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Thermal Resistance Characterization of High-Voltage SiC Power Module

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Thermal Resistance Characterization of High-Voltage SiC Power Module

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ABSTRACT

Researchers within the University of Arkansas Electrical Engineering Research Department have embarked on a project aimed at enhancing the thermal performance of high-voltage power modules. To aid in the progress of this project, the design, and development of a thermal tester device are needed. The primary objective of this device is to determine the various thermal properties of high-voltage power modules that the electrical engineering department has developed. Additionally, the project aims to facilitate electrical loading tests on power modules and provide researchers with the means to calibrate the power module in terms of thermal load. This project also possesses long-term capabilities that extend beyond its initial objectives. These include the optimization of the thermal path of the power module and its components, as well as the development of improved heat dissipation designs. The research team also plans to conduct further experiments involving cooling devices attached to the system, with the goal of obtaining comprehensive cooling curve measurement data. My current design incorporates a metal heat dissipation block with attached equally spaced thermocouples. This setup allows for approximate heat dissipation measurements to be taken at different distances from the initial heat source. These measurements when paired with Fourier's Law allow the operator to make conclusions on the thermal properties of different parts and components. In summary, this project involves assessing and optimizing the thermal performance of the power modules that have been produced by the electrical engineering department. The project aims to determine thermal properties, conduct thermal and electrical loading tests, and enable calibration of the power module in terms of thermal load. Future capabilities include further optimization, improved heat dissipation designs, and the acquisition of cooling curve measurement data.

CHAPTER 1: INTRODUCTION

1.1 Background

Within the field of power electronics, one of the most common issues is extreme thermal loading [1]. As different power electronic devices develop the capability to handle higher voltages, currents, and switching frequencies, the thermal load on the devices themselves can dramatically increase. High temperatures can cause semiconductors to overheat and burn out, as well as cause component degradation and damage [2].

Power electronics is a growing field of research, development, and manufacturing. Different industries such as medical equipment manufacturing, power transmission and generation, industrial production, and EV design and manufacturing utilize power electronics and more specifically high-voltage power modules to transport and convert energy and power [3]. Given the tremendous amount of new development within the field of power electronics, thermal testing devices can play a pivotal role in design and development.

Thermal testing and analysis can be conducted to better determine the capabilities of newly developed power electronics, and more specifically high voltage power modules when placed under thermal load [4], [5]. The data provided from thermal testing can be used to further develop the research and design efforts of power electronics. One of the main variables that is used as a key data point in power electronics design and development is thermal conductivity. Thermal conductivity is defined as the ability of a substance or material to conduct heat or move heat from one location to another [6]. The main goal of the thermal analysis device described in this report was to enable users to effectively measure the thermal conductivity of certain power electronics.

1.2 Literature review

Current thermal testing and analysis devices vary in capabilities, dimensional testing size, and testing methods. Some alternative testing technologies use infrared cameras and sensors that offer the ability to measure components at a distance and give a big-picture summation of thermal distribution. Other common testing methods involve thermogravimetric analysis, a process by which machines can monitor the change in mass of a sample as it is subjected to temperature changes [2]. The thermal tester device in question measures the heat transfer process via a method of conductive thermal analysis through the use of a thermocouple array. This method has been commonly used before, and some examples of current designs are as follows.

LW-9389 TIM Tester; ASTM D-5470 Thermal Interface Test Instrument [7]

This tester utilizes a design that implements a heating element and cold plate which are on opposing sides of the test specimen. The design also utilizes a hydraulic cylinder that applies a force load which keeps the test specimen in place. The main downside of this device is the fact that test specimens can only be tested accurately if they are uniform in material geometry. The test specimen also needs to be capable of withstanding compression from its top and bottom surface.

Peter Teertstra; Microelectronics Heat Transfer Laboratory Tester [8]

This apparatus resembles the LW-9389 TIM tester but provides the user the capability to test larger test samples. It also has the same disadvantages of not allowing the user to test large multi-material parts and calls for the user to apply a designated force load on the material in question. Another key design feature that both this tester and the LW-9389 tester utilize is a fully enclosed vacuum chamber which is used to minimize convective heat loss.

1.3 Objectives

The focus of the thermal analysis device consists of facilitating the testing of electronic components of varying sizes and shapes, emphasizing the assessment of their thermal properties. Additionally, the project seeks to enable researchers to conduct thorough thermal and electrical loading tests on diverse electrical components and substrates. One pivotal aspect of the project involves the translation of 3-D heat transfer into 1-D heat transfer, achieved through the utilization of a large volume heat dissipation block. The main power electronic components that will initially be tested are High Voltage SiC Power Modules. Through the methodology described in the following report, the thermal analysis device aims to provide researchers with the capability to accurately measure the thermal resistance of said High-Voltage SiC Power Modules.

Looking towards long-term capabilities, the device should ideally have the ability to aid in the potential optimization of thermal loading paths of high-voltage power modules and their subsequent components. This involves conducting further testing with cooling devices and other apparatuses integrated into the system, as well as adding additional measurement capabilities through various measurement instruments. To enhance versatility, the device should have the capability to gather data at different power input levels which can be selected by the user. After initial development and design, many potential improvements to the design and capabilities of the thermal analysis device will likely be suggested. These suggestions will also ideally be implemented into the system in the future to further improve upon the initial design. Through these multifaceted objectives, the project strives to contribute significantly to the understanding and optimization of thermal properties in power electronic components.

CHAPTER 2: METHODOLOGY

The device in question measures the heat transfer process via a method of conductive thermal analysis through the use of a thermocouple array. Thermocouples provide certain advantages over other measurement devices. One major advantage is enabling the user to determine the temperature of a medium at an exact point [9]. This can be critical in determining an exact temperature gradient. Many current designs for thermal analysis devices utilize thermocouple arrays to determine temperature distributions of different mediums. These devices utilize data acquisition modules to gather information and data from thermocouple arrays. In many cases, the medium being analyzed is hard-mounted to the tester by either a bolt assembly or some other spring mounting device. Often times there is also a hot and cold plate being used within the system to regulate temperature.

One disadvantage of conductive heat transfer analysis devices is both form factor and specified testing parameters. Many times, these devices are small in size and also only allow for testing of certain specified mediums. One goal of the thermal analysis device in question is to enable a wide variety of devices to be tested. This means allowing for devices of different geometries and materials to be tested accurately. This goal was met by using a large, machined block with a high level of mounting modularity, along with a very large mounting surface area.

