

EXPERIMENTALLY MEASURING THERMAL INTERFACE MATERIAL BASED ON ASTM D5470 THERMAL TESTER

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Abstract

Thermal Interface Materials (TIMs) play an important role in the thermal management of electronic packages, essential for maintaining the reliability and performance of electronic devices. As electronic components continue to shrink in size while increasing in power, the heat generated per unit area has risen significantly, presenting a critical challenge for thermal management solutions. This experiment focuses on the evaluation and characterization of various TIMs, including greases, and phase change materials, in their effectiveness at enhancing heat transfer between electronic components and their heat sinks. Experimental methods are employed to measure the thermal resistance and conductivity of selected TIMs, and the results are compared for those on manufacturer. In this experiment, a thermal interface material tester is developed based on the ASTM-D5470 standard test for thermal property testing of TIMs. thermal contact resistance values are plotted against variable interface thicknesses and the resulting model is used to extrapolate the resistance at an industry standard interface thickness of 0.1mm. The model resulted in a thermal resistance of $0.292 \text{ cm}^2\text{k/W}$ and a thermal conductivity of 3.64 W/mK .

Keywords: Thermal Interface Material (TIM), ASTM D5470, Thermal Conductivity, Thermal Resistance (Impedance), Contact Resistance, Heat Flux Measurement.

1. INTRODUCTION

As fast-changing electronics technology rapidly shrinks the size of components, the thermal challenge goes along for the ride. Demand for more capability and greater efficiency forces higher and higher power densities into smaller and smaller electronic devices. Thermal Interface Materials (TIM) are used to improve distribution of heat between integrated components and heat dissipating devices. TIM materials fill nano-sized imperfections caused by machining processes. These nano-sized gaps can decrease the thermal conductivity between two surfaces when only air is present. TIM materials come in a wide variety of chemistries depending on the needs of a component. Thermal grease and semi-adhesive TIM materials improve the reliability of integrated components and heat sinks.

TIMs help to fill in all the microscopic imperfections in the contact surfaces of the heat source (the part that gets hot, such as a processor) and the heat sink, which all serve to increase the thermal resistance at the interfaces. This, in turn, increases the amount of heat that gets conducted away from the source. The thermal conductivity of the TIM (as well as its thickness and how it is applied) affect the final thermal performance of the electronic package containing the electronic device. In this introduction, the focus is on how TIMs play a crucial role in meeting the thermal management requirements of modern electronic packages. Various types of TIMs are explored, including thermal greases, adhesive tapes, pads, and phase change materials, each having distinct characteristics

that make them suitable for different applications. Selecting the right TIM is vital as it not only impacts thermal resistance but also influences the reliability and lifespan of electronic devices. The continuous advancement of TIMs aims to improve thermal conductivities and reduce interface resistances, which in turn enhance the performance of electronic components and tackle the thermal obstacles posed by greater power densities.

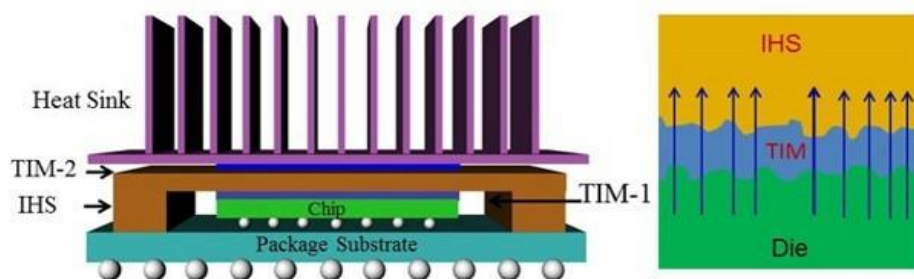


Figure 1: shows a common configuration for a flip chip package.

There are Two types of TIMs are used to facilitate heat removal from the chip:

TIM-1 is placed between the chip (or die) and the integrated heat spreader (IHS) -TIM-2 is placed between the IHS and the heat sink. The schematic on the right side in Figure 1 depicts the heat flow path. Note that the surfaces of the die and the IHS are typically not smooth and the TIM needs to flow well enabling good contact between the two surfaces in order to get good heat transfer. A subsequent post will discuss interfacial properties in more detail. In this series of posts, the focus will be on the most common type of TIM polymer-based thermal interface materials.

There are five main types Thermal Interface Materials (TIMs):

- Thermal grease
- Gap filler pads
- Thermal tapes/films
- Phase change materials
- Fully cured dispensed gap fillers

The most commercially available and widely used are thermal greases as they are cost effective and provide good thermal conductivity.

1.1 Thermal Grease

Thermal grease, commonly known as thermal paste or heat sink compound, is a type of Thermal Interface Material (TIM) utilized in electronics to improve heat transfer from components like CPUs, GPUs, or power transistors to their heat sinks. The main purpose of thermal grease is to fill in the tiny air gaps and surface imperfections between the heat source and the heat sink to prevent them from acting as thermal insulators, as air has a low thermal conductivity.

1.2 Composition

Thermal grease typically consists of a blend of a base fluid that can polymerize (often silicone or another synthetic oil) and thermally conductive fillers like zinc oxide, aluminum oxide, silver, or copper particles. The base fluid aids in spreading the fillers evenly across the surface, while the conductive particles increase the overall thermal conductivity of the compound.

1.3 Properties

Thermal grease is effective due to its key properties such as:

High Thermal Conductivity: Facilitating the efficient transfer of heat from the electronic component.

- **Low Thermal Resistance:** Reducing any barriers to the flow of heat.
- **Long-Term Stability:** It remains stable without deteriorating or drying out, ensuring sustained effectiveness during the device's lifetime.
- **Non-Conductive:** Preventing electrical shorts on crowded circuit boards by being electrically non-conductive.

1.4 Application

Thermal grease is applied to ensure optimal heat transfer and minimizes thermal resistance between the two flat surfaces.

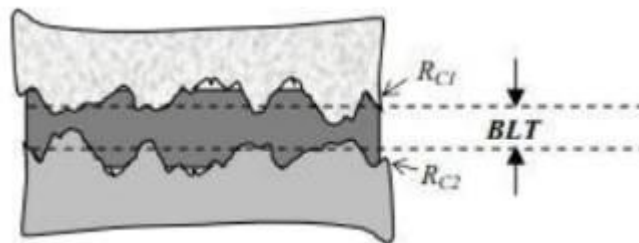


Figure 2: Inserting a TIM between two surfaces to increase surface contact

1.5 Thermal Resistance:

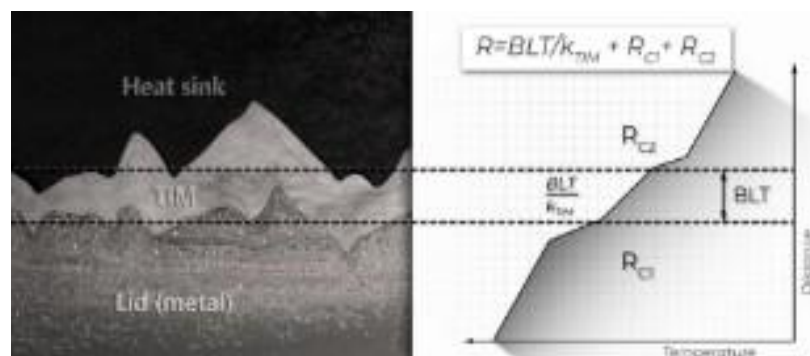


Figure 3: Thermal Impedance $R_{th} = R_{TIM} + R_{c1} + R_{c2}$.

Thermal Interface Material (TIM) between two surfaces helps to improve the contact between two surfaces. The overall thermal resistance that occurs when a TIM is placed between two surfaces includes the contact resistances at each interface as well as the innate thermal resistance of the TIM. The formula for calculating the total thermal resistance is:

$$\text{Eq.1} \dots\dots\dots R_{\text{combined}} = \frac{t_{\text{TIM}}}{k_{\text{TIM}} \cdot A} + R_{\text{C1}} + R_{\text{C2}}$$

Where;

R_{combined} denotes the total thermal resistance across the interface, k_{TIM} signifies the thermal conductivity of the TIM, t_{TIM} refers to the thickness of the TIM layer, and A stands for the area through which the heat transfer occurs. The R_{C1} and R_{C2} represent the contact resistances at the interfaces between the TIM and the two surfaces in question.

