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Evaluating the Thermal Conductivity of Potting Materials using the Hot-Wire Method

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Evaluating the Thermal Conductivity of Potting Materials using the Hot-Wire Method

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of the requirements for the degree of
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by

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Abstract

This thesis is focused on the evaluation of the thermal conductivity of certain potting materials, in particular Aluminum Nitride (AlN), thermal putty, and silicone oil using the "hot-wire" method in order to allow volume reductions of inductors, and thus, increase the power density of converters. The main objective of this thesis is then to study the behavior of these specific materials intended for high-density power converters by mixing them with different proportions and placing the resulting compounds into a can for calculating their thermal conductivities, in order to evaluate the effects on the power density of inductor-based converters.

One objective in calculating the thermal conductivity is to determine the duration of the various experiments since they are time-consuming. To this end, two rounds of experiments are performed up to 15 and 30 minutes, respectively, since there was a clear idea for the time needed for the various mixtures to reach steady-state temperatures. The "hot-wire" method is normally used to measure the thermal conductivity of a material. For this thesis work, the "hot-wire" method equipment needed for the experiments is adapted to the equipment available in the Engineering Research Center (ENRC) at the University of Arkansas. Errors occurring during the experiments could have many reasons; for example, external factors that affect external temperature readings (for example, individual performing tests in the same lab room and adding heat to the ambient, the thermocouple not being firmly placed on the resistor inside the can, errors in weighing the materials on the digital scale, etc). The analysis of the results for the 15-minute experiments has errors due to negative value results, so this time was not suitable for calculating the thermal conductivities. The experiments conducted to 30 minutes produced good results. Thus, the influence of time is important to get very good results. However, the experiments performed up to 30 minutes demonstrated a reduction in both maximum temperature rise and the time to reach a stable temperature which gives improvements in efficiency and performance in the system. Further experiment analysis of some other materials like silicone epoxy should be conducted to analyze the thermal conductivity behavior and determine if other materials can enable faster heat removal.

Acknowledgments

I would like to thank Dr. Juan Carlos Balda for giving me the opportunity of being part of his research group and for his advising during my honor's research. I also would like to thank the collaboration of the Ph.D. student, Shamar Christian, who directed me throughout this research work. Finally, the encouragement and support of family, close friends, and mentors made the writing process of this thesis possible.

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I. Introduction

I.1 Background

The alarming rate at which global pollution is increasing is a significant concern at different levels around the world. One of the causes of global pollution comes from typical passenger vehicles using internal combustion engines (ICE). According to the United States Environmental Protection Agency, a typical ICE passenger vehicle emits about 4.6 metric tons of carbon dioxide (CO_2) per year, but that number really varies depending on different features of the car such as the vehicle's fuel, the number of miles driven per year, etc. [1]. The concerns about environmental issues from these conventional vehicles have demanded more eco-friendly vehicles such as Electric Vehicles (EVs), Fuel Cell Electric Vehicles (FCEVs), and Plug-in Electric Vehicles (PEVs) that can be considered as partial solutions to reduce carbon emissions from the automotive industry [2]. The development of these types of vehicles is not an easy task because the electric powertrain for EVs requires volumetric specifications as well as high efficiency over a wide power range.

Inductors motors, permanent-magnet synchronous motors (PMSM), and switched-reluctance motors are generally used for propulsion in EVs. These motors are fed by inverters which are fed by a high voltage DC-DC converter. Active and passive electric components produce power losses in the form of heat. Size reduction of system components to accomplish target volumes for these EV electric powertrains require faster removal of the produced heat to maintain maximum temperatures below component limits. There are different types of powertrains for EVs; mainly, those having a battery pack supplying a traction inverter, and those using a DC-DC converter to interface the battery pack and the traction inverter. For those powertrains using DC-DC converters, their passive components representing often the largest volumes, in particular, inductors. In general, DC-DC converters can be divided into two main categories: hard-switched and soft-switched operation. The hard-switched DC-DC converter results in a better option due to its reduced component count since cost is important for EVs due to the high cost of the battery pack.

A brief review of developed isolated and non-isolated hard-switched DC-DC converter topologies suitable for EVs are presented.

a) *Isolated Bidirectional DC-DC Converters:* Isolation is achieved by using a transformer, but this adds losses and cost to the system. Nevertheless, the transformer can isolate the two voltage sources and provide the impedance matching between them needed for some applications. The operation of this circuit requires the use of the leakage inductance of the transformer as the main energy storing and transferring element. As presented in Fig. 1, due to the presence of the leakage inductance, L_{lk}, high turn-off voltage spikes are produced across the switches on the primary side during the transfer of energy from primary to secondary side.