The design and fabrication of this device involved the use of CAD software along with custom machining. The block that makes up the main portion of the tester is made of 6061 aluminum which has been machined to have evenly spaced thermocouple mounting holes. This block is stacked on top of an identical aluminum block which is submerged in an ice bath. The ice bath is kept at a constant temperature. The extra block and ice bath serve to enable the device to reach and maintain a steady state temperature. Each thermocouple mounting hole is drilled and tapped to fit 1/8th inch NPT tube fittings. These fittings are able to hold the 0.062-inch type T thermocouples. For testing, three thermocouples were used at different mounting positions. In order to provide the thermocouples, the ability to measure the temperature of the aluminum block, the holes are filled with oil before being capped with the thermocouple NPT fittings. The top block portion of the assembly is then lined with foam insulation to prevent heat loss due to convection. The tester sub-assembly is shown in CAD renderings in (*Figure 1*).

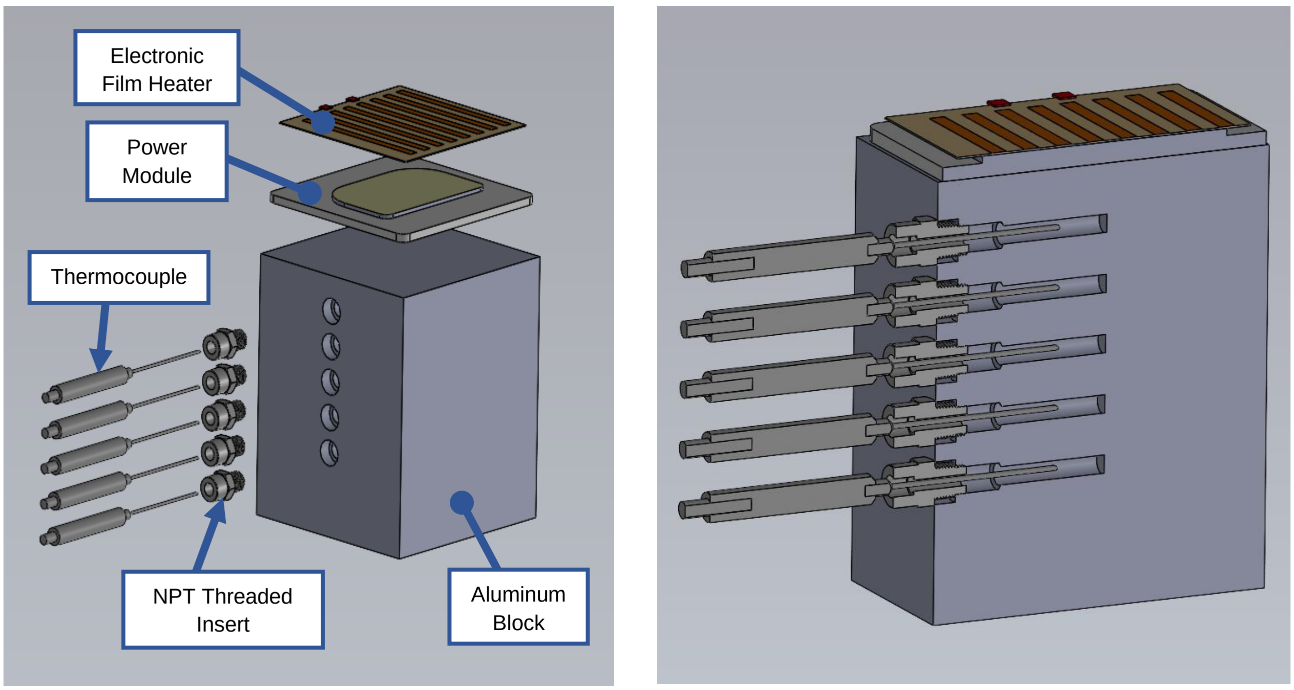


Figure 1. CAD renderings of Thermal Analysis Device Design

Using a power supply, the approximate wattage input of the thermal heaters can be determined. Within my setup, the thermocouples that are mounted to the tester block can be used to determine the temperature at different distances from the power modules and electronic film heaters. Once these values have been found, the values for the thermal resistance of the power modules can be calculated, along with several other thermal variables [10].