Total thermal impedance, R_{th} , is a better predictor of thermal performance than the thermal conductivity of the TIM material alone. Thermal impedance, R_{th} , the sum of all thermal resistances through the assembly is measured in Kelvin per Watt (K/W).

To enhance the thermal transfer efficiency between two surfaces interfaced by a TIM, it is essential to minimize this combined thermal resistance. Strategies to achieve this reduction include utilizing a TIM with higher thermal conductivity, reducing the thickness of the TIM layer (BLT), and employing a TIM that forms a minimal-contact resistance. Additionally, smoothing the interfacing surfaces and applying pressure can further lower the combined thermal resistance, thereby optimizing the heat dissipation process.

1.6 Phase Change Materials (PCMs)

They are substances that can store and release large amounts of heat energy as they change between solid and liquid states. PCMs are designed to absorb heat as they melt and release heat as they solidify, which can be particularly useful for thermal management in electronics but it will not be the focus study of this experiment.

1.7 Characteristics of PCMs

As thermal interface materials (TIMs) utilizing phase change materials (PCMs) usually exhibit the following properties:

- **Close Melting Point:** The melting point is typically aligned with the operational temperature of the electronic device to guarantee efficient heat absorption during standard usage.
- **High Latent Heat Capacity:** PCMs possess the ability to absorb or emit a significant amount of heat without a substantial temperature change (referred to as latent heat), aiding in maintaining the electronic component's temperature stability.
- **Thermal Conductivity:** Though PCMs generally demonstrate lower thermal conductivity in solid state, enhancements can be achieved by incorporating thermally conductive additives or structures.

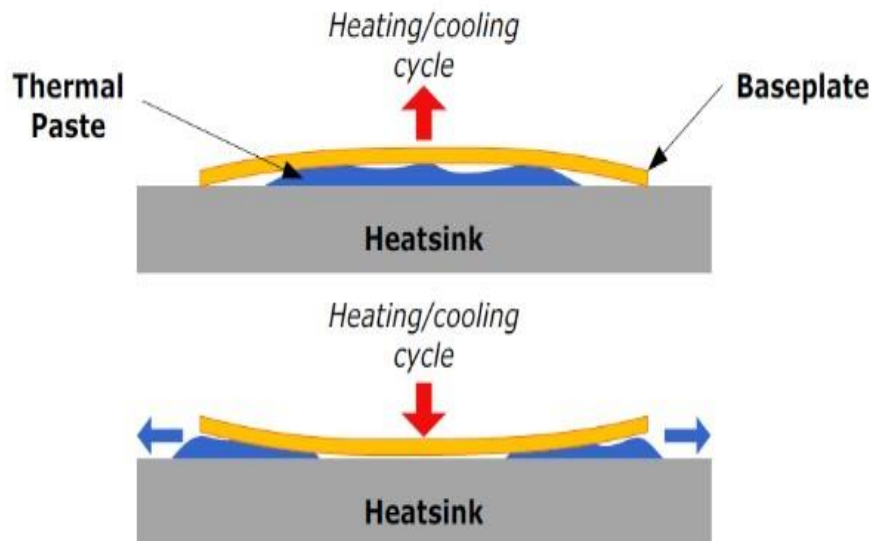


Figure 4: Phase change materials: Innovations in thermal management

The functionality of PCMs in TIMs Within electronic applications, when the device reaches the melting point of the PCM, the PCM starts to melt, absorbing a substantial portion of the heat produced. This transition from solid to liquid absorbs heat from the electronic component, assisting in averting sudden temperature increases. On the flip side, as the device cools and the PCM re-solidifies, it releases the accumulated heat, which can then be dispersed away from the device.

Table 1: Phase Change Material

Advantages	Disadvantages
• Temperature Regulation: PCMs can maintain a near-constant temperature over a wide range of heat fluxes.	• Lower Thermal Conductivity: In solid form, PCMs may not conduct heat as well as other TIMs, potentially requiring the addition of conductive materials.
• Thermal Shock Reduction: They can help reduce the likelihood of thermal shock to sensitive electronic components by absorbing peak heat loads.	• Leakage Risk: in liquid form, there is a risk of the PCM leaking out of the TIM application area, potentially causing damage or contamination. • Also, it has Cycling Durability: The repeated phase change cycles can lead to changes in the PCM's properties over time, affecting its thermal performance.

1.8 Thermally Conductive Elastomers

Thermally conductive elastomers are a form of Thermal Interface Material (TIM), which blends the attributes of thermal conductivity with the flexibly resilient nature of elastomeric materials. These materials are employed to improve the thermal connection between heat-producing electronic components and devices for dispersing heat, like heat sinks or heat spreaders. In selecting the most suitable Thermal Interface Material (TIM) for a specific application, it is crucial to take into account a range of factors to guarantee optimal

thermal efficiency, dependability, and user-friendliness. Below are key considerations to factor in when deciding on a TIM:

- **Thermal Conductivity:** This measures a material's efficiency in conducting heat, with higher thermal conductivity indicating superior heat transfer capability away from the component.
- **Thermal Impedance:** A comprehensive metric considering both the material's inherent thermal resistance and the resistances at the interface on each side of the TIM layer.
- **Application Temperature Range:** Important for ensuring the TIM can tolerate the temperatures expected by the electronic components.
- **Viscosity/Consistency (for greases and pastes):** Influences ease of application and the thickness of the layer applicable, which impacts thermal resistance.
- **Compliance and Conformability:** Incorporating the ability of the TIM to adapt to different surface conditions and address non-uniformities for effective thermal contact.
- **Elongation and Tensile Strength (for elastomers and pads):** Important for applications that may experience mechanical stress or require the TIM to maintain structural integrity.
- **Electrical Conductivity:** Many TIMs need to be electrically insulating to prevent short circuits, although some applications may require electrically conductive TIMs.
- **Pump-out Resistance:** The ability of a TIM to resist degradation or displacement out of
 - the interface area over time due to thermal cycling.
- **Ease of Application/Removal:** A TIM should be easy to apply and, if necessary, remove or clean up without leaving residue or damaging components.
- **Cure Time:** Some TIMs require a cure time to achieve their optimal thermal performance characteristics.
- **Durability and Aging Characteristics:** The TIM should maintain its performance over the expected life of the component without drying out,
- **Cost and Availability:** The cost of the TIM must fit the budget of the project, and the material should be readily available for production needs.

To summarize, Thermal Interface Materials (TIMs) play an important role in efficiently managing the heat produced by electronic devices by connecting heat-generating elements with heat dissipation mechanisms. With electronic systems becoming more powerful, smaller, and emitting more heat, the importance of TIMs is continually rising. The progress in TIM technology has resulted in a variety of materials, each designed with specific properties for diverse applications in consumer electronics, high-performance

computing, automotive technology, and aerospace sectors. Selecting and using TIMs accurately is essential, as it involves considering aspects like thermal conductivity, impedance, restrictions during application, and long-term reliability. As the industry progresses, creating TIMs with improved thermal efficiency, simpler application processes, and increased dependability remains a significant focus.

2. ANALYSIS OF HEAT TRANSFER IN ELECTRONIC PACKAGES

Analyzing heat transfer in electronic packages is a multifaceted process that involves understanding the mechanisms of heat transfer, the materials involved, and the physical configurations of the electronic components. As we know in electronic packages, heat is transferred via three primary mechanisms:

Conduction: Heat transfer through solid materials due to a temperature gradient. It is quantified by Fourier's law of heat conduction.

Convection: Heat transfer between a surface and a fluid (air or liquid coolant) moving over the surface. It is described by Newton's law of cooling.

Radiation: Heat transfer through electromagnetic waves, which can occur even across a vacuum.

For this experiment our mechanisms will be conduction since the heat will be transferred on the same material.

