# Thermal Paste Performance

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ME103: Experimentation and Measurements

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### Abstract

Efficient heat dissipation is critical for the performance and durability of modern electronic devices, particularly CPUs and GPUs. Since these components generate significant heat during operation, insufficient cooling can lead to thermal throttling, reduced efficiency, and potential hardware damage. Thermal pastes are vital intermediaries between processors and heatsinks, enhancing heat transfer by filling microscopic air gaps. Understanding the thermal conductivity of these thermal pastes is crucial for optimizing cooling system performance and ensuring device longevity. We aim to take a deeper look and validate the performance of various thermal pastes since the knowledge of efficient thermal solutions could benefit anyone, especially when powerful computing technology is so important.

The study used a controlled experimental setup with two aluminum blocks, thermocouples, and an insulating fiber blanket to measure the temperature gradient across various thermal paste layers to simulate CPU heat generation. Our findings were relatively accurate as thermal pastes with the higher known thermal conductivity values were able to transfer heat through the aluminum blocks more efficiently. However, our findings are met with some limitations as thermal paste thicknesses were not precisely controlled, and external factors (ambient temperature and humidity) were excluded.

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### 1. Introduction

The chip manufacturing industry has grown more than ever within the last decade. The increased need and demand for artificial intelligence, higher-performance gaming, crypto mining, and the ever-increasing computational demands of modern technology have fueled this growth. While these computational demands are powered by the chip, they must also rely on external hardware to reach extreme clock speeds. While consumers tend to prioritize performance metrics such as speed and efficiency, cooling advancements play a vital role in enabling these prioritized metrics to be.

One critical component of the thermal management assembly is the thermal paste, a material applied between the processor and heatsink to facilitate efficient thermal transfer. This paste plays a vital role in ensuring the heat generated from these high-performance processors can be conducted to the heat sink, where it can be appropriately dissipated into the surrounding environment.

The quality and composition of the thermal paste are vital to its effectiveness as these factors will influence its thermal conductivity, a key property in heat transfer that quantifies a material's ability to conduct heat. High thermal conductivity ensures minimal resistance to heat flow. It allows processors to operate at optimal temperatures to maintain their performance and longevity, as reaching high chip temperatures can lead to numerous issues that limit their performance, such as thermal throttling.

Despite abundant claims regarding the effectiveness of various thermal pastes [1],[2],[3], there is a lack of data-backed studies comparing their performance under controlled conditions. This project evaluates the performance of various thermal pastes by measuring temperature gradients across a layer of thermal paste between two aluminum blocks. The findings will help identify the most effective thermal pastes for efficient heat dissipation from the typical popular selections on the market, providing valuable insights for consumers and professionals in electronic/chip cooling.

## 2. Methods

To evaluate the performance of various thermal pastes, it was essential to design and assemble a setup specifically tailored for accuracy and reliability. To do so, our setup consisted of two custom-milled aluminum alloy blocks, which are seen in Figures 1 and 2 (note: composition of aluminum alloy was tested and certified), three K-type thermocouples with amplifiers, an insulated fiber blanket, a temperature-controlled hot plate, an ESP32, and a breadboard. We used the thermal pastes: Noctua NT-H2, Arctic MX-6, and Thermal Grizzly Kryonaut. The aluminum blocks in this assembly will act as the heat source and heat sink, simulating the CPU/GPU and heat sink that dissipates the heat. Since this experiment relied on precise temperature measurements, K-type thermocouples were chosen for their accuracy and ability to withstand high temperatures. The insulated fiber blanket was used to minimize heat loss, ensure a vertical heat flux through the aluminum blocks, and reduce lateral heat transfer. The temperature-controlled hot plate acted as the heat source (simulating the CPU/GPU), where heat is generated. Lastly, the ESP32 and breadboard were used for equipment calibration and data acquisition.

We measured the temperature gradient across two aluminum blocks with a layer of thermal paste sandwiched between them. This intermediate gradient serves as the thermal conductivity. Smaller gradients represent more efficient heat transfer, while larger gradients indicate less efficiency (more thermal resistance). Temperature measurements were taken by thermocouples embedded in the center of each aluminum block and the bottom of the lower aluminum block. The setup was designed to simulate heat dissipation in a CPU or GPU system and to ensure controlled conditions for meaningful comparisons between the various pastes, minimizing external influence that can affect temperature readings. The setup of this experiment can be pictured in Figure 3. Additionally, a control thermal paste is applied to the tips of the thermocouples and the hot plate, ensuring consistency across all trials and enhancing the heat transfer experienced by these components.