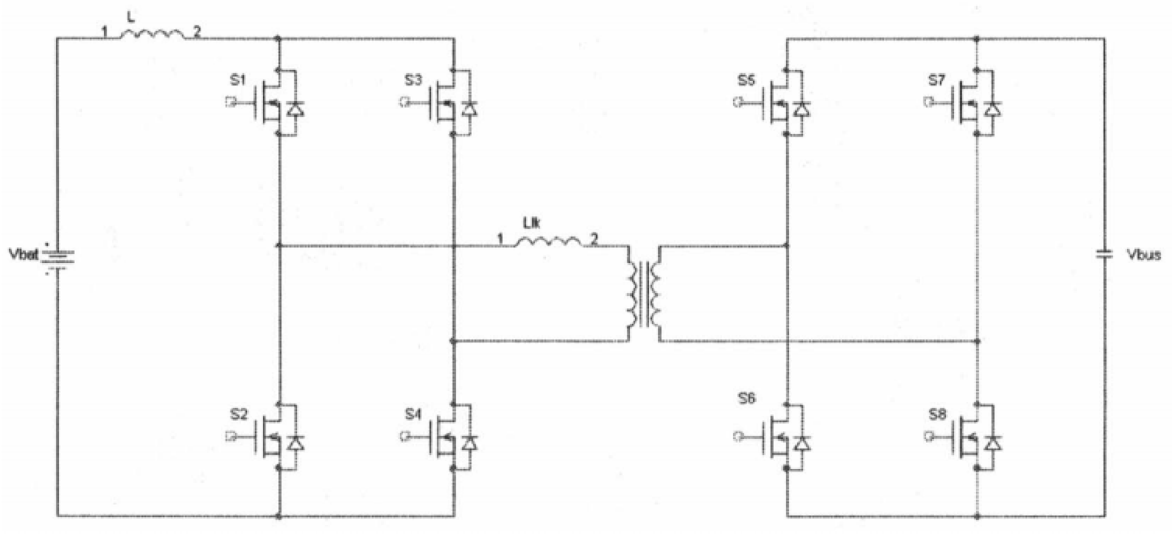

Figure 1. Conventional Bidirectional Full-Bridge Isolated Boost DC-DC Converter

b) *Non-isolated Bidirectional Boost-Buck DC-DC Converters:* The basic non-isolated bidirectional boost-buck DC-DC converter topology is a combination of a step-up stage when power flows from the battery to the high-voltage dc-link and a step-down stage when power flows in the opposite direction. The step-up stage is used to control the input voltage of the traction inverter while the step-down stage is utilized to allow the recovery of the vehicle braking energy into the battery. Fig. 2 shows this boost-buck topology employing a single-phase (or leg). For high-power applications, multiphase converters have the advantage of smaller device current stresses and better efficiencies. In Fig. 3, a three-phase bidirectional DC-DC converter where the phase switches are controlled with a 120-degree phase shift from each other is shown [3].

For EVs, the DC-DC converters might be further classified as unidirectional and bidirectional converters. The latter enables storing the braking energy in the battery pack improving the traction system efficiency. It not only improves efficiency but also reduces the system cost. Fig. 3 illustrates the topology of the interleaved bidirectional DC-DC converter.

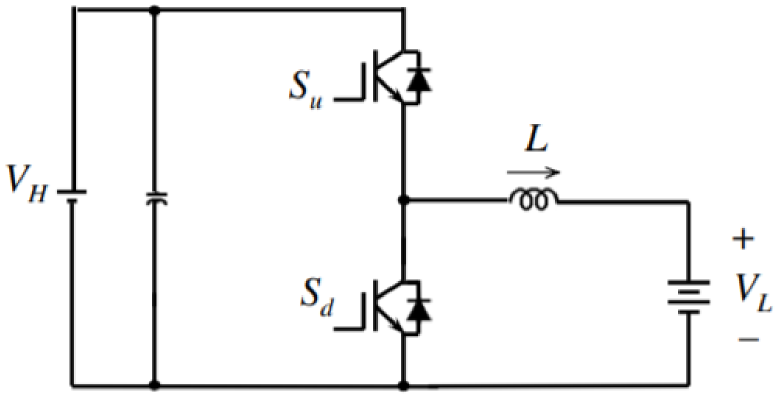

Figure 2. Single Phase Boost-Buck DC-DC Converter Topology

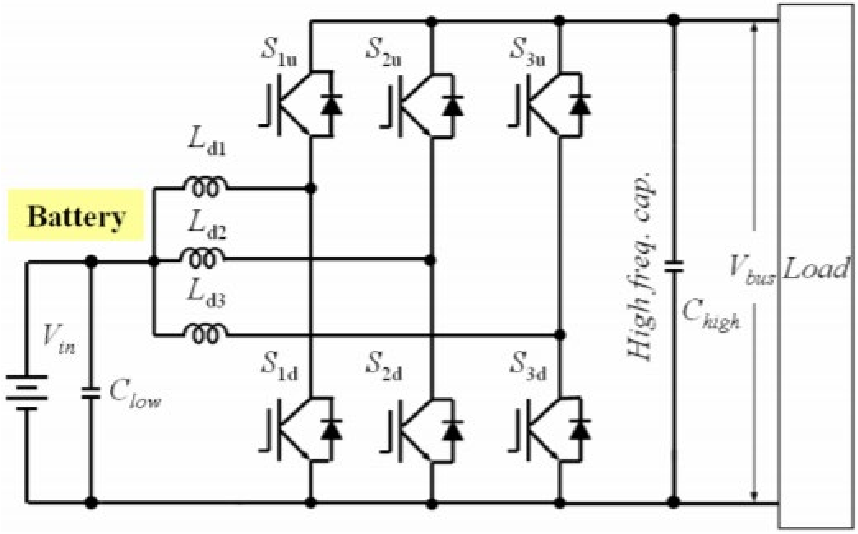

Figure 3. Interleaved Bidirectional DC-DC Converter

Only non-isolated converters for EVs will be considered for in this Honors whose main focus on comparing the thermal conductivities of selected potting compounds intended for fast removal of the heat produced within inductors used in these DC-DC converters.

I.2 Typical Topology of a Powertrain for Electric Vehicles

Fig. 4 shows a general topology of an EV electric powertrain that consists of the output of the battery pack connected to the input of a customized integrated DC-DC converter which supplies a traction inverter from the low-voltage battery to the high dc-voltage required by the high-power PMSM [4]. That is, the DC-DC converter performs the boost function.

A DC-DC converter basically converts unregulated DC input voltage to a regulated DC output voltage with a desired conversion efficiency typically greater than 90% [4].

