THERMOCOUPLE CALIBRATION DEVICE

by

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Executive Summary

Uncalibrated thermocouples cannot be used to generate data with any meaningful confidence interval. Relying on uncalibrated instruments can result in potential failure or undesirable results. Large quantities of thermocouples are expensive to calibrate, at an average market price of approximately $100 per thermocouple.

This project has resulted in the development of an accurate way of calibrating thermocouples to a known accuracy. Using this device, up to 16 thermocouples may be calibrated at once. The total system cost stands at approximately $3000. After using the system twice, calibrating 32 thermocouples, the cost of calibrating each thermocouple is less than the cost of having the thermocouples commercially calibrated. The device has no wear components and is projected to last many calibration cycles, resulting in a very low cost to calibrate each thermocouple. The overall uncertainty of a thermocouple calibrated using this device is under ±1°C, better than many calibrated off the shelf thermocouples.

This device currently consists of calibration from ambient to 300°C; however it is easily expanded to extend the temperature range to -40°C. The system is also expandable in order to calibrate up to 32 thermocouples simultaneously with another thermocouple input card for the DAQ chassis. This expansion would make the calibration device even more efficient and cost effective. Current and future testing aimed at increasing the overall accuracy of the system could potentially bring the overall uncertainty of a calibrated thermocouple to less than ±0.5°C.

INTRODUCTION

Sponsor Background and Needs

The goal of this project is to develop a thermocouple calibration unit with a high degree of confidence and accuracy. This thermocouple calibration device will be designed and developed at Cal Poly San Luis Obispo and delivered to Tesla Motors Inc.

To best utilize thermocouples, they must be calibrated to a known accuracy. Non-commercially produced thermocouples have unknown accuracies. The final deliverable will be a semi-automated device that produces a calibration curve for each thermocouple with a known confidence and accuracy.

Formal Problem Definition

- A finished thermocouple calibration unit that is capable of calibrating thermocouples produced by Tesla Motors Inc.

- Delivered to Tesla Motors' Palo Alto offices by June, 2012.

- The calibration unit will meet all performance goals set forth by Tesla Motors. Specific requirements have been provided and are outlined in Table 1. This unit will be supplied tested and validated.

As specified in the requirements provided by Tesla Motors, National Instruments LabVIEW will be the software used for data acquisition. Final output of reduced data will be in Microsoft Excel.

The finished unit will be of robust design with minimal required maintenance. Comprehensive design documentation will be made available along with a complete schematic of the design. A user- friendly manual will be included with the unit.

Table 1. Thermocouple calibration device formal engineering requirements, as provided by Tesla Motors (Olsen, 2011)

Specification	Parameter	Requirement	Risk	Compliance
1	Thermocouple Compatibility	Type T and Type K with standard connectors	L	S
2	Temperature Range	-40°C to 300°C	H	A,T
3	Device Temperature Accuracy	±0.05°C	H	A,T
4	Calibrated Thermocouple Temperature Accuracy	±0.5°C	H	A,T
5	Time to Calibrate	Less than 4 hours	M	A,T
6	Number of Thermocouples Calibrated	25 at a time	M	I

7	Number of Steady State Temperatures for Data Collection	Between 5 and 10	M	A,T
8	User Interface	No user intervention required during process	H	A,T
9	Output Format	Excel file	M	A,T
10	Calibration Software	LabVIEW	M	A,T
11	Deliverables	CAD files of any and all manufactured parts	L	A

Table 2. Risk Key

Key	Risk
L	Low
M	Medium
H	High

The fourth column of Table 1 indicates expected risk levels of individual requirements. The difficulty or importance of meeting a requirement is considered when assigning risk values (Table 2). The assigned risk values are relative. High risk requirements (H) are considered to be critical to functionality, the most difficult requirements to meet, or both. Medium risk requirements (M) are considered to be important for the function of the device, relatively difficult to achieve, or both. Low risk requirements (L) are the most straightforward requirements and do not necessarily have an impact on the overall function of the device. The risks assigned to requirements in Table 2 are an initial, speculative risk level. As the project progresses, a revised risk schedule may be provided.

Table 3. Compliance Key

Key	Compliance
A	Analysis
T	Test
S	Similarity to existing designs
I	Inspection

The compliance column of Table 2 indicates the method that will be used to ascertain whether or not a parameter meets its specific requirement. The types of compliance checks are listed in Table 4. Analysis refers to mathematical models, either on paper or computer models where appropriate. Test compliance will be verified after construction; physical testing will be used to verify compliance. Similitude will be used to verify compliance on appropriate parameters. The only parameter with a requirement that can simply be verified via inspection is the number of thermocouples capable of being calibrated at once, as seen in Table 2.

BACKGROUND

Existing Methods

Calibration is the process of applying a known input value to a measurement system for the purpose of recording the system output. The known value is commonly referred to as the standard; this can either be a static value or dynamic value depending on the desired system behavior (Beasley, 2000).

The National Institute of Standards and Technology (NIST) offer a thermocouple calibration service from -110°C to 315°C. They charge $557 per calibration point with a minimum of two calibration points and an accuracy of ±0.4°C. This is a comparison type calibration with direct traceability to national standards (National Institute of Standards and Technology).

Commercial services can be found that will calibrate individual thermocouples at up to five temperature points at a cost of approximately $100 per temperature point. These services utilize controlled temperature mediums through the use of cooling or heating baths and tube type furnaces. Alternatively, this equipment can be purchased and the calibration can be performed in house. Commercially available fluid baths are capable of operating at temperatures from -30°C to 200°C. Tube furnaces are commonly used to calibrate thermocouples at temperatures above 200°C. The temperature control equipment can be expensive; most fluid baths cost upward of $1000, and furnaces cost upward of $2000. If a small number of thermocouples need to be calibrated the commercial services are a cost-effective solution.

Calibration Methods

There are generally two types of calibration for thermocouples; primary and secondary:

- Primary calibration refers to the use of temperature stable fixed point cells of various materials as defined by ITS-90, such as the triple point of water, the triple point of argon, and the freezing point of tin. These fixed point cells are the standard for the calibration and are inherently static values. Instruments that are primary calibrated are usually used in labs and other areas where absolute accuracy is critical. ITS-90 defines the temperatures of individual fixed point cells down to ±0.00005°C in some cases; this makes accuracies of similar magnitudes possible (Preston-Thomas, 1990).
- Secondary calibration methods use a primary sensor as a reference. This is often called comparison calibration. Accuracy is lost, but dynamic calibration can be performed.

Thermocouples are usually calibrated at several different temperatures because the relationship between temperature and EMF is not linear. Data is recorded at steady state conditions so there must be a stable temperature differential in the thermocouple wire in order to obtain good results.

Specific Technical Data

Thermocouple Background

The two thermocouple types that need calibration are T and K type. Per American Society for Testing and Materials (ASTM) standard E230 the published minimum and maximum temperatures for Type T thermocouples are -270°C and 400°C, respectively. Type K thermocouples have a published range of -270°C to 1372°C. ASTM E230 also provides electromotive force (EMF) tables for various thermocouple types. Thermocouples are commonly used as temperature sensors due to the Seebeck effect. This effect describes an EMF generated as a function of a temperature gradient in the thermocouple wires. Using the ASTM tables, the voltage generated in a thermocouple wire can be measured and the temperature corresponding to this voltage found in the tables. These tables have a resolution of 1°C; the published resolution indicates an accuracy of ±0.5°C. Many assumptions are made when using the ASTM tables; it is incorrect to assume that they are accurate to ±0.5°C. In the same standard, ASTM indicates a tolerance of ±1.0°C or 0.75% as 'standard' and ±0.5°C or 0.4% as 'special' for Type T thermocouples. The tolerances on Type K thermocouples are less precise, ±2.2°C or 0.75% as 'standard' and ±1.1°C or 0.4% as 'special'. The ASTM also states that "…EMF-versus-temperature relationship may change with time…"(ASTM, 2011). Based on the published ASTM thermocouple standard, uncalibrated thermocouples should not be assumed to be accurate to more than ±0.5°C with any confidence.

Thermocouples are well understood and have been thoroughly analyzed. The ASTM provides not only a table of temperature and corresponding EMF for specific thermocouples, but also polynomial equations relating temperature and EMF. There are different equations for different temperature ranges to maximize accuracy, and the coefficients in the equations are provided to at least ten significant figures (ASTM, 2011).

Since these equations are available and are given to the number of significant figures they are, it can be assumed that most thermocouples of a given composition exhibit similar behavior. Given multiple thermocouples produced from the same stock of wire of the same gauge from the same manufacturer, all of the thermocouples will likely exhibit similar behaviors.

In calibrating instruments, the major sources of inaccuracies are bias error (or zero drift) and sensitivity error (or drift), hysteresis, and repeatability (Beasley, 2000), (Thorncroft, 2007). Hysteresis and repeatability are not errors that calibration is able to mitigate, so they must just be acknowledged and accounted for. Bias error and sensitivity error are usually related to the construction of the instrument, and in this case similar thermocouples will likely exhibit similar errors.

Thermocouples constructed using standard practices and standard thermocouple wire are frequently utilized. Without calibration, it can be assumed that the bias error of a Type T thermocouple is ±1.0°C or 0.75% and ±2.2°C or 0.75%, whichever is greater for Type K. In addition to this bias error for the thermocouple, there are other sources of error in a thermocouple circuit. The voltage of the thermocouple must be read via some type of electronic device. These devices, when added to the thermocouple circuit, affect the reading of the voltage of the thermocouple. The mechanism by which a thermocouple works, the Seebeck effect, requires that the voltage be measured with no current flow through the circuit (Beasley, 2000). In order to minimize current flow, devices used to read the thermocouple voltage must have very high input impedances. In long thermocouples, the internal resistance of the thermocouple wire can cause residual current.

Cold junction compensation introduces another source of error. Thermocouple voltages are calculated assuming that one junction of the device is at the desired measured temperature, and the other junction is at zero degrees Celsius. In order to simplify reading, most thermocouple voltage measuring devices include a built in temperature sensor (usually a thermistor) that measures the ambient temperature and then ‘corrects’ the thermocouple output voltage to the voltage the thermocouple would generate if one junction were at zero degrees Celsius. Both of these error sources are recognized by manufacturers of data acquisition devices (DAQ) commonly used for thermocouple reading. National Instruments’ NI 9214 High-Accuracy Thermocouple Module has the errors shown in Table 4. (National Instruments, 2011)

Table 4. National Instruments NI 9214 Thermocouple DAQ Accuracy (National Instruments, 2011)

Gain Error	0.03% typical at 25°C
Offset Error	2 μV typical at 25°C
Cold Junction Compensation Error	0.25 °C typical at 23°C

A design-stage uncertainty analysis of this DAQ results in an error of ±0.27°C for both Type T and Type K thermocouples between -40°C and 300°C. The magnitude of total error is similar in magnitude to the contribution from the cold junction compensation error. This indicates that the cold junction compensation error is the variable that must be minimized to improve system accuracy. Improving the cold junction error by an order of magnitude (to 0.025°C typical) results in an error reduced to ±0.1°C at 300°C and ±0.06°C at -40°C.

National Instruments provides a table of total measurement errors for different thermocouple types and different measuring temperatures. For a Type K thermocouple at 300°C, they indicate an accuracy of ±0.42°C. For Type T at 300°C, the accuracy is ±0.33°C (National Instruments, 2011). These accuracies include all measurement errors of the unit, including RMS noise, so they are slightly higher than the uncertainty analysis above which only takes gain, offset and cold junction errors into consideration. The magnitude of the error is similar, and it is still important to realize the contribution cold junction compensation has on the total uncertainty.

Applicable Standards

The ASTM is the organization that is primarily responsible for thermocouple standards and calibration methods in the US. There are over 25 ASTM standards dealing with thermocouples and temperature measurement. The standards applicable to this project can be found in Table 5. Other organizations also publish thermocouple standards for specific industries and groups. These include ISO, ANSI, IEC, SAE, MIL spec and others. These standards are usually very specific and are not considered appropriate in the scope of this project.

Table 5. Applicable ASTM Standards

Standard	Description
ASTM E230	Standard Specification and Temperature-Electromotive Force (EMF) Tables for Standardized Thermocouples
ASTM E2730	Standard Practice for Calibration and Use of Thermocouple Reference Junction Probes in Evaluation of Electronic Reference Junction Compensation Circuits
ASTM E1129	Standard Specification for Thermocouple Connectors
ASTM E220	Standard Test Method for Calibration of Thermocouples By Comparison Techniques

In addition to thermocouple standards, basic safety guidelines must be followed. The calibration unit is hazardous due to the temperature extremes. An exterior cover for the unit will be fabricated in order to prevent inadvertent contact with the copper blocks. A lock may be implemented in order to prevent the unit from being opened while it is at temperature extremes.

DESIGN DEVELOPMENT

Conceptual Designs

Single Fluid Isothermal Block

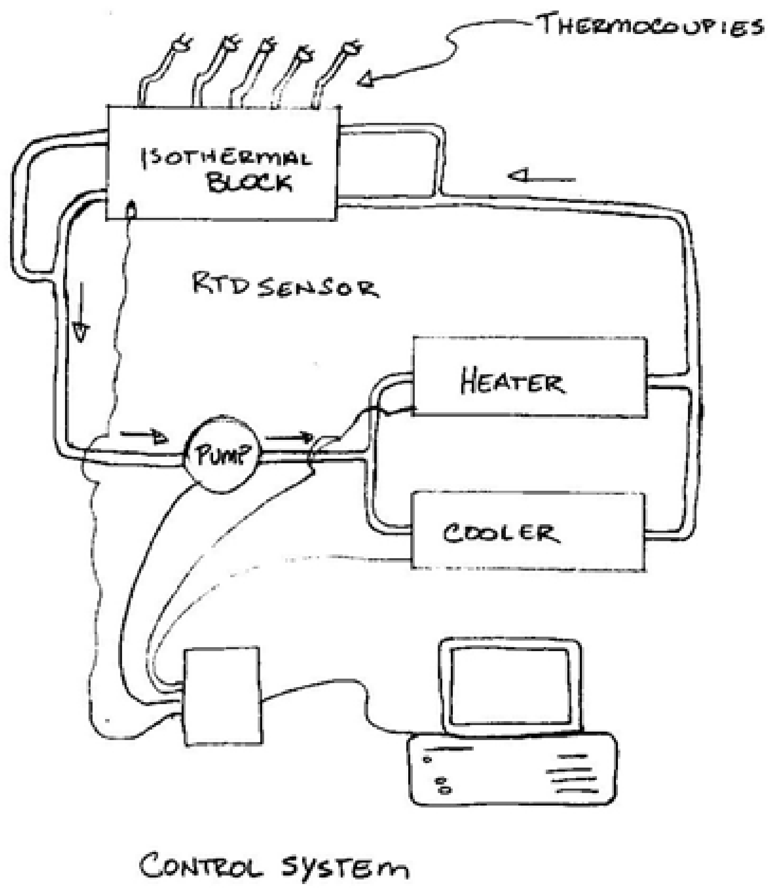

Figure 1. Schematic Diagram of Single Fluid Isothermal Block Concept.

In this concept, the thermocouple junctions to be calibrated are placed on a copper block and held in place with a clamp. There are fluid passages machined through the block. The locations and sizes of these passages are dictated by the placement of the thermocouple junctions on the block, the insulation of the block, and the desired time for the system to reach a steady state

temperature; all of these will be considered in order to eliminate temperature gradients in the surface temperature of the block at the thermocouples.

A fluid is pumped through these passages after flowing around a cooling or heating element which are controlled via LabVIEW. The fluid used is Clearco Pure Silicone Fluid, with a viscosity of 100cst. This fluid is purportedly stable across a temperature range from –55°C to 315°C (Clearco Products). A control loop is built into LabVIEW using a high precision thin film platinum resistance temperature detector (RTD) as the feedback sensor.

Once the ‘start’ button is triggered, the system turns on the fluid pump and the immersion cooler. When the minimum temperature of -40°C is reached, several data points are collected with LabVIEW; including the time of the measurement since the calibration began, the temperature recorded by the RTD and the voltages of each thermocouple. Several temperature measurements are recorded at this ‘steady state’. Once the data has been collected at this temperature, the system is allowed to move to another steady state temperature, with the control loop using the immersion cooler and the immersion heater to reach the next desired steady state temperature. Once the system has reached another steady state temperature, several more data points are collected. This process repeats until the system has reached and recorded data at a temperature of 300°C. After the data at 300°C has been recorded, the system turns off the temperature controller. Data reduction is then performed, with the data points collected for each thermocouple used to construct a relationship between the temperature of the sensing junction of the thermocouples and the voltage measured at the thermocouple leads. This is known as a calibration curve. A calibration curve (temperature as a function of voltage) will be output in Microsoft Excel for each thermocouple connected to the unit. A DAQ will be used to interface with a PC running LabVIEW; LabVIEW will be programmed to automate the process.

Thermoelectric Device

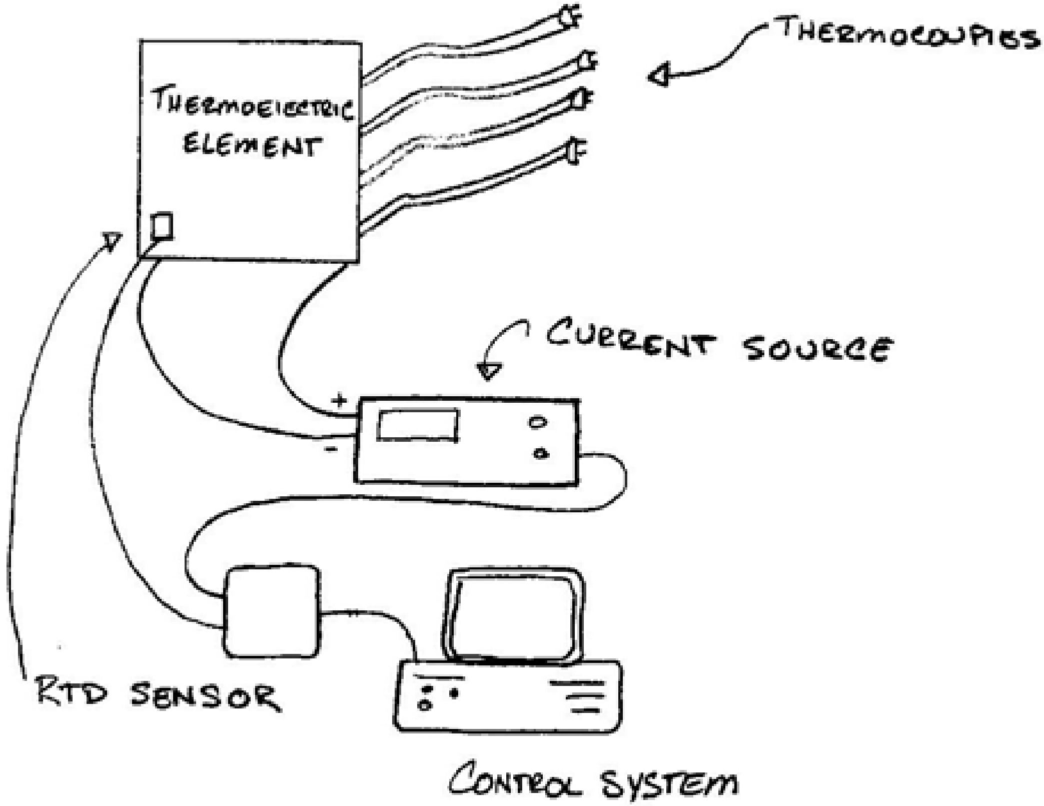

Figure 2. Schematic Diagram of Thermoelectric Device Concept

This concept is very similar to the previous design with regard to system control and data acquisition. A PC running LabVIEW is used as the controller with input and output done via a DAQ system. An RTD sensor is used as the feedback sensor in the temperature control loop. Rather than using an immersion heater and cooler to control a fluid temperature which in turn controls the temperature of an isothermal block, a thermoelectric device is used. A thermoelectric device operates on the Peltier effect which states that current flow through specific dissimilar semiconductors results in the cooling of one junction and heating of the other junction of two dissimilar semiconductors. A thermoelectric device contains many of these junctions wired in series, but thermally parallel. A controlled current source is used to control the temperature of the surface of the element. By varying the current from the current source, the temperature of the thermoelectric device can be controlled. The thermocouples to be

calibrated are surface mounted to one side of the thermoelectric device. The other side of the thermoelectric device requires a heat management system, such as a finned heat sink and fan, or a water-cooled heat exchanger. The max acceptable temperature difference across the two sides of the thermoelectric device is around 80°C (TE Technology, 2010).