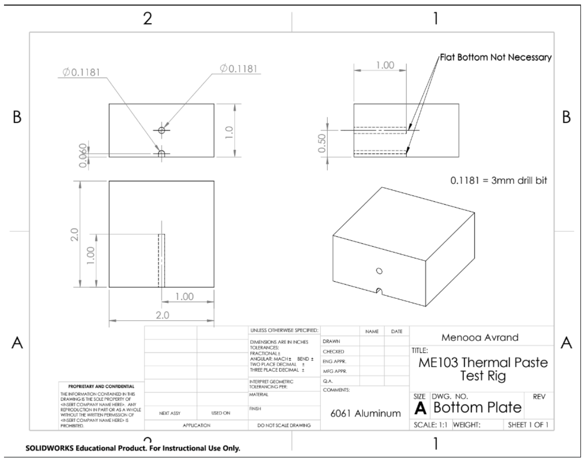


**Figure 1** - *Mechanical drawing of the bottom block of our experimental setup. The bottom semicircular hole ensures the block is flush with the hot plate when the thermocouple is inserted.*

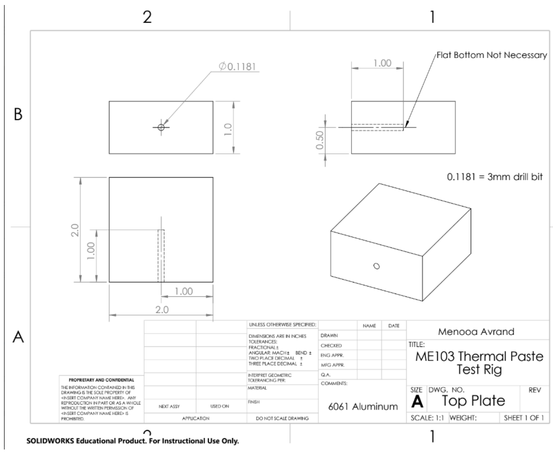


**Figure 2**—*Mechanical drawing of the top block of our experimental setup. The hole is reserved for the third thermocouple, which measures the temperature above the thermal paste.*

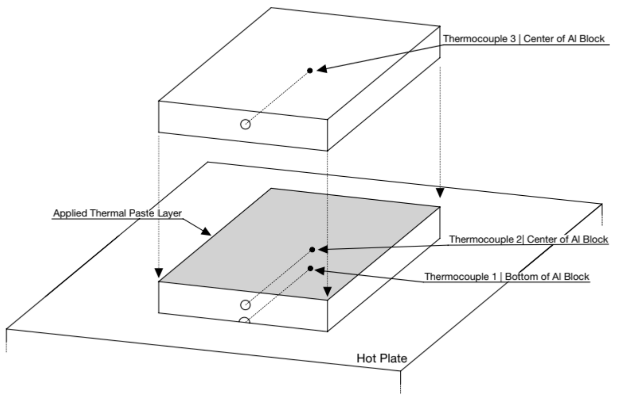


**Figure 3** - *Three-dimensional representation of the experimental setup with the three thermocouples, thermal paste to be tested, and the hot plate.*

After the experiment setup, we started calibration for the K-type thermocouples. Wires connected the respective GPIO pins to the amplifiers. To each of these amplifiers, a thermocouple was connected and secured using the screw terminals. Additionally, we had an electric tea kettle with water as part of our calibration materials. Pictures of our setup can be seen through Figures 4 and 5.

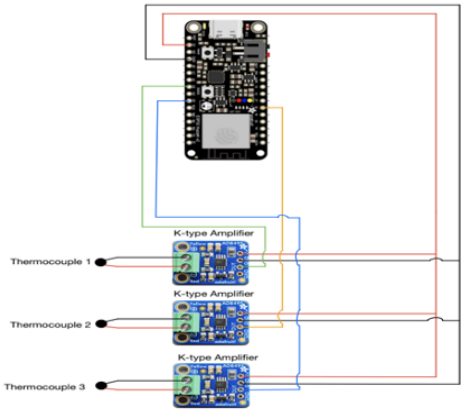


**Figure 4** - *Schematic of wiring diagram for thermocouple calibration*

Calibration of a thermocouple requires a known reference temperature to map the voltage reading to an accurate temperature. We calibrate thermocouples with two known reference temperatures: Ice-water mixture at 0°C and boiling water at 100°C. First, we placed a thermometer in boiling water and used the recorded temperature on the thermometer as the reference temperature. We note that the temperature reading from the thermometer once the water was boiling read 95°C. The manufacturer's thermometer specifications read ±1.5°C ([Model B60700-1500]). However, other factors such as heat loss due to the electric kettle's low insulation temperature (due to the cover not being in place and allowing steam to dissipate into the air), uneven heat distribution within the kettle, and possibly the thermometer itself might have contributed to the observed discrepancy.