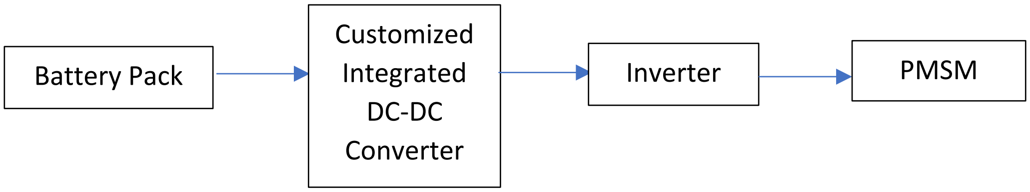

Figure 4. Diagram of an Electric Powertrain for EVs

I.3 Motivation and Proposed Approach

EVs need high power density from their electrical components such as batteries, converters, motors, and generators for operation. The total power density of the converters in EVs is mainly limited by the inductors, one of the components with the highest volume in DC-DC converters. Traditionally, air flow cooling is used for power inductors as a method to remove produced heat, but transferring the generated heat to the outside of the converter is challenging. Thus, a doable method for rapidly and effectively conducting heat away from power components to the heatsink to reduce the volume of the inductors. This requires removing the heat faster, so using thermally-conductive potting materials are very important to accomplish volume reductions. The potting compound fills the component (inductor) enclosure entirely, leaving no air gaps and helps the thermal flow across the inductor [5]. Another advantage of using potting materials is that the thermal transfer flow from the surface of the coils to the cold-plate results in reliability improvements [2]. It is also important to mention that the management of the heat generated by high power devices like power inverters and converters with any method is not that easy due to several factors such as the dc-biased currents, thermal problems, etc. Therefore, the purpose of this Honors thesis is to evaluate the thermal conductivity of specific potting materials like Aluminum Nitride (AlN), thermal putty, and silicone oil using the “hot-wire” method in order to enable volume reduction of inductors and thus increase the power density of DC-DC converters. This particular technique is used because it is well established and one of the most popular ones for measuring thermal conductivities. In addition, the required equipment for the various experiments is available at the ENRC laboratory.

I.4 Organization of the Thesis

The rest of this thesis is organized as follows: Chapter II addresses the thermal flow of the inductor and presents the theoretical aspects of the “hot-wire” method to be used in Chapter III for calculating various parameters. Chapter III evaluates the experimental results for two different times: 15 and 30 minutes with a goal of determining the influence of the time to obtain good results. Chapter IV contains the conclusions, suggestions for future work, and the Reference section provides the literature used throughout this thesis

II. Thermal Management Formulation

II.1 Introduction

In any power conversion process, a small amount of power is always lost in the form of heat affecting the performance and reliability of an electronic circuit by increasing the operating temperature. Thus, the principles of thermal management are employed to overcome high-temperature problems. In general, thermal management consists of both the study of the heat generation and flow in electronics circuits and techniques for controlling the temperature rise. Moreover, proper thermal management is very important due to system requirements increasing the power density in converters.

As stated previously, inductors dominate the size of switching power converters. Losses in magnetic cores and windings lead to temperature increases, so thermal flow performance is critical for designing magnetics that are not overdimension. In general, magnetic components are usually custom-designed for minimum loss under application specific size constraints [6].

Natural air flow cooling does not remove heat very fast resulting in inductors with the lowest power-density [7]. Thermally conductive potting materials enable faster rates for heat removal, and thus permit not reaching the saturation temperatures of the materials used to fabricate inductors (e.g., nanocrystalline cores). An example of the thermal paths of a potted inductor is illustrated in Fig. 5. Therefore, the evaluation of such materials improving the inductor thermal flows is of interest. A key figure of merit is the thermal conductivity playing a crucial role in the design of any thermal system. There are many techniques available to evaluate the thermal conductivity of bulk and thin materials within a broad temperature range. The “hot-wire” method is commonly used for thermal characterization of the potting materials [8]-[9].

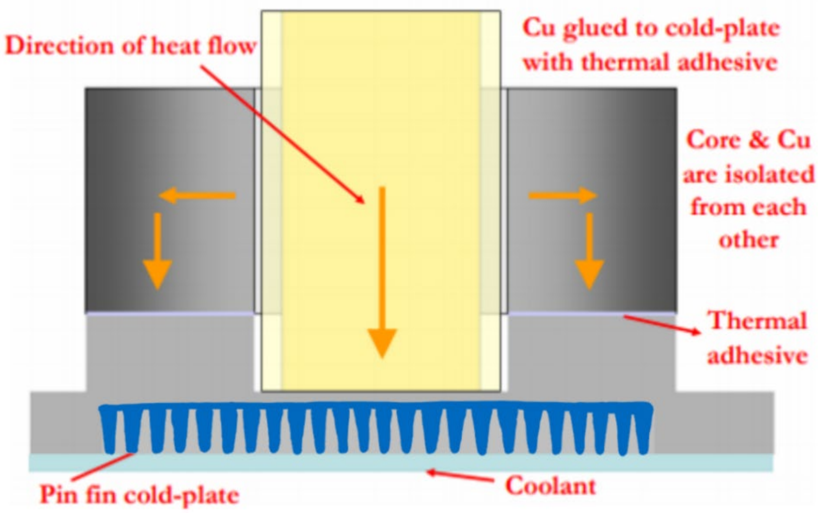

Figure 5. Inductor Core and Copper Thermal Structure

II.2 The “Hot-Wire” Method

The measurement methods for bulk materials can be divided into two categories: steady-state methods and transient methods. The steady-state methods measure thermal properties by establishing a temperature difference that does not change with time. In contrast, transient methods normally measure time-dependent energy dissipation process of a sample [8]. Both methods have their own advantages and limitations and the selected method will depend on the material to be tested, including thermal properties.