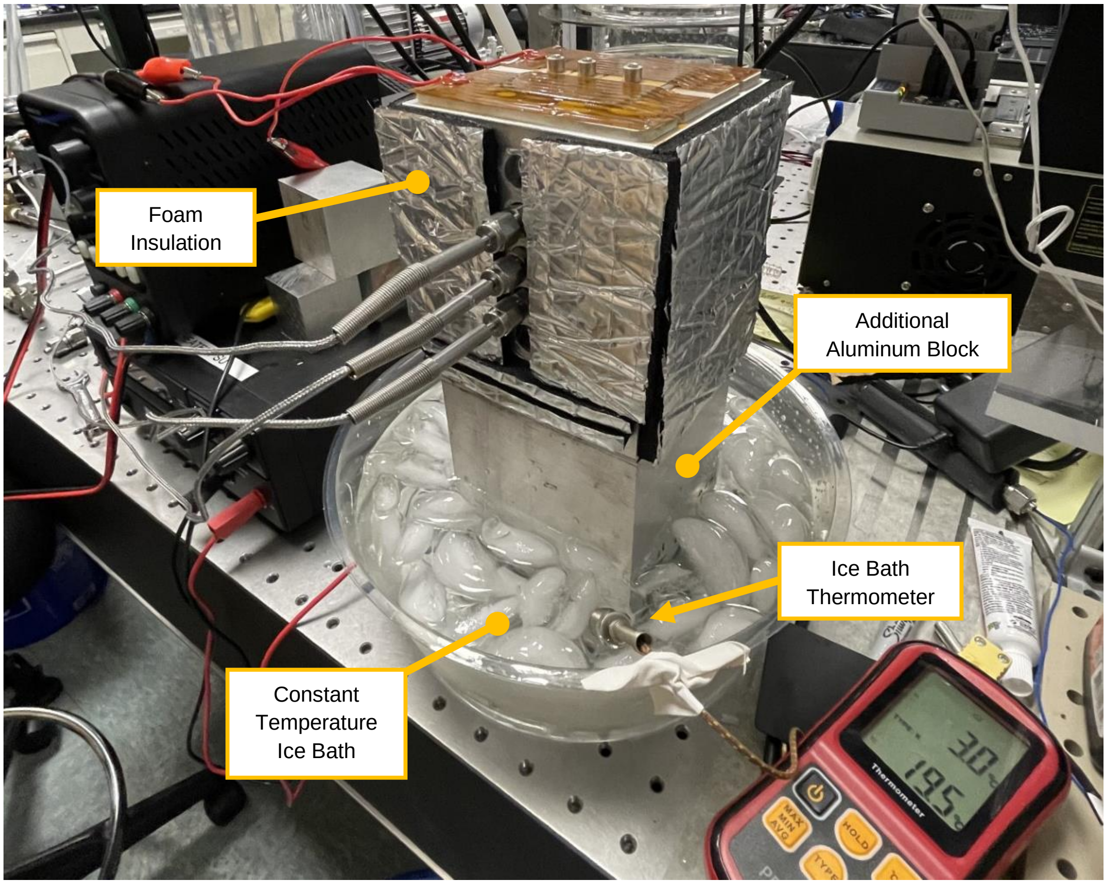


Figure 2. Image of Complete Thermal Analysis Tester Assembly

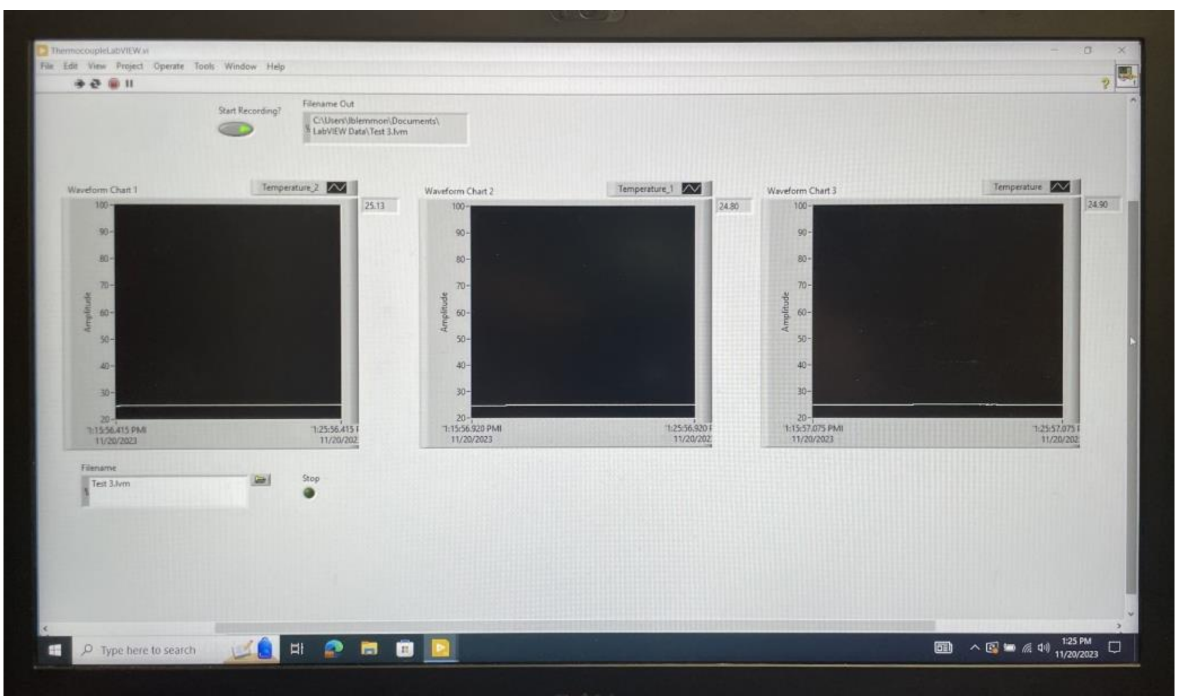


Figure 3. DAQ Output Software Window (LabVIEW)