We then wrote a script that iterates and calculates a parameter within a linear equation for the k-type thermocouple and its respective amplifier to map the voltage reading to the temperature measured on the thermometer. This process was done simultaneously with all three thermocouples in boiling water, with the code calculating a respective calibration parameter for each thermocouple. Additionally, we applied this method to ice water to confirm the validity of our calibration.

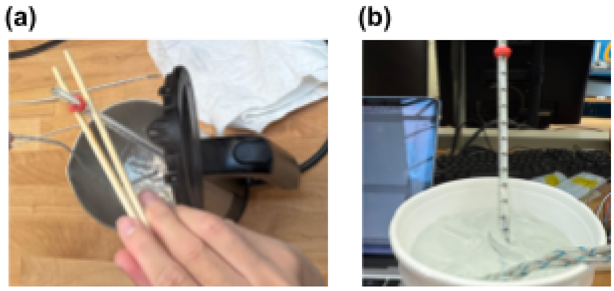


**Figure 5** - *Calibration of thermocouples using (a) boiling water and (b) ice water*

The parameter was calculated based on the temperature reading of 100 data points, all with a 0.5-second spacing between them. These results were averaged to obtain a reliable parameter value. Once this parameter was found, the thermocouples could be used to find the temperature.

As stated, the experiment setup consisted of two equal-in-dimension aluminum blocks stacked on each other, with the thermal paste of interest applied as a layer between them. The dual block structure is then placed on a hot plate, to which a separate control thermal paste (different from the thermal paste being tested) is applied between the bottom block and the hot plate. Two holes were bored for the thermocouples directly to the volumetric center of each block. One final hole was bored along the bottom side of the bottom block, exposing the bore channel to the hot plate. This hole was so the bottom block could sit flush on the hot plate with the thermocouple exposed to the hot plate. The thermocouples were then inserted into these three holes, and the control thermal paste was applied to the tips of the thermocouple for better thermal conductivity.

Additionally, both blocks' top and bottom surfaces were machined to achieve the smoothest possible finish, minimizing the impact of surface roughness on heat transfer. The engineering drawings of these two blocks are shown in Figures 1 and 2, and the final machined blocks are shown in Figure 6.

**Figure 6** - *Aluminum alloy machined blocks created from the engineering drawings that will be used for the experiment.*

A highly insulating fiber blanket was wrapped around the blocks and secured with aluminum tape. This was done to ensure that the heat flux throughout the blocks travels linearly upward through the center of the block structure and not through the sides. Once the setup was established with the thermal paste we wanted to test, we turned the hot plate to a set temperature and ran code to collect the temperature reading data from each thermocouple. This data was saved as a .csv on the ESP using Thonny. The reading for each thermocouple was formatted into a respective column, and using MATLAB, we smoothed the data to account for any sensor noise and plotted the Temperature vs. Time curve for each thermocouple.

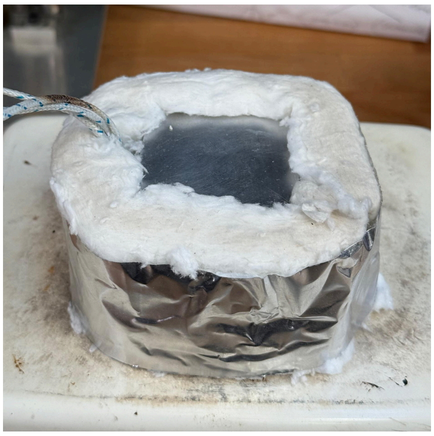

**Figure 7**—*This image shows our experimental setup. Once thermal paste was applied to the necessary regions, and the thermocouples were inserted, an insulating layer and aluminum tape were wrapped around the setup. This ensured our experiment remained insulated and heat from the hotplate traveled only vertically.*

## 3. Results

After collecting data while applying constant heat from the hot plate for various thermal pastes, including the case with no thermal paste, we generated the time vs. temperature plots below. In these plots, the blue line indicates the temperature of the hotplate, the red line represents the temperature at the center of the bottom aluminum block, and the orange line represents the temperature at the center of the top aluminum block. The resulting plots are presented below.

