Capstone Engineering Project to Design an Apparatus for Testing the Thermal Impedance and Apparent Thermal Conductivity of Different Thermal Interface Materials

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Abstract
Since their initial development, central processing units (CPUs) have increased their power output capabilities and decreased in size. Heat sinks are incorporated in electrical design to cool components faster and prevent overheating, but contact resistance at the CPU-heat sink interface impedes cooling. Surface roughness on the CPU and heat sink faces prevents them from perfectly mating; therefore, air pockets with low thermal conductivities develop at the interface and prevent effective heat transfer. Thermal interface materials (TIMs) have high thermal conductivities and can deform to fill the voids created by the surface roughness. Commercial machines are available to test the thermal properties of experimental TIMs but are very expensive. This capstone engineering project aims to design, build, and test a cost-effective TIM tester that will still measure accurate and precise values for the apparent thermal conductivity and thermal impedance of various TIMs.

Keywords
Thermal interface material, apparent thermal conductivity, thermal impedance, heat transfer, design

Introduction
One of the most significant challenges inhibiting the development of electronic devices is the excessive heat buildup created by micro-electrical components. Central processing unit (CPU) manufacturers like Intel enhance their products' power capabilities every year while reducing their physical size. There is no end in sight to these continuous improvements. The demand is greater than ever to develop methods and materials capable of dissipating the heat produced from these micro-electrical components. Heat sinks that contact these components are frequently used to transfer heat from the device to its surroundings quickly. However, the surface roughness on the heat source faces and the heat sink prevent them from perfectly mating. Figure 1 illustrates the situation created by the surface roughness at the heat source-heat sink interface.

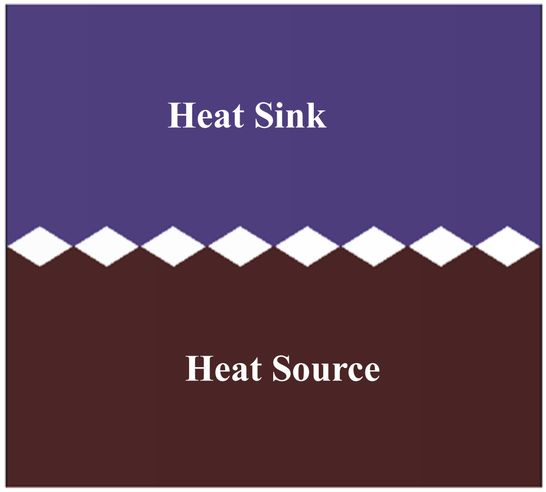

Figure 1. An imperfect mating surface is created by the roughness of the heat source and heat sink. As a result, air pockets with low thermal conductivity develop and prevent effective heat transfer.

It is possible to reduce surface roughness by polishing, but this process adds time and cost to manufacturing. Instead, thermal interface materials (TIMs) have been developed to combat the thermal dissipation issue. TIMs are highly conductive and can deform to fill the air pockets created at the interface. Additionally, TIMs must be able to withstand the variable thermal loading over time. Figure 2 illustrates how TIMs fill the air pockets and increase the rate of heat transfer.

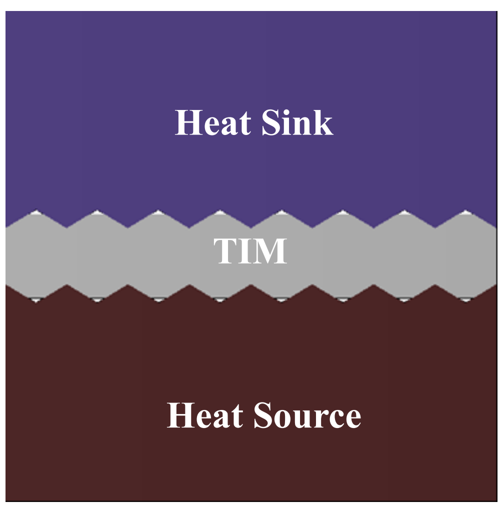

Figure 2. The ideal TIM possesses a high thermal conductivity and can deform to fill in any air pockets.

Problem Definition

Since there is a demand for better TIMs, ASTM standard D5470-12 was developed to provide the methods and conditions required to test the apparent thermal conductivity and thermal impedance of various TIM types. Apparent thermal conductivity is the thermal conductivity of heterogeneous materials whereas thermal conductivity is used for homogeneous materials[2]. Thermal impedance is a material's resistance to heat flow and is a function of material thickness[2]. Commercial manufacturers have developed highly automated testing machines that can determine a TIM's thermal properties but are highly expensive. We received a quote for $50,000 from a manufacturer.