In order to overcome the disadvantages of the steady-state methods such as parasitic heat losses and contact resistance of temperature sensors, the transient methods are more flexible and convenient as the process of performing the measurements is faster. The “hot-wire” method is a transient method and is normally implemented to calculate the thermal conductivities of potting materials providing faster thermal flow from the surface of inductor coils to a cold plate located at the bottom, and thus, ensuring good temperature management of the operating conditions of the entire system [8]-[9]. Historically, the transient “hot-wire” method is a well-established absolute method for the measurement of the thermal conductivity of gases, liquids, nanofluids, melts, and solids [9]. This method is so unique because of its wide variety of applications and very low uncertainty. The thermal conductivity of the medium is determined by observing the rate at which the temperature of a very thin metallic wire increases with time after a step change in voltage is applied to it, thus creating a linear source of constant heat flux per unit length in the medium that leads to a temperature rise over time.

Thermal conductivity, K, is an indication of the material heat conducting capability. For different experiments, the thermal conductivity is normally calculated from measurements using the “hot-wire” method. Stalhane and Pyk employed this method in 1931 to measure the thermal conductivity of solids and powders [8]. This method is based on the fact that a thermal pulse for a finite time with constant power produces isothermal lines in an infinite homogeneous medium initially at thermal equilibrium [8]. Thus, it employs transient measurements of the temperature rise caused by a linear heat source (the so-called "hot-wire") embedded in the tested potting material. A temperature sensor (i.e., a thermocouple) is placed inside the test sample (e.g., a cylinder) to measure the sample temperature over time. Theoretically, the method assumes an idealized "one-dimensional radial heat flow" inside the test sample with infinite length and infinitesimal diameter as shown in Fig. 6 [8]. If the wire is heated by passing a constant electrical current through it, (i.e., by Joule's effect), the rise in its temperature will be dependent on the thermal conductivity of the surrounding material.

The thermal conductivity using data obtained experimentally is calculated as follows:

$$\mathrm{K} = \frac{P * (R_2 - R_1)}{A * \ \Delta t} \quad \left(\frac{W}{m * K}\right) \tag{1}$$

where P is the power (which is the rate of the transferred of energy per unit time given by the power supply (W)), R_2 is the radius of the used cylinder in meters, R_1 is the radius of the resistor in meters, A is the cylinder area determined as follows: 2*π*R_2*L, where L is the length of the cylinder in meters, and $\Delta t = (T_1 - T_2)$ which is the difference between the internal and external temperatures in Kelvin.

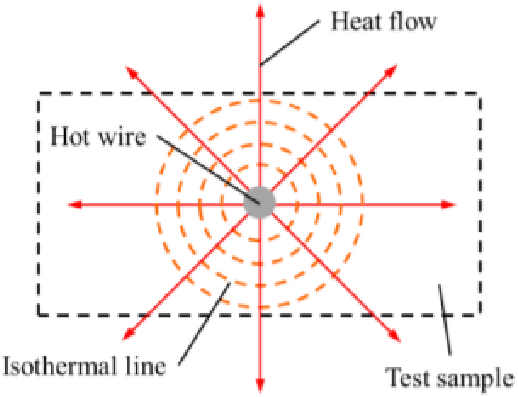

Figure 6. One-Dimensional Radial Radial Heat Flow [8]

III. Experimental Results of the Conducted Potting Materials Experiments

III.1 Introduction

This chapter addresses the experimental results from two experiments using the same potting materials but different time durations since the measurements are time-consuming, and hence, testing beyond the required time does not add value to the calculations. The results will be analyzed in order to draw conclusions as the best approach to remove heat from potted inductors. It is important to note that overall, determining the thermal conductivity of any material with less than 5% error is a challenging task because there are some potential error sources that might affect the final results such as the room convection, radiation heat losses, and bad temperature measurements [8]. In addition, there are some other important aspects to consider when selecting any measurement technique: thermophysical properties of the sample to be tested, sample geometry and size, and material preparation method [8].

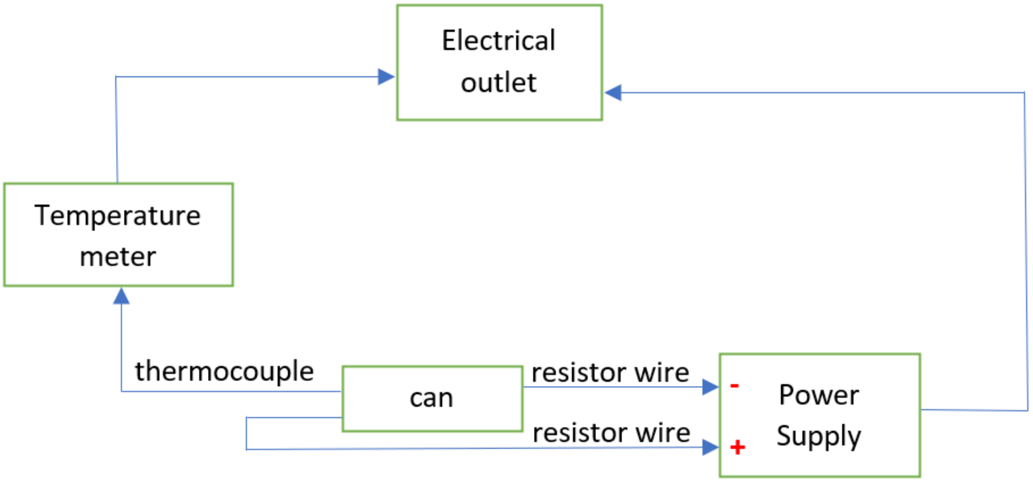

Figure 7. Experimental Setup Block Diagram

Fig. 7 shows in block diagram form the connections for the experimental setup used to conduct both experiments. The system developed for this method, particularly, considers the thermocouple or temperature sensor that is attached to a load resistor of 2.7 Ω for the first round of experiments (lasting 15 minutes,) and a load resistor of 20 Ω for the second round of experiments (lasting 30 minutes) which is then soldered to wires of 127.83 mm length at the ends, and encapsulated in an aluminum cylindrical can with cap. The samples inside the can are weighted using a small digital scale and then, the can is placed on a heatsink during testing. This assembly is connected to a DC power supply. The thermocouple is attached to a temperature reader that measures the internal temperature and a thermal camera, FLIR i7, was used to measure the external temperature.

