320	NA	NA	NA	0.0005	0.00106	NA	0.0012
2	R_prec	(ohms)	1	NA	NA	NA	NA	0.01	NA	0.0100
2	Qdot_side	(W)	0.432							0.1529
3	balancing factor	(unitless)	1	NA	NA	NA	NA	NA	0.25	0.25
3	T_hot	(ºC)	94.6							2.0404
3	T_cool	(ºC)	71.04							0.6359
3	T_infi	(ºC)	23.6	NA	NA	NA	NA	1	NA	1.0000
3	A_side	(in^2)	59.704							0.5501
	A_side	(m^2)	0.039							0.000355
3	R"_side	(m^2 *K/W)	5.280							1.315
4	t_side	(in)	8	NA	NA	NA	NA	0.5	NA	0.5000
4	t_side	(m)	0.2032							0.0127
4	k_side	(W / (m*K))	0.04	NA	NA	NA	NA	0.01	NA	0.0100
4	h	(W / (m^2*K))	5	NA	NA	NA	NA	3	NA	3.0000
5	t_meas	(in)	2.98885							0.0262
5	width	(in)	4.9911							0.0212
5	length	(in)	4.9967							0.0188
2	Qdot_bottom	(W)	0.675							0.6988
3	k_bottom	(W / (m*K))	0.09	NA	NA	NA	NA	0.01	NA	0.0100
3	A_spec	(m^2)	0.0161							0.000091
3	t_bottom	(in)	0.72	NA	NA	NA	NA	0.125	NA	0.1250
	t_bottom	(m)	0.018							0.003
3	T_htr1	(ºC)	98.543	64800	1.960	2.1446	0.017	0.1732	5.3275	5.3303
4	T_htr1 non-isc	(ºC)	NA	3	4.303	2.1446	5.327	NA	NA	5.3275
3	T_guard	(ºC)	90.014	64800	1.960	2.7405	0.021	0.1732	6.8077	6.8099
4	T_guard non-is	(ºC)	NA	3	4.303	2.7405	6.808	NA	NA	6.8077
1	ΔT	(ºC)	23.60							2.1372
2	ΔT disturb bias	(ºC)	NA	NA	NA	NA	NA	negligible	NA	0.0000
2	T_hot	(ºC)	94.637695	172800	1.960	2.4373	0.011	0.1061	2.0376	2.0404
3	T_hot non-isothe	(ºC)	NA	8	2.365	2.4373	2.038	NA	NA	2.0376
2	T_cool	(ºC)	71.04	216000	1.960	0.879	0.004	0.0949	0.6288	0.6359
3	T_cool non-isotl	(ºC)	NA	10	2.262	0.879	0.629	NA	NA	0.6288
1	Δx	(in)	2.9589							0.0337
	Δx	(m)	0.075							0.001
2	t_meas	(in)	2.9889	20	2.093	0.04	0.021	0.015625	NA	0.0262
2	1/2 t_groove	(in)	0.0150	NA	NA	NA	NA	0.0150	NA	0.0150
2	1/2 t_groove	(in)	0.0150	NA	NA	NA	NA	0.0150	NA	0.0150
1	A_spec	(in^2)	24.9390294							0.1416
	A_spec	(m^2)	0.0161							0.000091
2	width	(in)	4.991	20	2.093	0.03	0.014	0.015625	NA	0.0212
2	length	(in)	4.9967	20	2.093	0.02	0.011	0.015625	NA	0.0188