Problem Solution

The high cost for commercial TIM testers has prompted many institutions to develop their own TIM testers at a fraction of the cost. Our client is Dr. Chandan Roy, an assistant professor of mechanical engineering at Mercer University. He specializes in heat transfer and thermal management and has conducted previous research involving TIMs. He wants to continue researching TIMs at Mercer, and he has tasked us with designing and building a TIM tester for Mercer.

Extensive research of other institutions' designs revealed that common design challenges include[3-8]:

1. Measuring in-situ thickness during testing.
2. Applying heating and cooling during testing.
3. Applying and measuring constant, uniform pressure during testing.
4. Determining length of meter bars and location of temperature sensors.
5. Choosing proper insulation to simulate one-dimensional heat flow.
6. Maintaining meter bar alignment.
7. Maximizing the overall precision of the device.

Calculating Thermal Impedance & Apparent Thermal Conductivity

ASTM D5470-12 specifies two main methods of measuring apparent thermal conductivity for a TIM. One relies on knowing the heat flow in the meter bars (method 1), and the other relies on knowing the thermal conductivity of the meter bar material (method 2). We used method 1 for our design. In this method, total thermal impedance is calculated using Equation 1 at different TIM thicknesses[1].

$$\theta = \frac{A}{Q} * (T_H - T_C) \tag{1}$$

Where A is the cross-sectional area of the meter bar contacting the TIM specimen, Q is the heat flow applied to the apparatus, T_H is the temperature of the surface of the hot meter bar contacting the TIM specimen, and T_C is the temperature of the surface of the cold meter bar contacting the TIM specimen. T_H and T_C can be linearly extrapolated from thermocouple measurements along the meter bar as long as those measurements are in an area of uniform heat flux and the distances between thermocouples is known. Equations 2 and 3 will be used to calculate T_H and T_C, respectively[2].

$$T_H = T_2 - \frac{d_2}{d_1} * (T_1 - T_2) \tag{2}$$

$$T_C = T_3 + \frac{d_4}{d_3} * (T_3 - T_4) \tag{3}$$

T_1, T_2, T_3, and T_4 are temperatures measured by the thermocouples in the hot and cold meter bars, and d_1 is the distance between T_1 and T_2, d_2 is the distance from T_2 to the surface of the TIM in contact with the hot meter bar, d_3 is the distance between T_3 and T_4, and d_4 is the distance from T_3 to the surface of the TIM in contact with the cold meter bar. Total thermal impedance measurements are plotted versus measured thickness, and the reciprocal of the slope of the line created by the plot is the apparent thermal conductivity of the specimen[2]. The general schematic for this method is shown in Figure 3.

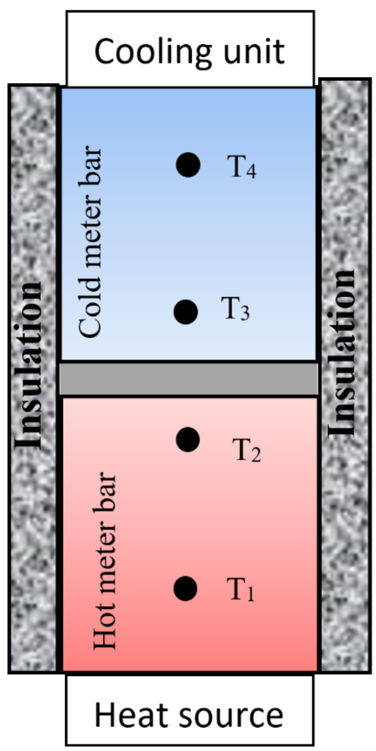

Figure 3. General schematic of a typical TIM tester setup.

Final Design

Three designs were compared using merit criteria to select the final design. Figures 4 and 5 show the front and side view of the final design. The TIM tester is comprised of three different sub-assemblies*: the heater block, inner housing*, and *outer housing*. The overall length, width, and height of the unit without the press screw is 15” x 6” x 16”, respectively.