Single Fluid Open Loop Submerged Thermocouples

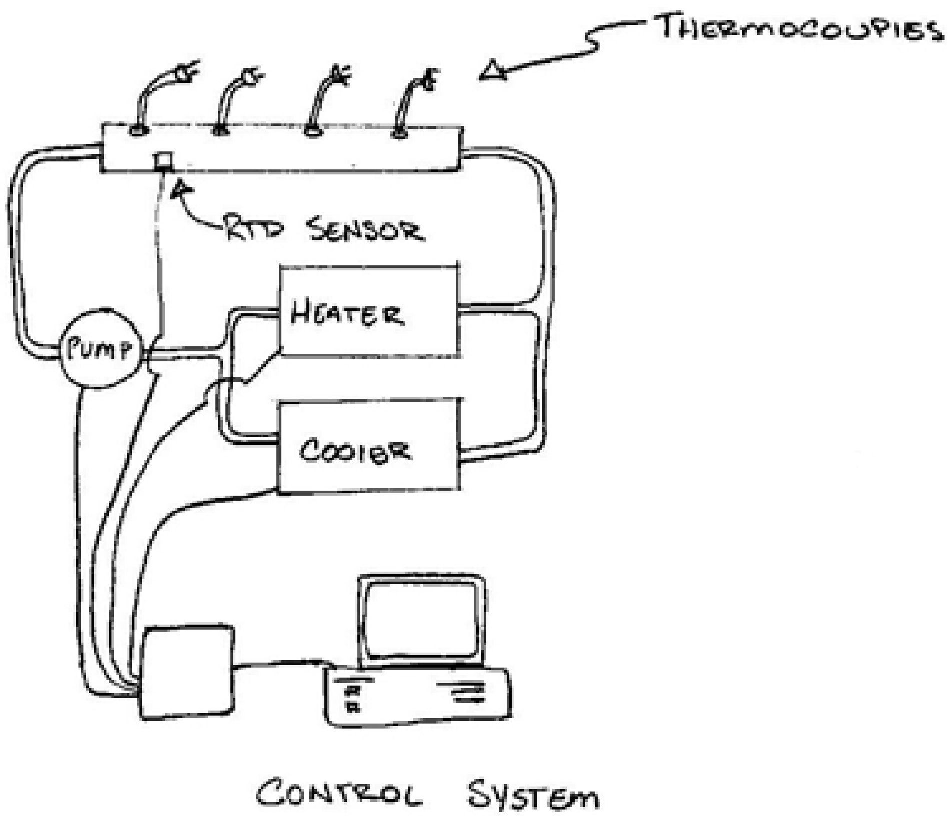

Figure 3. Schematic Diagram of Single Fluid Open Loop Concept

This concept is again similar to the first, with a heat transfer fluid being circulated through a heat exchanger loop. A submerged cooling coil and resistance heater are used to control the temperature of the working fluid. In this design, the thermocouples are inserted directly into the working fluid. This design eliminates the need for an isothermal block, which makes the overall design less complex. The design does require that a heat transfer fluid be found that is capable of stability across a range of temperatures from -40°C to 300°C. As stated in the first design concept, Clearco Pure Silicone Fluid is purportedly stable across this entire temperature range. With the open loop system, fluid evaporation at high temperatures can possibly be a safety concern.

Multiple Fluid Closed-Loop Isothermal Block

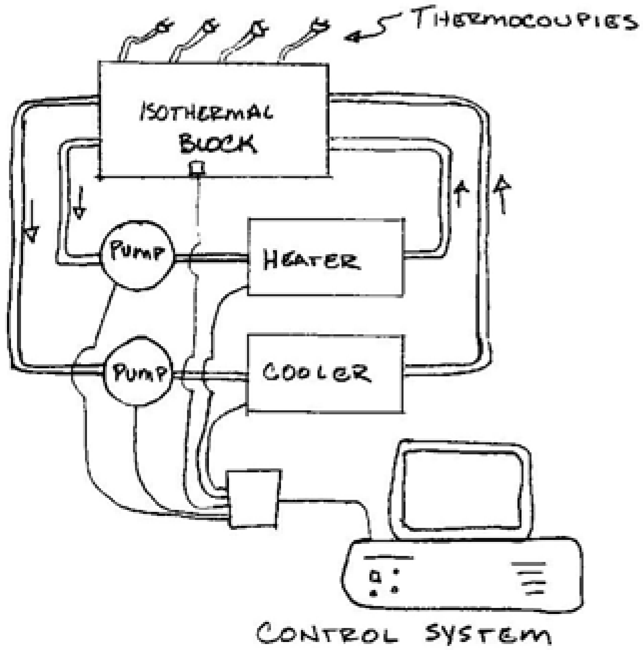

Figure 4. Schematic Diagram of Multiple Fluid Closed-Loop Isothermal Block Concept

This design concept utilizes two working fluids, one that is suitable for cooler temperatures (-40°C to the transition point) and one that is suitable for high temperatures (from the transition point to 300°C). This design also utilizes the isothermal block concept, with the thermocouple junction surface mounted to the block and an RTD sensor surface mounted to the same block. LabVIEW is used both as a controller for the temperature of the isothermal block and for data recording. Once the system has collected all the data, it is exported to Excel to output calibration curves for each thermocouple.

Triple Point Fluid

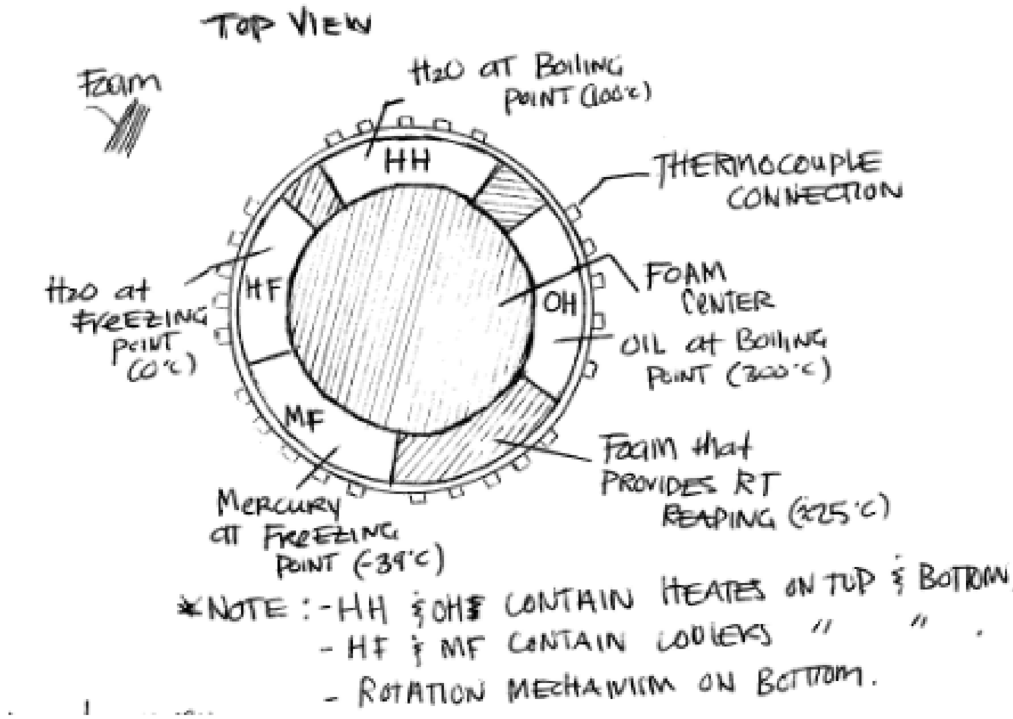

Figure 5. Diagram of Triple Point Fluid Concept

The Triple Point system is a more complex idea. This device's main function is to incorporate boiling and freezing points of some common fluids using a mechanical device. The benefit of this is that these states will ensure precise temperatures.

The Triple Point system consists of tree fluids: water, oil and mercury. There will be two stages containing water. One will contain water at its boiling point (HH) and the other at its freezing point (HF). Water will provide the calibration points at two temperatures, 100ºC and 0ºC. Another stage will contain oil (OH). Oil's boiling, which is 300ºC ensures the device will reach the highest required calibration point. Mercury at its freezing point will be the lowest point in the calibration curve. The next stage will be insulated space (look at drawing for visual). This space will provide a calibration point at the room temperature, making an ultimate count of five calibration points.

Each container will be theoretically isothermal and separated by insulation. In order to ensure that the process can be assumed to be isothermal, copper will be the preferred material for these containers. The purpose of the insulation is to ensure that the temperatures do not inter-mingle with each other otherwise causing an unwanted temperature gradient. There will also be a center foam/insulation unit for the same purpose.

Ultimately this system runs by having a set of five thermocouples at each station. They will be connected through the thermocouple connection slots. Once the thermocouples have reached the desired temperature, which through analysis an exact time constant can be calculated, the system's center will rotate moving the next station to the next set of thermocouples. This rotation will occur mechanically, rotating after the time constant has been met. This will go on for a total of five times; giving each thermocouple a chance at each temperature point. Ultimately using LabVIEW, as well as and RTD sensor, a calibration curve will be generated in Excel.

Utilize Existing Fluid Bath Calibrators

A possible solution to this calibration problem is to utilize off the shelf calibration baths. These baths are available in many different configurations and temperature ranges. Common calibration baths are open systems and utilize only one heat transfer fluid. It may be possible to modify a commercially available fluid bath to achieve a wider temperature range. It is also possible to modify or completely bypass the fluid bath's original control system and user interface in order to meet the requirements of this project. A high accuracy temperature sensor will be required for the temperature control loop, which would be automated and controlled via LabVIEW. With a system that utilizes existing baths, it would not be possible to calibrate thermocouples over the entire temperature range. Due to the initial cost of fluid baths, the necessary modifications and the inability to meet the temperature range requirements, the existing fluid baths are not considered as a possible solution.

Design Discussion

Concept Selection

Table 6. Concept Decision Matrix

Metric \ Concept	Single Fluid Iso. Block	Thermoelectric Device	Single Fluid Submerged TC	Multiple Fluid Iso. Block	Triple Point Fluid
Thermocouple Compatibility (T & K)	3	3	3	3	3
Temperature Range (-40 to 300°C)	1	1	1	3	3
Device Temperature Accuracy	2	1	2	2	3
Time to Calibrate (< 4hr)	3	3	3	3	3
Number of Thermocouples Calibrated	3	2	3	3	2
Number Data Points (> 5)	3	3	3	3	2
Total	15	13	15	17	16

The decision matrix is used to compare each concept with regard to the requirements found in Table 2. Top level analysis for each system to determine respective limitations is used to populate the matrix. A score of three indicates that the system is capable of meeting the requirement with no limitations or problems. A score of two indicates the system may be capable of meeting the requirement, but with difficulty. A score of one indicates the system will not be capable of meeting the requirement.

The thermocouple type capability is not a problem for any of the systems; each system would be able to work with any thermocouple type. This criteria is proven via inspection, there is no analysis necessary to prove this.

The temperature range requirement is a difficulty for many systems. The single fluid systems are limited by the temperature range of the fluid. The heating and cooling elements would not be limitations. There are commercially available fluids that have published stable temperature ranges from -40°C to 300°C. These fluids exhibit a large change in viscosity over this temperature range however, and the fluid may have pumping problems that result in non-uniform temperatures through the system. In addition to the viscosity problem, the fluids are at or near

boiling point at atmospheric pressure which could potentially result in a dangerous situation involving potentially harmful gasses and requiring a closed system that is capable of withstanding pressures above atmospheric. The thermoelectric device has difficulty meeting the temperature range requirements due to the construction process of thermoelectric devices. Most are soldered, with some flame brazed aluminum options, with a max temp of no more than 300. The choice of fluids in the triple point model allows the temperature range to meet the requirements.

The accuracy of the temperature of the systems is related to the thermal mass of the system. A design with a larger thermal mass will inherently be more stable, and therefore be capable of a higher thermal stability and accuracy. The thermoelectric device has a low thermal mass and the construction method (multiple semiconductor junctions) minimizes the possibility of having an isothermal surface for thermocouple attachment.

The time to calibrate is also a function of the thermal mass of the system. The higher the thermal mass, the more energy and or time required to change temperature. The triple point concept and the thermoelectric concept both have the potential to minimize the time required to perform the calibration. A quick analysis indicates that it will be possible to have the concepts utilizing fluids perform the required temperature sweep for the calibration within the required time period using a common 110v power source.

Having the capability to meet the quantity of thermocouples to be calibrated requirement is a limitation of both the thermoelectric device and the triple point concept. The fluid systems are all capable of being scaled in size to allow any number of thermocouples to be calibrated simultaneously. The thermoelectric device has fundamental physical limitations, the largest commercially available having no more than approximately 6400 square millimeters of available heat transfer surface area. A heat transfer plate could potentially be attached to the thermoelectric device in order to increase the surface area, but that increases the required heat pumping capabilities of the thermoelectric device and is not physically realistic. The triple point fluid only scores two in regard to the number of thermocouples due to the complexity of mounting the thermocouples.

With the exception of the triple point concept, all of the systems have no limitations concerning the number of data points collected. The triple point concept is only capable of calibration at the same number of points as the number of elements contained in the system; in this case it is five. More could be added, but it would require a system redesign and could not be done easily.

Once this design was chosen, components were sourced. Pumps capable of operation at both low and high temperatures are both difficult to find and expensive. In addition to the pump, the fluids themselves are volatile, and having the two fluids running through a single copper block at once would mean that both fluids would be well outside of their operating temperatures at some point during the calibration process. The low temperature fluid would be above its boiling point at 300°C, and pressures of well over 1000psi were expected. A decision was then made to split the block into two separate blocks and have the user manually switch over the thermocouples at the appropriate point in the calibration process.

Once the decision had been made to completely separate the hot and cold circuits, the fluid pressure was no longer a problem. The pump operating temperature was still a problem. During a design review it was suggested that we remove the fluid completely. This would remove the need for both pumps and fluids. Eliminating the fluid meant the thermal mass of the system also decreased; a design parameter tested later using FEA.

DESCRIPTION OF THE FINAL DESIGN

Detailed Design Description

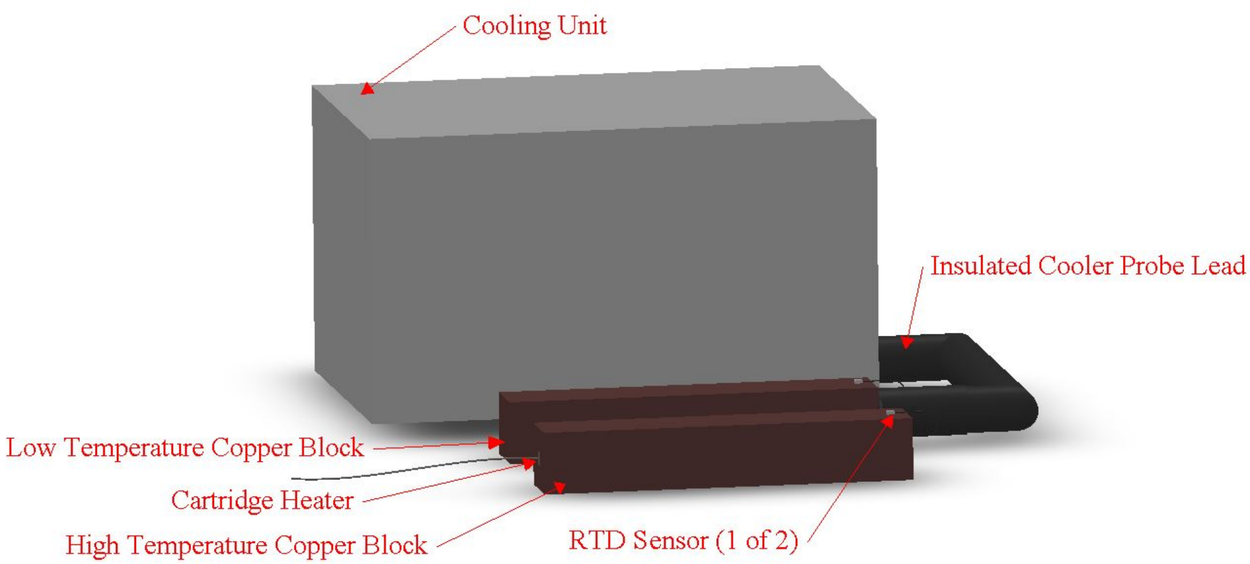

Figure 6. Annotated schematic of thermocouple calibration device (insulation suppressed).

The final design utilizes two separate copper blocks as controlled temperature mediums for the thermocouple calibration. The low temperature calibration (below ambient) is performed with one block and the high temperature calibration (above ambient) is performed with the other. The critical parts of this calibration unit are the two copper blocks which act like thermal reservoirs. Using LabVIEW and a control loop, the blocks can be brought to a specific calibration temperature and maintained at that temperature. This allows a large quantity of thermocouples to be calibrated simultaneously, as the entire block is at one specific temperature. The isothermal concept requires excellent insulation and geometric symmetry. The RTD sensor and thermocouples are in direct contact with the copper block. The RTD is embedded into the block, while the thermocouples are compressed between two parts of the block with screws. The block itself is two halves, starting out as a 1”x1” block of pure (99.9%) copper. The two halves bolt together to contain the heating/cooling element and capture the thermocouples. With the heater, thermocouples and RTD all in contact with the block, the entire assembly is surrounded by

cellular glass insulation. During the calibration process the thermocouples are removed from one block and transferred to the other. Direct contact conduction is utilized to heat and cool the blocks. A stainless steel cartridge heater is used as a heat source of the high temperature calibration block and a vapor-compression cycle cooler with a stainless steel probe is used as heat sink for the low temperature calibration block. RTD sensors are embedded in each block for a reference temperature source. National Instruments data acquisition units are used for data collection. National Instruments LabVIEW is used to collect data and control the system. Cellular glass insulation is used to insulate the system and minimize heat transfer to the surroundings. A protective housing surrounds the entire system in order to reduce heat transfer and prevent inadvertent exposure to temperature extremes by the user. The user connects the thermocouples to the block, places the insulation on the block and runs the LabVIEW program. LabVIEW controls the temperature and collects data, the output is an excel file with a temperature and voltage correlation for each thermocouple. For this project, the cold side was omitted and only the hot side calibration was performed.

The overall system uncertainty due to the various electronic components can be seen in table 7. These uncertainties assume an isothermal, steady state condition. This condition should be achievable due to the thermal mass of the copper and the effectiveness of the insulation, along with an effective temperature control loop. Verification of the isothermal condition is done by calibrating several thermocouples outside the system, with an ice bath and hot bath. These thermocouples are then positioned along the length of the block and the temperature is brought up to the temperature of the hot bath. If the temperatures measured along the length of the block are equal to or less than the overall system uncertainty at that measurement (approx. ±0.50°C) then the isothermal, steady state assumption is a valid assumption. The RTD sensor has been tested for accuracy using the NI hardware and known temperature mediums; an ice bath and boiling water and the temperature measurement fell within the uncertainty range. Based on these results, we can say with confidence that the total system uncertainty is similar to the total theoretical uncertainty in table 7. Further testing is ongoing for verification.

Table 7. Theoretical Total System Uncertainty

System Temperature (°C)	Thermocouple System Error	RTD Sensor System Error	RTD Accuracy	Total Uncertainty
-40	± 0.46°C	± 0.20°C	± 0.10°C	± 0.51°C
0	± 0.37°C	± 0.20°C	± 0.06°C	± 0.42°C
300	± 0.42°C	± 0.30°C	± 0.39°C	± 0.65°C

Based on measurements taken in several tests performed for mounting methods, a clamping-type mounting method was chosen. More test information can be found in the design verification section. Based on the mounting method, and calculations that can be found in the appendix, the torque of the fastening hardware can be related to the surface pressure between the copper block halves. This mounting pressure is the pressure experienced by the thermocouples being clamped. Further testing is ongoing in order to explore the potential correlation between fastener torque and thermocouple response. Based on initial observations, the relationship is highly nonlinear and as long as a certain torque is reached, then there is little change in thermocouple response with increasing torque.

Table 8. Thermocouple Mounting Pressure

Torque (in-lbf)	P_{ave} (psi)
1	98
2	196
3	294
4	392
5	491
6	589

Cost Breakdown

Table 9. Cost Breakdown / Bill of Materials for Thermocouple Calibration Device

Quantity	Manufacturer	Description	Part No.	Cost (Est.)	Totals
1	National Instruments	16 Channel High Accuracy Thermocouple Board	NI 9214	$1,299	$1,299
1	National Instruments	4 Channel RTD Board	NI 9217	$493	$493
1	National Instruments	4 Bay DAQ USB Chassis	NI cDAQ-9174	$699	$699
1	National Instruments	4 Channel Relay Board	NI 9481	$169	$169
1	FTS Systems	Immersion Cooler	FC55-A01	$1,850	$1,850
1	Watlow	Firerod Cartridge Heater	J7A50	$51.52	$51.52
2	Pyromation	Platinum RTD Sensor	R5T185K48R284-003-00-18-K3024-2	$172.70	$345.40
2	McMaster Carr	1"x1"x12" Copper Block	89275K53	$52.52	$105.04
1	Pittsburgh Corning	FOAMGLAS Cellular Glass Insulation	4”x18”x24”	$20.88	$20.88
1	NTE	120V 15A Relay	R47-5A15-120	$16.47	$16.47
1	-	.025 inch Aluminum Sheet	-	$40	$40
					$5089.31

Component Selection

Copper was chosen as a heat transfer medium due to its exceptional thermal conductivity and relatively high melting point. Copper blocks were selected to increase the thermal mass of the system and therefore insure thermal stability and uniformity. Aluminum was also considered but rejected due to a higher coefficient of thermal expansion and lower melting point. The copper is in the system as a thermal reservoir, stabilizing the temperature for calibration. An FEA analysis using Abaqus indicated that the originally specified thermal mass was excessive. The system was thermally stable with a much smaller volume of copper than originally specified. The copper dimensions were accordingly adjusted to 1”x1”x8”. This saves material cost in copper and power cost. With sufficient insulation, the system is still extremely thermally stable. A recess is machined into each block in order to house the heating and cooling elements. Both elements are stainless steel which has a thermal expansion coefficient similar to that of copper, minimizing thermal stresses. Aluminum was also considered but was rejected due to its relatively low melting point.