<u>Time vs. Temperature Plot: No Thermal Paste</u>

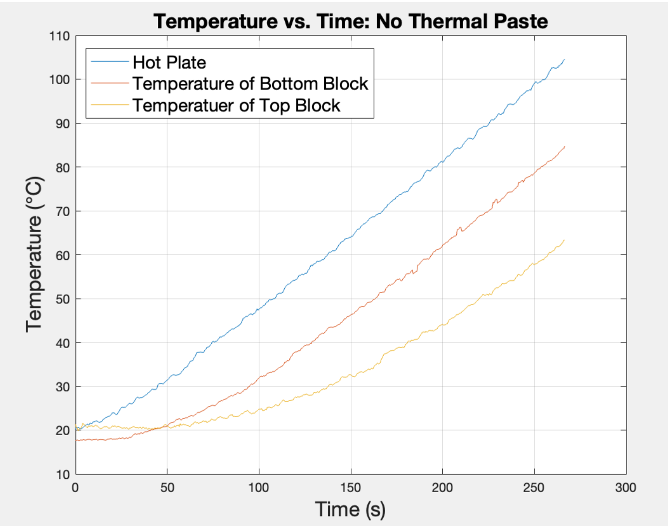


**Figure 8** - *Temperature vs. time plot for the setup with no thermal paste between blocks. The heat was applied until the hot plate reached temperatures above ~100* ℃.

<u>Time vs. Temperature Plot: Thermal Paste #1 (Noctua NT-H2)</u>

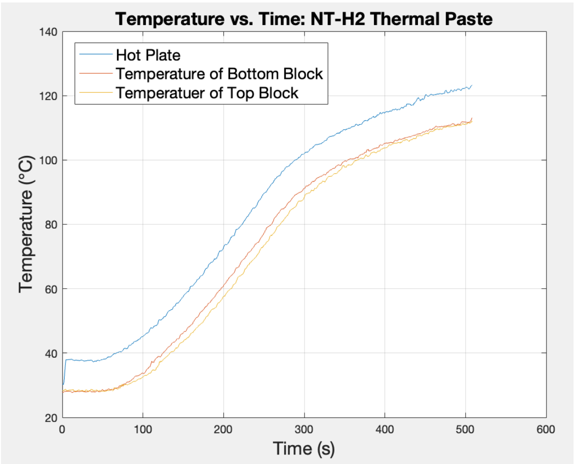


**Figure 9** - *Temperature vs. time plot for the setup with the NT-H2 paste between blocks. The heat was applied until the hot plate reached temperatures above ~100* ℃.

Time vs. Temperature Plot: Thermal Paste #2 (Arctic MX-6)

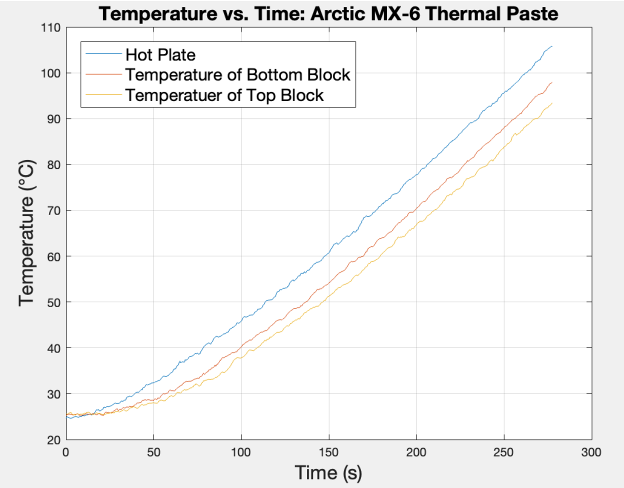


**Figure 10** - *Temperature vs. time plot for the setup with the Arctic MX-6 paste between blocks. The heat was applied until the hot plate reached temperatures above ~100 ℃.*

Time vs. Temperature Plot: Thermal Paste #3 (Thermal Grizzly Kryonaut)