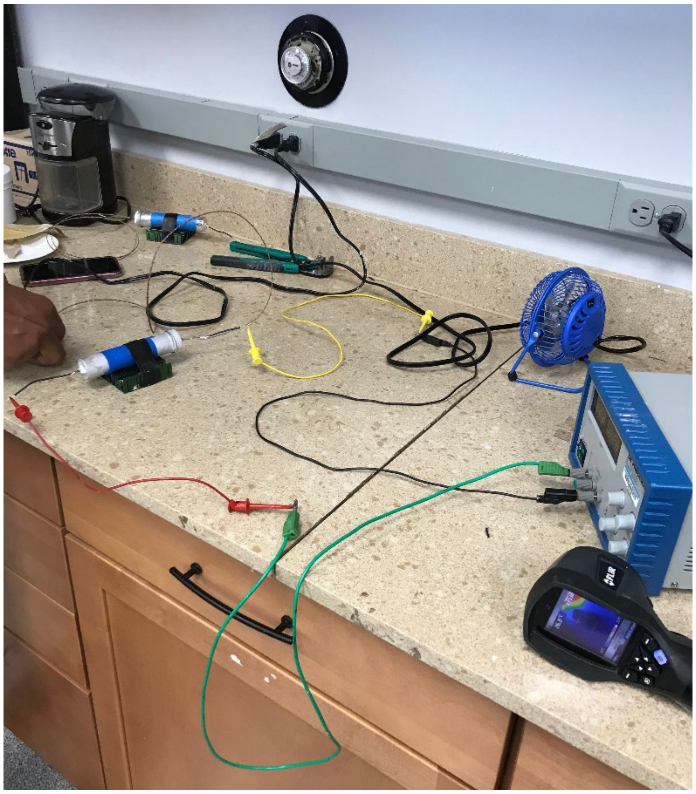

Figure 8. Experimental Setup System

The first round of experiments consists of limiting the test up to 15 minutes using the components given in Table 1. This time was selected to avoid thermal run away for the load resistor of 2.7 Ω. The second round of experiments involves testing the materials up to 30 minutes with another load resistor (i.e., 20 Ω) to determine if running the experiments to temperature values closer to steady-state values could have an influence or be necessary for the calculation of the thermal conductivity. Therefore, the differences between both rounds of experiments are the measurement time as well as the resistance and power rating of the load resistors.

Table 1. Components Used in the Experiments

Names of the Components	**Description**
DC Regulated Power Supply	Supplies a constant DC voltage to the load
2.6 oz. Aluminum Screw Top Can with Cap	Measurement cell
Load Resistor of 2.7 Ω and 20 Ω	Heat source
Thermocouple Wire K-Type 1m	Temperature sensor
Digital Temperature Meter	Measures the internal temperature
FLIR i7 Thermal Camera	Measures the external temperature
Digital Scale	Measures and display the weight of the material
Heatsink	Increases the heat flow away from the hot device

The proposed method performs transient state measurements of the effective thermal conductivity parameter of samples with different ratios of AlN powder (with 150 W/m*K thermal conductivity) mixed with thermal putty of 10 W/m*K. AlN powder is also mixed with silicone oil (with around 0.6 W/m/K thermal conductivity @ 20°C.) Those materials will be mixed at different proportions and tested to evaluate the mixture's thermal conductivity. In addition, air and the putty itself will be tested, each one separately to provide additional information.

Table 2 presents all the conducted experimental cases in order.

Table 2. List of all Experiment Cases

Experiment	Materials
1	Air
2	Putty
3	70 AlN / 30 Putty
4	60 AlN / 40 Putty
5	50 AlN / 50 Putty
6	70 Putty / 30 AlN
7	60 Putty / 40 AlN
8	105 g AlN/ 50ml Silicone Oil
9	105 g AlN/ 30ml Silicone Oil

III.2 Experimental Results

III.2.1 15-Minute Experiments

Tables 3 to 20 present the results from the experiments performed for up to 15 minutes. These results are presented in graphical form through Figs. 9 to 12 for better visualization. The first experiment consists of just air. This is the base measurement as there is no material inside the can. The power is calculated by multiplying the current and voltage given by the power supply.

Table 3. 15-Minute Experiments: Air

Time (minutes)	Internal Temp of air (ºC)	External Temp of air (ºC)	Power of air (W)
0	26.2	27.8	5.58
1	51.3	28.0	5.58
2	80.0	31.2	5.58
3	100.8	34.8	5.58
4	116.2	37.2	5.58
5	127.7	40.1	5.58
6	136.8	42.3	5.58
7	143.8	43.5	5.58
8	149.0	45.6	5.58
9	152.7	47.1	5.58
10	155.7	47.7	5.58
11	158.4	48.8	5.58
12	160.6	49.4	5.58
13	162.4	49.5	5.58
14	163.7	50.1	5.58
15	164.9	51.1	5.58

The second experiment consists of just silicone putty having a thermal conductivity of 10 W/mK at 25°C. It is soft and ultra highly compressible for low stress applications and suitable to fill gaps from 0.25 mm to 8mm.