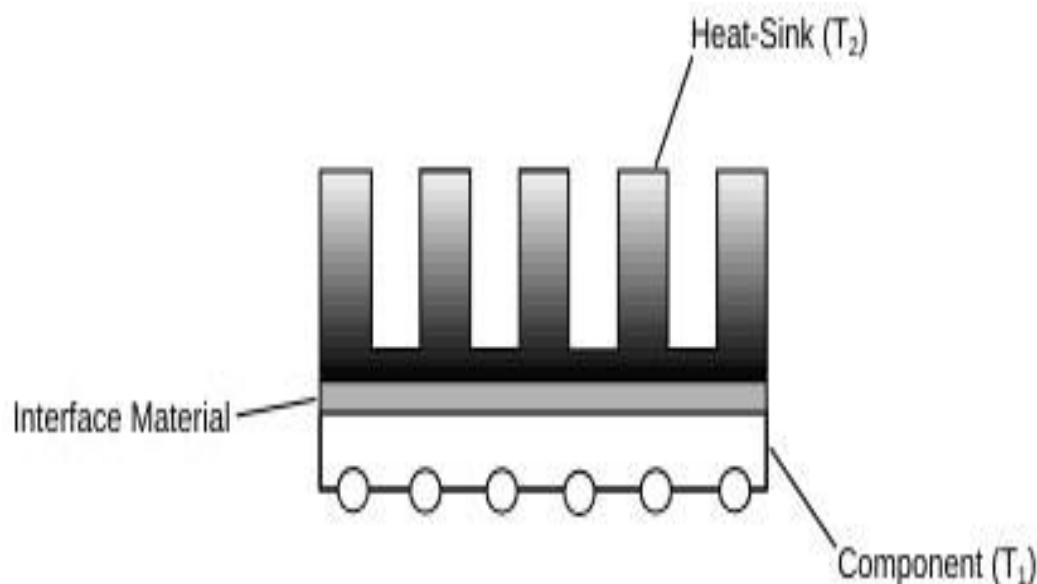


Figure 5: thermal interface application

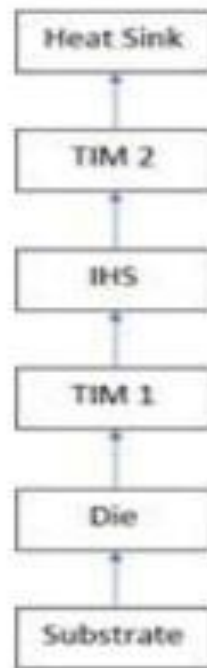


Figure 6: Diagram of heat Transfer of BGA package

2.1 Conduction in BGA Package

In a BGA package, conduction occurs as follows:

- a. **From die to substrate:** Heat generated by the semiconductor die is transferred to the substrate by the materials attached to the die. This can involve multiple layers of different materials, including possible deflector layers.
- b. **Through the solder balls:** Heat is continuously transferred from the substrate through the solder balls to the printed circuit board (PCB).
- c. **Through the PCB:** The heat eventually propagates through the PCB, which can then dissipate into the surrounding environment or into any associated heating elements.

2.1.1 Fourier's Law of Heat Conduction:

Fourier's law is fundamental for analyzing heat conduction through different layers of the BGA package:

$$Q' = -k \cdot A \cdot \frac{\Delta T}{L}$$

Where,

Q' is the heat transfer rate (W),

k is the thermal conductivity of the material (W/m·K),

A is the cross-sectional area perpendicular to the direction of heat transfer (m^2),
 ΔT is the temperature difference across the material (K), L is the thickness of the material layer (m).

2.1.2 Thermal Resistance Network

Conduction can also be analyzed using the concept of thermal resistance, similar to where each component's thermal resistance is:

$$R_{th} = \frac{L}{kA} \quad \text{Eq.3}$$

2.1.3 Detailed Numerical Simulation

For a detailed and accurate analysis, especially when the BGA package involves complex geometries and materials, numerical simulation methods such as Finite Element Analysis (FEA) are employed. These tools can solve the heat equation:

$$\nabla \cdot (k \nabla T) + q''' = \rho c_p \frac{\partial T}{\partial t} \quad \text{Eq.4}$$

∇

represents spatial derivatives

T is the temperature distribution,

q''' is the heat generation per unit volume (W/m^3),

ρ is the density of the material (kg/m^3),

c_p is the specific heat capacity of the material ($J/kg \cdot K$), is the rate of change of temperature with time.

3. ASTM D5470 HEAT TRANSFER ANALYSIS

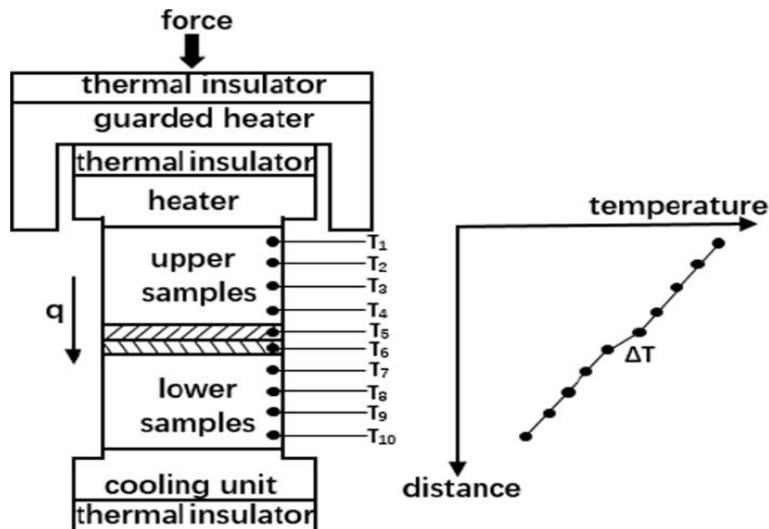


Figure 7: Temperature data point locations in experimental setup

At figure 7 it shows the setup for an ASTM D5470 thermal interface material (TIM) test, which measures the thermal impedance and conductivity of materials used between heat-generating components and heat sinks. The standard equations consider four data points for temperature collection in this experiment, but for a more accurate result for the thermal resistance calculation, eight data points will be needed. Above figure shows the locations of all eight data points that will be used to find the temperature gradient in thermometer bars which will help obtain more accurate temperature drop measurements and thermal contact resistance calculations.

The four overviews for the setup of this experiment (ASTM D5470) are Guarded Heater, Upper and lower samples, Cooling unit, and temperature gradient.

Guarded Heater: The heater applies controlled heat to the surface samples while thermally isolated from the environment. The "guard" ensures that the heat flows only in the desired direction.

Upper and Lower Samples: The test objects are placed between the upper and lower samples, which are equipped with temperature sensors from the example figure (T1 to T10) monitoring the temperatures at various points.

Cooling Unit: The cooling unit dissipates the heat away from the lower samples. This helps to maintain a temperature gradient across the test material.

Temperature Gradient: The temperature gradient across the samples is depicted on the right side of the diagram, illustrating how the temperature changes from the heated side to the cooled side.

Equations use for ASTM D5470

1- Heat transfer rate

$$\text{Eq.5} \dots\dots\dots (Q' = - k \cdot A \Delta T / L)$$

Where,

K: Thermal conductivity of the material,

A: Cross-sectional area of the sample,

ΔT : Temperature difference across the sample,

L: Thickness of the sample.

Equation 5 is used to determine the thermal conductivity of the material being tested by measuring the heat flux through the sample and the temperature difference across it.

2-Heat Flux(q):

The heat flux equation is a more general form of Fourier's Law and can be applied to measure heat transfer through the material.

Heat flux equation for this system will:

$$\text{Eq.6} \dots \dots \dots q = \frac{Q}{A} = -k \frac{dT}{dx} = -k \frac{\Delta T}{x}$$

Where,

Q is total heat transfer rate A is cross-sectional area, dT/dx is temperature gradient.