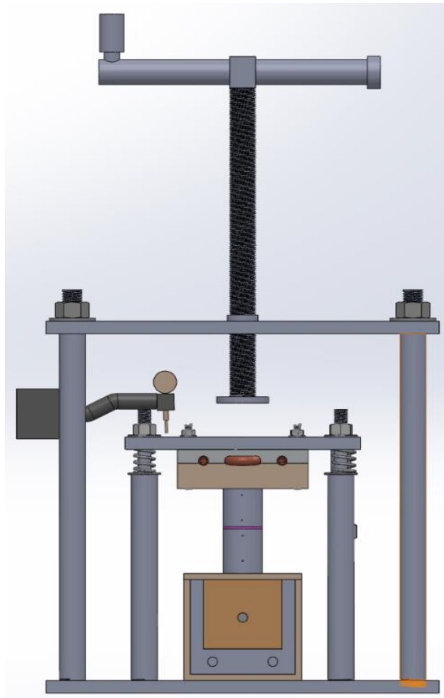

Figure 4. Front view of the final design. The screw press applies a compressive force onto the inner housing which compresses the TIM. Springs located in-line with the inner housing support bars return the top plate of the inner housing to its original position.

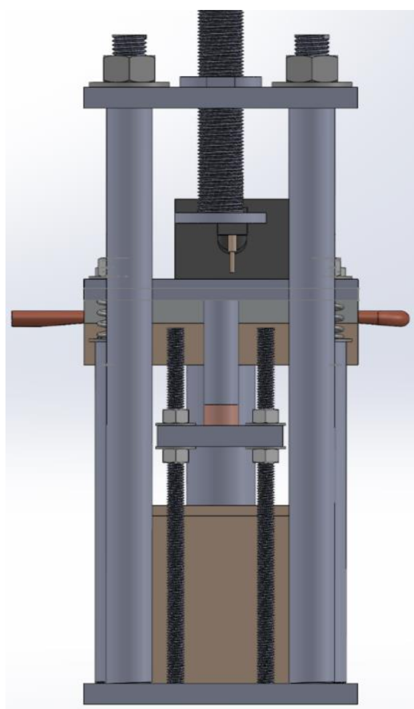

Figure 5. Pressure is recorded by a load cell (small brown cylinder) that is supported by an adjustable-height platform. The load cell button is compressed by an identical diameter bar

protruding from the bottom surface of the inner housing top plate.

The Heater Block

Figure 6 showcases the design of the heater block assembly. The purpose of the heater block is to provide a temperature gradient across the bottom meter bar, and the power source is a cylindrical cartridge heater (⅜"x 2") that is embedded in the center of the aluminum block. The faces of the heater block are insulated using wood paneling to ensure the heat flow is one-dimensional through the meter bar. A U-shaped guard heater is also implemented below the heater block to ensure heat does not dissipate through the side and bottom faces of the central heater block. Two cartridge heaters set at a lower power output are employed in the guard heater and are spaced apart to heat the guard heater more uniformly.

The bottom meter bar is threaded and screws into the top face of the heater block. The front face of the guard heater is exposed, so the block does not continue to heat up and add additional heat flow through the meter bars. The wood paneling surrounding the entire assembly is joined together using wood screws.

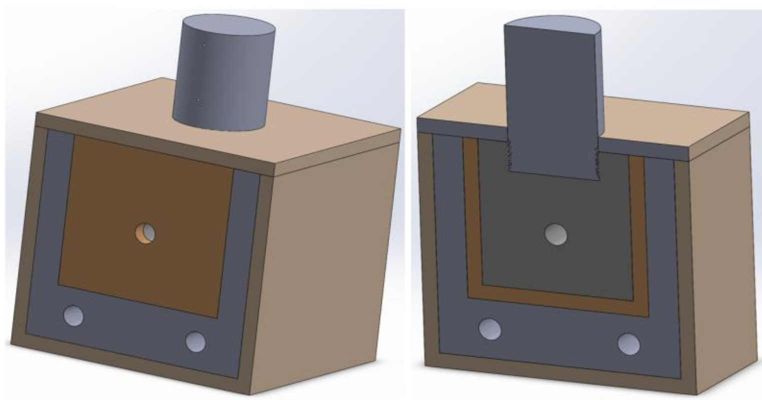

Figure 6. The heater block assembly employs cartridge heaters to heat the central block and guard heater blocks while insulating wood paneling ensures all of the heat generated passes through the meter bars. Piping insulation around the meter bars is not shown.

The Inner Housing

Figure 7 showcases the overall design of the inner housing assembly with the heater block assembly positioned. The inner housing aids to control the height of the cold meter bar, cold plate, and platform that the load cell rests on. The cold plate will function as the devices heat sink, and the load cell will be used to record the pressure used to compress the specimen.