Table 4. 15-Minute Experiments: Putty

Time (minutes)	Internal Temp of putty (ºC)	External Temp of putty (ºC)	Power of putty (W)
0	26.5	28.3	5.70
1	29.7	30.2	5.70
2	32.4	32.2	5.70
3	33.9	33.7	5.70
4	35.5	35.2	5.70
5	36.7	36.0	5.70
6	37.7	37.4	5.70
7	38.9	38.4	5.70
8	39.9	38.9	5.70
9	40.7	39.9	5.70
10	41.6	40.1	5.70
11	42.1	42.0	5.70
12	43.2	42.4	5.70
13	43.9	42.5	5.70
14	44.5	43.1	5.70
15	45.2	43.4	5.70

Table 5. 15-Minute Experiments: 70% AlN with 30% Putty

Time (minutes)	Internal Temp of 70% AlN and 30% putty (ºC)	External Temp of 70% AlN and 30% putty (ºC)	Power of 70% AlN and 30% putty (W)
0	25.0	25.6	5.41
1	36.1	27.0	5.41
2	45.0	30.2	5.41
3	50.0	32.1	5.41
4	54.4	35.2	5.41
5	57.2	37.4	5.41
6	59.4	39.3	5.41
7	61.7	40.8	5.41
8	63.3	42.1	5.41
9	65.0	43.3	5.41
10	66.1	44.4	5.41
11	67.2	44.8	5.41
12	68.3	45.1	5.41
13	69.4	47.2	5.41
14	70.6	47.8	5.41
15	71.1	48.0	5.41

Table 6. 15-Minute Experiments: 60% AlN with 40% Putty

Time (minutes)	Internal Temp of 60% AlN and 40% putty (ºC)	External Temp of 60% AlN and 40% putty (ºC)	Power of 60% AlN and 40% putty (W)
0	24.4	25.5	5.58
1	37.2	25.8	5.58
2	50.0	28.3	5.58
3	58.3	31.0	5.58
4	63.9	33.1	5.58
5	67.2	35.7	5.58
6	71.7	37.9	5.58
7	74.4	39.9	5.58
8	77.2	41.4	5.58
9	79.4	42.7	5.58
10	81.1	43.4	5.58
11	82.8	45.2	5.58
12	84.4	46.5	5.58
13	85.6	47.0	5.58
14	86.7	48.2	5.58
15	87.8	49.0	5.58

Table 7. 15-Minute Experiments: 50% AlN with 50% Putty

Time (minutes)	Internal Temp of 50% AlN and 50% putty (ºC)	External Temp of 50% AlN and 50% putty (ºC)	Power of 50% AlN and 50% putty (W)
0	25	25.0	5.62
1	41.7	25.4	5.62
2	57.8	27.0	5.62
3	69.4	28.8	5.62
4	78.3	30.9	5.62
5	86.1	33.5	5.62
6	89.4	35.5	5.62
7	93.3	37.3	5.62
8	95.6	39.0	5.62
9	98.9	40.7	5.62
10	101.1	41.7	5.62
11	103.3	43.0	5.62
12	105.0	44.1	5.62
13	106.7	44.9	5.62
14	108.3	45.9	5.62
15	110.0	46.6	5.62

Table 8. 15-Minute Experiments: 70% Putty with 30% AlN

Time (minutes)	Internal Temp of 70% putty and 30% AlN (ºC)	External Temp of 70% putty and 30% AlN (ºC)	Power of 70% putty and 30% AlN (W)
0	25.6	25.2	5.66
1	44.4	26.6	5.66
2	59.4	29.0	5.66
3	68.9	32.0	5.66
4	75.0	35.9	5.66
5	80.0	38.9	5.66
6	83.3	39.2	5.66
7	86.1	41.8	5.66
8	88.9	44.2	5.66
9	91.1	44.6	5.66
10	92.8	46.0	5.66
11	94.4	48.5	5.66
12	96.1	48.4	5.66
13	96.7	49.0	5.66
14	98.3	50.2	5.66
15	99.4	51.1	5.66

Table 9. 15-Minute Experiments: 60% Putty with 40% AlN

Time (minutes)	Internal Temp of 60% putty and 40% AlN (ºC)	External Temp of 60% putty and 40% AlN (ºC)	Power of 60% putty and 40% AlN (W)
0	25.6	27.5	5.66
1	37.2	28.0	5.66
2	47.2	30.0	5.66
3	53.3	32.3	5.66
4	57.8	34.6	5.66
5	61.1	36.6	5.66
6	63.9	37.8	5.66
7	66.7	40.0	5.66
8	68.3	41.6	5.66
9	70.6	43.1	5.66
10	72.2	44.2	5.66
11	73.3	46.2	5.66
12	75.0	47.0	5.66
13	76.1	47.9	5.66
14	77.2	48.7	5.66
15	78.3	49.7	5.66

Table 10. 15-Minute Experiments: 105g AlN with 50ml Silicone Oil

Time (minutes)	Int Temp of 105g AlN/50ml oil (ºC)	Ext Temp of 105g AlN/50ml oil (ºC)	Power of 105g AlN/50ml oil (W)
0	25.6	27.2	5.66
1	33.9	29.3	5.66
2	40.6	32.0	5.66
3	44.4	34.6	5.66
4	47.8	36.5	5.66
5	50.6	37.8	5.66
6	52.8	39.7	5.66
7	54.4	40.9	5.66
8	56.1	42.2	5.66
9	57.8	43.3	5.66
10	58.9	44.6	5.66
11	60.6	45.7	5.66
12	61.7	46.4	5.66
13	62.8	47.4	5.66
14	63.3	48.1	5.66
15	64.4	49.0	5.66