4. HEAT TRANSFER ANALYSIS OF ASTM D5470 SETUP

Heat Flow: The heat flows from the guarded heater, through the TIM (thermal interface material), to the cooling unit. For the heat flow a clear diagram and equation for the setup of ASTM D5470 experiment will be the following:

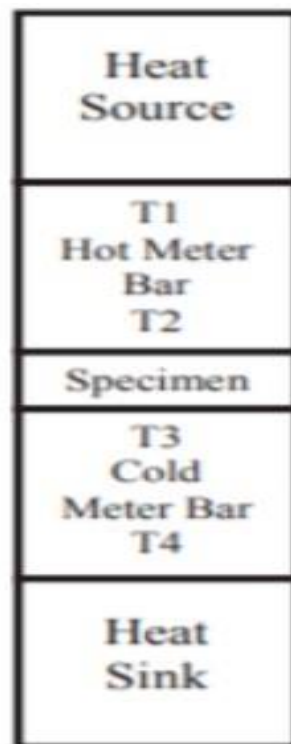


Figure 8 Diagram of ASTM D5470

T_H is the temperature at the bottom surface of the TIM sample. T_C is the bulk thermal resistance of the sample.

Temperature Gradient: The temperature sensors capture the temperature at various locations across the TIM to establish the gradient.

Thermal Impedance: The difference in temperature across the TIM and the measured heat flux are used to determine the thermal impedance of the TIM, which is crucial for evaluating its effectiveness.

Conductivity: The thermal conductivity of the TIM can then be determined from the heat flux and temperature difference measurements using the formula provided.

5. ASTM D5470 EXPERIMENTAL SETUP

5.1 ASTM D5470 Experimental

To be able to measure the thermal conductivity and thermal resistance of this experiment, a 3D model was drafted by SolidWorks and AutoCad. The selected type of material is 6061 Aluminum with the base dimension of 11.9 in L X 5.99 in W, which is the foundation of the experimental setup. The bottom block is also a 6061 Aluminum block of size 2 in x 2 in x 2 in (approximately 50.8 mm x 50.8 mm x 50.8 mm) and has nine 0.394 in (10 mm) holes drilled all the way through from one side to the other; this serves as the heat sink for this experiment.

Above the heat sink are two 6061 Aluminum bars which will be the hot and cold meter bars that transfer the heat from the heat source to the heat sink. Between the meter bars, the thermal interface material will be placed and tested. The heat source is made up of two 12-volt heater cartridges that will be placed inside an aluminum block, and above that is a piece of insulation. Then a guard heater, which has one cartridge heater inside it to minimize heat loss from the top of the heat source.

The metal rods seen in the setup are to stabilize the weights added and to ensure equal distribution of the force applied to the top of the meter bars. To obtain 1-Dimensional heat transfer, the entire setup was wrapped with 0.5 in (12.7 mm) thick insulating fabric; this will prevent any heat transfer from the sides of the meter bars while heat is traveling through them towards the bottom of the metal bars. To ensure the heat sink is actively cooling, a desk fan set to the maximum setting was placed in front of the heat sink.