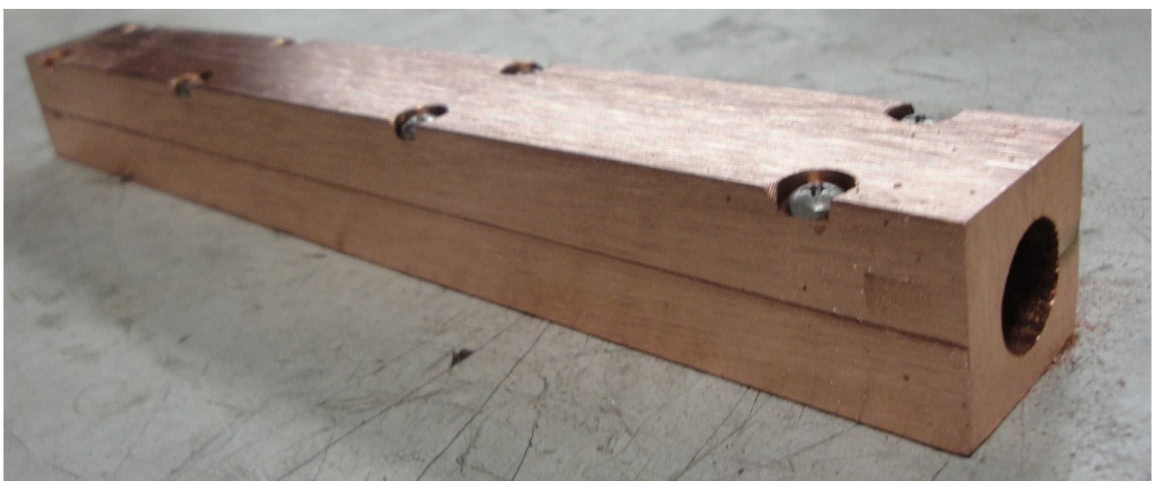

Figure 7. Copper Heat Transfer Block

For the low temperature calibration block the specified heat removal device is a vapor-compression cycle cooler with a stainless steel probe. Other devices were considered but the heat removal rates required at low temperatures (-40°C) dictated a vapor compression cooler. The cooler specified is produced by FTS systems and has a stainless steel probe as the evaporative element. With the probe set into a copper block, heat may be removed from the block at up to 70 watts of heat removal at -40°C. The device uses R1270 refrigerant which is a very environmentally friendly refrigerant. The stainless probe is 7 inches long and ¾ inch in diameter. The probe is inserted into a recess machined into the copper block and removes heat via conduction. The unit operates off a common 110VAC circuit and is controlled via LabVIEW. The unit is controlled via a relay that turns the unit on and off when necessary to reach or maintain a temperature set point.

The heater used in this design is an electric cartridge heater. This heater is an electric resistance type heater that is controlled through LabVIEW and used to bring the high temperature block up to and maintain at a certain temperature. The cartridge heater specified is manufactured by Watlow and is a 7 inch long, ½ inch diameter tubular heater. It operates on 120VAC and is capable of 600 watts of output power. This model uses nickel-chromium resistance wire and a stainless steel outer sheath. The heater is controlled in a similar way to the cooler, with LabVIEW controlling an output relay that turns another power relay on or off to control the temperature.

Resistance Temperature Detectors (RTDs) were chosen as the sensor for their very desirable characteristics. The high accuracy models usually use platinum as a sensor media, which is stable across a wide temperature range and has a very linear relationship between temperature and resistance. Compared to thermocouples, the other sensors used for large temperature range measurements, RTDs exhibit much higher accuracies. Compared to thermistors, RTDs have a much slower response time and a lower sensitivity. Thermistors are not suitable for the temperature ranges produced with this calibration device. RTDs exhibit little temperature drift with time and are highly repeatable. Four wire configurations, the type specified in this design increase the accuracy of the RTD. The multiple wire configurations minimize the effects of the resistance of the lead wires, in addition to self-heating. A 1/5 class B accuracy RTD was chosen for this project due to very high accuracy.

For the electronics, inputs and outputs compatible with LabVIEW were selected. The thermocouple input is National Instruments (NI) high accuracy 24 bit 16 channel isothermal input module. This module has an internal isothermal junction block with several cold-junction compensation sensors. It is compatible with most thermocouple types, including T and K. Accuracy information can be found in the background section of this document. The RTD resistance is measured with a separate NI board, capable of monitoring up to four individual four wire sensors. A four channel NI relay board was selected for output capabilities. This board is capable of controlling relays or units in order to control system temperatures. The chassis has slots for up to four boards, so another thermocouple board can be added in order to increase the number of thermocouples that will be calibrated, up to 32.

Cellular glass is used as the insulation for the system due to its excellent temperature stability, low cost, and low thermal conductivity. Few insulating materials are readily available that are capable of meeting the temperature requirements, cellular glass has a published temperature range of -260°C to 480°C. Other insulating media such as rigid calcium silicate and mineral wool were considered, but rejected due to incompatible temperature ranges or high thermal conductivity. The system is projected to loose less than 80 watts of heat at 300°C with two inches of insulation surrounding the block. This insulation is also rigid enough to be easily machined and provide structure for the system. The copper blocks will be placed directly on the cellular glass. The specific product specified was chosen for its origin in the United States, as the material is relatively fragile and prone to shipping damage.

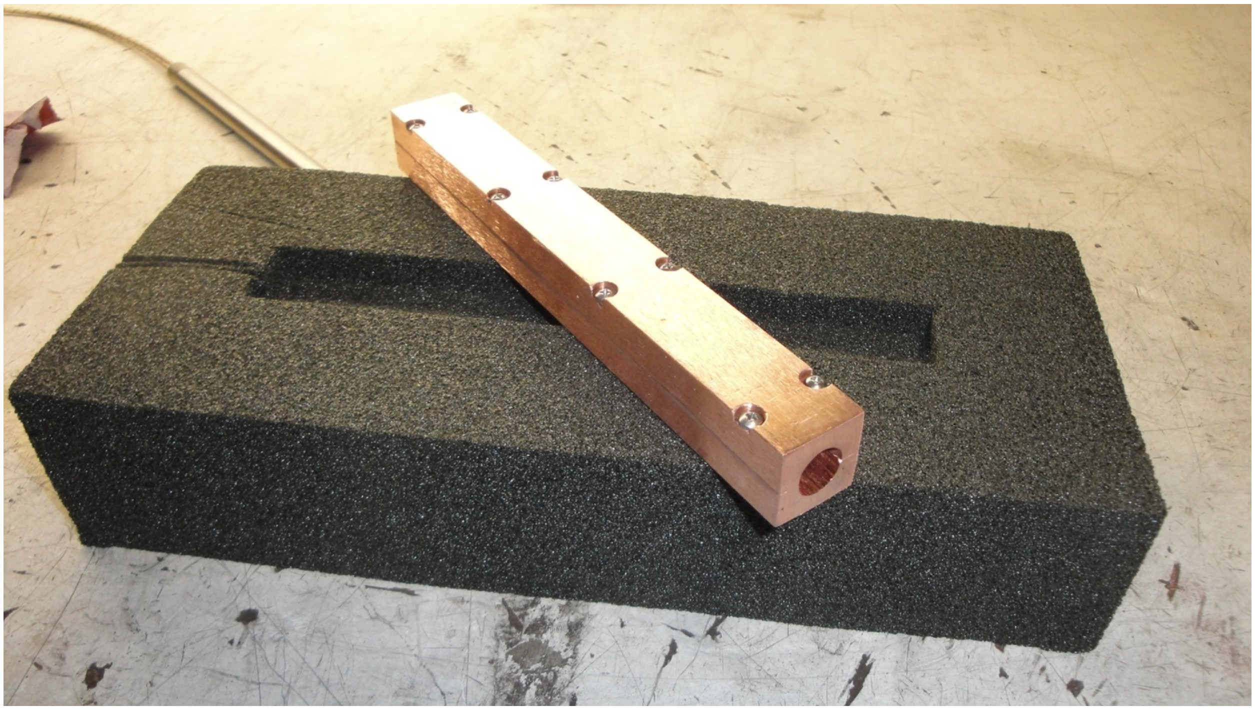

Figure 8. Copper Heat Transfer Block and Cellular Glass Insulation

Instructions for Use

In order to perform calibration, the user must have access to a PC with National Instruments LabVIEW installed. The DAQ chassis is connected to this computer, and the LabVIEW program is loaded. The latest version of LabVIEW was used for the code development, LabVIEW 2011, so the user must have access to an equal or more recent version of LabVIEW. The NI chassis is connected to the computer via a USB cable, and all cards should be inserted into the chassis and the chassis plugged in. Thermocouples must be attached to the NI card with the provided binding post terminals. It should be verified that the RTD sensor is correctly connected to the RTD card and the relay is connected to the I/O card. With the computer on and LabVIEW open, the thermocouples can be attached to the copper block.

First, the case must be opened and the insulation covering the blocks must be removed. The insulation is very fragile and easily damaged, so great care should be taken when removing or replacing the insulation. The top piece of insulation can simply be picked up off the top of the block. With the upper insulation removed, the screws holding the two sides of the copper block can be loosened using a 3/32" Allen Head hex wrench. The screws may be simply loosened or completely removed depending on the preference of the user. The thermocouples can then be placed on the copper block, along the surface towards the front of the case on the flat surface around the mounting bolt holes. It is important to make sure the thermocouples are not touching the heating element or clamping screws. It may be easier to use masking tape or a similar low tack tape to hold the thermocouples in position along the insulation while the tips are aligned along the copper block. With all the thermocouples placed appropriately, the top half of the block should be replaced and the mounting hardware tightened to 3 in-lbf. The top of the insulation can then be replaced and the cover of the case closed.

With the computer on and the thermocouples mounted, the power can be connected to the case. The calibration program should then be run in LabVIEW. Once this process is done, the calibration data can be analyzed and attached to each thermocouple in whatever means is convenient, either electronic or as a hard copy. The thermocouples should be labeled before they are removed from the NI card's binding posts, in order to insure the correct calibration data is related to the correct thermocouple. Caution should be used after calibration; the copper block will remain hot for a long period of time if the insulation is left covering it. LabVIEW can be used to monitor the temperature of the block as it cools down. In order to let the system cool down more quickly, the top piece of insulation may be carefully removed. Care must be taken in

order to prevent anyone or anything coming into contact with the hot copper block if the insulation is removed.

Checklist:

Before RUNS

- Turn on the computer. Open designated LabVIEW files. Make sure only LabVIEW and Excel are running at this time (this ensures the computer wont crash).
- Clamp the thermocouples. Make sure that they are all evenly distributed. This should be done with care (make sure the heater is unplugged).
- Check insulation. Ensure that the copper block is properly placed, and properly secure.
- Make sure all mounting bolts are tight and appropriately torqued.
- Verify that LabVIEW is working properly.
- Plug in the heater (plug in the back of the case).

RUNS:

- Once all devices are properly powered and the LabVIEW programmed is launch, start the program.
- Monitor the computer to make sure nothing inappropriate is happening (keep an eye on the system temperature).
- If problems occur, unplug the heater.

PRODUCT REALIZATION

Manufacturing Processes

Many of the components used in this calibration device are off the shelf. The parts requiring manufacturing or assembly include the heat transfer block, the insulation, the exterior housing, and the electrical wiring. In addition, the computer code that runs the system and records data was developed, and is covered in a following section.

The copper blocks are sourced from McMaster Carr. The copper is available in foot length increments. The block was first cut to length using a band saw. Next the eight holes were drilled into the block using a drill press. The heads were counter bored on the drill press after the holes were bored. With the holes bored the block was cut in half lengthwise using a band saw with a fence. The cut face was then faced using a fly cutter on a mill. The mill was also used to cut the recess for the cartridge heater using a ball end mill. The threads were manually tapped into all of the threaded hole locations after the mill work. The holes in the upper half of the block were bored out after the mill work in order to reflect the fact that they are clearance holes. Copper cuts easily with sawing processes, but care must be taken in drilling, milling and tapping processes. The material is very soft and very thermally conductive, so the work piece must be flooded with coolant and sharp tooling should be used. Cutting speeds that are too fast have a tendency to gall the material and overheat it and cause it to weld to the cutter or to the base material. Similarly tapping must be performed slowly with sufficient cutting fluid, backing out the tap frequently to remove the chips from the hole.

The cellular glass foam was cut to size using a saw process. The foam is extremely fragile and prone to brittle cracking in addition to being easily crushed, so it is not possible to clamp the material using conventional processes. The material is very soft and cuts very easily with light pressure with any type of saw. For this example, a fine tooth hacksaw was used. To create the cutout in the center of the foam, a router with a ½ inch straight bit was used in conjunction with a dust collection system.

The aluminum exterior case was manufactured using standard procedures; a sheet metal brake, a sheet metal shear, a drill press and rivets. Each piece was cut out per the drawings with a shear and then marked and bent. The pieces were clamped together and 1/8” holes drilled for the rivets

using either a drill press or a hand drill and a wood backing plate. Any trim cuts were performed using hand shears.

The wiring for this hardware is rather straightforward, with one relay used to control the heater from the output from LabVIEW. A standard 15A 120V connector is installed into the case to ease transport and installation. The case is grounded with a jumper wire from the case to the ground on the 3 wire 120v plug. The outlets from the plug go directly to the relay that then goes to the heating element. The output from the NI relay connects to the relay. All wires are insulated multi-strand copper that are connected using crimp connectors or binding posts.

Code Development

In order to accomplish the task of data acquisition and analysis we employed the use of National Instruments LabVIEW software. We used the newest version of LabVIEW so that any compatibility issues with using new National Instruments DAQ systems would be removed. Though we could not meet the goal of full automation, the program can collect all of the temperatures and voltages required for calibration and output that file to excel. Additionally, temperatures can be manually input so that multiple calibration points can be collected for the calibration curve.

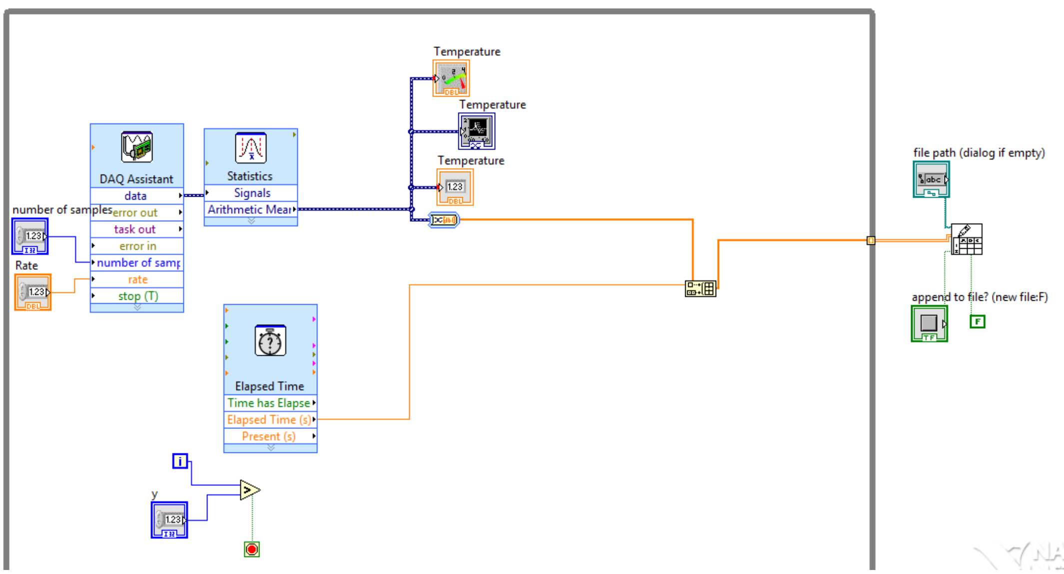

Figure 9. DAQ Collection Code for Output to Spreadsheet

In Figure 9 the readings from the thermocouples and the RTD are collected using the DAQ assistant module within LabVIEW. If you click on this module you can change the parameters of the data being collected as well as change what channels you want to collect the data from. All of these data points are fed into an array which is then converted to a standard spreadsheet format usable in any program that utilizes spreadsheet files.

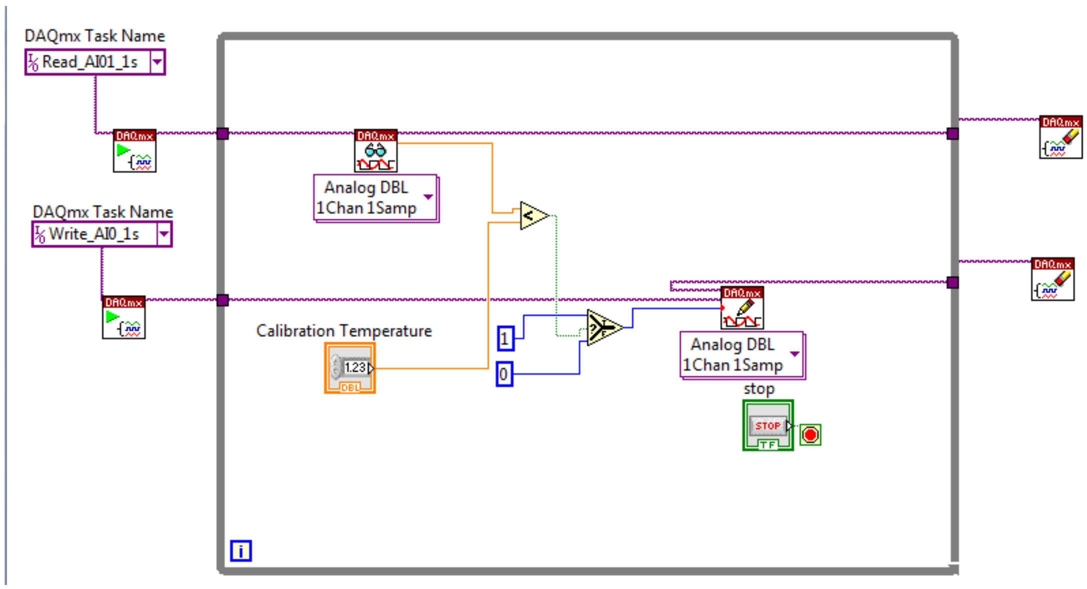

Figure 10. Control System for Cartridge Heater

Figure 10 displays the control loop for the cartridge heater with the feedback being the temperature signal from the RTD. For this to work the read task should be set to the RTD channel, and the write task set to the output board connected to the DAQ system. This controls the 120V relay which turns the heater on and off. When you input the calibration temperature you desire, the heater will turn on until the temperature is reached.

Future/Upgrades

An assembly similar to the assembly produced for the hot side calibration is to be produced for the cold side calibration. The copper block is very similar, as are the insulation and the case. The only major difference is the diameter of the recess that must be machined in order to accept the cooling probe. The cold side calibration assembly would not need the relay or the power connection required by the hot side. The cooler would then need to be connected to the output relay from the NI chassis, in whatever way seems appropriate. A LabVIEW loop similar to the hot calibration program would be adapted to the cold calibration system.

For both systems, more testing and validation must be performed. As outlined previously, the effects of mounting pressure need to be more thoroughly. In addition, more tests should be performed in order to validate the isothermal, steady state assumption. These tests should be performed at various temperatures, in non-steady state and in steady state conditions, and during both heating and cooling. As observed with thermocouples, and any system with a first order response, it may be beneficial to take data both while the system is heating and while the system cools off in order to take data on the way ‘up’ and on the way ‘down’ if true steady state conditions cannot be achieved. Additionally, more RTD sensors may be specified if there is a temperature gradient within the block that needs to be calibrated for.

The LabVIEW code is under constant development and is the area most needing improvement. It is believed that the code could potentially almost fully automate the process; bringing the system to preset steady state temperatures, taking several data points at that temperature, and then moving on to another set point. Once the data is collected, an equation could be developed based on the data points taken. Ideally, the process would output an equation for each individual thermocouple calibrated, attached to the input channel of each respective thermocouple.

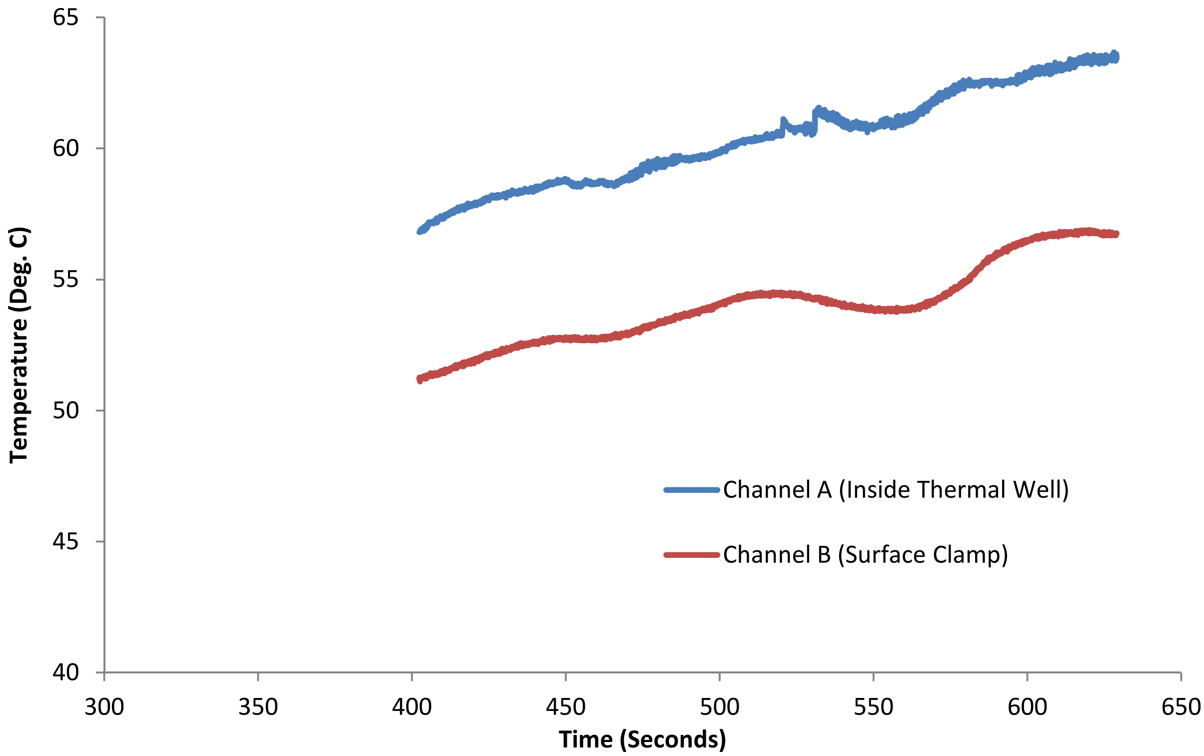

Figure 11. Thermal Well Temperature Validation Test Data

The first method tested in our mounting validation testing was the thermal well concept suggested by Tesla. This mounting method was more complex than other methods and required the thermocouple to not touch the walls of the thermal well. From the data you immediately notice there is a lot of noise in the measurement. This is due to the free convection currents created by the temperature difference between the wall and the air and causes the slight fluctuations in temperature. Over the course of the test the two temperatures read were always at a constant temperature difference. This was purely because of the locations of the thermocouples and the inherent temperature gradients in the block, this will be greatly improved with thermal insulation and having a steady state temperature.