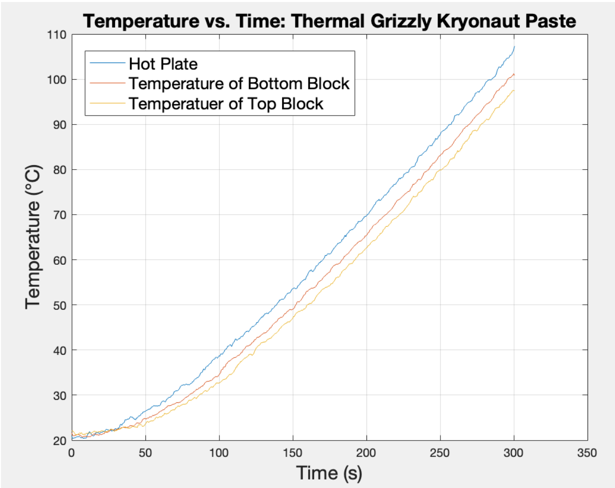


**Figure 11** - *Temperature vs. time plot for the setup with the Arctic Thermal Grizzly Kryonaut paste in between blocks. The heat was applied until the hot plate reached temperatures above ~100 ℃.*

A typical CPU/GPU chip reaches approximately 80°C under a semi-heavy load[3],[4]. In this setup, the hotplate, heated to +80°C, simulates the chip, while the center of the top Al block represents the heatsink, where heat transfer occurs. In a real-world application, a fan would dissipate heat from the heatsink.

Consequently, we can use the ΔT between the hotplate and the center of the top aluminum(Al) block to determine the best-performing case scenario. Higher ΔT values indicate poor thermal conductivity of the thermal paste, as heat accumulates in the hotplate instead of being efficiently transferred to the top aluminum block. To calculate ΔT, we analyzed the temperature vs. time plots shown in Figures 8 - 11. Specifically, we identified the data point index where the hot plate temperature reached 80°C and subtracted the correlating thermocouple temperature value from the top of the plate. This approach lets us determine ΔT while the hot plate simulates an approximated semi-heavy CPU load.

| **Thermal Paste and Change in Temperature between Thermocouple #1 and Thermocouple #3** | |
|---|---|
| **Thermal Paste** | **ΔT (°C)** |
| No Thermal Paste | 36.48 |
| Noctua NT-H2 | 15.55 |
| Arctic MX-6 | 11.15 |
| Thermal Grizzly Kryonaut | 7.66 |

**Table 1** - *The ΔT values represent the temperature difference between the bottom thermocouple (one attached to the hot plate) and the thermocouple on the top (above the thermal paste). This was our metric for evaluating the performance of thermal paste. The ΔT is taken from the midpoint of the transient climb.*

Analyzing the temperature vs. time plots, we noticed the rate of temperature increase varies between the setups, as evidenced by the slope of the curves during the heating phase. For instance, in the setup for "No Thermal Paste," the temperature of the top aluminum block rises significantly slower compared to the setups using thermal paste between the aluminum block interfaces, which indicates poor thermal conductivity. This confirms our expectations since, with no thermal paste, there is no medium to efficiently bridge the microscopic air gaps between the aluminum surfaces and facilitate heat transfer. Among the thermal pastes tested, the Noctua NT-H2, Arctic MX-6, and Thermal Grizzly Kryonaut demonstrate steeper slopes in the temperature curves for the top block, implying faster heat transfer due to improved thermal conductivity. Notably, the Kryonaut paste exhibits the steepest slope and smallest ΔT, confirming its superior performance.

Additionally, there are minimal visible changes in slope across the transient phase for the setups with thermal pastes, verifying we have consistent heat transfer properties throughout the experiment. This observation aligns with our expectations, as thermal conductivity is an intrinsic property and should remain constant. This consistency contrasts with the “No Thermal Paste” setup, where heat accumulation at the hot plate is more pronounced, leading to a gradual but inefficient temperature increase on the top block. These findings and observations highlight the importance of thermal paste in ensuring efficient heat transfer, as well as the impact of its quality on overall performance. Lastly, we also observed a correlation between the price and quality of the thermal paste, with the most expensive option delivering superior performance.