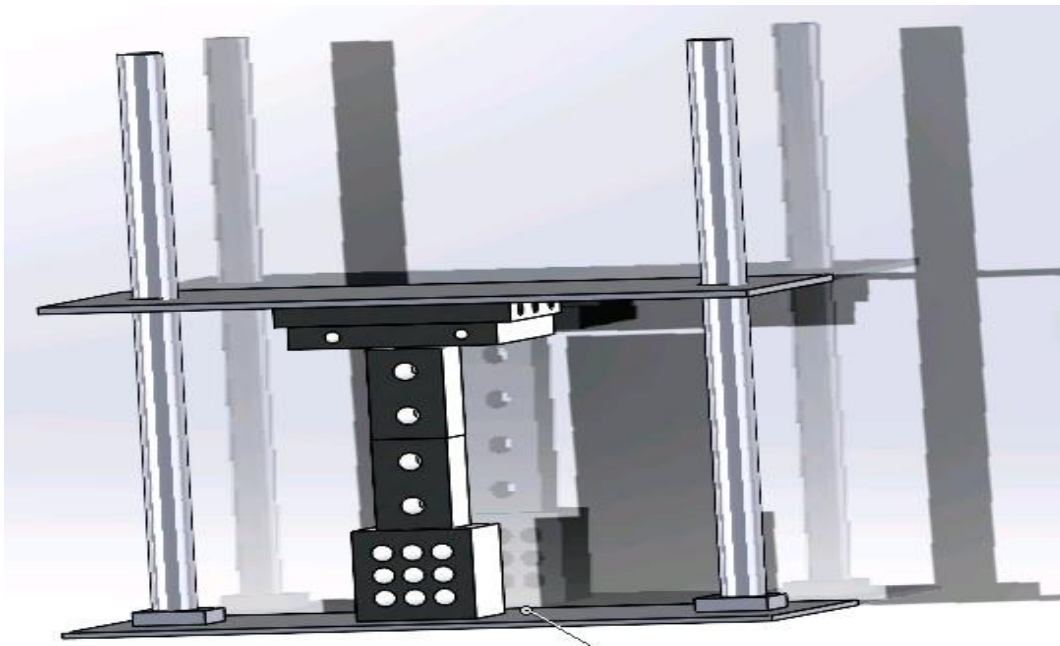


Figure 9: 3D model of ASTM D5470 -Setup SolidWorks

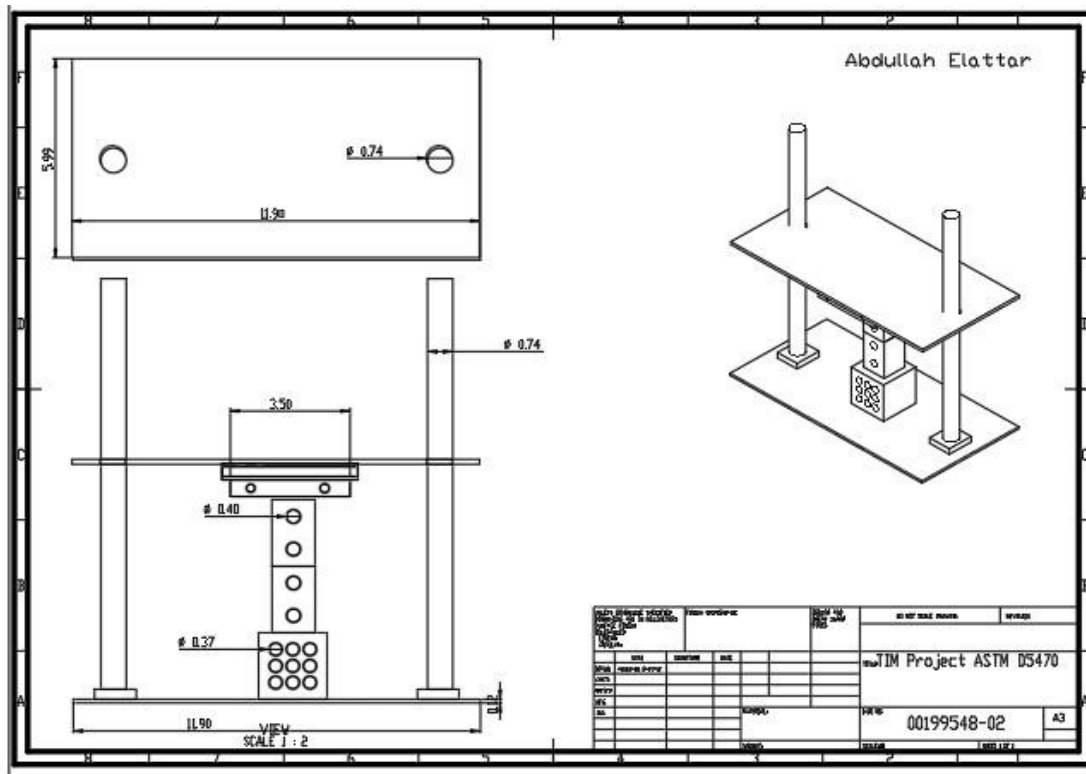


Figure10: schematic of ASTM D5470 experiment at Solid works

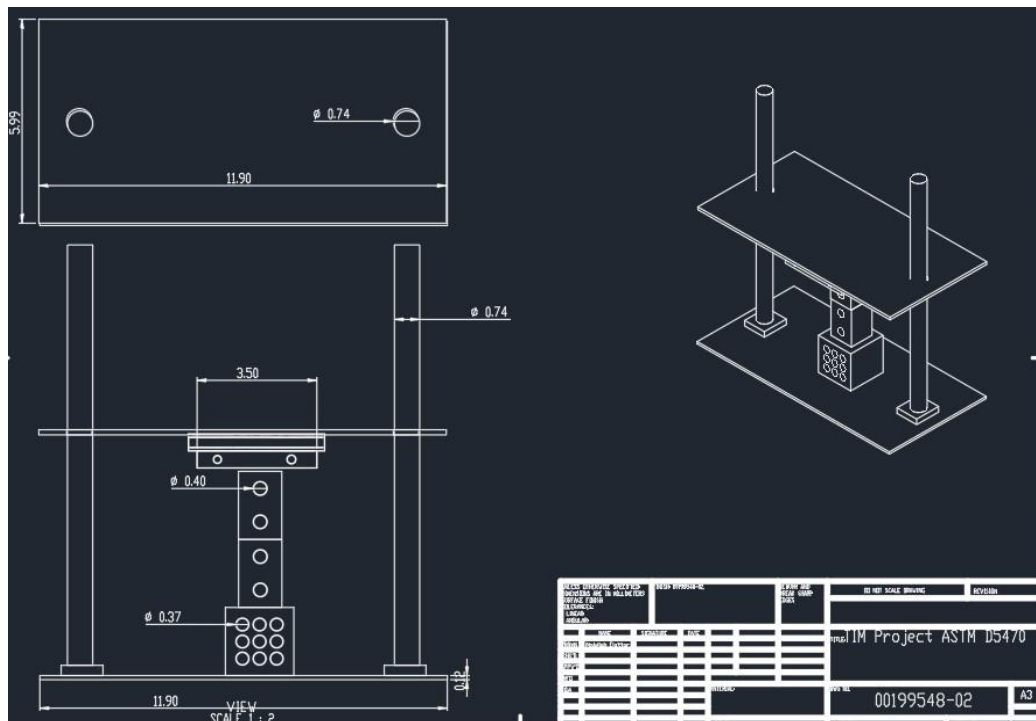


Figure 11: 2D Drawing of ASTM D5470 using AutoCad

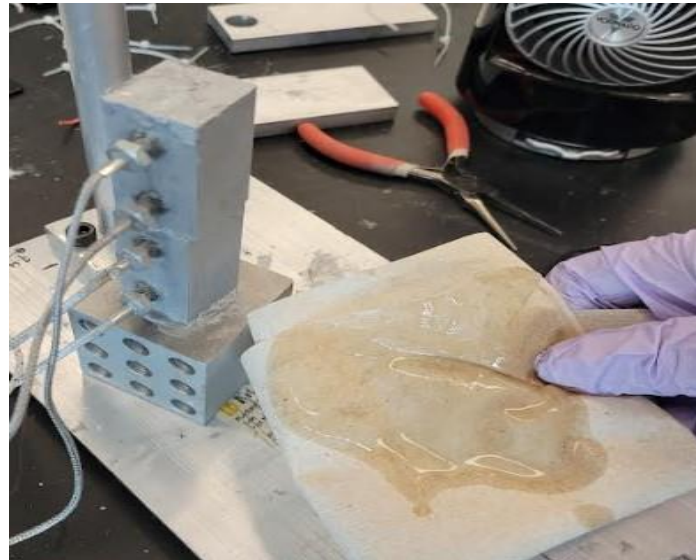


Figure 11: test bench without putting the heat insulation

Figure 11 shows the 4 thermocouples inserted into the metal bars. Figure 12 showed the heat insulation was covered by the metal bars. The insulation in the ASTM D5470 setup is crucial for directing heat transfer, improving measurement accuracy, and ensuring safety, thereby enabling more precise evaluation of thermal interface materials under standardized conditions.

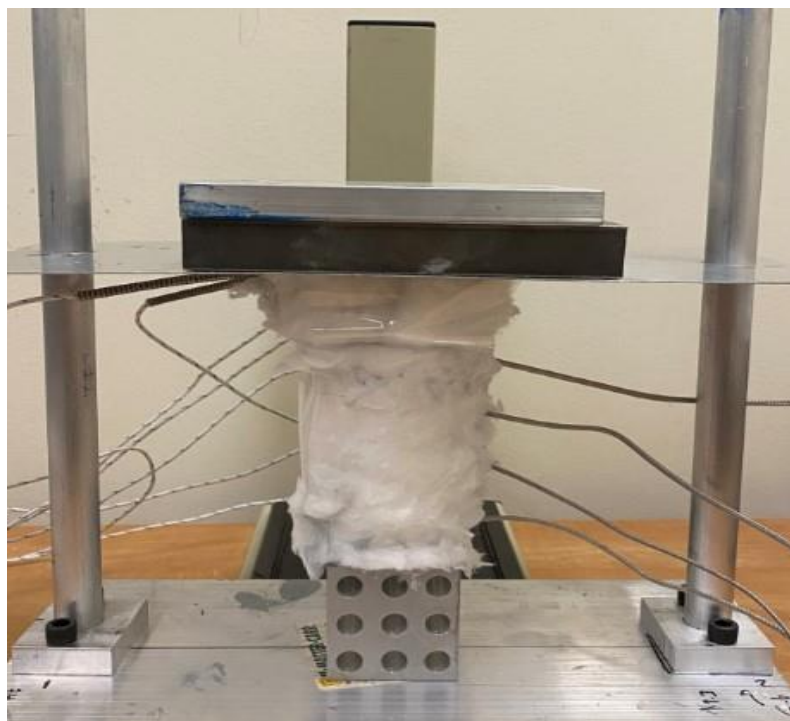


Figure 12: shows the experimental with the heat insulation

5.1.1 Temperature Measurements and Experimental Equipments

To measure and find the temperature across metal bars, a temperature monitoring system is required for this experiment. Two wires of source of 12 V were used in the experiment and set up above the two metal bars that had thermocouples inserted on them. The primary role of the 12 Volt heater cartridge is to generate heat. By doing this, it initiates the thermal gradient necessary for the experiment. This gradient is crucial for studying how heat moves through different materials, specifically the thermal interface material (TIM) placed between the hot and cold meter bars. For the voltage heat source a MASTECH DC power supply was used in this experiment.