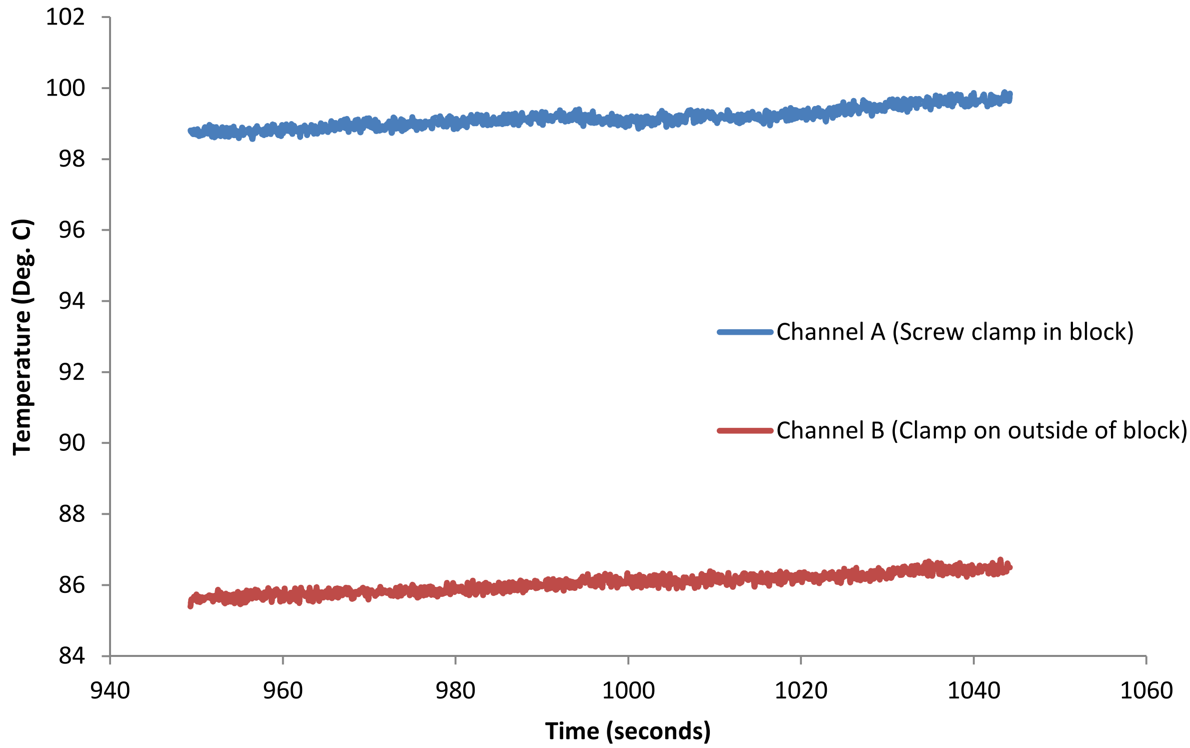

Figure 12. Clamp mounting method Validation Test Data

The clamp method proved to be much more reliable and robust. The mounting of the thermocouples took very little time and the readings were surprisingly accurate with only a small amount of random noise. All of the temperature readings indicated a very smooth curve and a very steady temperature once it reached steady state. This method was selected for its ease of use, speed at which the experiment is set up and the very consistent temperature readings.

Thermocouple Calibration Device DVP&R													
Report Date:	2/16/2012		Sponsor:	Tesla					Component/Assembly			REPORTING ENGINEER:	
TEST PLAN										TEST REPORT			
Item No	Specification or Clause Reference	Test Description	Acceptance Criteria	Test Responsibility	Test Stage	SAMPLES TESTED		TIMING		TEST RESULTS			NOTES
						Quantity	Type	Start date	Finish date	Test Result	Quantity Pass	Quantity Fail	
1	Labview Test	Does it work?	one run	All	PV	1	D	2/28/2012	TBD				
2	Thermocouple Read	Does it read it?	at least 4 runs	All	PV	1	C	3/8/2012	TBD				
3	Sensor Read	Does it read it?	one run	All	PV	2	C	3/8/2012	TBD				
4	Insulation	Does it work?	one run	All	PV	1	C	3/8/2012	TBD				
5	Cold Block	Does it reach Temp?	a couple runs	All	DV	1	B	3/13/2012	TBD				
6	Cold Block	Temp Gradient?	a couple runs	All	DV	1	B	3/13/2012	TBD				
7	Hot Block	Does it reach Temp?	a couple runs	All	DV	1	B	3/15/2012	TBD				
8	Hot Block	Temp Gradient?	a couple runs	All	DV	1	B	3/20/2012	TBD				
8	Clamp	Verification	a couple runs	All	PV	2	C	3/22/2012	TBD				
10	or Thermal Well	Verification	a couple runs	All	PV	1	C	3/22/2012	TBD				
11	Completely Built	Verification	multiple runs	All	DV	1	D	3/27/2012	TBD				

Sample Type -
Describe the sample to be tested (see sample level)

Sample Level - -
A = Prototype (Handmade)
B = Prototype (Tooled)
C = Production Tool (Not Process)
D = Production Tool and Process

TBD- to be decided

Figure 13. Thermocouple Calibration Device DVPR

CONCLUSIONS AND RECOMMENDATIONS

Based on the performance of the calibration system at this point, we feel confident that the system is capable of meeting most of the original engineering specifications. The customer, Tesla Motors, requested the simplification of the system by removing the below ambient calibration. Our device meets all the requirements with the exception of full automation and the accuracy requirement. The accuracy of the system is most affected by the off the shelf hardware and the associated hardware. With some reworking it would be possible to significantly increase the overall system accuracy, most critically by looking at the cold junction compensation built into the thermocouple input device.

The total calibration time is less than 4 hours based on the power of the heater and the thermal mass of the block. The unit is currently capable of calibrating 16 thermocouples at a time and is expandable to 32 with the addition of another thermocouple input card. Alternatively, with both the hot and cold calibration blocks running, 16 thermocouples could be calibrated on the cold side while 16 are calibrated on the hot side, and then they are changed over mid calibration. In this way 32 thermocouples could be simultaneously calibrated without trying to get 32 thermocouples to line up on the same block.

With the addition of the cold side block and further work on LabVIEW and other procedures as outlined in the Future/Upgrades section, all of the original engineering requirements would potentially be met.

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APPENDIX A

Project Scope and Requirements.docx

Received 29 September, 2011 from Reid Olsen (rolsen@teslamotors.com)

Thermocouple Calibration Device

Project Definition

The Thermocouple Calibration Device will be able to calibrate multiple thermocouples to an accuracy an order of magnitude greater than the thermocouples themselves. Each thermocouple will need to be labeled with an identifier that can track the calibration constant determined by a curve fit graph of collected data. The system must be fully automated once operation has begun.

Specific Requirements

- Calibrate 25 thermocouples at one time
- An order of magnitude more accurate than Type T and Type K thermocouples
- -40° to 300° C range
- Take between 5 and 10 measurements over the given range to increase accuracy of calibration constant
- Four hour cycle time
- No user intervention or monitoring required during operation
- Report output in Excel, data acquired through LabView
- CAD files for all machined parts

QFD

Thermocouple Calibration Device	Weighting	Thermocouple Type Compatability	Number of Thermocouples	Temperature Range	Time to Run	Number Data Points	User Interface	Output	Accuracy	Power Requirements	Noise	Heat Rejection	Complexity	Robustness	Efficiency	Benchmarks: NIST Calibration	Benchmarks: Commercial Calibration	Benchmarks: In-House Calibration
Type T&K	15	●														●	●	●
25 Thermocouples	5		●				○						○	○	○	Δ	○	○
-40℃ to 300℃	5			●	○	○			○			●	○	○	○	●	●	●
5-10 Measurements	10			○	●	●			○							○	●	●
4 Hours	10			●	●	○					○	●		○	○	Δ	Δ	○
1 Button Operation	15						●	○					●	○		●	●	Δ
Output (.xls)	10	○	○				○	●					○			●	●	○
Labview	10						○	○					○	○		●	●	○
±0.1℃	15			○					●				●			●	○	Δ
110VAC	5			○	○					●	○				●	●	●	○
																40	42	32
Total	100	105	55	165	130	95	150	125	120	25	45	75	240	135	85			
Relative Totals		7	4	11	8	6	10	8	8	2	3	5	15	8	5	100		

● = 5	Strong Correlation
○ = 3	Medium Correlation
Δ = 1	Small Correlation
Blank	No Correlation

Figure A-1. QFD for Tesla Motors thermocouple calibration device. This figure shows the specific requirements and what importance they play (Done for academic reasons).

The Quality Function Deployment (QFD) method is used to help define requirements and understand a problem. In this instance the sponsor (Tesla) has provided detailed requirements and a specific problem. In a project with a less well defined problem, the QFD method is invaluable. The QFD used for this project is seen in Figure 1. On the left hand side of the figure are customer provided requirements. Along the top are usually more specific requirements that may be assigned values. Those values would go along the bottom of the figure. In this case the

figure is configured differently, with the specific requirements provided by the customer on the left and more general requirements along the top. The QFD was still used as a discussion point as each value on the figure has been decided by the group after much discussion and consideration. In the end, it was found that the closest competitor to our design goal would be sending the thermocouples off to be calibrated by a commercial entity. The cost/accuracy ratio is the deciding difference between the commercial calibration and NIST calibration. After finishing this QFD we can see that the complexity of the project will be the most critical attribute. This is understandable; the goal is to construct a calibration device and accurate calibrations are rarely simple. The QFD also confirms the importance of the user interface and calibration temperature range.