				Nth						
	thermal conductivity	(W / (m*K))	2.2324	0.3453	15.5%					
LEVEL		**units**	**nominal**	**# pts**	**stud t**	**stdev**	**PRECISION**	**BIAS**	**OTHER**	**Nth**
1	Qdot	(W)	12.579							0.8320
2	V_htr	(volts)	40.1	NA	NA	NA	0.005	0.2203	NA	0.2204
2	V_prec	(volts)	0.345	NA	NA	NA	0.0005	0.002035	NA	0.0021
2	R_prec	(ohms)	1	NA	NA	NA	NA	0.01	NA	0.0100
2	Qdot_side	(W)	0.498							0.1763
3	balancing factor	(unitless)	1	NA	NA	NA	NA	NA	0.25	0.25
3	T_hot	(ºC)	104.7							3.5944
3	T_cool	(ºC)	78.37							0.7158
3	T_infi	(ºC)	23.3	NA	NA	NA	NA	1	NA	1.0000
3	A_side	(in^2)	59.704							0.5501
	A_side	(m^2)	0.039							0.000355
3	R"_side	(m^2 *K/W)	5.280							1.315
4	t_side	(in)	8	NA	NA	NA	NA	0.5	NA	0.5000
4	t_side	(m)	0.2032							0.0127
4	k_side	(W / (m*K))	0.04	NA	NA	NA	NA	0.01	NA	0.0100
4	h	(W / (m^2*K))	5	NA	NA	NA	NA	3	NA	3.0000
5	t_meas	(in)	2.98885							0.0262
5	width	(in)	4.9911							0.0212
5	length	(in)	4.9967							0.0188
2	Qdot_bottom	(W)	0.758							0.7932
3	k_bottom	(W / (m*K))	0.09	NA	NA	NA	NA	0.01	NA	0.0100
3	A_spec	(m^2)	0.0161							0.000091
3	t_bottom	(in)	0.72	NA	NA	NA	NA	0.125	NA	0.1250
	t_bottom	(m)	0.018							0.003
3	T_htr1	(ºC)	110.479	64800	1.960	2.3764	0.018	0.1732	5.9033	5.9059
4	T_htr1 non-isc	(ºC)	NA	3	4.303	2.3764	5.903	NA	NA	5.9033
3	T_guard	(ºC)	100.912	64800	1.960	3.1584	0.024	0.1732	7.8459	7.8478
4	T_guard non-is	(ºC)	NA	3	4.303	3.1584	7.846	NA	NA	7.8459
1	ΔT	(ºC)	26.32							3.6650
2	ΔT disturb bias	(ºC)	NA	NA	NA	NA	NA	negligible	NA	0.0000
2	T_hot	(ºC)	104.689178	172800	1.960	4.2975	0.020	0.1061	3.5928	3.5944
3	T_hot non-isothe	(ºC)	NA	8	2.365	4.2975	3.593	NA	NA	3.5928
2	T_cool	(ºC)	78.37	216000	1.960	0.9917	0.004	0.0949	0.7094	0.7158
3	T_cool non-isoth	(ºC)	NA	10	2.262	0.9917	0.709	NA	NA	0.7094
1	Δx	(in)	2.9589							0.0337
	Δx	(m)	0.075							0.001
2	t_meas	(in)	2.9889	20	2.093	0.04	0.021	0.015625	NA	0.0262
2	1/2 t_groove	(in)	0.0150	NA	NA	NA	NA	0.0150	NA	0.0150
2	1/2 t_groove	(in)	0.0150	NA	NA	NA	NA	0.0150	NA	0.0150
1	A_spec	(in^2)	24.9390294							0.1416
	A_spec	(m^2)	0.0161							0.000091
2	width	(in)	4.991	20	2.093	0.03	0.014	0.015625	NA	0.0212
2	length	(in)	4.9967	20	2.093	0.02	0.011	0.015625	NA	0.0188

Vita

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Education

B.S., Mechanical Engineering May 2010, Pennsylvania State University

Honors and Awards

Schreyer Honors Scholar

Association Memberships

American Society of Mechanical Engineers

Professional Experience

ConocoPhillips Refining ME Intern 06/2009-08/2009

Linden, New Jersey

- Analyzed stresses and forces on a new pump and piping system using Caesar II computer software to ensure the system was within the ASME Codes and API Standards
- Performed a re-rate for a pressure vessel at a new temperature using the CodeCalc computer program to conform to the ASME Pressure Vessel and Boiler Codes
- Designed new gaskets for two heat exchangers to stop leaks

General Electric Sensing/ME Intern 05/2007 - 08/2008
St. Marys, Pennsylvania

- Designed two machines on SolidWorks to validate, laser engrave and crimp a gasket on car temperature sensors
- Learned and worked with machine designers to engineer the machines and then helped construct the machines
- Designed and helped build other testing fixtures