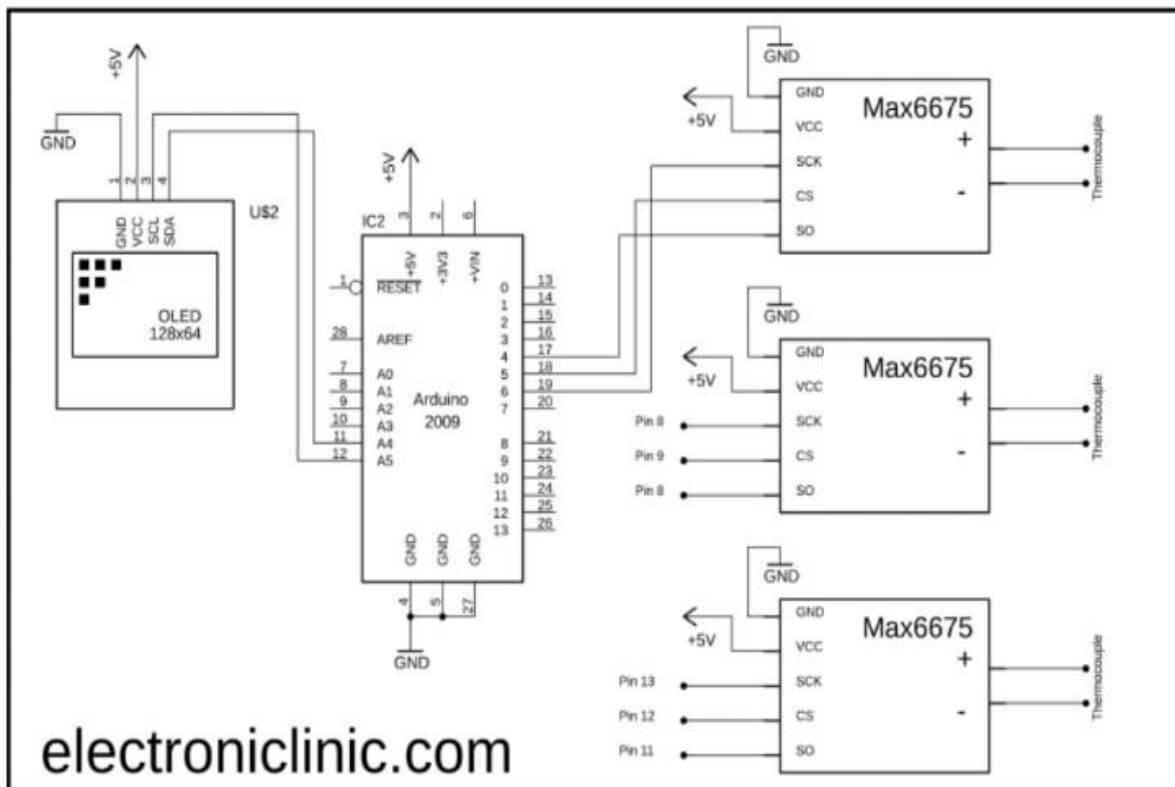


Figure 13: a schematic of Arduino MAX 6675

Figure 13 shows the wiring diagram for the controller and modules, courtesy of electronicclinic.com. The diagram shows only 3 modules, but the 4th module connects to pins 1,2 and 3 on the controller. The method used to measure the temperature was by utilizing an Arduino Uno Rev 3 controller along with Max 6675 temperature modules and K-type thermocouple. By using an Arduino controller, the cost is significantly reduced while maintaining good accuracy. The controller needed to be programmed in order to be coupled with the Max modules. Refer to the appendix for the programming script for the controller. Figure 14 shows the Max-6675 module and the K-Type thermocouple. There are many types of thermocouples that can be used to measure temperature but in this case the K-Type was chosen. K-Type thermocouples have an operating temperature of -

270 degrees celcius to 1260 degrees celsius, which definitely covers the temperatures that will be produced in this experiment. K-type thermocouple are desired in most applications due to their reliability and accuracy, as well as their low cost.



Figure 14: shows the K-Type of thermocouple selected for this experiment

Table 2: below shows the equipment's used to complete the build of this experiment

Item	Description	Quantity
Temperature Monitoring System		
Arduino Uno Rev 3	Controller module	1
Max-6675	Temperature modules	4
K-Type Thermocouple	Temperature sensors	4
Bread board	Wiring modules to controller and power	1
Power Source		
MASTECH DC Power Supply	Voltage source for heaters	1
12V heater cartridge	Heat source for setup	3
Calorimeter		
6061 Al metal block	1x1x2" for meter bars	2
	2x2x2" for heat sink	1
	2x2x0.5" for heater and guard heater blocks	2
6061 Al metal sheet	12x12x0.125"	2
Ceramic fiber insulation	Insulating test bench	1

5.1.2 Applied Pressure

Pressure is important to this experiment by facilitating proper physical contact between the thermal interface material (TIM) and meter bar surfaces. This interaction is necessary for precise evaluation of thermal resistance and conductivity. Additionally, pressure mimics the real-life scenario where TIMs experience compression between components, impacting their efficiency.

By replicating these conditions, the experiment offers more accurate insights into the behaviors and characteristics of TIMs under operational pressures. Therefore, the application of pressure is essential in obtaining dependable and uniform data on the performance of thermal interface materials. Including the weight of the two aluminum blocks used for the heat source and guard heater, the total weight applied to this experiment was 9420.12 grams with a surface area of 1 square inch.

Calculation of Pressure:

1. Convert the Weight from Grams to Pounds:

The weight was given in grams (9420.12 grams). 1 gram equals approximately 0.00220462 pounds.

Converting:

9420.12 grams $\times$ 0.00220462 pounds/gram = 9420.12 grams $\times$ 0.00220462 pounds/gram

2. Eq.13----- $P = \frac{W}{A}$ (Square (Pounds inch))

Result of Pressure Found

With the found Area and Weight, the total pressure of this experiment was found approximately **20.77 psi and 0.143 in MPa.**

Surface Roughness

The surface of the meter bars where the thermal interface material is to be placed were machined using a mill with a 5 mm diameter cutter. Milling left the meter bars with perfectly flat surfaces that are suitable to place the thermal interface material on. However, the surface roughness was not accurately measured for this experiment. As the thermal interface material being used was semi-liquid,

i.e., it can flow, the assumption was made that the material will be able to fill in most of the air gaps between the two surfaces. This will however cause the data to be slightly off as the experiment requires an ideal surface that has been filed down and smooth. It is important to know that surface roughness of this experiment will reduce air gaps and increase thermal resistance.

Also, it improved the contact area and increased the actual contact area between the thermal interface material and the meter bars, thus enhancing thermal transfer. Researchers found that the interface surface was flat to approximately two microns per centimeter and had a surface roughness value of 1.6 micrometers.

Interface Thickness



Figure 15.1: Measuring the thickness using calipers

To determine the thickness of thermal paste in the ASTM D5470 test, I began by applying the paste evenly across the surface of one meter bar using a spreader or stencil to control thickness. Before assembling, the thickness was measured by using calipers by first measuring the metal bars (1 and 2) without the TIM and then re-measuring them after applying the TIM as shown on Fig 15.1 as given the result of 96mm. This provided an accurate reading of the TIM layer thickness. During the experiment, I maintained consistent pressure to ensure even distribution and recorded the test conditions and results.

Corsair's TM30 thermal paste, a high-performance and commonly used TIM, was applied in this experiment. According to Corsair, the recommended application thickness for TM30 thermal paste ranges between 0.05mm and 1.5mm with an applied pressure of 40 to 80 psi. As previously mentioned, the thickness and pressure applied to a TIM can vary according to the type of TIM and its application, so there is no fixed specification.



Figure 15: Thermal Paste used to this experiment

Thermal interface materials (TIMs)

Such as thermal grease, are important for their role in heat transfer between contact surfaces using ASTM D5470 TIMs effectively to fill micro-air gaps and surface irregularities, which If not filled, will act as a thermal insulator. The TIM reduces the TIM, with the possibility of measuring greater accuracy, standardization of testing and

procedures, reflecting the evaluation of the project that determines the evaluation. Skilled penance-man -Ensures consistent, reliable data necessary for policy development. mal Interface Material. During the experiment, the metal bars were cleaned a couple times before applying TIM as you can see on below Fig 16.

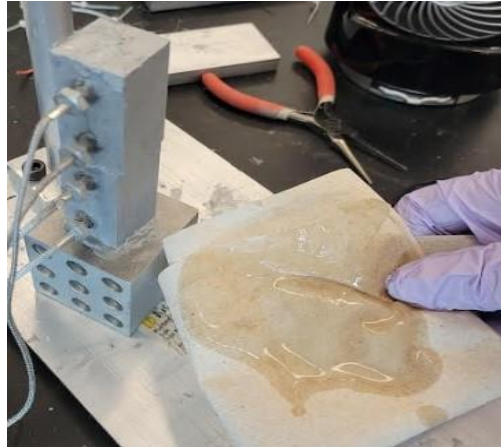


Figure 16: cleaning the metal bars using alcohol

For more information about the TIM used for this experiment, the GENNEL G107 thermal grease is a high-performance, silver-based thermal paste designed for a wide range of applications, ensuring efficient heat transfer from CPUs, GPUs, and other critical components to heat sinks. This non-electrically conductive, non-toxic, and non-corrosive formula boasts a thermal conductivity greater than 3.17 W/m-k, making it ideal for use not only in computers and gaming consoles like Xbox but also in high-power LED systems and industrial ovens. Each package includes 100 grams of the G107 thermal paste and a thermal paste spatula for easy application. This paste is particularly suitable for the ASTM D5470 experiment, where its high temperature resistance and superior thermal properties can be quantitatively analyzed to ensure optimal performance in heat management solutions.

Thermal Conductivity	>3.17W/m-k
Thermal Resistance	<0.067°C-in2/W
Net Weight	100g
Color	Silver
Package Includes	1 x GENNEL G107 100g Silver thermal grease paste, 1 x Thermal paste spatula

Figure 17: TIM Data by Manufacturer

Experimental Procedures

Starting using alcohol to clean the metal bars as you can see on figure 16 from the old experiment to ensure the new experiment will have accurate results.