APPENDIX B

System Schematic/Exploded View/Parts Drawings

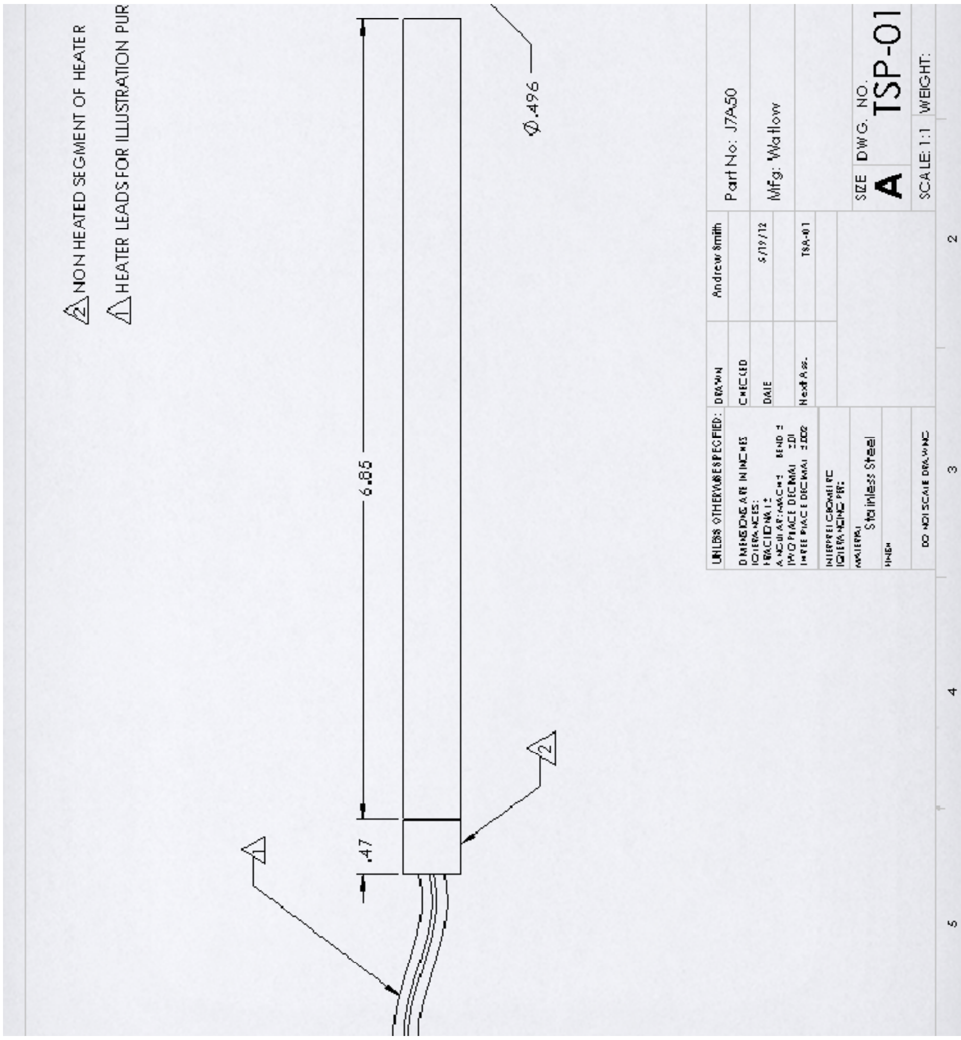

Figure A-2. Heater Drawing

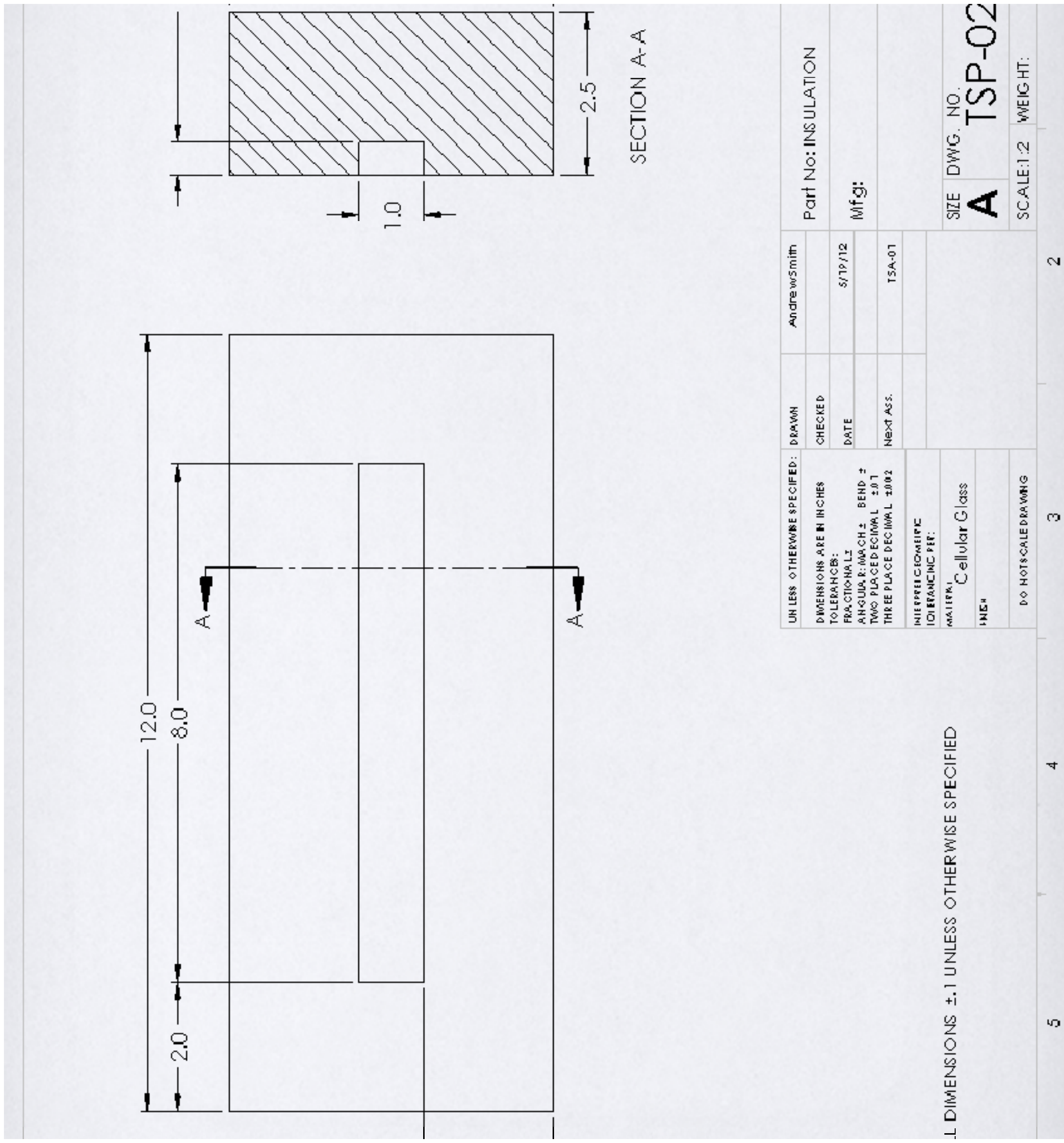

Figure A-3. Insulation Drawing

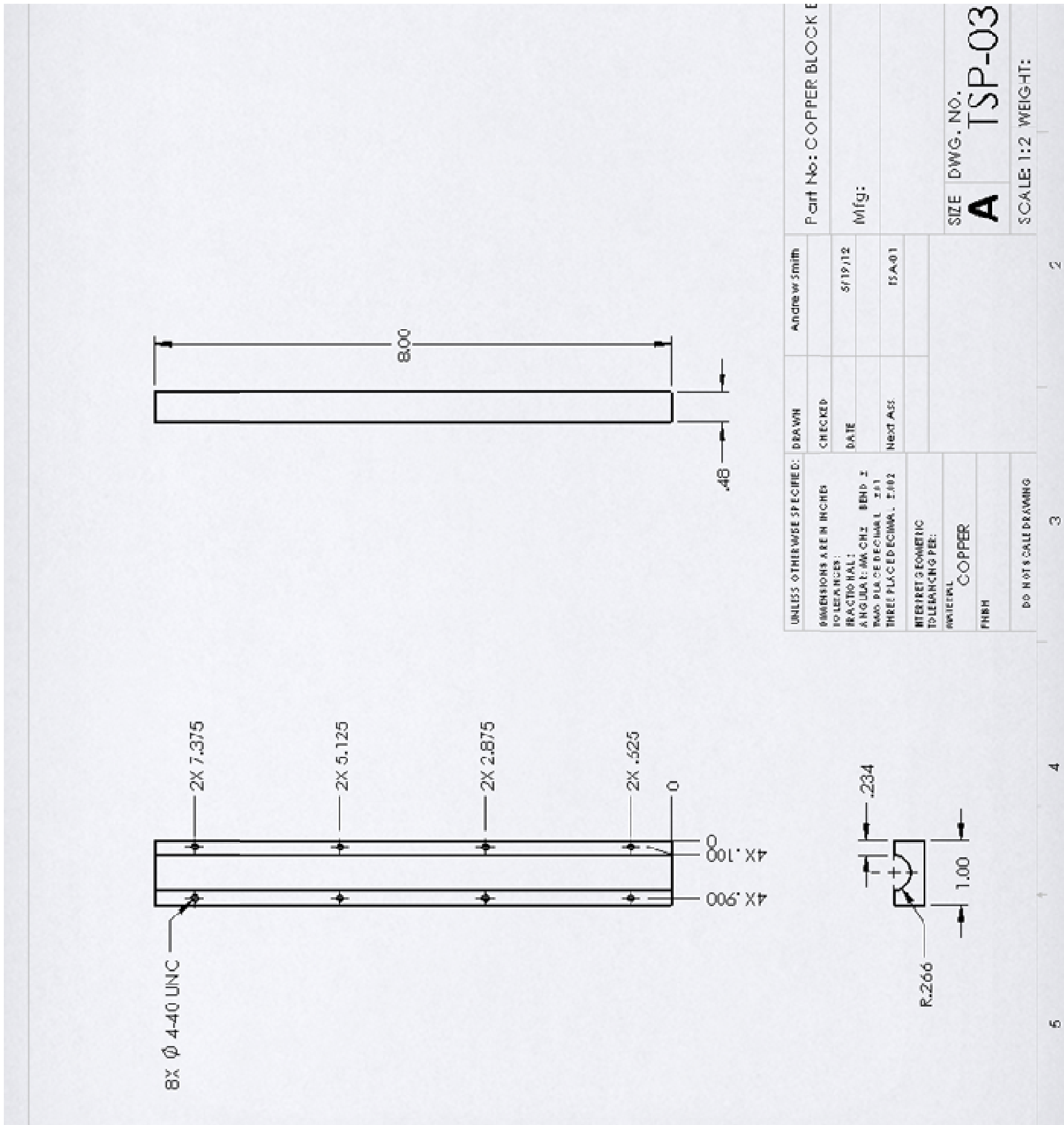

Figure A-4. Copper Block Bottom Drawing

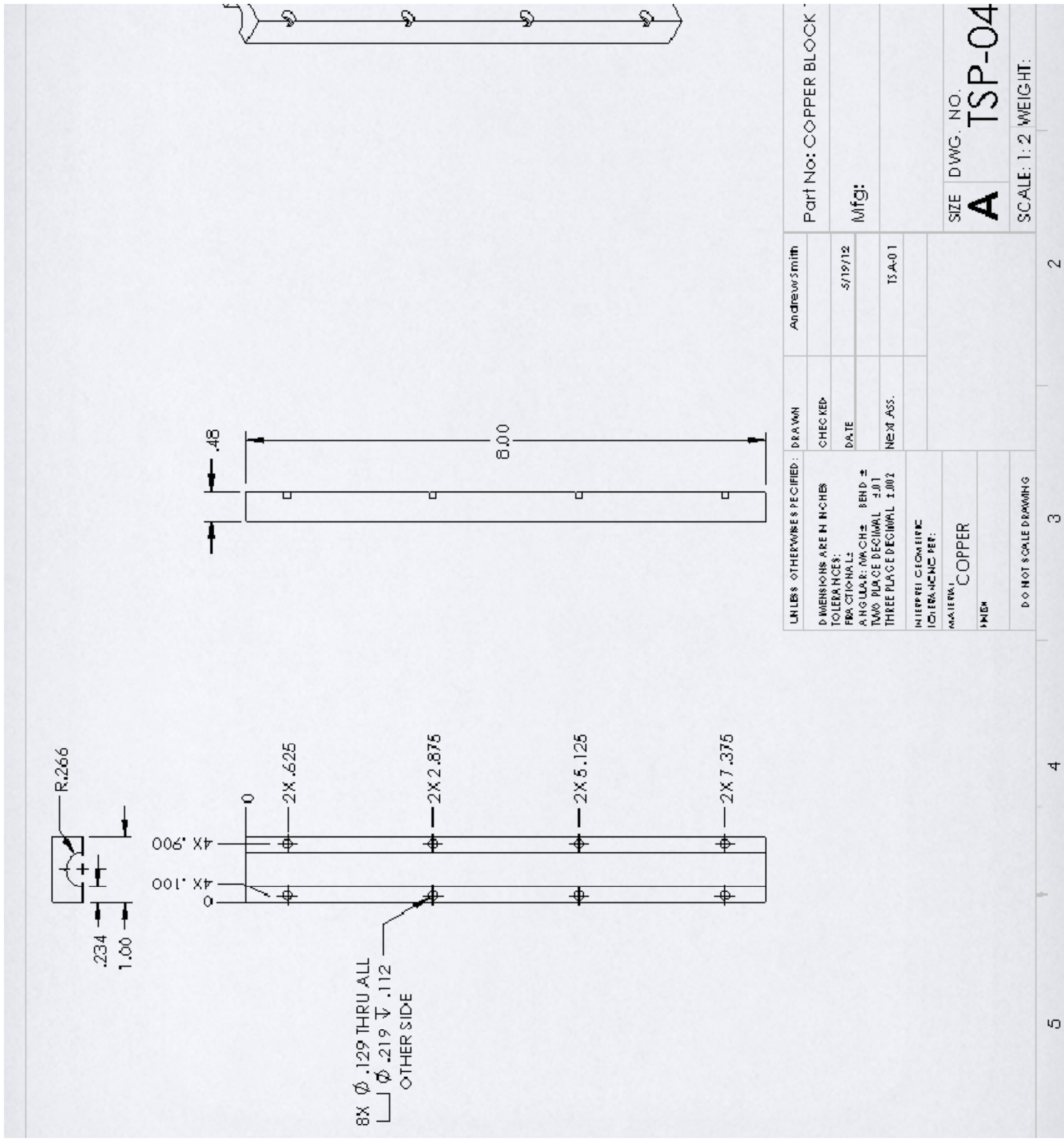

Figure A-5. Copper Block Top Drawing

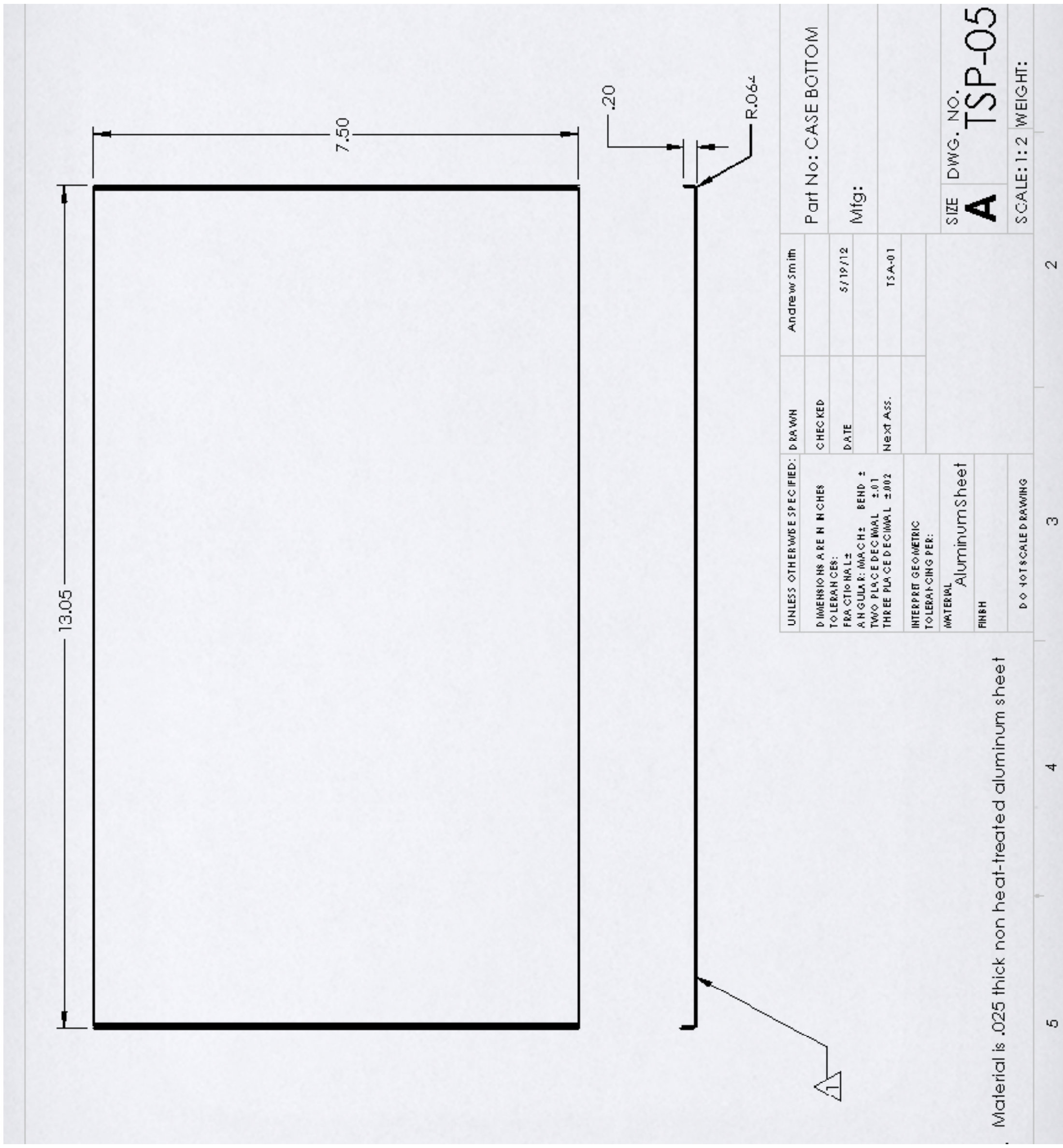

Figure A-6. Case Bottom Drawing

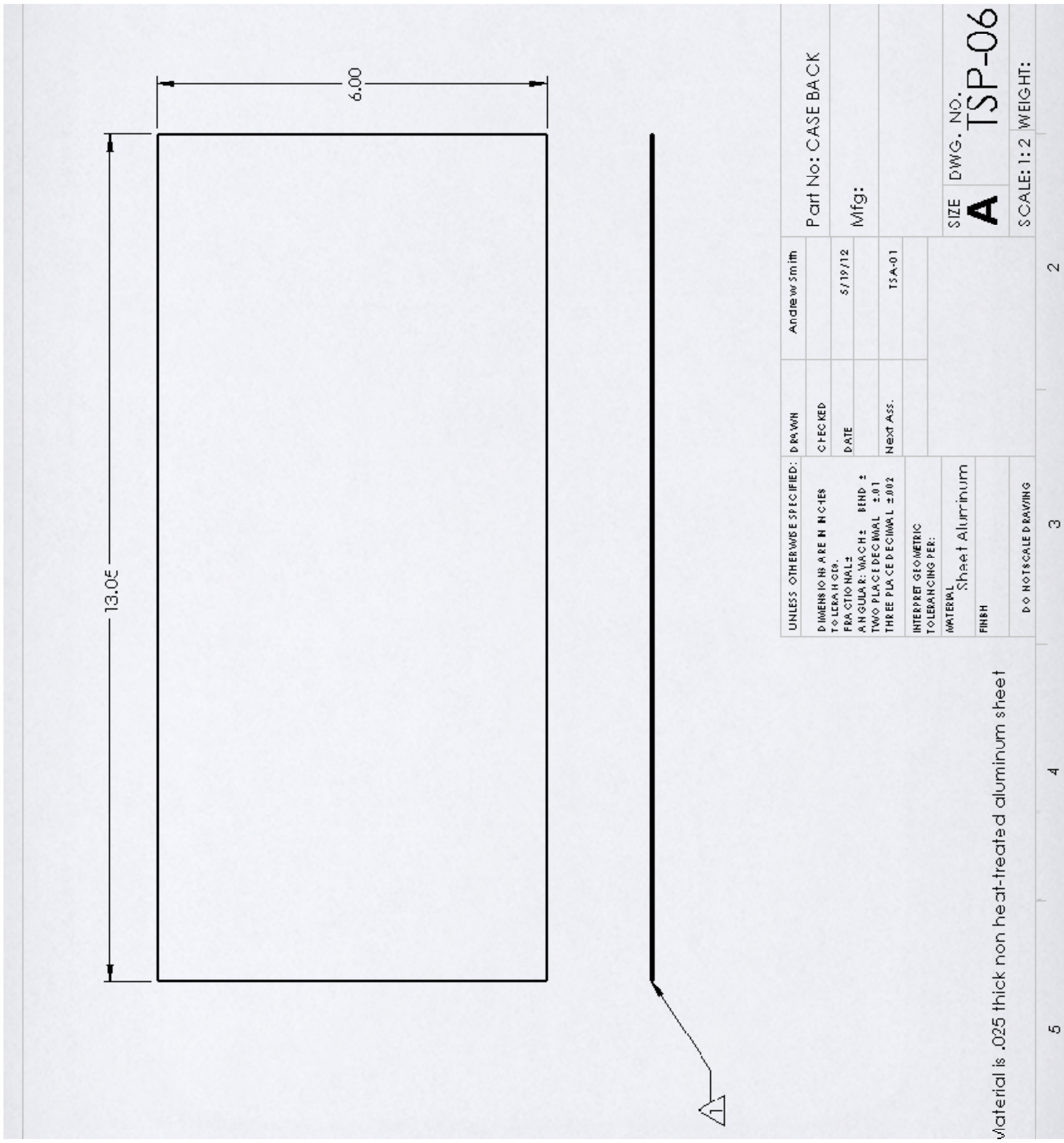

Figure A-7. Case Back Drawing

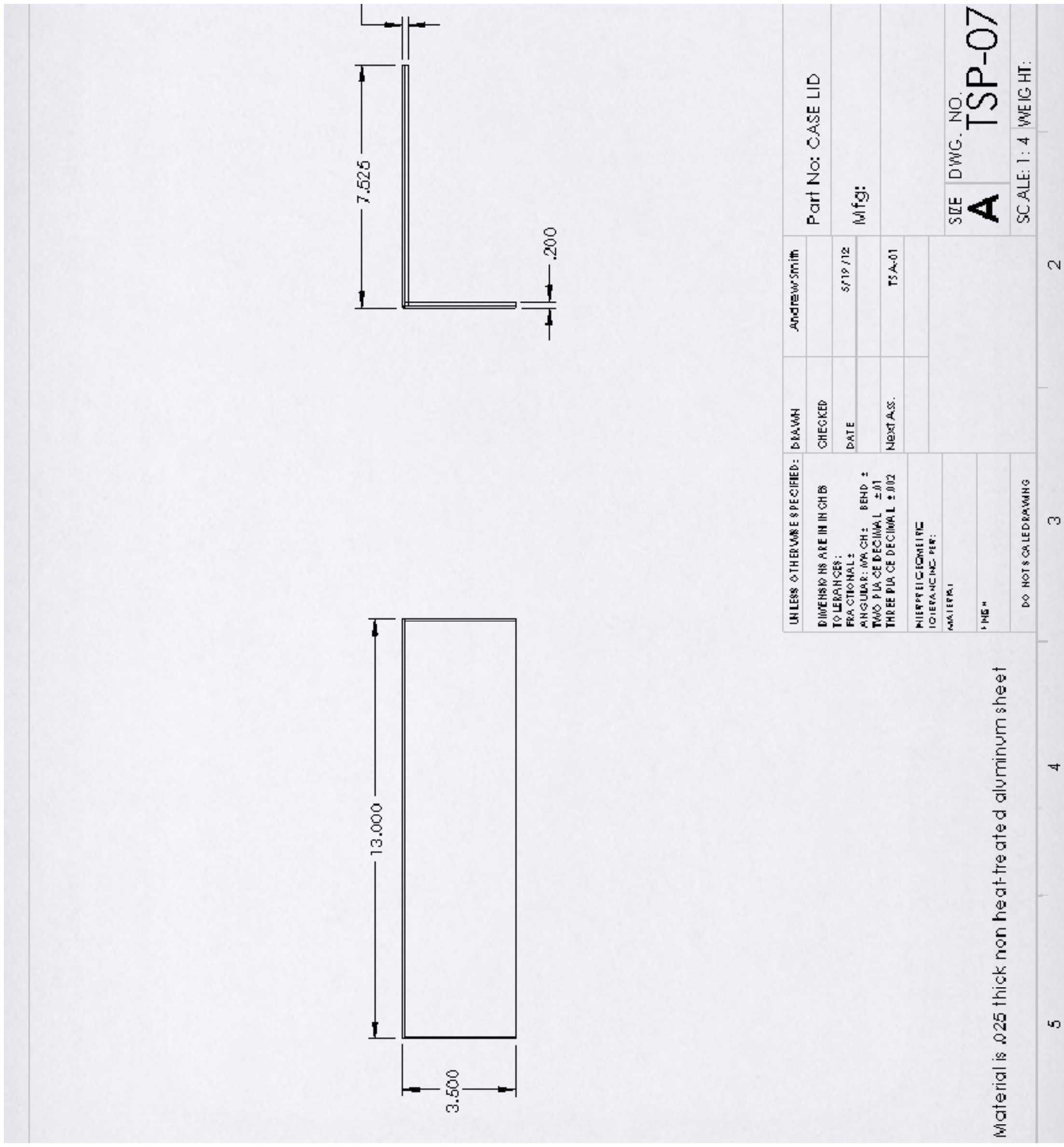

Figure A-8. Case Lid Drawing

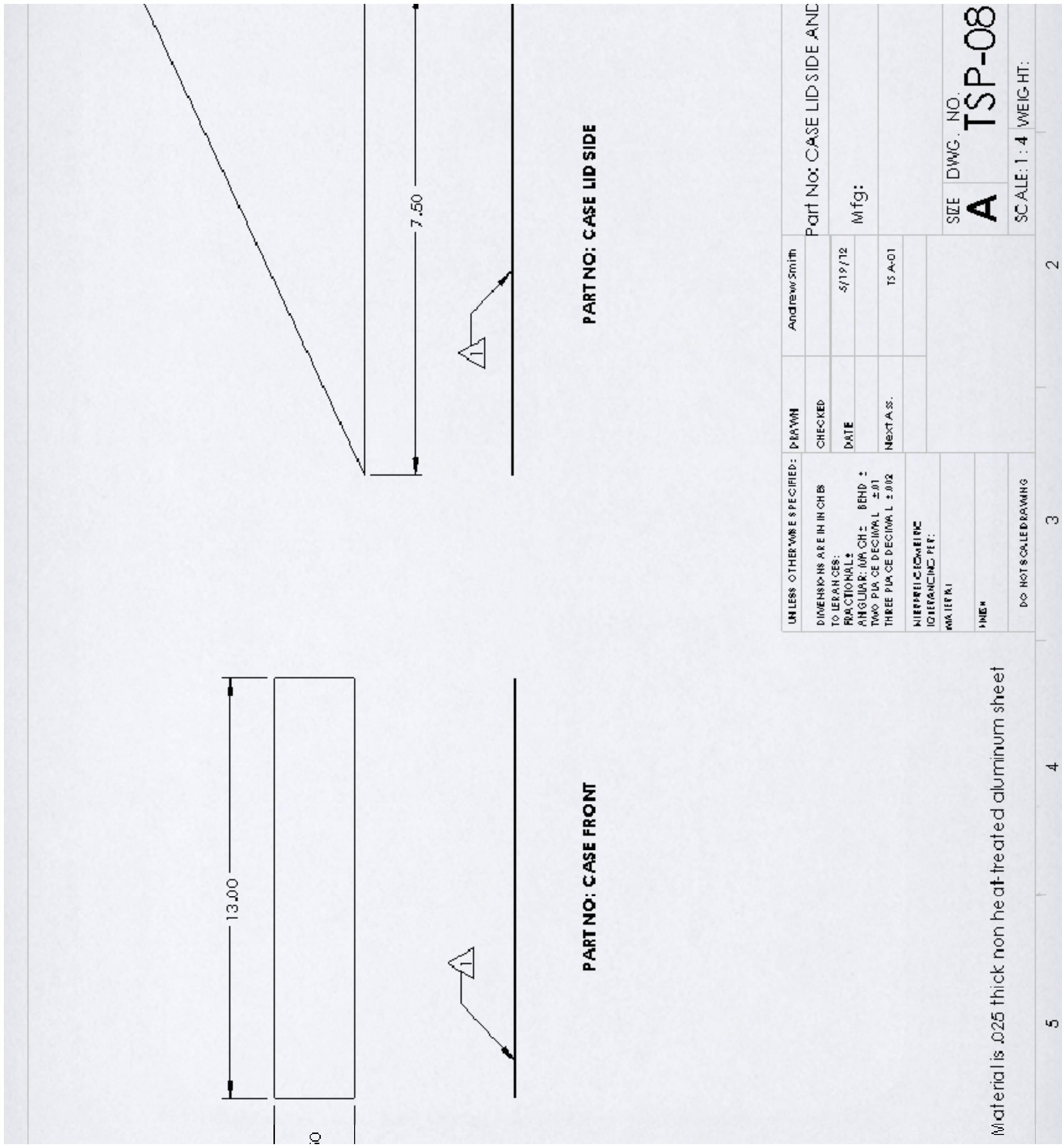

Figure A-9. Case Front and Case Lid Side Drawings

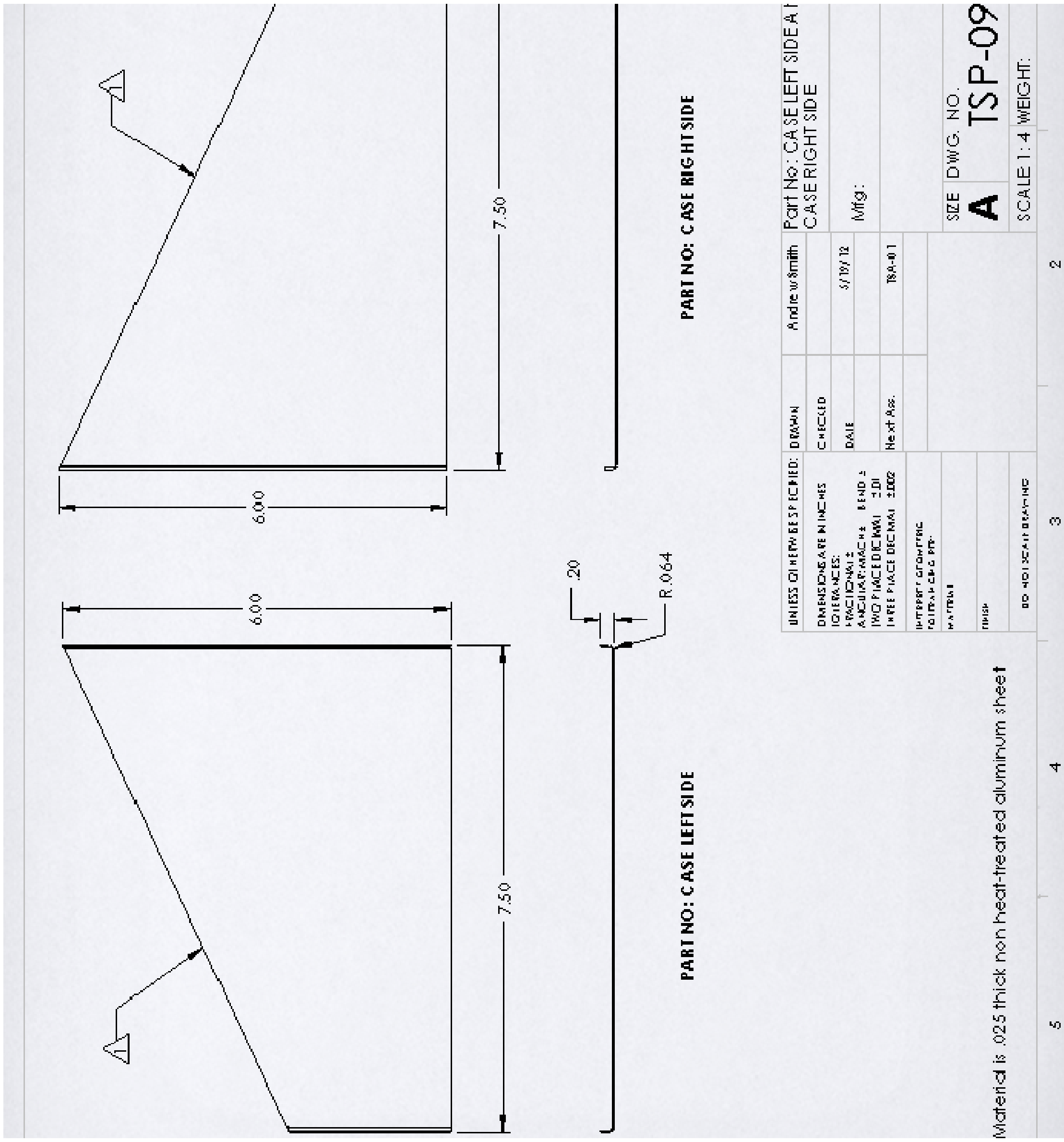

Figure A-10. Case Left and Right Side Drawings

External Case Exploded View and Pictoral View

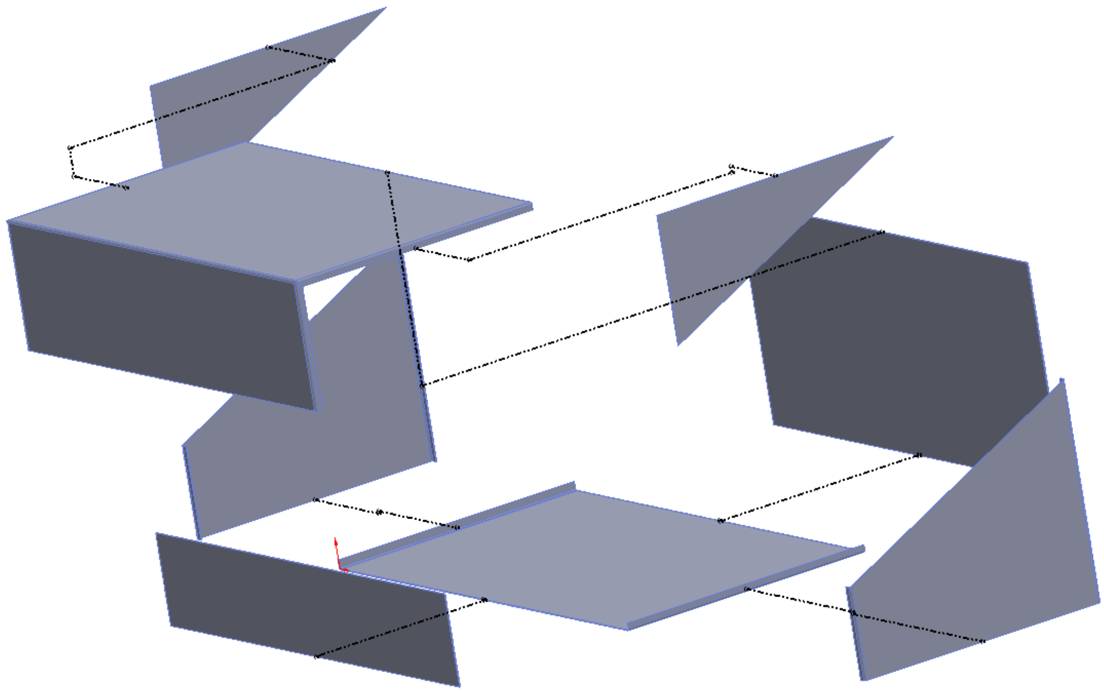

Figure A-11. Case Exploded View

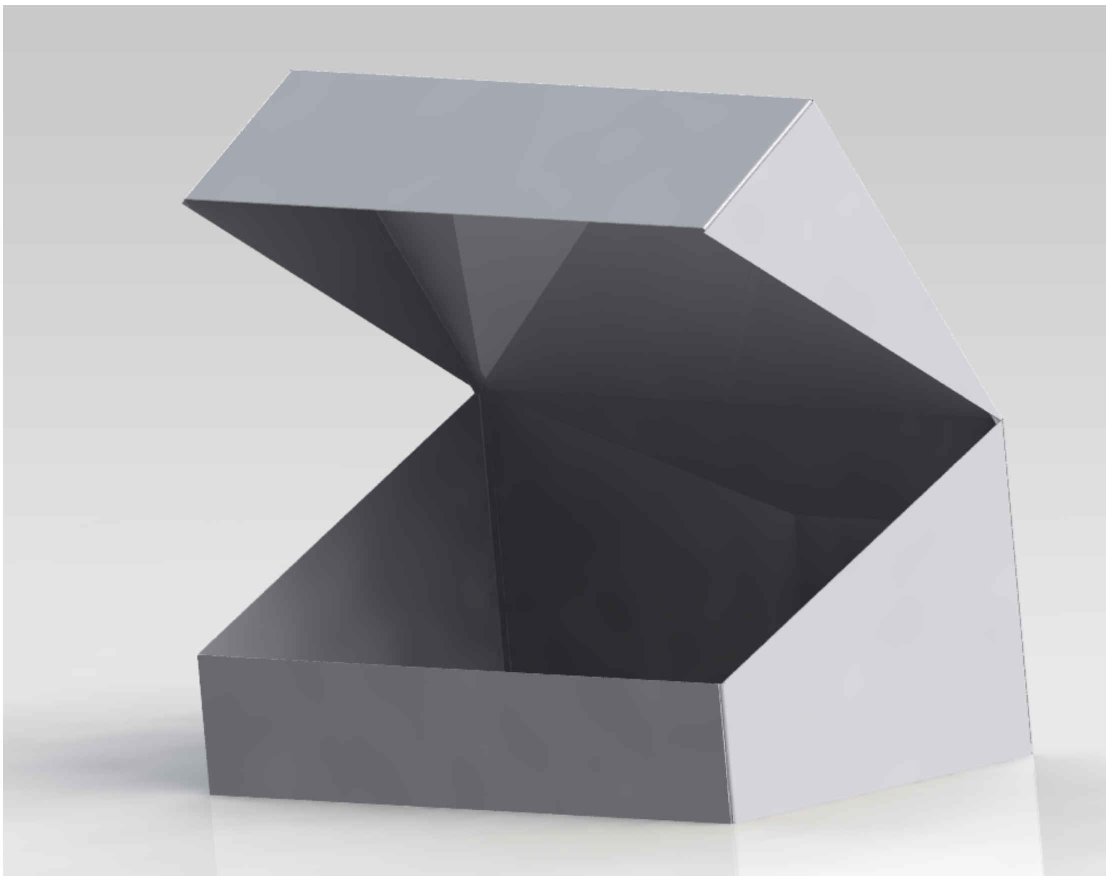

Figure A-12. Case Pictoral View

APPENDIX C

Vendors

Vendor	Components	Pricing
National Instruments	16 Channel High Accuracy Thermocouple Board NI 9214 4 Channel RTD Board NI 9217 4 Bay DAQ USB Chassis NI cDAQ-9174 4 Channel Relay Board NI 9481	\$1,299 \$493 \$699 \$169
McMaster Carr	1"x1"x12" Copper Block hardware	\$52.52
Insul-Therm International Commerce, CA 90040 323-728-0558	Pittsburgh Corning FOAMGLAS Insulation 4"x18"x24" Block	\$20.88
Thermal Devices Mt. Airy, MD 21771 301-831-7550	Watlow Firerod Cartridge Heater FR-J7A50TD	\$51.52
Pyromation Inc. Fort Wayne, IN 46825 260-484-2580	RTD Sensor - R5T185K48R284-003-00-18-K3024-2	\$172.70

APPENDIX D

Data Sheets

Cartridge Heater

Cartridge Heaters

FIREROD

Applications and Technical Data

Tolerances

Diameter:

1 inch units: ±0.003 inches (±0.076 mm)

All other units: ±0.002 inches (±0.0508 mm)

Length:

All units to 4½ inches (115 mm) long: ±3⁄32 inch (±2.4 mm)

⅛ inch diameter units over 4½ inches (75 mm) long: ±3 percent

All other units over 4½ inches (115 mm) long: ±2 percent

Wattage:

⅛ inch units: +10 percent, -15 percent

All other units: +5 percent, -10 percent

Resistance:

⅛ inch units: +15 percent, -10 percent

All other units: +10 percent, -5 percent

Resistance changes with temperature. There are three circumstances under which resistance can be measured:

1. Room temperature (before use): nominal ohms are 90 percent of ohm's law calculation.
2. Room temperature (after use): nominal ohms are 95 percent of ohm's law calculation.
3. At temperature (during use): depending on application nominal ohms are approximately 100 percent of ohm's law.

Camber:

Units to 12 inches long: 0.005 inch per six inch length. Standard camber tolerance varies as the square of the length, in feet, is multiplied by 0.020 inches. For example, a 36 inch FIREROD has a camber tolerance of 0.020 inches X $(3)^2$ = 0.180 inches. Normally, slight camber does not present a problem since the heater will flex enough to fit into a straight, close fit hole.

Component Recognition File Numbers

UL® component rated to 240V~(ac)
CSA component rated to 240V~(ac)
VDE component rated to 240V~(ac)

Note: Not all options or combination of options are covered. UL®, CSA and VDE marking is available upon request.

Electrical Data

The *Electrical Data* table will assist you in selecting the correct FIREROD heater for your application, according to available voltage, amperage and wattage.

Please note, some combinations of minimum and maximum wattages are not available on the same heater diameter. Also, if you need to exceed limitations shown, contact your Watlow sales engineer or authorized distributor.

Number Of Circuits ⑤		
Diameter in.	1-phase	3-phase
¾	3	1
1	5	2

FIREROD Diameter in.	Volts Max.	Amp Max. ①	Minimum Watts@120V② Heater Length			Maximum Watts				
			1 in. (25 mm)	1½ in. (38 mm)	2 in. (50 mm)	120V 1-phase	240V 1-phase	480V 1-phase	240V 3-phase	480V 3-phase
⅛	240	3.1	—	8	5	360	720	—	—	—
¼	240	4.4⑥	100	55	40	525	1050	—	—	—
⅜	240	6.7	65	35	25	800	1600	—	④	—
½	240	9.7	40	25	20	1,160	2,320	—	④	—
⅝	480	23.0	35	20	15	2,760	5,520	11,000	④	—
¾	480	23.0	30	15	10	2,760 ③	5,520	11,000	9,550	19,100
1	480	23.0	—	15	10	2,760 ③	5,520	11,000	9,550③	19,100 ③

① Determined by the current carrying capacity of standard internal parts and standard lead wire. Alternate material may be available.

② Determined by the limitation of space for resistance winding. For minimum wattage of 240V~(ac) multiply value by four.

③ Higher wattages are available using more than one set of power leads. Multiply the wattage from the table by the applicable factor.

④ Consult the Watlow factory in St. Louis, Missouri, for data.

⑤ On ¾ inch diameter units, either three single- phase circuits or one three-phase Delta or Wye circuit is available. On one inch diameter units, either five single-phase or two three-phase Delta circuits are available.

⑥ For ¼ inch units with thermocouple maximum amperage is 3.1.

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FIREROD

Maximum Allowable Watt Density

The following four charts detail maximum allowable watt densities for applications involving metal heating or steam, air and gas heating. Please review these respective charts and applicable data to determine the correct watt density for your application.

Correction Factors:

Also note, these graphs depict FIRERODs used in steel parts. Therefore, for either stainless steel or aluminum and brass, refer to applicable correction factors:

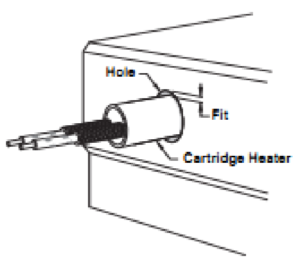
① For stainless steel, enter the graph with a fit 0.0015 inch (0.04 mm) larger than actual.

② For aluminum and brass, enter the graph with a temperature 38°C (100°F) above actual temperature.

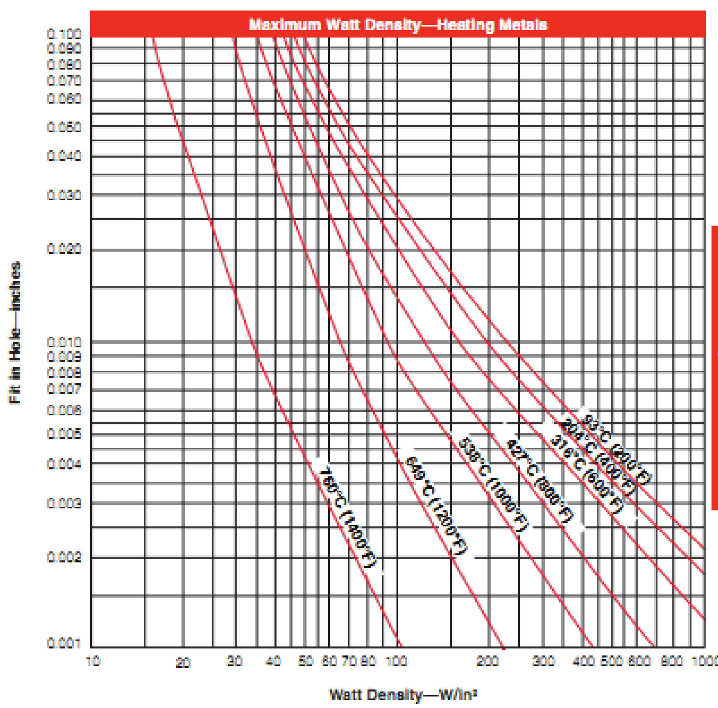
Heating Metals

The *Maximum Watt Density—Heating Metals* chart will tell you either the maximum hole fit or recommended watt density of the heater. Enter the chart with either known variable, part fit in hole dimension or W/in². Then find the application temperature by reading up or over on the chart.

If the fit of the heater in the hole dimension is not known, it is easily determined. Subtract the minimum diameter of the FIREROD (nominal diameter minus tolerance) from the maximum hole diameter. For example, take a hole diameter of 0.500 minus a heater diameter of 0.496 ±0.002 inch. The hole fit would be 0.006 inch. For FIREROD heaters in square holes or grooves, contact your Watlow sales engineer or authorized distributor for the fit in hole dimension.