## 4. Discussion

Our data demonstrated a clear relationship between the types of thermal paste used and the temperature gradient across the aluminum blocks. Pastes with better performance and quality resulted in lower temperature gradients, indicating better heat transfer. Our result demonstrated variations in thermal performance across the tested pastes, with the rankings from best to least effective as follows: Thermal Grizzly Kryonaut, Arctic MX-6, Noctua NT-H2, and lastly, no thermal paste. The K-type thermocouples positioned directly at the center of the aluminum blocks allowed for precise measurements of the temperature gradient, which is critical for identifying subtle differences in performance. Meanwhile, the insulating fiber blanket successfully reduced lateral heat loss, ensuring that the measured temperature differences accurately reflected the performance of the thermal paste rather than external influences. Multiple trials ran without the insulating fiber blanket indicated lateral heat loss, which caused larger temperature gradients and less accurate readings of thermal paste performance. The consistent application of thermal paste and controlled experimental setup minimized variability, ensuring reliable comparisons between pastes.

These results (in the order Thermal Grizzly Kryonaut, Arctic MX-6, Noctua NT-H2, no thermal paste) are consistent with third-party sources and manufacturer specifications. According to Thermal Grizzly and a third-party source, Giancarlo Dalmedico from The Overclock Page[5], the thermal conductivity for the ‘Thermal Grizzly Kryonaut’ thermal paste is around 12.5 W/mK. Following that, third-party sources AWD-IT[6] and ElectronicsHub[7] indicate that the thermal conductivity for the ‘Arctic MX-6’ paste ranges from about 8.5 W/mK to 10.5 W/mK. Lastly, third-party user Igor’s LAB[8] tested that the ‘Noctua NT-H2’ thermal conductivity ranged from about 1.9 W/mK to 2.7 W/mK. Comparing against third-party users validates our thermal paste ranking results, as the higher thermal conductive pastes performed better than those that were lower in thermal conductivity.

It is essential to acknowledge differences between these pastes because of each manufacturer's specific formulations. Since thermal pastes typically contain a combination of base materials and conductive fillers (silver, aluminum, ceramic, etc.) to enhance thermal conductivity, varying concentrations, physical properties, and additives can widely influence the paste’s ability to transfer heat. In this case, the ‘Thermal Grizzly Kryonaut’ paste uses aluminum in its conductive filler, which tends to have the highest thermal conductivity.[9] The ‘Arctic MX-6’ paste uses carbon micro-particles, which are much less conductive than aluminum.[10] Lastly, the ‘Noctua NT-H2’ paste uses metal oxide micro-particles in its conductive filler, which is lower in thermal conductivity.[11] This physical element that differentiates each manufacturer makes each of their pastes unique in their respective way and could explain why there are performance differences.

However, some limitations remain in terms of the experiment. Due to its micron-scale thickness, the thickness of the applied paste needed to be more precisely controlled and measured, and it could influence the results, as a thicker or uneven layer might alter heat transfer efficiency. Additionally, while the experiment was designed for controlled conditions, it does not account for real-world scenarios where external factors such as airflow could affect the thermal performance.

Further studies could focus on refining the application process to ensure uniform paste thickness and exploring the long-term stability of pastes under continuous thermal cycling, including additional environmental factors such as ambient temperature or humidity.

## 5. Supplementary Work

The goal was originally to calculate the thermal conductivity for each respective thermal paste and use that as our performance metric. However, we originally used a non-temperature-controlled hot plate that was only capable of supplying heat at a constant rate. This setup never allowed us to reach a constant temperature within the experiment. This was an issue as the scientific model we were using assumed heat transfer through the hot plate at steady state.

$$\dot{Q} = \frac{T_1 - T_2}{R_1} = \frac{T_2 - T_3}{R_2 + R_3 + R_4}$$

Hence, we used a temperature-controlled hot plate with a PID controller due to issues with the non-temperature-controlled hot plate, leading to transient data. With this, data was obtained starting from room temperature to ~50℃. From here, the steady-state data was isolated and analyzed. Unfortunately, the temperature-regulated hot plate itself yielded strange results because even though we could obtain steady-state data, we observed that the noise from our measurements severely impacted our temperature measurements. The temperature-controlled hot plate operated very slowly, causing the temperatures between the bottom and top thermocouples to lag only slightly. Considering that the noise within our measurements had a similar magnitude to the variations in temperature, these results affected our ability to process the data as the temperature readings between the three thermocouples during steady state would intertwine, as we see in Figure 12.

Additionally, we noticed that the temperature taken from the middle and top thermocouples was hotter than the hot plate thermocouple. Assuming a uniform heat transfer from the hot plate's surface to our block, this would not be possible. We hypothesized that this was due to the hot plate's non-uniform heat transfer, potentially due to a non-uniform heating element. This would have resulted in a varied heat transfer, one that would not fit our mathematical model. Hence, we were unable to analyze it accurately.