Table 11. 15-Minute Experiments: 105g AlN with 30ml Silicone Oil

Time (minutes)	Int Temp of 105g AlN/30ml oil (ºC)	Ext Temp of 105g AlN/30ml oil (ºC)	Power of 105g AlN/30ml oil (W)
0	25.0	24.5	5.94
1	25.0	26.7	5.94
2	26. 7	28.4	5.94
3	28.3	29.7	5.94
4	30.0	32.4	5.94
5	32.2	33.2	5.94
6	33.9	35.6	5.94
7	35. 6	36.7	5.94
8	37. 8	36.9	5.94
9	38. 9	40.0	5.94
10	40. 6	41.4	5.94
11	41.7	42.2	5.94
12	42. 8	43.3	5.94
13	43. 9	44.4	5.94
14	45.0	45.2	5.94
15	46.1	45.8	5.94

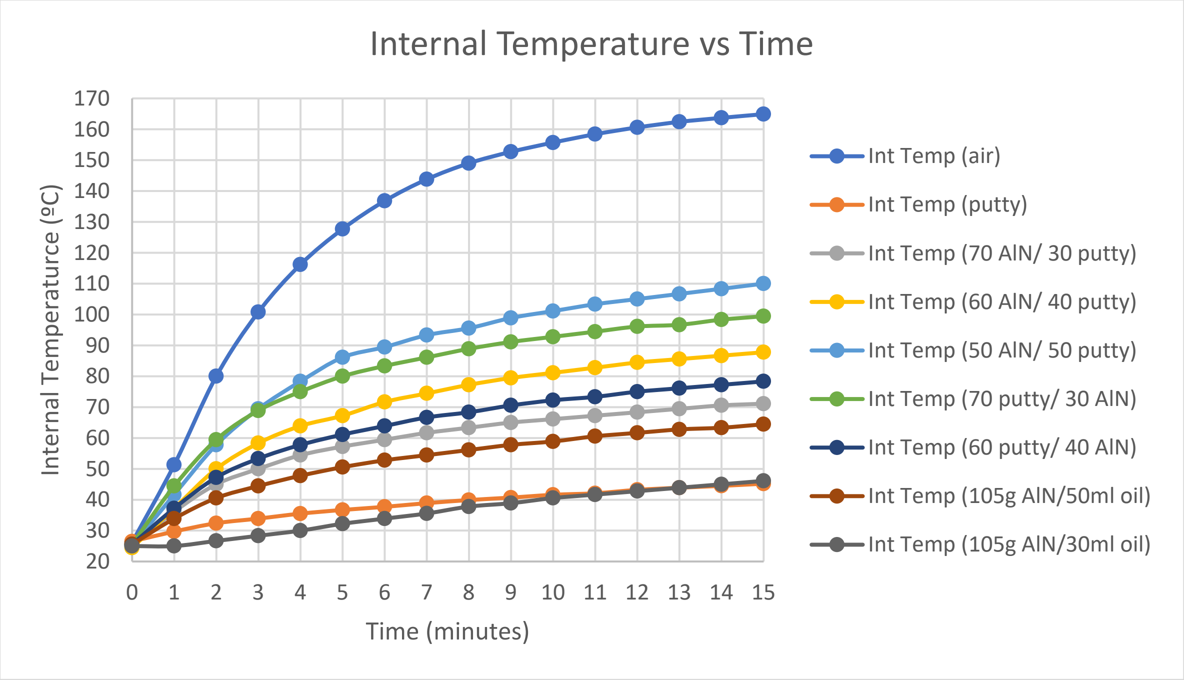

Figure 9. Internal Temperature vs Time Plot for the 15-Minute Experiments

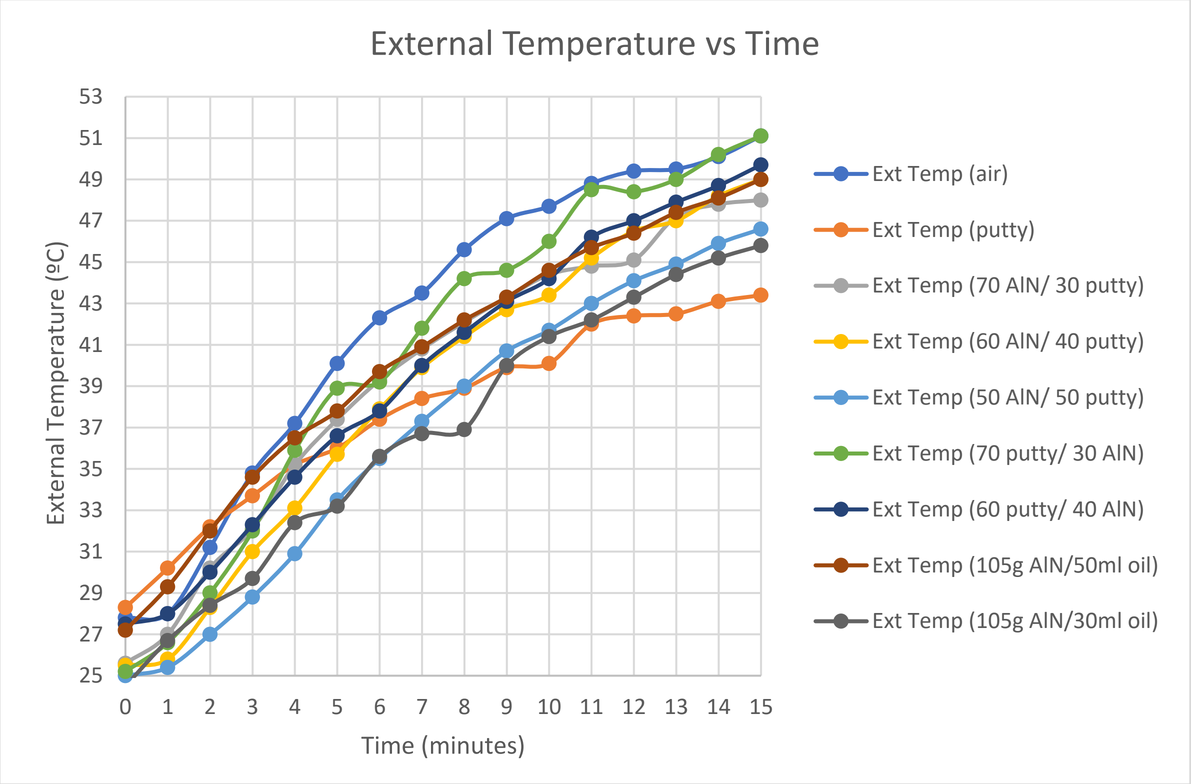

Figure 10. External Temperature vs Time Plot for the 15-Minute Experiments

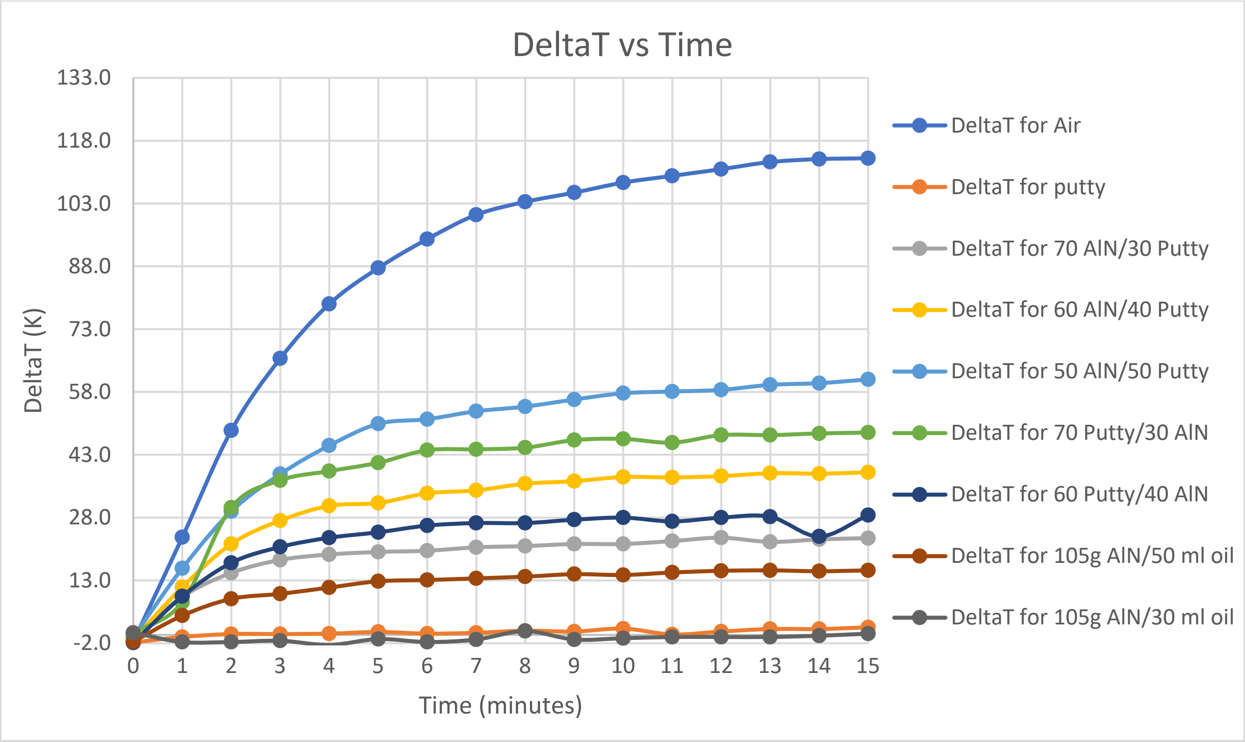

Figure 11. DeltaT vs Time Plot for the 15-Minute Experiments

Figs. 9 to 11 illustrate that the waveforms are not clearly reaching steady-state values when the experiments are conducted up to 15 minutes.