Fit in hole = maximum hole I.D. minus minimum heater O.D.



PHYSICAL AND THERMAL PROPERTIES OF FOAMGLAS® ONE™ INSULATION

PHYSICAL PROPERTIES	ASTM			EN ISO
	SI	**ENGLISH**	**Method**	**Method**
Absorption of Moisture (Water % by Volume)	0.2%	0.2%	C 240	EN 1609 EN 12087
	Only moisture retained is that adhering to surface cells after immersion			
Water-Vapor Permeability	0.00 perm-cm	0.00 perm-in	E96 Wet Cup Procedure B	EN 12086 EN ISO 10456
Acid Resistance	Impervious to common acids and their fumes except hydrofluoric acid			
Capillarity	None			
Combustibility & Reaction to Fire	Noncombustible - will not burn Flame Spread 0 Smoke Development 0		E 136 E84	EN ISO 1182 (Class A1)
Composition	Soda-lime silicate glass – inorganic with no fibers or binders			
Compressive Strength, Block	620 kPa	90 psi	C 165 C 240 C 552	EN 826 Method A
	Strength for flat surfaces capped with hot asphalt.			
Density	120 kg/m^3	7.5 lb/ft^3	C 303	EN 1602
Dimensional Stability	Excellent—does not shrink, swell or warp			EN 1604 (DS 70/90)
Flexural Strength, Block	480 kPa	70 psi	C 203 C 240	EN 12089 (BS450)
Hygroscopicity	No increase in weight at 90% relative humidity			
Linear Coefficient of Thermal Expansion	9.0 x 10^{-6}/K 25°C to 300°C	5.0 x 10^{-6}/°F 75°F to 575°F	E 228	EN 13471
Maximum Service Temperature	482° C	900° F		
Modulus of Elasticity, Approx.	900 MPa	1.3 x 10^5 psi	C 623	EN 826 Method A1
Thermal Conductivity	W/mK 0.040 @ 10°C 0.042 @ 24°C	Btu-in/hr.ft^2.°F 0.28 @ 50°F 0.29 @ 75°F	C 177 C 518	EN 12667 EN 12939 ($\lambda_{D\ (90/90)}$ ≤ 0.041 W/mK @ 10° C)
Specific Heat	0.84 kJ/kg.K	0.18 Btu/lb.°F		
Thermal Diffusivity	4.2 x 10^{-7} m^2/sec	0.016 ft^2/hr		

Note: FOAMGLAS® ONE™ is manufactured to meet or exceed the minimum requirements of *ASTM C552-07 Standard Specification for Cellular Glass Insulation* (or most recent revision). Unless otherwise specified, measurements were collected using ASTM guidelines at 24°C (75°F) and are average or typical values recommended for design purposes and not intended as specification or limit values. Values under EN ISO are declared as limit values under the specific set of standard test conditions. Properties may vary with temperature. Where testing method or reporting values differ between ASTM and EN ISO methodologies, values are denoted within parentheses in the EN ISO column.

RTD

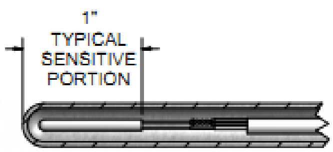
Configuration Code RT01

RTD Assemblies with Extension Leadwire

Configuration Code RT02

RTD Assemblies with Sheath Terminations

The RTD elements illustrated and described on this page are designed to measure temperature in a variety of process and laboratory applications. These RTDs are specifically designed for use in two different process temperature ranges and will provide accurate and repeatable temperature measurement through a broad range. Low range RTDs are constructed using Teflon®-insulated, silver-plated copper internal leads with potting compounds to resist moisture penetration. High range RTDs are constructed with nickel internal leads inside swaged MgO insulated cable to allow higher temperature measurements at the RTD element and provide higher temperature lead protection along the sheath. The following tables allow customer selection of standard element materials, tolerances, sheath diameters, mounting fittings and terminations. Custom-built assemblies with non-standard specifications are available upon request.



ORDER CODES

Example Order Number: R5T185L (1-1) 48 (1-2(A)) 3 (1-3) - 006 (1-4) - Page RTD-2 - Page RTD-3 - Page RTD-4 - Page RTD-5

1-1 Single Platinum RTD Elements / **1-2 Available Sheath Diameters 316SS**

CODE	TOLERANCE[1]	BASE RESISTANCE @ 0 °C (R_0)	TEMPERATURE COEFFICIENT	CODE			
LOW RANGE WIRE WOUND (-200 to 200) °C [-328 to 392] °F				*1/8" O.D.*	*3/16" O.D.*	*1/4" O.D.*	*3/8" O.D.*
R1T185L	Grade B	100 Ω	α = 0.003 85 °C⁻¹	28	38	48	68
R3T185L	Class AA	100 Ω	α = 0.003 85 °C⁻¹	28	38	48	68
R5T185L	(1/5) Class B	100 Ω	α = 0.003 85 °C⁻¹	28	38	48	68
R1T192L	Grade B	100 Ω	α = 0.003 92 °C⁻¹	28	38	48	68
R3T192L	Class AA	100 Ω	α = 0.003 92 °C⁻¹	28	38	48	68
LOW RANGE THIN FILM (-50 to 200) °C [-58 to 392] °F							
RBF185L	Class B	100 Ω	α = 0.003 85 °C⁻¹	28	38	48	68
RAF185L	Class A	100 Ω	α = 0.003 85 °C⁻¹	28	38	48	68
RBF195L	Class B	1000 Ω	α = 0.003 85 °C⁻¹	28	38	48	68
HIGH RANGE WIRE WOUND (-200 to 600) °C [-328 to 1112] °F							
R1T185H	Grade B	100 Ω	α = 0.003 85 °C⁻¹	28	38	48	68
RAT185H	Class A	100 Ω	α = 0.003 85 °C⁻¹	28	38	48	68
R1T192H	Grade B	100 Ω	α = 0.003 92 °C⁻¹	28	38	48	68

[1] Refer to RTD tolerance information in the general information section for calculations to determine specific tolerance at temperature.

1-1 Duplex Platinum RTD Elements / **1-2 Available Sheath Diameters 316SS**

CODE	TOLERANCE[1]	BASE RESISTANCE @ 0 °C (R_0)	TEMPERATURE COEFFICIENT	CODE		
LOW RANGE WIRE WOUND (-200 to 200) °C [-328 to 392] °F				*3/16" O.D.*	*1/4" O.D.*	*3/8" O.D.*
R1T285L	Grade B	100 Ω	α = 0.003 85 °C⁻¹	38	48	68
R3T285L	Class AA	100 Ω	α = 0.003 85 °C⁻¹	38	48	68
R5T285L	(1/5) Class B	100 Ω	α = 0.003 85 °C⁻¹	38	48	68
R1T292L	Grade B	100 Ω	α = 0.003 92 °C⁻¹	38	48	68
R3T292L	Class AA	100 Ω	α = 0.003 92 °C⁻¹	38	48	68
LOW RANGE THIN FILM (-50 to 200) °C [-58 to 392] °F						
RBF285L	Class B	100 Ω	α = 0.003 85 °C⁻¹	38	48	68
RAF285L	Class A	100 Ω	α = 0.003 85 °C⁻¹	38	48	68
RBF295L	Class B	1000 Ω	α = 0.003 85 °C⁻¹	38	48	68
HIGH RANGE WIRE WOUND (-200 to 600) °C [-328 to 1112] °F						
R1T285H	Class B	100 Ω	α = 0.003 85 °C⁻¹	38	48	68
RAT285H	Class A	100 Ω	α = 0.003 85 °C⁻¹	38	48	68
R1T292H	Grade B	100 Ω	α = 0.003 92 °C⁻¹	38	48	68

[1] Refer to RTD tolerance information in the general information section for calculations to determine specific tolerance at temperature.

1-4 Length

CODE
3 Digit 'X' Length

1-3 Element Connection

CODE	DESCRIPTION
2	2-wire
3	3-wire
4[1]	4-wire

[1] Not available in duplex

1-2A

CODE	NOMINAL SHEATH DIAMETER (inches)	TIP DIA. O.D. (inches)	TIP LENGTH (inches)
88R48	1/2	1/4	1 1/4
68R38	3/8	3/16	1 1/4
48R28	1/4	1/8	1 1/4

REDUCED-TIP RTD's

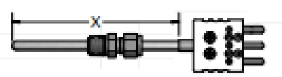
Table 1-2A lists RTD elements with reduced tip sheaths. To order, use order code numbers from Tbl. 1-2A in place of straight sheath order code numbers from Tbl. 1-2. Other reduced tips are available upon request. EXAMPLE: R1T185L88R483-006.