The experimental procedure begins with measuring the thermal contact resistance at the interface between the two metal bars without applying any thermal interface materials. The setup is completely insulated all-round the metal bars and the heat source and the desk fan is switched on and directed towards the heat sink as you can see on figure 18. Then heater cartridges are connected to a variable voltage power source which is turned on and set to 12V DC (Using 12V because the heat sensors or cartridge used for this experiment is designed to provide a specific balance of power and safety for various applications). Then the Arduino controller is connected to the PC and data begins to be fed to a spreadsheet file that records all four thermocouple readings. The apparatus is allowed to operate continuously for more than 1 hour to ensure equilibrium is reached and then data is recorded for 1 hour. Time increments for data collection is 1 second, so in 1 hour there will be 3600 temperature measurements for each thermocouple. It is important to note that all trials were done at room temperature and atmospheric pressure.

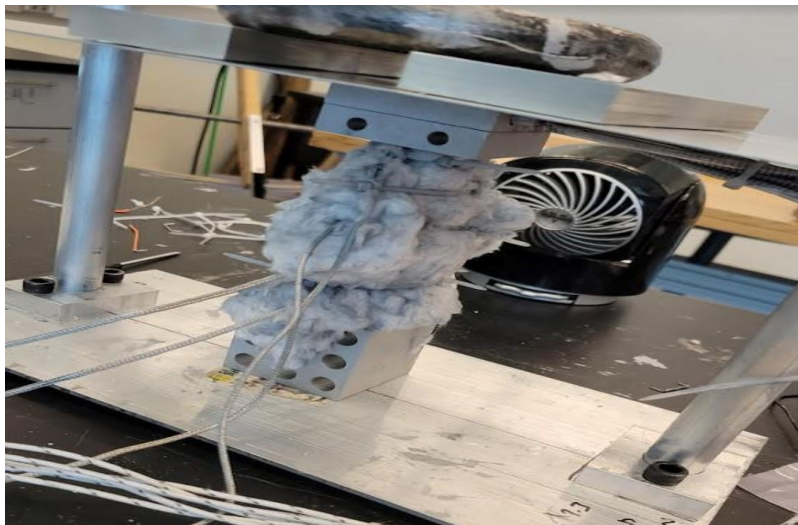


Figure 18: placing the weight and set the fan directed towards the heat sink

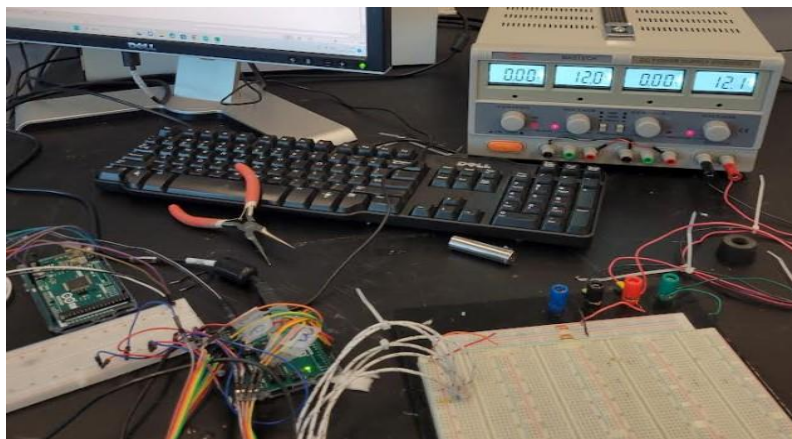
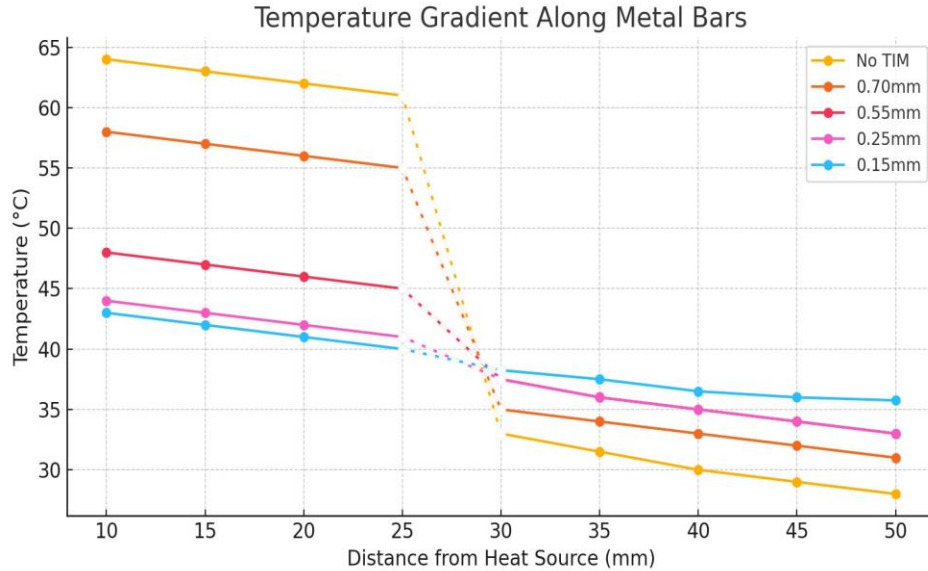


Figure 20: Connected Ardiuno with the circuit boards and heat cartridge connected to DC power Supply

5.2 Results and Discussion



Before getting the above data, the temperature fluctuates initially but reaches equilibrium after approximately 60 minutes. Once equilibrium is achieved, data is being collected consistently for a period of 1 hour to ensure stable readings across the metal bars. After sufficient data has been recorded for each trial, the power source is switched off, and the insulation is removed to allow the metal bars to gradually return to room temperature. This process ensures that the thermal properties are accurately captured in a controlled environment.

The latest temperature gradient analysis across different thermal paste thicknesses reveals nuanced insights into thermal management efficacy. The graph depicts temperature variations from the heat source, starting at 0mm, extending to 50mm near the heat sink. For the configuration without any Thermal Interface Material (TIM), the temperature curve initiates at approximately 64.4 °C, tapering off to about 33 °C. This significant temperature reduction along the bar highlights a pronounced gradient, indicative of substantial thermal resistance and minimal conductivity in the absence of TIM.

Examining the curve associated with 0.70mm TIM, there is a noticeable moderation in temperature decline, commencing at 58 °C and ending around 31 °C. This milder gradient reflects improved heat dissipation facilitated by the TIM, which enhances the thermal bridge between contact surfaces. Further reductions in TIM thickness to 0.55mm, 0.25mm, and 0.15mm progressively show decreasing temperature gradients.

The observed trends from the trials underscore the pivotal influence of TIM thickness on optimizing thermal conductivity. Thinner TIM applications are shown to be particularly

effective, offering less obstructive heat transfer and achieving a more uniform thermal distribution across the interfacing metal surfaces.

5.2.1 Thermal Contact Resistance

Table 3: Resistances and other calculated values

Thickness (mm)	Resistance ($\text{cm}^2\text{k/W}$)	Uncertainty %	Thermal Conductivity (W/mK)	Heat Transfer (xW/4m^2)	Conductance ($\text{W/cm}^2\text{K}$)
0.15	0.27	2.04	3.64	14.7110	3.67
0.25	0.45			12.01	2.19
0.55	1.00			9.92	0.99
0.70	1.37			8.11	0.73

To analyze the thermal contact resistance, conductivity, heat transfer, conductance, and associated uncertainty of the material, a MATLAB script was used. The script extracted temperature data from excel files containing thermocouple readings for all four probes in each trial, calculated the required values, and compiled the results for varying interface thicknesses.

The calculated results for interface thicknesses of 0.15 mm, 0.25 mm, 0.55 mm, and 0.70 mm are presented in the above table, which includes resistance, thermal conductivity, heat transfer, and conductance values.

Examining the data reveals an exponential relationship between the thickness of the TIM and the thermal contact resistance. For example, the thermal contact resistance increased from $0.272 \text{ cm}^2\cdot\text{K/W}$ at 0.15 mm thickness to $1.365 \text{ cm}^2\cdot\text{K/W}$ at 0.70 mm thickness.