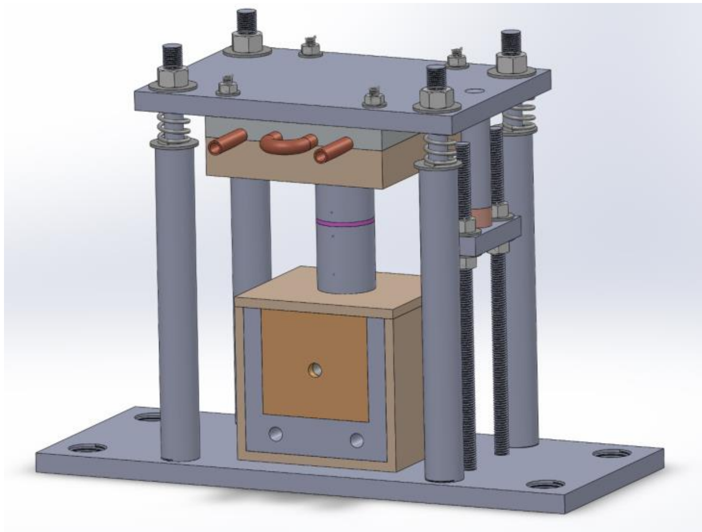

Figure 7. The inner housing consists of an aluminum base plate with four identical aluminum bars supporting an aluminum top plate that is mounted to the cold plate using nuts and bolts. Springs rest on the stepped portion of the support bars and support the top plate. Two threaded rods on the right side of the inner housing support the load cell which rests on top of an adjustable height platform.

The cold meter bar has a larger diameter lip at its top face, so it is supported by an insulating wooden block fastened to the cold plate and aluminum plate. An aluminum plate that is wider than the cold plate is utilized in the fastened assembly to avoid compromising the cold plate tubing. A cross section of the fastened assembly is shown below in Figure 8. The cold plate is connected to a chiller that will maintain the water at 20°C.

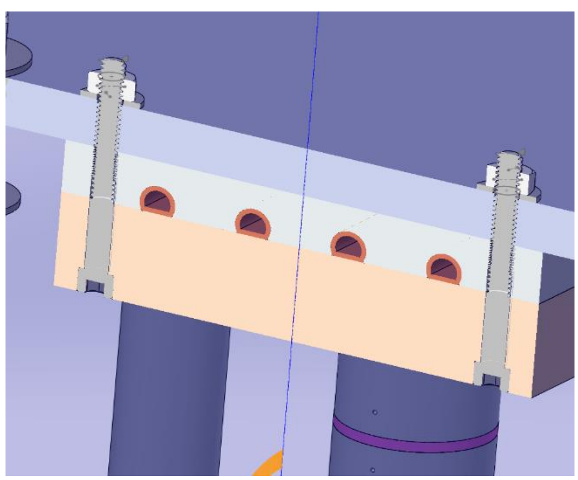

Figure 8. Cross section of the aluminum plate-cold plate-wood block fastened assembly. This design avoids compromising the cold plate tubing, and the top meter bar can be moved freely up and down as the support bar springs compress and extend.

The middle plate and cold meter bar heights are supported and controlled by four identical stepped bars that use springs to resist a compressive load applied on the top face of the aluminum plate-cold plate assembly. The springs chosen are suitable for the range of small loads that will be applied to compress the members. The stepped portion of the support bars is threaded, so nuts are used to control the initial height of the cold meter bar without any load on it. The nuts act as a mechanical stop as the load is released.

The hot meter bar and cold meter bar will maintain alignment by creating a small rectangular cutout on the top face of the base that will correctly position the heater block. Piping insulation (not shown in model) will be wrapped around the meter bars, as well.

The load cell is suspended in the air by a platform with two threaded rods going through the platform. Its position can be adjusted by turning the bottom nuts. A small, threaded aluminum bar screws into the bottom face of the middle plate and transfers the compressive force applied by the press screw shown in Figure 4. Figure 9 is shown below and provides a zoomed in view of the load cell.