Teflon® is a registered trademark of E. I. du Pont de Nemours and Company.

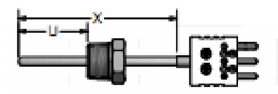
Optional Sheath Mounting Fittings and Bends

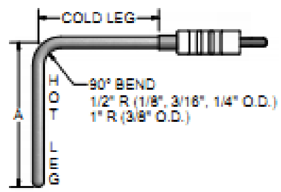
Select Sheath Mounting or Bend Options as desired from tables below.

COMPRESSION FITTING

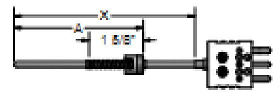


FIXED BUSHING

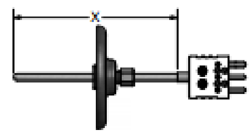




BAYONET CAP and SPRING (OPTION 13A)



ADJUSTABLE FLANGE (OPTION 14)



ORDER CODES

Example Order Number: **R5T185L483-006 - 01A,304 - PAGE RTD 3 - PAGE RTD 4 - PAGE RTD 5** (2)

2-1 No Fitting or Bend Options

CODE	00

2-2 One-time Adjustable Compression Fittings

CODE	TYPE	NPT SIZE (inches)	PRESSURE RATED	AVAILABLE SHEATH DIAMETERS (inches)
01A	303 stainless steel	1/8	NO	1/8, 3/16, 1/4
05A	316 stainless steel	1/8	YES	1/8, 3/16, 1/4
05B	316 stainless steel	1/4	YES	1/8, 3/16, 1/4, 3/8
05C	316 stainless steel	1/2	YES	1/8, 1/4, 3/8
15A	Brass	1/8	NO	1/8, 3/16, 1/4
15B	Brass	1/4	NO	3/16, 1/4, 3/8
15C	Brass	1/2	NO	1/4, 3/8

2-3 Re-adjustable Compression Fittings

CODE	TYPE	NPT SIZE (inches)	AVAILABLE SHEATH DIAMETERS (inches)
10A	303 stainless steel	1/8	1/8, 3/16
10B	303 stainless steel	1/4	1/4, 3/8
10C	303 stainless steel	1/2	1/4, 3/8
12A	316 stainless steel	1/8	1/8, 3/16, 1/4
12B	316 stainless steel	1/4	1/8, 3/16, 1/4, 3/8
12C	316 stainless steel	1/2	1/8, 1/4, 3/8
11A	Brass	1/8	1/8, 3/16, 1/4
11B	Brass	1/4	1/8, 3/16, 1/4, 3/8
11C	Brass	1/2	1/4, 3/8
19C	Spring-loaded SS well fitting	1/2	3/16, 1/4

Teflon® gland standard 204 °C [400 °F] max. For lava gland 649 °C [1200 °F] max. opt. 10A and 10B only use letter suffix "L" after compression fitting order code. EXAMPLE: 10AL for lava gland.

2-6 Miscellaneous Options

CODE	TYPE	AVAILABLE SHEATH DIAMETER (inches)
13A _ _ [1]	Spring-loaded bayonet fitting	1/8, 3/16
14	Adjustable flange with brass compression fitting	1/8, 3/16, 1/4, 3/8
16A	Spring-loaded adjustable bayonet compression fitting	1/8

[1] When ordering fixed bayonet fitting specify dimension "A". EXAMPLE: order code 13A06 is for a fixed bayonet adapter with 6" A Dimension.

2-5 Fixed Bushings

CODE 316 SS	MOUNTING THREAD NPT (inches)	AVAILABLE SHEATH DIAMETERS (inches)
8A _ _ [1]	1/8	1/8, 3/16, 1/4
8B _ _ [1]	1/4	1/8, 3/16, 1/4, 3/8
8C _ _ [1]	1/2	1/8, 3/16, 1/4, 3/8
8D _ _ [1]	3/4	1/8, 3/16, 1/4, 3/8

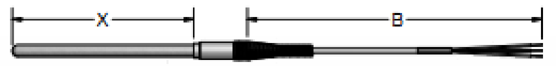
[1] When ordering fixed bushings, specify order code above, plus insertion length "U", as measured from hot tip to bottom of threaded bushing. EXAMPLE: order code 8A06 is 1/8" NPT, 316 SS bushing located 6" from hot tip.

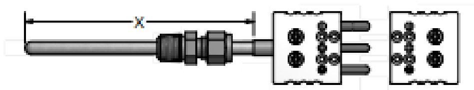
2-4 Sheath Bends

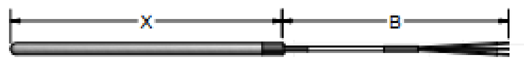
CODE	DESCRIPTION
2 _ _	Sheath bent 45°
3 _ _	Sheath bent 90°

2" minimum hot leg length

When ordering bend options, specify hot leg dim. "A". EXAMPLE: order code 206 is a 45° bend with 6" hot leg. Total sheath length is Table 1 "X" length = hot leg plus cold leg.







RT02 ORDER CODES RT01

Example Order Number:

R5T185L483-006-00 - [3-1: 4, MC] or R5T185L483-006-01A,304 - [3-2: 16] - [PAGE RTD-4] - [PAGE RTD-5]

3-1 Plug and Jack Sheath Terminations

CODE	DESCRIPTION
4[1]	Standard plug
5[1]	Standard jack
6[2]	Miniature plug
7[2]	Miniature jack
	Options
MC	Mating connector
CL	Compression L bracket to hold plug to sheath
[1] If used with 3/8" O.D., option CL must be specified [2] Not available with 1/4" O.D. or 3/8" O.D. sheath	

3-1 Sheath Terminations

CODE	DESCRIPTION
22[1]	3" individual leads with terminal pins
[1] High temp RTDs are supplied with 1" long transition	

3-2 Leadwire transitions

(Requires Table 4 and 5 selections)

CODE	DESCRIPTION
13[1]	Same size transition with heat-shrink tubing 104 °C [220 °F]
15	Extension leadwire transition with relief spring 204 °C [400 °F]
16	Extension leadwire transition with heat-shrink tubing 104 °C [220 °F]
18[1]	Same size transition without heat-shrink tubing 204 °C [400 °F]
19	Extension leadwire transition without spring or heat-shrink tubing 204 °C [400 °F]
	Options
HT[2]	High temperature potting 538 °C [1000 °F] not available with option 13 or 16
[1] Not available with flex armor	
[2] Not available with option 13 or 16. When specifying high temp potting with Flex Armor option 19 must be selected.	

3-2 Threaded Fittings with Extension Leadwire

(Requires Table 4 and 5 selections)

CODE	DESCRIPTION
6HN23	1/2" x 1/2" NPT steel hex nipple
8HN23	1/2" x 1/2" NPT stainless steel hex nipple
9HP23	1/2" NPT stainless steel bushing (no process threads)
8RNDC23	3/4" process x 1/2" NPT stainless steel hex nipple

STANDARD PLATINUM RTD ASSEMBLIES - Pyromation standard RTD assemblies are constructed using either wire-wound platinum elements or thin-film elements with a reference resistance of 100 ohms at 0 °C, a temperature coefficient 0.003 85 °C^{-1} and which are in accordance with the following standards:

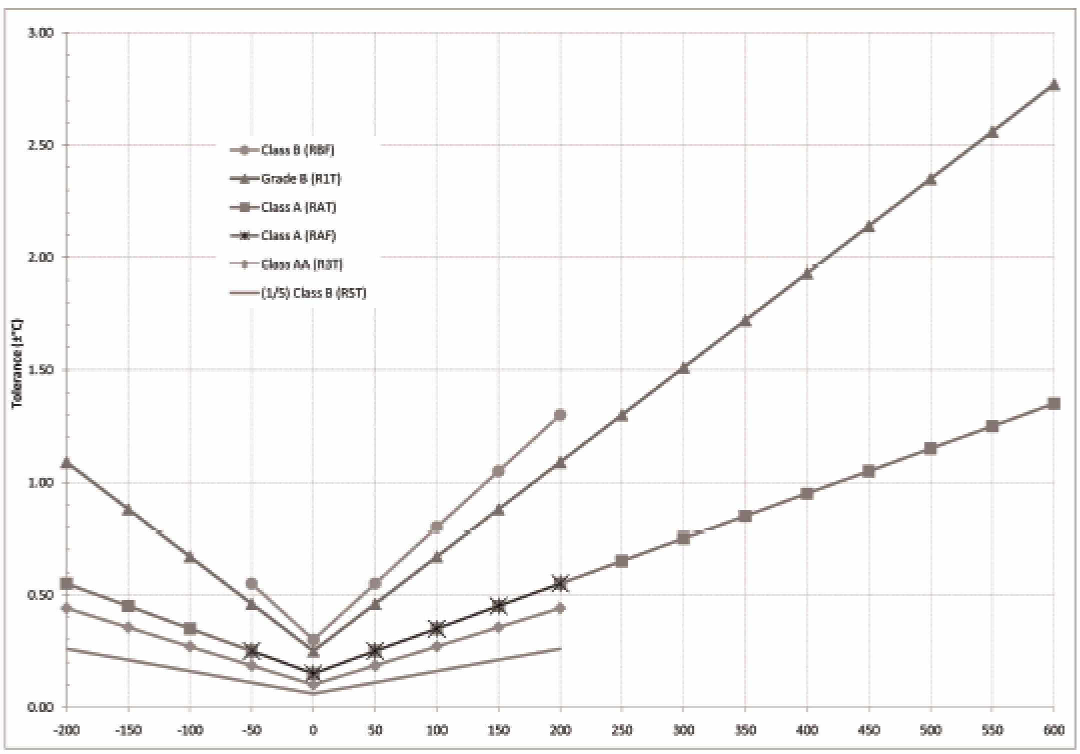
1. International Standard, IEC 60751 2. American Standard, ASTM E1137

TEMPERATURE		IEC CLASS B [1] ± (0.12% × R_o) Ω		ASTM GRADE B [1] ± (0.1% × R_o) Ω		IEC CLASS A [1] ± (0.06% × R_o) Ω		IEC CLASS AA [1] ± (0.04% × R_o) Ω		(1/5) IEC CLASS B [2] ± (0.02% × R_o) Ω	
		± (0.3 + 0.005 |t|) °C		± (0.25 + 0.0042 |t|) °C		± (0.15 + 0.002 |t|) °C		± (0.1 + 0.0017 |t|) °C		± (0.06 + 0.001 |t|) °C	
°C	[°F]	°C	[°F]	°C	[°F]	°C	[°F]	°C	[°F]	°C	[°F]
-200	[-328]			1.09	[1.96]	0.55	[0.99]	0.44	[0.79]	0.26	[0.47]
-100	[-148]			0.67	[1.21]	0.35	[0.63]	0.27	[0.49]	0.16	[0.29]
-50	[-58]	.55	[0.99]	0.46	[0.83]	0.25	[0.45]	0.19	[0.34]	0.11	[0.20]
0	[32]	.30	[0.54]	0.25	[0.45]	0.15	[0.27]	0.10	[0.18]	0.06	[0.11]
100	[212]	.80	[1.44]	0.67	[1.21]	0.35	[0.63]	0.27	[0.49]	0.16	[0.29]
200	[392]	1.3	[2.34]	1.09	[1.96]	0.55	[0.99]	0.44	[0.79]	0.26	[0.47]
300	[572]	1.8	[3.24]	1.51	[2.72]	0.75	[1.35]				
400	[752]	2.3	[4.14]	1.93	[3.47]	0.95	[1.71]				
500	[932]	2.8	[5.04]	2.35	[4.23]	1.15	[2.07]				
600	[1112]			2.77	[4.99]	1.35	[2.43]				

Where: |t| = value of temperature without regard to sign, °C

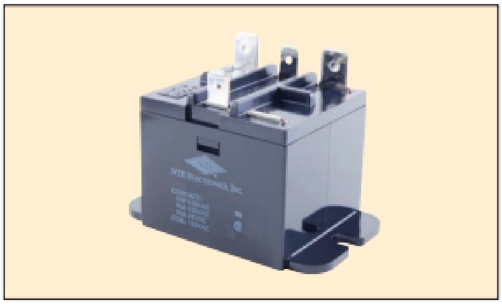
[1] The equations represent values for 3- and 4-wire PRTs. Caution must be exercised with 2-wire PRTs due to lead resistance.

[2] This tolerance can only be met with a 4-wire PRT.

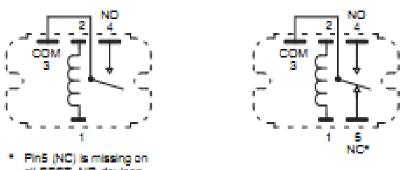


Features

- Miniature Relay Ideal for Switching Motor Load Lamp Load, Heater, etc.
- Creepage Distance of more than .08"
- Upper Mounting Bracket Type for Easy Wiring and Mounting
- .187" (4.75mm) Quick Connect Coil Terminals
- .250" (6.35mm) Quick Connect Terminals for Load

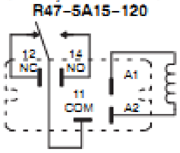


SPST–NO, 1 Form "A" SPDT, 1 Form "C"



* Pin5 (NC) is missing on all SPST–NO devices.

SPDT, 1 Form "C"
R47–5A15–120



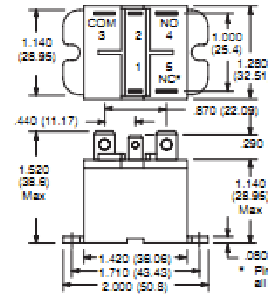
AC OPERATED						
NTE TYPE No.	Nom. Voltage	Contact Arr.	Coil Res. Ohms (Typ)	Approx. Nom. Power	Max. Contact Cur. @ 24VDC or 220VAC	Diag No.
R47–1A15–24	24VAC	SPST–NO	–	1.3VA	15A	D43a
R47–1A15–120	120VAC	SPST–NO	–	1.3VA	15A	D43a
R47–5A15–24	24VAC	SPDT	–	1.3VA	15A	D43a
R47–5A15–120	120VAC	SPDT	–	1.6VA	20A/10A *	D43b

* 250VAC, Resistive, 25°C

R47 Series

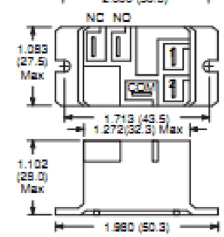
General Purpose, 15 Amp, AC SPST–NO & SPDT Relay for HVAC, Appliance Controls, and Copiers.

D43a



* Pin5 (NC) is missing on all SPST–NO devices.

D43b



Electrical Specifications

Contact

Rating: 15 Amp @ 28VDC (resistive load)
15 Amp @ 120VAC (inductive load)
10 Amp @ 240VAC (inductive load)
1HP @ 120VAC
20A/10A, 250VAC (resistive load) **R47–5A15–120 ONLY**

Material: AgCdO
AgSnOInO **R47–5A15–120 ONLY**

Resistance: 30mΩ (max.)
75mΩ (at 1A at 5VDC or 12VAC) **R47–5A15–120 ONLY**

Coil

Coil Voltages: See Chart
Pick–up Voltages: 80% of nominal Coil Vltg.
Drop–out Voltages: 30% of rated voltage (min.)
Resistance: See Chart

Operational Characteristics

Timing Values: . . . . **Operate Time:** 20 mS (max.)
. . . . **Operate Time:** 15 mS (max.) **R47–5A15–120**

Insulation Characteristics

Dielectric Strength: 2000VAC, 50/60Hz for 1 minute
(1000VAC between open contacts)
2500V_{rms} **R47–5A15–120 ONLY**
(1500VAC between open contacts)

Insulation Resistance: 100MΩ min. (at 500VDC)
1MΩ min. **R47–5A15–120 ONLY**

Environmental Characteristics

Operating: –10°C to +55°C

Life

Mechanical: 10,000,000 operations min
5,000,000 operations min **R47–5A15–120 ONLY**

Weight

Std: 1.55 oz (44 grams) approx
Std: 1.16 oz (33 grams) approx **R47–5A15–120 ONLY**

APPENDIX E

Fluid Loop Systems

POWER/ENERGY REQUIREMENTS

ASSUMPTIONS – PERFECTLY INSULATED, UNIFORM HEATING+COOLING,
– NO CHANGES IN PROPERTIES W/ TEMP

4 lb OF HEAT TRANSFER FLUID
– SPECIFIC HEAT = 0.36 BTU/LbF (CIGARCO SILICONE)
$m_F = 1.814$ kg (ROUND UP TO 2 kg)
$C_{p_F} = 1507$ J/kg K

HEAT TRANSFER (ISOTHERMAL) BLOCK
~ 10" x 4" x 3" = 120 in^3 = 0.002 m^3
$\rho_c = 8933$ kg/m^3 (HEAT TRANSFER - INCOPERA + DEWITT)
$C_{p_c} = 385$ J/kg K
$m_c = 18$ kg (THIS IS EXTREMELY HIGH!)
$E = mc\Delta T$

$$E = \left[18\,kg\left(385\,\frac{J}{kg\,K}\right) + 2\,kg\,(1507\,J/kgK)\right](340\,K)$$

$$E = [6930 + 3014]\,kg\,J/kgK\,(340\,K)$$

$E = 3381$ kJ
TO DO SWEEP IN ~3 hrs (10800 s)

POWER = 313 WATTS THIS IS FINE WITH A 120V, 10A SUPPLY

IN REALITY, COPPER WILL BE ~ 5 kg OR LESS

SO...
$m_c = 5$ kg

$$E = [5\,kg\,(385\,J/kgK) + 2\,kg\,(1507\,J/kgK)](340\,K)$$
E = 1680 J
POWER = 156 WATTS

Isothermal Block

THERMAL EXPANSION OF ISOTHERMAL BLOCK

$L = 10 in$

$L = 254 mm$

$L = 0.254 m$

$\alpha_{AL} = 23 \times 10^{-6} m/m°C$ AT 20°C

$\alpha_{CU} = 17 \times 10^{-6} m/m°C$ AT 20°C

$\Delta T = 340°C$

$\Delta L = \alpha L \Delta T$

$\Delta L_{AL} = 23 \times 10^{-6} \frac{m}{m°C} (0.254 m)(340°C)$

$\Delta L_{AL} = 0.001986 m$

$\Delta L_{AL} = 2 mm$

$\Delta L_{CU} = 17 \times 10^{-6} \frac{m}{m°C} (0.254 m)(340°C)$

$\Delta L_{CU} = 1.47 mm$

Triple Point Fluid

Power/Energy Requirements

Assumptions – Insulation (100%)
– Uniform Heating/cooling

*Note: look @ water @ boiling because it has the highest specific heat.

$m_{FH} = 5\,kg$ (Fluid, H_2O)

$C_{FH} = 421.9\ J/kgK$

Note: – $m_{copper} \approx 10\,kg$ (Guess)
– const. Temp.

Heat exchange

$E = mc\Delta T$

$= [10\,kg(385\ J/kgK) + 5\,kg(421.9\ J/kgK)](373K)$

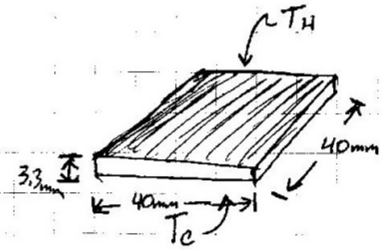
$E = 2222.9\ kJ$

$P = E \times 3\,hrs\left(\frac{3600\,s}{1\,hr}\right) \approx 205.8$ watts (This works)

* all other systems w/ lower specific heats means less power.