Similarly, the conductance decreased from $3.674 \text{ W/cm}^2\cdot\text{K}$ to $0.732 \text{ W/cm}^2\cdot\text{K}$, demonstrating that thicker TIM layers significantly reduce heat transfer efficiency between the surfaces. These results highlight the critical role of TIM thickness in determining thermal performance.

The average uncertainty associated with these calculations was found to be $\pm 2.04\%$, calculated based on the propagated uncertainties of heat transfer and temperature gradients.

This ensures that the results are reliable and can be confidently used in further analyses or practical applications. The average thermal conductivity of the material was calculated as $3.64 \text{ W/m}\cdot\text{K}$ and for across all thicknesses, as expected.

This value was derived based on the calibrated heat transfer through the interface and the surface area in contact. Heat transfer values decreased with increasing thickness, from 14.71 W/m^2 at 0.15 mm to 8.11 W/m^2 at 0.70 mm, due to the increased thermal resistance. These findings align with theoretical expectations and emphasize the impact of TIM thickness on thermal management systems.

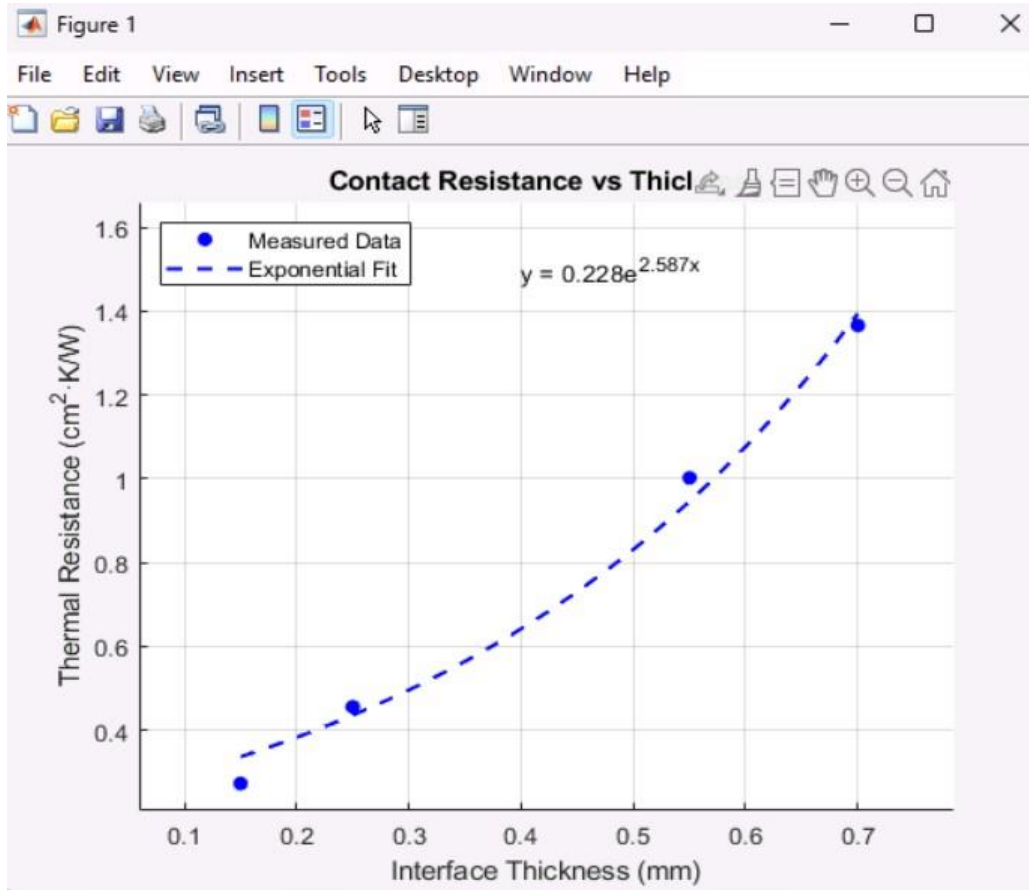


Figure 21: Matlab graph for Contact Resistance vs Thickness

The experimental values for thermal contact resistance display a clear exponential relationship between interface thickness and thermal resistance, as shown in the graph. Although the data points might initially appear linear, their exponential behavior becomes apparent upon close examination. As the thickness of the TIM layer increases, the thermal resistance also rises exponentially. This occurs because adding more thermal interface material introduces more barriers to efficient heat transfer, resulting in a lower overall thermal performance.

Manufacturers of TIMs, such as FujiElectric, typically recommend an optimal interface thickness of 0.1mm for maximum efficiency. This standard is widely used because thinner TIM layers reduce the thermal contact resistance while still sufficiently filling any air gaps or voids between contact surfaces. As mentioned earlier, the thickness of TIMs can vary depending on the application and type of material used. However, the 0.1mm thickness serves as a practical reference for further calculations. The trend line for the data was fitted using the equation $Y = 0.228e^{2.587 \cdot 0.1}$ which was used to extrapolate the thermal contact resistance for the G107 thermal paste at the recommended thickness of 0.1mm. Using this trend line equation, the calculated thermal resistance at 0.1mm thickness was

found to be $0.292 \text{ cm}^2 \cdot \text{K/W}$. This value provides a useful comparison with the published manufacturer data.

The comparison with manufacturer data, as shown in **Table 4**, indicates that the experimental values fall well within the published specifications for the G107 thermal paste. The manufacturer's maximum thermal resistance specification is $0.4322 \text{ cm}^2 \cdot \text{K/W}$ while the experimentally derived value is significantly lower at $0.292 \text{ cm}^2 \cdot \text{K/W}$ which confirms the accuracy of the experimental procedure. Moreover, the thermal conductivity of the G107 thermal paste was found to be 3.62 W/mK which is higher than the manufacturer's claim of 3.17 W/mK . This difference (approximately 14.87%) suggests that the TIM is more thermally efficient than the minimum standard set by the manufacturer, further validating the reliability of the experimental setup and its results. The extrapolated interface thickness required to achieve the manufacturer's published thermal resistance value of $0.4322 \text{ cm}^2 \cdot \text{K/W}$ was calculated to be 0.2618 mm . This result provides valuable insight into the performance of the G107 TIM when applied at different thicknesses and serves as a useful benchmark for optimizing TIM applications in future experiments. In conclusion, the experimental results demonstrate a clear correlation between TIM thickness and thermal resistance, confirming that thinner layers offer superior thermal performance. The close match between the experimental data and manufacturer specifications validates the experimental procedure and provides a solid foundation for further investigations into the thermal properties of TIMs.

Table 4: Comparison Between Experimental and Manufacturer Values

G107 TIM	Experimental (0.1mm thickness)	Manufacturer Published (Thickness unknown)	Experimental (Using manufacturer resistance value)
Thermal Resistance ($\text{cm}^2 \cdot \text{K/W}$)	0.292	<0.432	-
Thermal Conductivity (W/mK)	3.64	>3.17	-
Interface Thickness (mm)	-	-	0.2618

6. CONCLUSION

The objective of this project was to develop an experimental test bench capable of accurately characterizing the thermal properties of thermal interface materials (TIMs). These properties include thermal contact resistance, thermal conductivity, and heat transfer.

The test bench incorporated components such as heating cartridges, an Arduino-controlled temperature monitoring system using MAX-6675 modules and K-type thermocouples, as well as precision aluminum metal used to fabricate the calorimeter. A MATLAB script was employed to analyze the data received from the thermocouples, enabling the calculation of key thermal properties, which were then compared with manufacturer-provided data. The experimental results revealed an exponential increase in thermal resistance with increasing TIM thickness, as anticipated. Using the trend line equation derived from the experimental data, the thermal resistance at a standard TIM thickness of 0.1mm was found to be $0.292 \text{ cm}^2 \cdot \text{k/W}$. This value is significantly lower than the manufacturer's maximum specification of $<0.4322 \text{ cm}^2 \cdot \text{K/W}$, confirming that the experimental setup provided accurate and reliable data. Furthermore, the average thermal conductivity of the TIM was experimentally measured to be 3.64 W/mK , which is higher than the manufacturer's published value of $>3.17 \text{ W/mK}$, demonstrating that the TIM exhibits superior thermal performance. The consistency of these results suggests that the experimental setup was effective, and the data is reliable for further use.

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