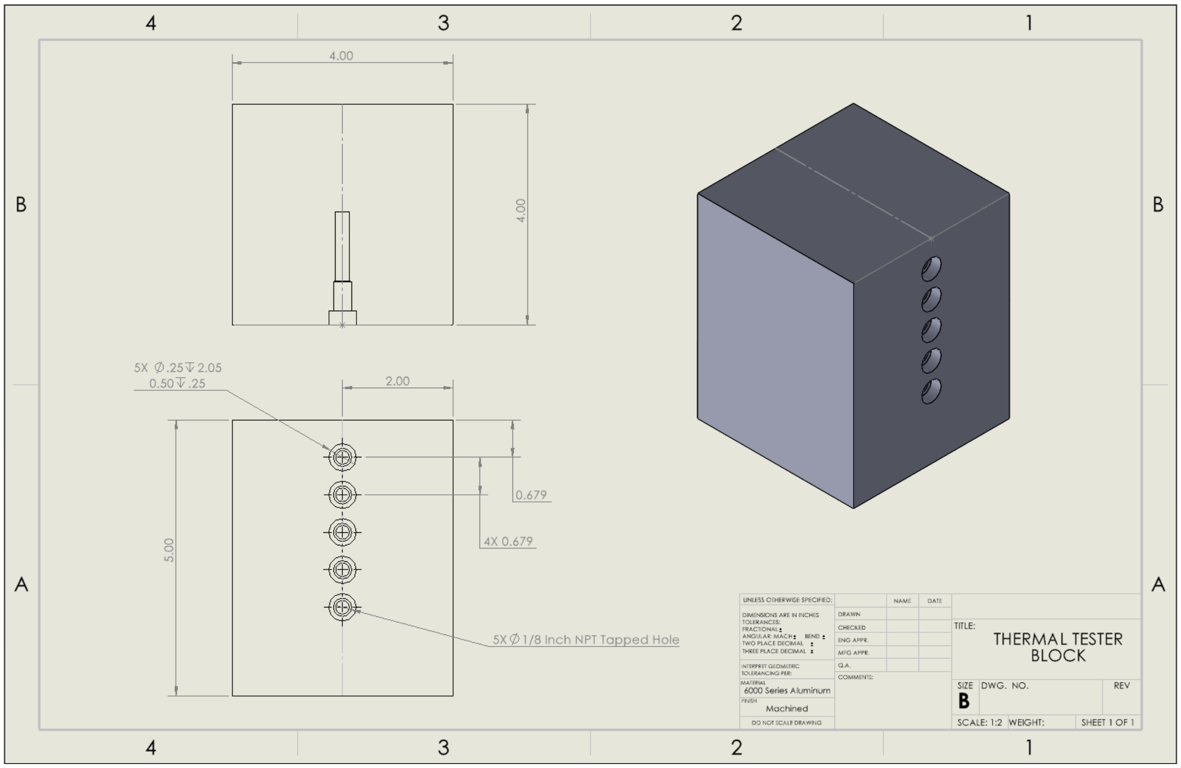


Figure 4. CAD Drawing Image of Machined Block

The completed assembly image shown in (*Figure 2*) displays the final iteration of the tester design used to complete final testing. Shown in (*Figure 4*) is the dimensioned CAD drawing for the 6061 aluminum block that was used within the thermal analysis device assembly. The drawing is shown in inches, but the exact dimensions for hole spacing are in millimeters. Each hole is 17.25 millimeters apart, and the first hole is exactly 17.25 millimeters from the top surface of the block. Each hole is tapped with 1/8th inch NPT taps. This allows for through bored male connector fitting to be threaded into the block. This connector fitting can then be used to house the thermocouples used in the system. Before attaching the fittings and thermocouples, the holes are filled with 2-cycle engine oil. This oil is very minimal in volume, and it mimics the thermal properties of the aluminum block which it is surrounded by. Within (*Appendix IV*) there is a complete bill of materials for the entire thermal analysis tester assembly.

All data that was collected by the thermocouples is controlled by a Lab View DAQ controller, which allows the device to record data simultaneously at the three locations where the different thermocouples are mounted inside the aluminum block. The Lab View program shown in (*Figure 3*) was custom-programmed to enable users to gather all data needed from the experiment. In order to properly record data, the thermocouples used are calibrated using the assembly ice bath. It is also important to note that the temperature of the film heaters being used is controlled by a central power supply and must be continually monitored.

While conducting preliminary testing and analysis, it was found that in order to reach steady state temperature within a reasonable timeframe, the system needs to be placed within a small ice bath which should be kept at a constant temperature. In order to monitor the temperature of the ice bath, a handheld thermometer may be used. The system should be further validated through the use of an infrared camera which can determine the temperature of the assembly at a steady state. All in all, the entire test setup allows for many different data points to be collected. Testing and setup of the device were planned and carried out as follows below.

Experimental Testing Process:

1) Calibrate thermocouples using an ice bath.
2) Set up and run the designated LabVIEW program.
3) Place assembly into constant temperature ice bath.
4) Set Lab View to record data without input power from electronic heaters.
5) Turn on the power supply and validate the desired film heater temperatures.
6) Run the tester until the system reaches a steady state and monitor film heater temperatures.
7) Once at the steady state, turn of power supply and output temperature curve data.

CHAPTER 3: RESULTS AND DISCUSSION

Shown in (*Figure 5*) are some preliminary testing images. These tests were done to determine the capability of different methods for heating the high-density power module. Also, upon initial testing, a few design improvements were noted and implemented. It was also a goal of the initial test to determine the capabilities of the data acquisition setup.

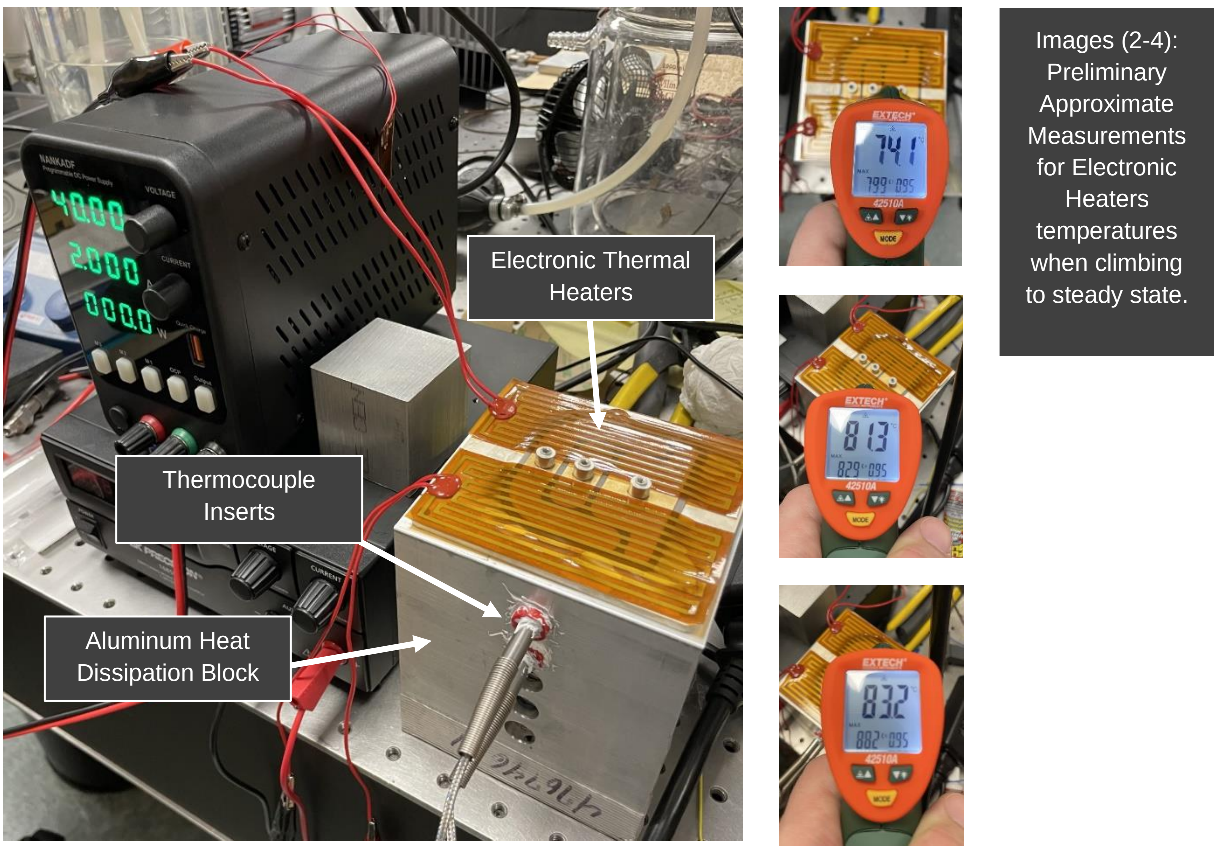


Figure 5. Thermal resistance Tester with IR Measurement of Heater Temperatures.

Three separate tests were conducted on the thermal analysis device. Each test utilized a different design which was continually improved. The results of each test are shown in (*Appendix III*). The final tester design resulted in an ideal outcome. The graph shown in (*Figure 6*) utilizes a comparison of time versus temperature in Celsius for each thermocouple.