PRELIMINARY CALCULATIONS – FREE CONVECTION

FOR THERMOELECTRIC DEVICE
LAIRD THERMATEC HT8,12,F2,4040,TA,W6
SPECS: Q_{max} (@ T_H = 25°C) = 72 W
I_{max} " = 8.5 A
V_{max} " = 14.4 V
ΔT_{max} " = 63°C
Q_{max} (@ T_H = 200°C) = 87 W
I_{max} " = 7.7 A
V_{max} " = 22.8 V
ΔT_{max} " = 88°C



ASSUME AMBIENT CONDITIONS OF:
T_∞ = 25°C
u_∞ = 0 m/s

ASSUME HOT SIDE T_H = 200°C
ASSUME ΔT = 80°C, T_C = 120°C
ASSUME EFFECT OF HEAT TRANSFER OUT OF SIDES IS NEGLIGIBLE
FOR TOP, T_{f_H} = (200+25)/2 = 112.5°C = 385.5 K
FOR BOTTOM, T_{f_C} = (120+25)/2 = 72.5°C = 345.5 K
FROM HEAT TRANSFER
@ T = 350 K K = 0.030 W/mK, ν = 20.92 × 10^{-6} m²/s, α = 29.9 × 10^{-6} m²/s, Pr = 0.70, β = 0.00285 1/K
@ T = 386 K K = 0.0327 W/mK, ν = 24.87 × 10^{-6} m²/s, α = 36.45 × 10^{-6} m²/s, Pr = 0.693, β = 0.002591 K^{-1}

$$Ra_L = \frac{g\beta(T_s - T_\infty)L^3}{\nu\alpha}$$

$L = \frac{A_s}{P}$ FOR HORIZONTAL PLATES

A_s = 0.0016 m²
P = 0.16 m
L = 0.01 m

$$Ra_L = \frac{g\beta(T_s - T_\infty)L^3}{\nu\alpha}$$

FOR TOP PLATE (HOT SIDE)

$$Ra_{L_H} = \frac{9.81\,m/s^2\,(0.002591\,K^{-1})(175\,K)(0.01\,m)^3}{(24.87\times10^{-6}\,m^2/s)(36.45\times10^{-6}\,m^2/s)}$$

$$Ra_{L_H} = 4906.8$$

FOR BOTTOM PLATE (COLD SIDE)

$$Ra_{L_C} = \frac{9.81\,m/s^2(0.00285\,K^{-1})(95\,K)(0.01\,m)^3}{(20.92\times10^{-6}\,m^2/s)(29.9\times10^{-6}\,m^2/s)}$$

$$Ra_{L_C} = 4246.24$$

CORRELATION FOR UPPER SURFACE, HOT PLATE

$$\overline{Nu}_L = 0.54\,Ra_L^{1/4}$$

$$\overline{Nu}_L = 0.54(4907)^{1/4}$$

$$\overline{Nu}_L = 4.52$$

CORRELATION FOR LOWER SURFACE, HOT PLATE

$$\overline{Nu}_L = 0.27\,Ra_L^{1/4}$$

$$\overline{Nu}_L = 0.27(4246)^{1/4}$$

$$\overline{Nu}_L = 2.18$$

$$\bar{h} = \frac{K}{L}(\overline{Nu}_L)$$

FOR UPPER PLATE

$$\bar{h}_H = \frac{0.0327\,\frac{W}{mK}}{0.01\,m}(4.52)$$

$$\bar{h}_H = 14.78\,W/m^2K$$

FOR LOWER PLATE

$$\bar{h}_L = \frac{0.030\,\frac{W}{mK}}{0.01\,m}(2.18)$$

$$\bar{h}_L = 6.54\,W/m^2K$$

NEWTON'S LAW OF COOLING

$q = \bar{h} A_s (T_s - T_\infty)$

FOR LOWER SURFACE

$q_L = 6.54 \frac{W}{m^2 K} (0.0016 m^2)(95 K)$

$q_L = 0.994 W$

FOR UPPER SURFACE

$q_H = 14.78 \frac{W}{m^2 K} (0.0016 m^2)(175 K)$

$q_H = 4.14 W$

NEGLECTING RADIATION HT, AT STEADY STATE CONDITIONS, STILL AMBIENT CONDITIONS ($u_\infty = 0 m/s$), FREE CONVECTION ONLY TO MAINTAIN $T_H = 200°C$ & $T_L = 120°C$ REQUIRED POWER INPUT $\cong$ 5 WATTS WHICH IS MINIMAL.

ONE UNIT IS 40x40mm, SO TO PROVIDE ENOUGH ROOM FOR 25 THERMOCOUPLE JUNCTIONS, ANOTHER UNIT SHOULD BE USED OR A THERMALLY CONDUCTIVE PLATE SHOULD BE ATTACHED.

IT IS EXPECTED THAT A FIN-TYPE HEAT SINK WILL BE AFFIXED TO COLD SIDE

REDO, ASSUMING: $T_H = 300°C = 573 K$

$T_c = 220°C = 493 K$

$T_\infty = 25°C = 298 K$ $\quad$ $w = 0.05 m$

$u_\infty = 0 m/s$ $\quad$ $l = 0.05 m$

$A_s = 0.0025 m^2$

$L = 0.0125 m$

$T_{f_H} = 435.5 K$ $\quad k = 0.0363 W/mK$, $\nu = 30.66 \times 10^{-6} m^2/s$, $\alpha = 44.62 \times 10^{-6} m^2/s$, $Pr = 0.688$ $\quad \beta = 0.0023 K^{-1}$

$T_{f_c} = 395.5 K$ $\quad k = 0.0338 \frac{W}{mK}$, $\nu = 26.4 \times 10^{-6} m^2/s$, $\alpha = 38.3 \times 10^{-6} m^2/s$, $Pr = 0.69$ $\quad \beta = 0.0025 K^{-1}$

TOP PLATE (HOT SIDE)

$$Ra_{L_H} = \frac{9.81\,\frac{m}{s^2}(0.0023\,K^{-1})(275\,K)(0.0125\,m)^3}{30.66\times10^{-6}\,m^2/s\,(44.62\times10^{-6}\,m^2/s)}$$

$$Ra_{L_H} = 8858$$

FOR BOTTOM PLATE (COLD SIDE)

$$Ra_{L_C} = \frac{9.81\,m/s^2(0.0025\,K^{-1})(195\,K)(0.0125\,m)^3}{26.4\times10^{-6}\,m^2/s\,(38.3\times10^{-6}\,m^2/s)}$$

$$Ra_{L_C} = 9238$$

UPPER SURFACE OF HOT PLATE

$$\overline{Nu}_L = 0.54\,Ra_L^{1/4}$$

$$\overline{Nu}_{L_H} = 5.24$$

LOWER SURFACE (ALSO HOTTER THAN T_∞)

$$\overline{Nu}_{L_C} = 0.27\,Ra_L^{1/4}$$

$$\overline{Nu}_{L_C} = 2.65$$

FOR UPPER SURFACE -

$$\bar{h}_H = \frac{0.0363\,W/m^2K}{0.0125\,m}(5.24)$$

$$\bar{h}_H = 15.22\,W/m^2{\cdot}K$$

FOR LOWER SURFACE -

$$\bar{h}_L = \frac{0.0338\,W/m^2K}{0.0125\,m}(2.65)$$

$$\bar{h}_L = 7.17\,W/m^2{\cdot}K$$

$$q = \bar{h}A_s(T_s - T_\infty)$$

$$q_H = 15.22\,W/m^2K\,(0.0025\,m^2)(275\,K)$$

$$q_H = 10.46\text{ WATTS}$$

$$q_L = 7.17\,W/m^2K\,(0.0025\,m^2)(195\,K)$$

$$q_L = 3.50\text{ WATTS}$$

AT A HOT SIDE OF 300°C AND A ΔT OF 80°C ($T_C = 220°C$)
POWER REQUIREMENT @ STEADY STAT ≅ 15 WATTS.

Design Stage Uncertainty Propagation

UNCERTAINTY PROPAGATION - THERMOCOUPLE READING

ANALYZING NATIONAL INSTRUMENTS NI 9214 THERMOCOUPLE DAQ

COLD JUNCTION COMPENSATION ERROR - 0.9°C (-40 TO 70°C) MAX
0.25°C (23°C) TYPICAL

OFFSET ERROR - 2×10^{-6} V TYPICAL
8×10^{-6} V MAX

GAIN ERROR - 0.03% (25°C) TYPICAL
0.15% MAX (-40 TO 70°C)

A/D CONVERTER - 24 BIT
VOLTAGE RANGE - ± 78.125 mV

UNCERTAINTY IN A/D CONVERTER

$$\frac{2(78.125)\,mV}{2^{24}} = 9 \times 10^{-9}\,V$$

OFFSET ERROR

2×10^{-6} V TYPICAL
8×10^{-6} V MAX

$$u_{DAQ} = \pm\left((9 \times 10^{-9})^2 + (2 \times 10^{-6})^2\right)^{1/2} \quad \text{TYPICAL}$$
$$u_{DAQ} = \pm\left((9 \times 10^{-9})^2 + (8 \times 10^{-6})^2\right)^{1/2} \quad \text{MAX}$$
$$u_{DAQ} = \pm 2\,\mu V \text{ TYPICAL}$$
$$\pm 8\,\mu V \text{ MAX}$$

AS EXPECTED, 24 BIT A/D CONVERTER DOES NOT APPRECIABLY CONTRIBUTE TO UNCERTAINTY

CONVERTING μV ERROR TO °C ERROR, DETERMINE STATIC SENSITIVITY FROM ASTM TABLE

TYPE K - 0.0415 mV/°C AT 300°C

0.039 mV/°C AT 0°C

0.037 mV/°C AT -40°C

TYPE T - 0.058 mV/°C AT 300°C

0.039 mV/°C AT 0°C

0.035 mV/°C AT -40°C

UNCERTAINTY PROPAGATION - THERMOCOUPLE READING CONT.

TYPE K

TEMPERATURE	UNCERTAINTY MAX	UNCERTAINTY TYPICAL
300°C	±0.19°C	±0.048°C
0°C	±0.21°C	±0.051°C
-40°C	±0.22°C	±0.054°C

TYPE T

TEMPERATURE	UNCERTAINTY MAX	UNCERTAINTY TYPICAL
300°C	±0.14°C	±0.034°C
0°C	±0.21°C	±0.051°C
-40°C	±0.23°C	±0.057°C

TOTAL DAQ SYSTEM UNCERTAINTY

TYPE K

AT 300°C

$$U_{MAX_{K300}} = \left[(0.9°C)^2 + (0.45°C)^2 + (0.19°C)^2\right]^{1/2}$$

$$U_{MAX_{K300}} = \pm 1.02°C$$

$$U_{TYP_{K300}} = \left[(0.25°C)^2 + (0.09°C)^2 + (0.048°C)^2\right]^{1/2}$$

$$U_{TYP_{K300}} = \pm 0.27°C$$

AT -40°C

$$U_{MAX_{K-40}} = \left[(0.9°C)^2 + (0.06°C)^2 + (0.22°C)^2\right]^{1/2}$$

$$U_{MAX_{K-40}} = \pm 0.93°C$$

$$U_{TYP_{K-40}} = \left[(0.25°C)^2 + (0.012°C)^2 + (0.054°C)^2\right]^{1/2}$$

$$U_{TYP_{K-40}} = \pm 0.26°C$$

TYPE T

AT 300°C

$$U_{MAX_{T300}} = \left[(0.9°C)^2 + (0.45°C)^2 + (0.14°C)^2\right]^{1/2}$$

$$U_{MAX_{T300}} = \pm 1.02°C$$

$$U_{TYP_{T300}} = \left[(0.25°C)^2 + (0.09°C)^2 + (0.034°C)^2\right]^{1/2}$$

$$U_{TYP_{T300}} = \pm 0.27°C$$

UNCERTAINTY PROPAGATION - THERMOCOUPLE READING CONT.

TYPE T

AT -40°C

$$U_{MAX_{T-40}} = \left[(0.9°C)^2 + (0.06°C)^2 + (0.23°C)^2\right]^{1/2}$$

$$U_{MAX_{T-40}} = \pm 0.93°C$$

$$U_{TYP_{T-40}} = \left[(0.25°C)^2 + (0.012°C)^2 + (0.057°C)^2\right]^{1/2}$$

$$U_{TYP_{T-40}} = \pm 0.26°C$$

IF COLD JUNCTION COMPENSATION ERROR IS REDUCED BY AN ORDER OF MAGNITUDE;
0.09°C MAX, 0.025°C TYPICAL

THEN MAX TOTAL ERROR

$$U_{TOT_{MAX}} = \pm 0.5°C \text{ AT } 300°C$$
$$\pm 0.25°C \text{ AT } -40°C$$

TYPICAL ERROR

$$U_{TOT_{TYP}} = \pm 0.1°C \text{ AT } 300°C$$
$$\pm 0.06°C \text{ AT } -40°C$$

Thermal Expansion Calculations

MATERIAL FOR ISOTHERMAL BLOCKS

ALUMINUM PROPERTIES: $\alpha = 22.2 \times 10^{-6} \frac{m}{mK}$ (LINEAR)

MELTING POINT ≈ 650°C

COPPER PROPERTIES: $\alpha = 16.6 \times 10^{-6} \frac{m}{mK}$ (LINEAR)

MELTING POINT ≈ 1080°C

TOTAL LENGTH CHANGE FOR 12" LONG BLOCK, $\Delta T = 340°C$

$$\frac{\Delta L}{L} = \alpha \Delta T$$

$$\Delta L = \alpha \Delta T L$$

ALUMINUM

$$\Delta L_{AL} = 22.2 \times 10^{-6} \frac{m}{mK} (340K)(0.3048m)$$

$$\Delta L_{AL} = 0.002301m$$
$$\Delta L_{AL} = 0.0906in$$

COPPER

$$\Delta L_{CU} = 16.6 \times 10^{-6} \frac{m}{mK} (340K)(0.3048m)$$

$$\Delta L_{CU} = 0.00172m$$
$$\Delta L_{CU} = 0.0677in$$

ΔL OF COPPER IS ~ 2/3 LESS THAN ALUMINUM

Insulation Comparison Calculations

COMPARING INSULATIONS

FOAM GLASS – DENSITY – $120 kg/m^3$

k_{AVE} – 0.043 W/mK / 0.039 W/mK

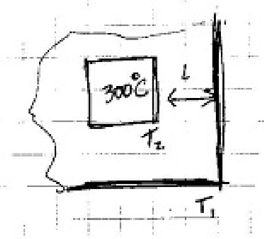
k_{MAX} – 0.046 W/mK / 0.042 W/mK

THERMAL EX. – 9×10^{-6} °C^{-1}

CALCIUM SILICATE – DENSITY – $14.5 lb/ft^3$

K VALUE – ~~0.73~~ $\frac{BTU}{hr\,ft\,°F}$ $0.103 \frac{W}{mK}$

ASSUMING COPPER IS AT 300°C = 573K



$$\dot{q} = k \frac{(T_2 - T_1)}{L}$$

FOR $L = 2''$ (50.8mm)

T_1 = 100°C (373K)

FOAM GLASS

$$\dot{q} = 0.046 \frac{W}{mK} \left(\frac{200K}{0.0508m} \right)$$

$$\dot{q} = 181.1 \; W/m^2$$

CALCIUM SILICATE

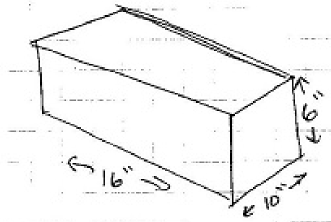
$$\dot{q} = 0.103 \frac{W}{mK} \left(\frac{200K}{0.0508m} \right)$$

$$\dot{q} = 405.5 \; W/m^2$$

FOAM GLASS TEMP RANGE – -450°F TO 900°F (-260 TO 480°C)

CALCIUM SILICATE TEMP RANGE – -18°C TO 650°C

ASSUMING TOTAL OUTSIDE DIMENSIONS



≈16" x 10" x 6" = 0.4064 m x 0.254 m x 0.1524 m

SURFACE AREA = 2(0.254·0.1524) + 2(0.4064·0.254) + 2(0.464·0.1524)

AREA = 0.4253 m^2

LOSSES ≅ 77 WATTS AT 300°C w/2" FOAM GLASS

WHAT ABOUT 3"?

$q'' = 0.046 \frac{W}{mK} \left(\frac{200K}{0.0762m}\right)$

$q'' = 120.7\ W/m^2$

q = 51 WATTS @ 300°C w/3" FOAM GLASS

FOAM COMES IN 24" x 18" x 6" SIZE

Low Temperature Block Time To Temperature Calculations

TIME TO TEMPERATURE

COPPER DENSITY = $8940\ kg/m^3$

COPPER MASS →

$V = (2 \times 2 \times 12)\,in^3 - (\pi(0.375\,in)^2 \cdot 7\,in) - (\pi(0.7\,in)^2 \cdot 2.4\,in)$

VOLUME = $41.2\,in^3$

VOLUME = $6.9 \times 10^{-4}\,m^3$

MASS = 6.15 kg

$C_{p_{cu}} = 0.39\ kJ/kg\,K$

ENERGY TO TEMP = $0.39 \frac{kJ}{kg\,K}(6.15\,kg)(65\,K)$

ASSUME AMBIENT = 25°C, $\Delta T = 65\,K$

ENERGY = 155.9 kJ

TIME TO TEMP

AVE POWER OF COOLER (25°C TO -40°C) = 165 WATTS

TIME TO -40°C = $\frac{155900\,J}{165\,J/s}$

TIME = 945 s

TIME = 15.75 min

* THIS ASSUMES NO HEAT LOSS

HEAT LOSS THRU INSULATION - LOW TEMPERATURE

$\dot{q} = K \frac{T_2 - T_1}{L}$

$T_2 = -40°C$
$T_1 = 25°C$
$K = 0.046\ W/mK$ (FOAM GLASS INSULATION)

$\dot{q} = 0.046 \frac{W}{mK} \frac{(65K)}{0.0508m}$

$\dot{q} = 58.9\ W/m^2$

ASSUMING SURFACE AREA ≅ $0.4253m^2$

$\dot{q} = 58.9 \frac{W}{m^2}(0.4253m^2)$

$\dot{q} = 25$ WATTS @ $-40°C$

TIME TO TEMPERATURE

COOLER POWER @ $-40°C$ = 70 WATTS
HEAT LOSS @ $-40°C$ = 25 WATTS

SO FROM $-30°C$ TO $-40°C$

~ 50 WATTS AVAILABLE

$TIME = 390 \frac{J}{kg\,K}(6.15kg)(10K)\left(\frac{1}{50\frac{J}{s}}\right)$

TIME = 479.7s

TIME = 8 MINUTES

ΔT	AVAILABLE POWER	HEAT LOSS	TIME REQUIRED
25°C TO 0°C	200W	10W	5.25 MIN
0°C TO -10°C	185W	10W	2.3 MIN
-10°C TO -20°C	170W	10W	2.5 MIN
-20°C TO -30°C	120W	10W	3.6 MIN
-30°C TO -40°C	70W	10W	8 MIN

TOTAL TIME ~ 22 MIN

Thermocouple Mounting Pressure

THERMOCOUPLE MOUNTING PRESSURE

$\text{TORQUE} = K F_i d$

K = TORQUE FACTOR (FRICTION) = 0.2 - ASSUME NO LUBRICATION
F_i = PRELOAD FORCE
d = SCREW MAJOR DIAMETER

SCREW SIZE = 4-40

$d = .112\,\text{in}$
$\text{TORQUE} = 4\,\text{in}\cdot\text{lbf}$ ASSUMING LOW TORQUE, BRASS SCREWS

$$F_i = \frac{\text{TORQUE}}{Kd}$$

$$F_i = \frac{4\,\text{in}\cdot\text{lbf}}{0.2(.112\,\text{in})}$$

$$F_i = 179\,\text{lbf}$$

$$P_{AVE} = \frac{n F_i}{A}$$

$A = 3.64\,\text{in}^2$ AREA OF COPPER CONTACT
$n = 8$ NUMBER OF SCREWS

$$P_{AVE} = \frac{8(179\,\text{lbf})}{3.64\,\text{in}^2}$$

$$P_{AVE} = 393\,\text{psi}$$

APPENDIX F

Gantt Chart

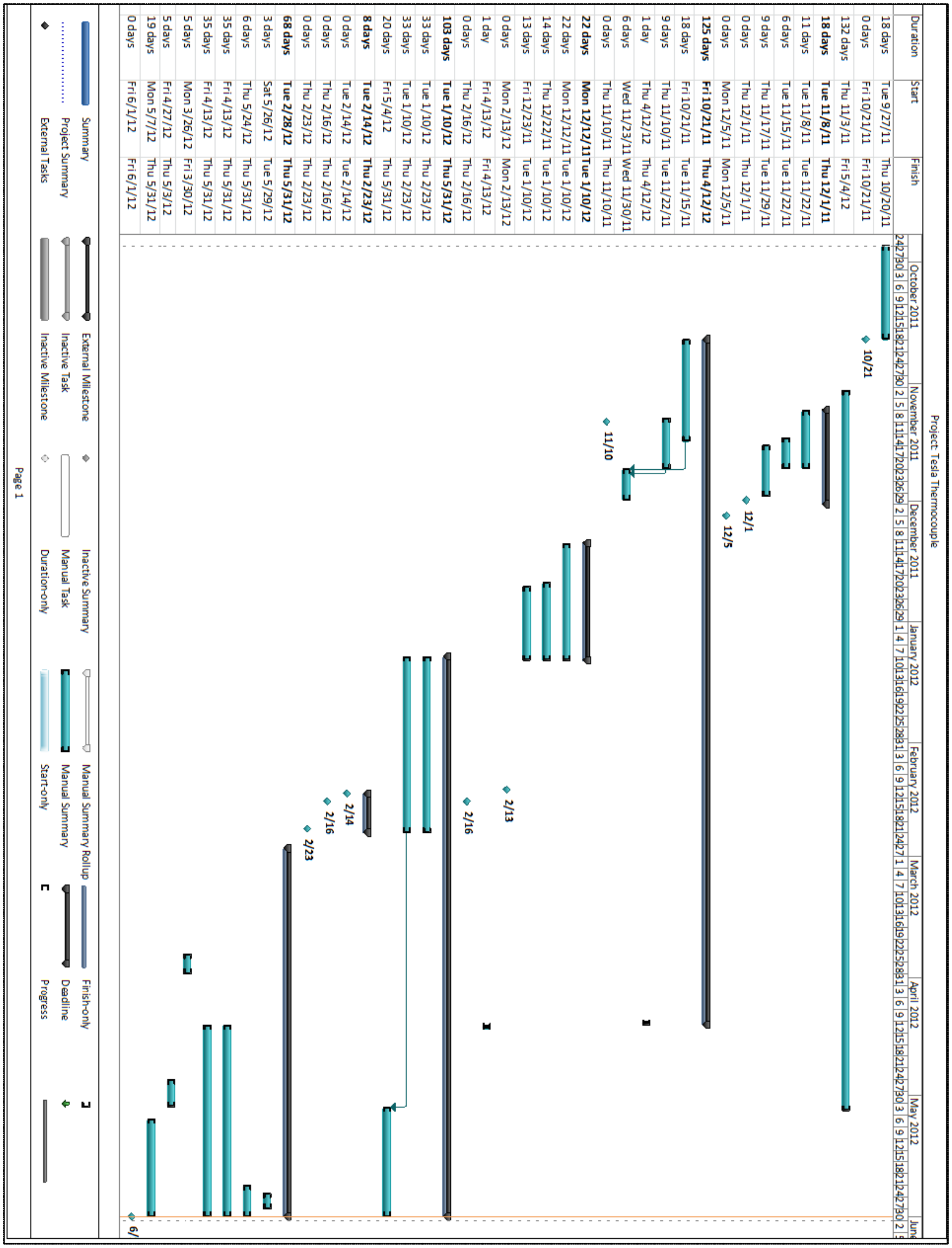


Figure A-13. Gantt Chart