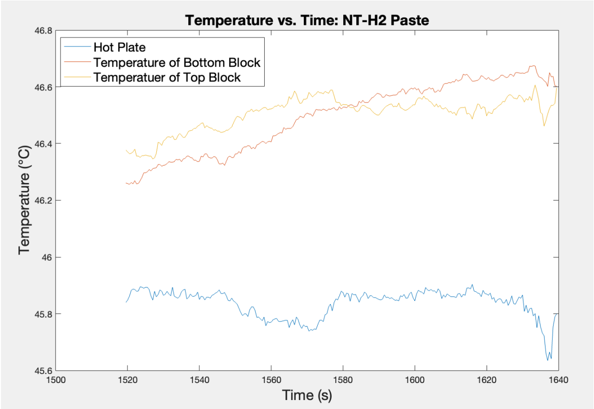


**Figure 12**—*Temperature vs Time of NT-H2 Paste of data taken after the hot plate was left to reach 50℃ for 20 minutes, ensuring a steady state.*

This did not allow us to use the previous heat transfer equations to observe the thermal conductivity. Doing this, we would sometimes receive negative thermal conductivity values, and when taking the average across a range of steady-state calculations, we would receive a skewed value for thermal conductivity.

Per the professor's request, we also did a calibration curve to ensure the relationship was linear. We started the reading at 0℃ and turned on the kettle until it reached 100℃. We can see around 0℃, there is an initial decrease, likely due to the thermocouples being placed in the icy water. We stopped taking measurements shortly after the water was boiling when the temperature plateaued around 100℃. We can see the linear calibration curve, which shows that we are not experiencing any issues with our thermocouples. Instead, there could be some other externalities that did not allow us to measure and calculate our k values accurately. We also soldered the wiring to the amplifiers, as well as the k-type thermocouples, to ensure the screw terminals are not introducing noise or resistance fluctuations due to loose connections or oxidation over time, potentially impacting measurement accuracy. Additionally, we braided the wires to help reduce noise. However, even with the soldered connections and braided wires, we observed the same results with little to no reduction in the noise.

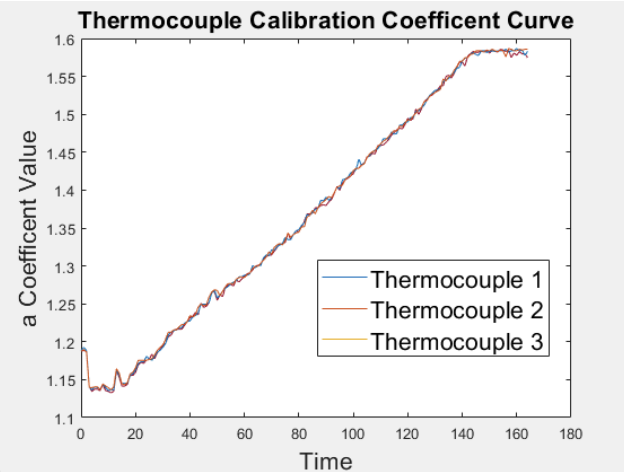


**Figure 13** - *Coefficient Value vs. Time Plot for Thermocouple Calibration Coefficient Checking*

## 6. Conclusion

The experiment compared the performance of popular thermal pastes on the market by measuring the temperature gradient across a controlled aluminum block setup. The results highlight the significant impact of thermal paste choice on heat dissipation efficiency, with lower temperature gradients indicating superior performance. These findings provide valuable insights for selecting thermal pastes for electronic cooling applications. The study addresses the need for data-driven comparisons in the existing literature by focusing on temperature gradients as a direct performance measure. Future research should explore more advanced materials, consider real-world conditions to enhance the practical applicability of these results, and consider the cost. The outcomes of this study lay a foundation for better-informed decisions in thermal management, benefiting both consumer electronics and industrial applications.

One uncertainty we note is that the thermal paste we used on the tips of the thermocouples and the bottom of the hotplate was the Arctic MX-6 (which had mediocre performance from our results). Although the temperatures remained constant across all trials, the thermal paste could insulate the thermocouple tip and not allow the most accurate temperature reading. Also, the amount of thermal paste applied to each thermocouple was not measured.

## Acknowledgments

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