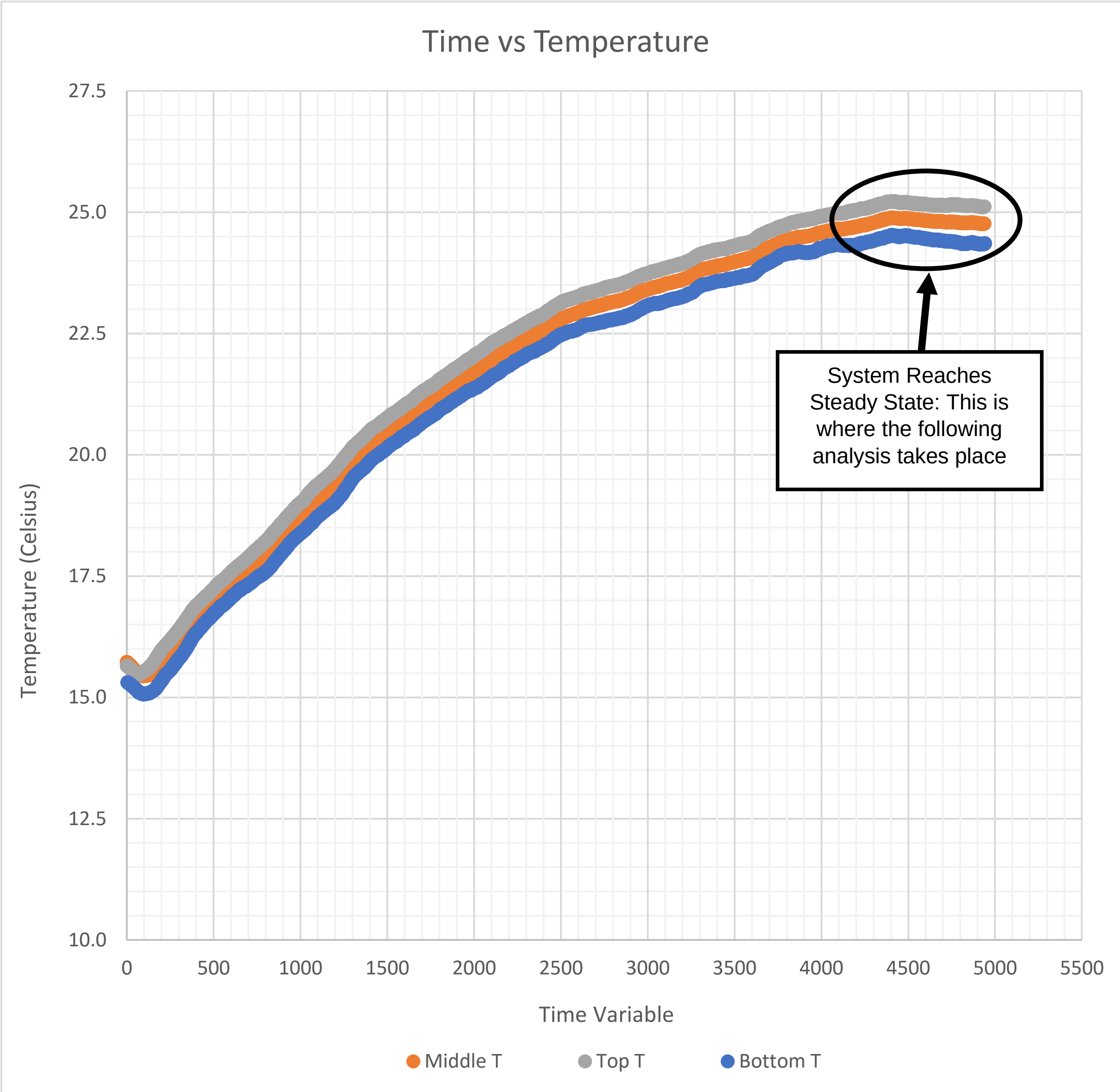


Figure 6. Test Data Output Measured to Steady State (Time vs. Temperature)

As seen in (*Figure 6*), the final test that was completed resulted in a linear relationship between temperature and relative thermocouple spacing. This outcome verified that the desired temperature gradient was achieved within the experiment. The data shown in (*Figure 6*) also signifies that there is still some residual heat lost in the system. The experimental setups for preliminary tests are shown in (*Appendix IV*).