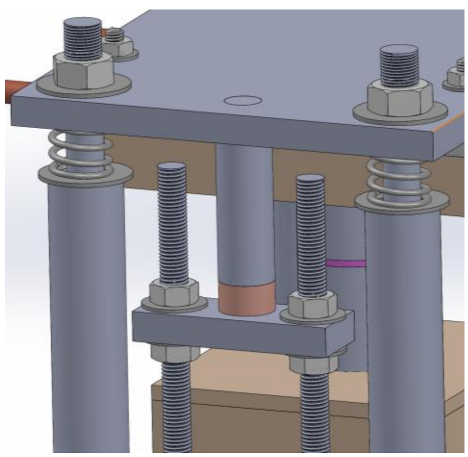

Figure 9. The load cell (small brown cylinder) is compressed by an aluminum bar that is threaded and screwed into the bottom face of the middle plate. The threaded rods and nuts allow the height of the load cell to be adjusted when different thickness TIMs are tested.

The Outer Housing

The final rendering of the outer housing with the heater block and inner housing is shown below in Figure 10. The outer housing has two functions. The first is to provide a thread for the press screw which will apply the compressive load. The second is to provide a means of measuring the in-situ thickness.

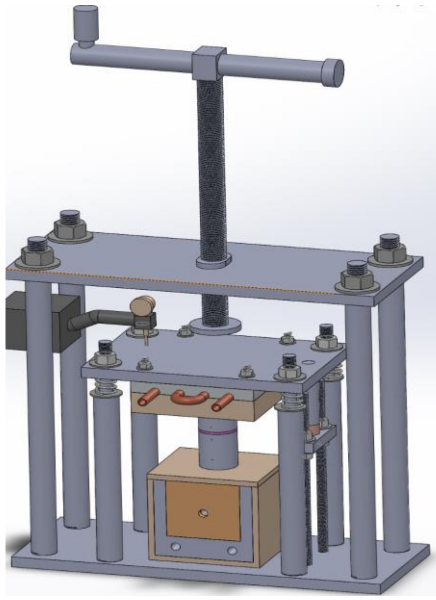

Figure 10. Isometric view of the final design. The outer housing is used to support the manual press screw that applies the compressive load onto the middle plate of the inner housing. A precision dial indicator is positioned above the middle plate of the inner housing. As the middle plate is compressed, the change in thickness can be recorded as the dial indicator probe freely glides down. The dial indicator clamp (black box) is attached to one of the support bars, and the clamp's flexible arms can be adjusted to change the height of the dial indicator.

The top plate of the outer housing is supported by four identical stepped bars that are threaded around the smaller diameter step. The height of this top plate is to remain fixed. A manual press screw applies the compressive load onto the top plate of the inner housing. The springs used for the inner housing will compress, and the change in thickness of the TIM will be recorded by a precision dial indicator that is supported by a flexible arm attached to a base that clamps around one of the outer housing bars.

The dial indicator probe can freely slide up and down as it maintains contact with the middle plate of the inner housing, and the TIM's in-situ thickness will be determined by subtracting the change in thickness from its original thickness. The original thickness will be measured using calipers before applying it to the hot meter bar. The base will be situated on one of the supporting bars, and the flexible arm allows the user to position the dial indicator appropriately. The measuring range of the indicator is 1 inch, so it will need to be positioned just above the inner housing middle plate. The change in thickness will be on the order of micrometers, so staying within measuring range will not be an issue.

Data Collection

Critical data to be used in the calculation of apparent thermal conductivity include the temperature readings from the thermocouples and the thickness of the TIM during testing. The applied pressure must be reported with the value calculated for thermal conductivity, as well. The measurements for pressure and temperature are recorded by the thermocouples placed within the meter bars and the load cell, respectively. The group of thermocouples and the load cell will be connected to a data acquisition unit. The TIM's thickness during testing will be determined by subtracting the change in thickness after the load has been applied from the initial thickness prior to being placed in the unit.

Total automation is an appealing feature of most commercial TIM units and consequently is why they are so expensive. Our design is considerably less expensive since more work is required by the user to conduct the test and collect data, but this also introduces additional uncertainty.

Thermocouple Locations

For each TIM specimen, the apparent thermal conductivity will be calculated from a plot of the specimen's thermal impedance versus thickness. The thermal impedance is the temperature difference between the two isothermal faces of the TIM divided by the heat flux through it. The contact resistances between the faces of the TIM and meter bar are included in the calculation of thermal impedance [2]. The temperatures at each face of the TIM can be linearly extrapolated from the thermocouple data as long as the thermocouples are in areas of uniform heat flux within the meter bars.