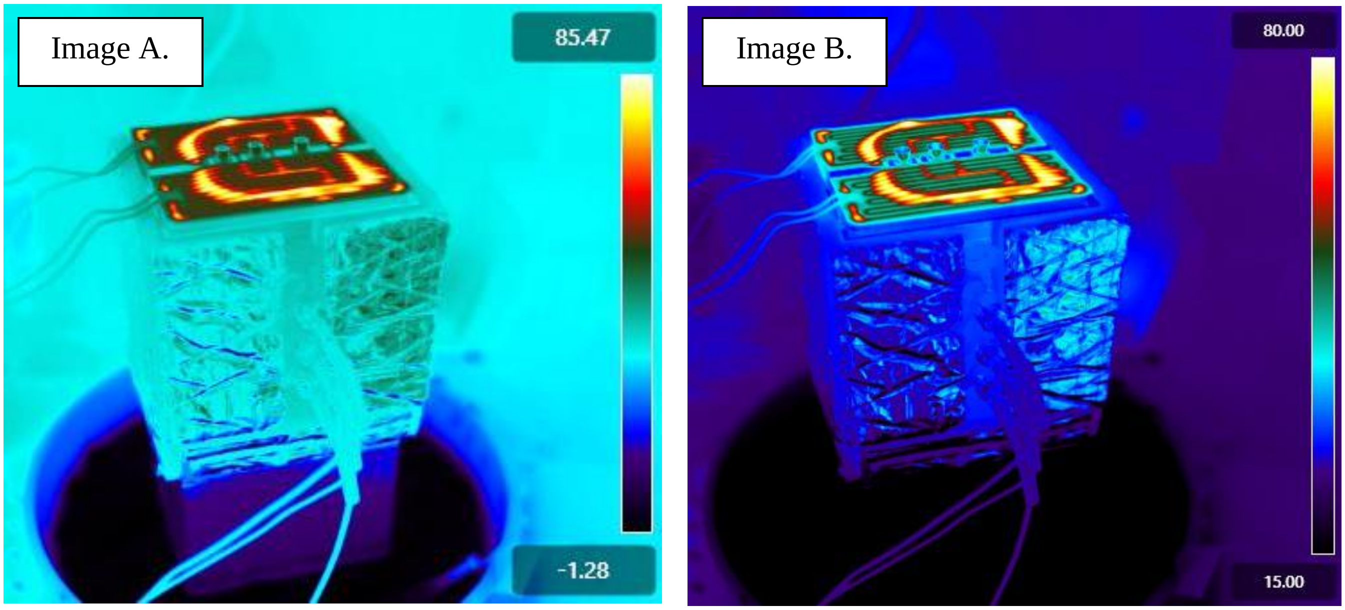


Figure 7. Steady State Infrared Images Taken During Testing

The images shown in (*Figure 7*) are photos which were taken with an infrared camera of the system at steady state. Image A is represented in a larger color scale range that illustrates the total temperature difference of the system. Image B shows a smaller temperature range and allows the viewer to better visualize the temperature difference in the assembly. The ice bath temperature shown in this image should not be used as an exact measurement, as the camera was also visualizing the ice cubes within the bath as large cold spots. The actual measured temperature of the ice bath was between 3 and 4 degrees Celsius. These infrared images allow for the temperature of the electronic heaters to be visualized as well. It is important to note that the insulation that was used to counteract possible heat dissipation within the system makes it harder to visualize the temperature gradient of the block. The temperatures that can be seen within the images in (*Figure 7*) further validate that the temperature of the block at steady state resides at around 25 degrees Celsius.

Position:	Distance (mm)	Distance (m)	Temperature (SS)	Temperature (SS - K)
1 (34.50mm)	34.50	0.03450	25.193914	298.343914
2 (51.75mm)	51.75	0.05175	24.874219	298.024219
3 (69.00mm)	69.00	0.06900	24.509951	297.659951

dT/dz	Units
-0.019825014	C/mm
-19.82501449	C/m
-19.82501449	K/m
Aluminum 6061 Thermal Cond (k)	Units
152	W/mk

Heat Flux (Q dot - dT/dz)	Units
3013.402203	W/m^2

Table 1. Heat Flux via Temperature Gradient Measurements

The data tabulated above in (*Table 1*) is used to calculate the value for the heat flux of the entire system using the temperature gradient found at steady state. This data gives a value of 3013.402 Watts per meter squared for the heat flux. The data tabulated below in (*Table 2*) can be used to calculate the theoretical heat flux through the system based on the input power from the electrical heaters within the assembly. This data gives a value of 2649.863 Watts per meter squared for heat flux. Further explanation of said calculations is shown in (Appendix I).

Area	Units
0.009660877	m^2

Power Per Module	Units
12.8	Watts
Number of Modules	
2	
Total Power	Units
25.6	Watts

Heat Flux (Q dot - Heaters)	Units
2649.862947	W/m^2

Table 2. Heat Flux via Theoretical Power Input

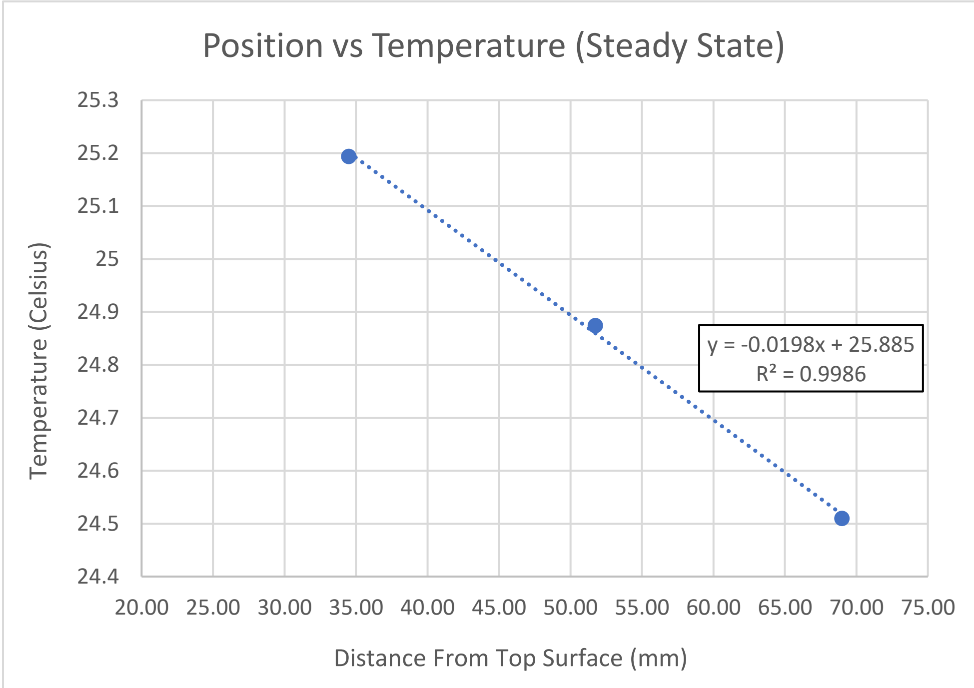


Figure 8. Position vs Temperature Plot at Steady State

Q diss (Heat Dissipation)	Units
29.11210803	Watts
Q Load (Heat Load - Heaters)	Units
25.6	Watts
Q Loss (Heat Loss)	Units
3.512108034	Watts

Table 3. Heat Dissipation, Load, and Loss Data in Watts.

Shown in (Table 4) is the calculated value of the overall thermal resistance of the power module, being tested, which was equal to 0.5707 Celsius per Watt. This value is similar to predicted values for thermal resistance from FEA analysis which equaled roughly 0.20 Celsius per Watt.

Top Heater Temperature	Units
42.500	Celsius
Bottom Temperature (Mount Surface)	Units
25.885	Celsius

Average Thermal Resistance of Power Module	Units
0.57072473	Celsius/Watt

Table 4. Thermal Resistance Measurement via Temperature Gradient Data

The outcome of the validation tests that were completed showed that the thermal analysis testing device provides its user the ability to accurately determine a temperature gradient when a substrate or medium is placed on its top surface. Overall, the data which is collected from this device can be used to also help determine ideal geometries for cooling instruments, as well as the thermal conductivity of the material or medium that is being tested. One conclusion that was concerning was the difference in the heat flux calculated using the electronic heater power input and the heat flux found from the measured temperature gradient.

This difference is most likely due to a few different factors. It should be noted that the ice bath in which the assembly is placed provides an unknown energy source to the system in the form of cooling. The difference in the input power and the calculated output power is shown in (*Table 3*). If this device were to be redesigned or further developed, there are several improvements that could be implemented. One possible area of improvement would be the number of thermocouples being used within the system. Utilization of a greater quantity of thermocouples would allow for the system to gather more accurate data. It would also be ideal if the system could be heated via actual electrical power which could be provided to the power module being tested. The electrical heaters which are used work well, but seem to have variable temperature distribution, as well as provide a potential area for thermal losses. Another potential source of error could be coming from air gaps between the top surface of the aluminum block and the bottom surface of the test specimen. This should be accounted for in further testing through the use of thermal paste. Potential measurement errors can also be mitigated by using a mounted thermocouple which should be used to measure the top surface temperature of the power module, instead of data collected from the IR camera output.

APPENDICES

Appendix I Heat Flux Calculations:

$\dot{Q}_h = Q_h \div A_s$

$Q_h = N_m * P_m = 25.6$ W (12.8 Watts per 2 heaters)

$A_s = x_{dim} * y_{dim} = 0.009660877$ m^2

$\dot{Q}_h = Q_h \div A_s = 2649.86$ W/m^2

<u>1-D Heat Transfer Linear EQ:</u> **T = a*x + b**

b = Surface Temp
x = Distance from heat source
a = dT/dz = $\frac{\dot{Q}}{k_c}$

$\frac{dT}{dz}$ = Total dT/dz (Celsius or Kelvin per meter) = 19.825 K/m

$\dot{Q}_z = k_c \frac{dT}{dz} = 3013.4022$

$\dot{Q}_z = Heat\ Flux\ from\ Temperature\ Gradient = 3013.4022$
$\dot{Q}_h = Heat\ Flux\ from\ Electronic\ Heaters = 2649.86$

$Q_z = \dot{Q}_z * A_s = 29.112$

$Q_z = Heat\ Load\ from\ Temperature\ Gradient\ Calculations$
$Q_h = Heat\ Load\ from\ Electronic\ Heaters$

$Q_L = Q_h - Q_z$
$Q_L = Heat\ Loss\ in\ System = 3.512$

<u>Average Thermal Resistance of Power Module:</u>

$T_T = Top\ Temperature\ Value$
$T_B = Bottom\ Temperature\ Value$

$R = (T_T - T_B)/Q_z = Average\ Resistance\ of\ Power\ Module$

Appendix II Bill of Materials:

A. Materials for the test section

Component	Price	Quantity	Total Cost	Vendor
6061 Aluminum Block (5×4×4)	$110.45	2	$220.90	Midwest Steel and Aluminum
Stainless Steel Tube Fitting 1/8 in NPT	$11.31	3	$33.93	Swagelok
Clear Plastic Plant Saucer - Deep	$0.98	1	$0.98	Lowes
Electronic Film heaters (24 V - 30 W)	$19.78	2	$39.56	Amazon
Type T Thermocouples (0.062 in Diam - 1.25 in Length)	$71.50	3	$214.50	OMEGA Engineering
Total Cost:			**$509.87**	

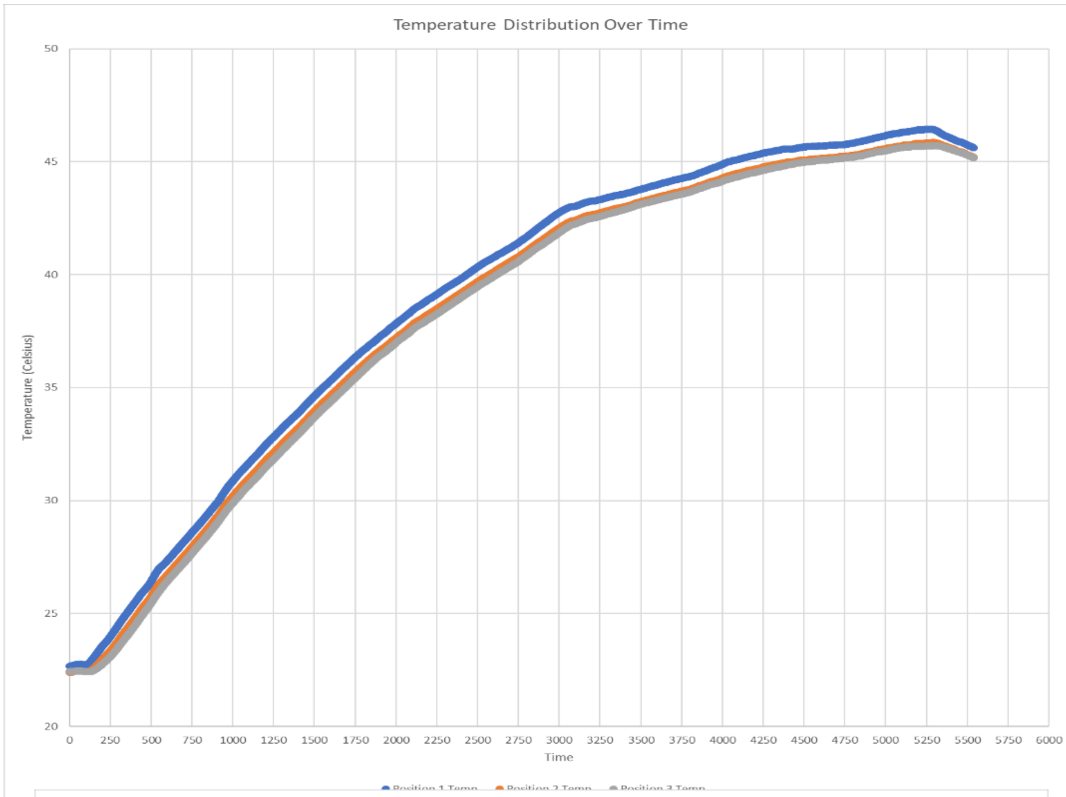
B. Devices for operations and data acquisition