To determine the minimum height of the first thermocouple from the hot meter bar bottom face, Ansys IcePak was used to determine where the heat flux became uniform through the meter bars. Figure 11 displays the IcePak simulation results. The length of each meter bar is 2 inches, while the sample TIM material is 0.02 inches thick. The TIM's thickness and apparent thermal conductivity used in the simulation are similar to values for other known TIMs. The heat flux becomes uniform 2.5cm above the bottom face of the hot meter bar when using the TIM from our model. The cartridge heater output power is 75W in this simulation. This power output was chosen so that the average temperature across the TIM was 50°C[2]. The power output will be adjusted for each TIM in order to achieve the 50°C requirement, so the first thermocouple will be placed slightly above 2.5cm to ensure its location possesses uniform heat flow for different TIMs. Insulation was employed around each face of the heater block and the entire length of the meter bar-TIM assembly so that heat flow was one dimensional through the meter bars.

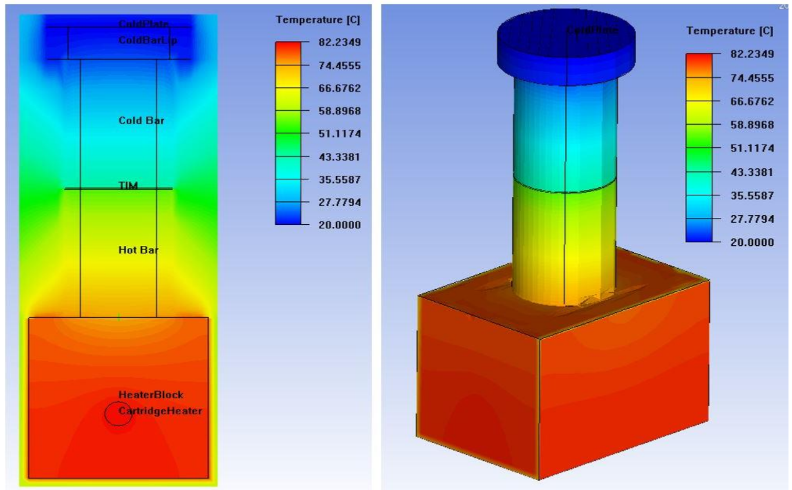

Figure 11. IcePak model results. The first thermocouple must be placed at a minimum height of 2.5cm from the bottom face of the hot meter bar in order to linearly extrapolate the temperature at each TIM interface. The first thermocouple will be placed at a distance greater than this as a design "safety" factor to ensure the thermocouple is in a zone of uniform heat flux.

Insulation Analysis

Insulating the meter bar and heater block will allow us to assume one-dimensional heat flow through the meter bars. The heat flow used in Equation 1 can be determined from the voltage and current applied to the cartridge heater.

The insulation chosen to surround the meter bars is 2-inch-thick fiberglass pipe insulation. An analysis of the critical radius for this insulation was calculated, and the analysis shows that the critical radius for the insulation is much smaller than the outer radius of the insulation used. Therefore, the insulation thickness is great enough to assume one-dimensional heat flow through the meter bars.

ASTM D5470-12 also specifies the minimum R-value needed for insulation between the main heater and the guard heater shown in Figure 3[2]. Oak wood board was selected as the insulation separating the main heater and guard heater as it is readily available and inexpensive. Our analysis shows that a standard thickness of ¼" oak wood board is sufficient to meet the minimum R-value.

Uncertainty Analysis

Preliminary uncertainty analysis for the TIM tester was conducted to estimate the accuracy of the measurements taken by the design. Using Kline and McClintock's equation for design stage uncertainty[9], the uncertainty for thermal impedances measured by the TIM tester should be less than 10% of the total measurement. The exact value will vary depending on the cartridge heater power, initial TIM thickness, thermocouple measurements, and several other factors.

Initial Testing & Budget

Three different tests will be used to verify that the TIM tester is working properly. The first test will be a series of checks to ensure all the individual instruments are working properly and that the other design features are functioning. The next test will ensure that the TIM tester can repeatedly withstand the high temperatures that will be applied during testing. The last test will check the accuracy and repeatability of the apparatus by using the TIM tester to test TIMs with known properties multiple times. The results will then be compared with known values.

The total anticipated cost of this project including tax and shipping is $8,372. The most costly instrument used is the chiller which costs around $6,000.

Summary & Conclusion

To conclude, our chosen design for a TIM testing apparatus is cost-effective, with an approximate budget of $8,500 compared to commercial TIM testers that can cost around $50,000. The design conforms to ASTM D5470-12 and has a design stage uncertainty of less than 10% for the measurement of total thermal impedance.

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