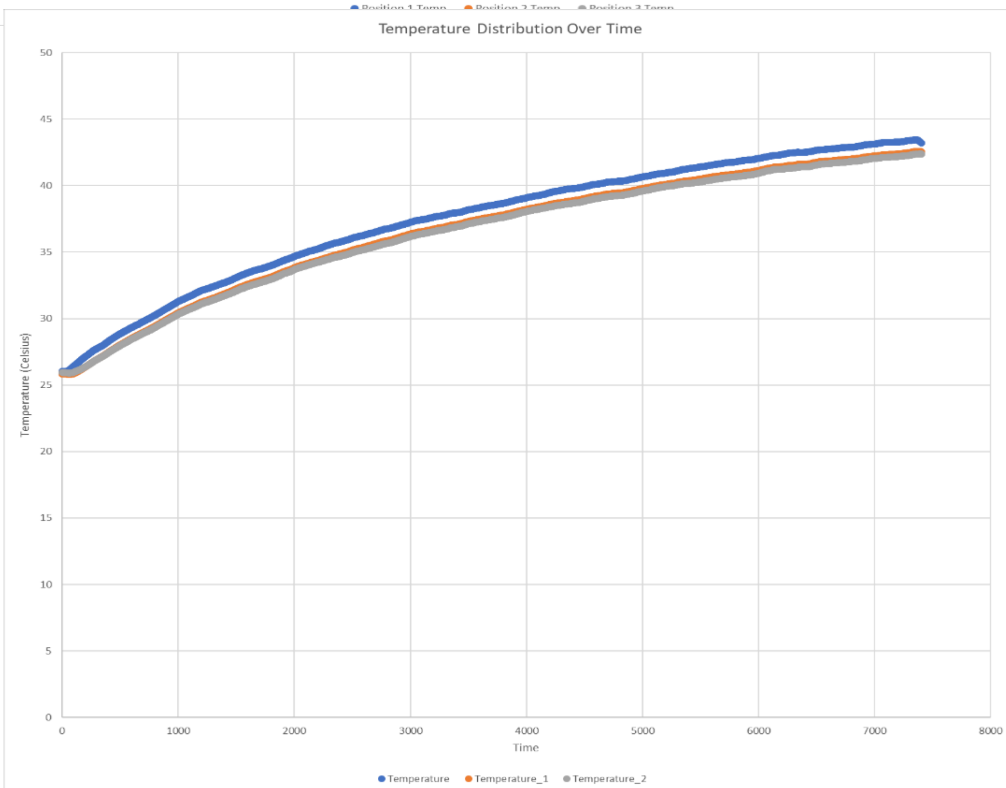
Component	Price	Quantity	Total Cost	Vendor
NI cDAQ-9174 Chassis	$1,554	1	$1,554	National Instruments
NI 9210 DAQ Card – Thermocouple	$621	1	$621	National Instruments
NANKADF DC Power Supply	$99.99	1	$99.99	Amazon
Total Cost:			**$2,274.99**	

C. Additional devices for system calibration and measurements

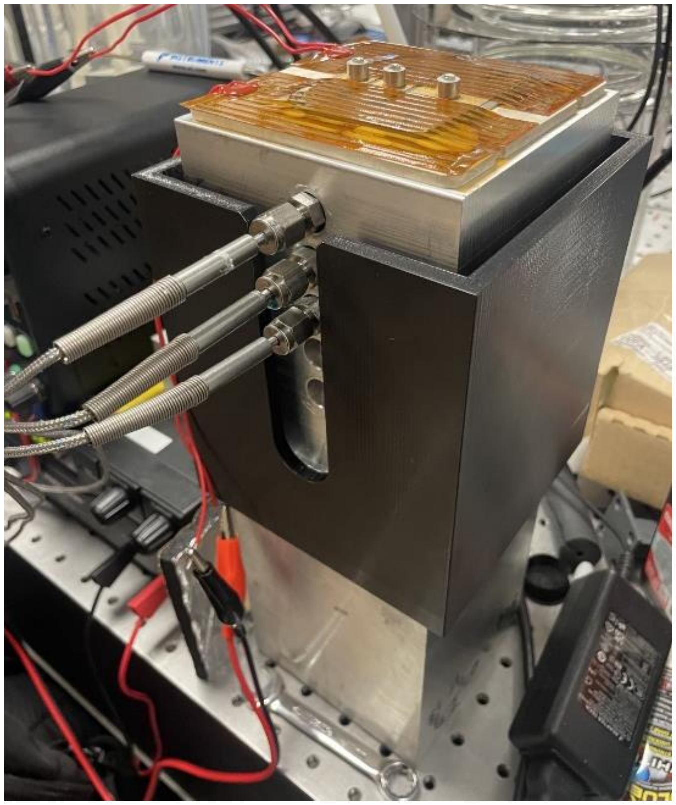
Component	Price	Quantity	Total Cost	Vendor
FLIR A655sc Infrared Camera	$21,030	1	$21,030	Teledyne FLIR
Extech Infrared Thermometer	$100.05	1	$100.05	McMaster-Carr
Total Cost:			**$21,130.05**	

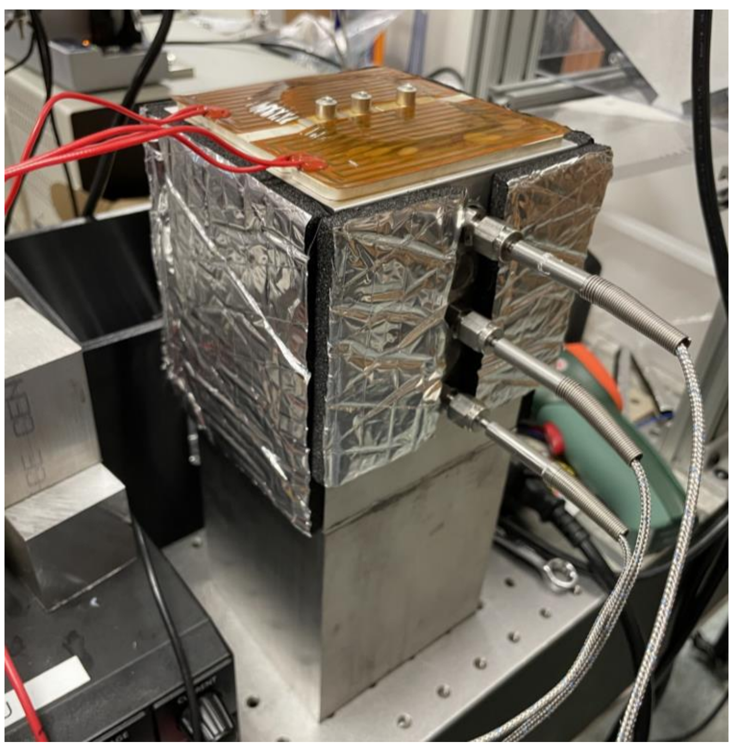
Appendix III Preliminary Test Data:





Appendix IV Preliminary Test Setups:





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