Table 12. 15-Minute Experiments: Air - Summary of Data

Time (mins.)	**R2 (m)**	**R1 (m)**	**Power (W)**	**Length (m)**	**Area (m^2)**	**Heat Flux (W/m^2)**	**T2 (ºC)**	**T2 (K)**	**T1 (ºC)**	**T1 (K)**	**DeltaT (K)**	**K (W/m*K)**
0	0.0133	0.0049	5.58	0.1278	0.0107	521.79	27.8	301.0	26.2	299.4	-1.6	-2.7557
1	0.0133	0.0049	5.58	0.1278	0.0107	521.79	28.0	301.2	51.3	324.5	23.3	0.1892
2	0.0133	0.0049	5.58	0.1278	0.0107	521.79	31.2	304.4	80.0	353.2	48.8	0.0904
3	0.0133	0.0049	5.58	0.1278	0.0107	521.79	34.8	308.0	100.8	374.0	66.0	0.0668
4	0.0133	0.0049	5.58	0.1278	0.0107	521.79	37.2	310.4	116.2	389.4	79.0	0.0558
5	0.0133	0.0049	5.58	0.1278	0.0107	521.79	40.1	313.3	127.7	400.9	87.6	0.0503
6	0.0133	0.0049	5.58	0.1278	0.0107	521.79	42.3	315.5	136.8	410.0	94.5	0.0467
7	0.0133	0.0049	5.58	0.1278	0.0107	521.79	43.5	316.7	143.8	417.0	100.3	0.0440
8	0.0133	0.0049	5.58	0.1278	0.0107	521.79	45.6	318.8	149.0	422.2	103.4	0.0426
9	0.0133	0.0049	5.58	0.1278	0.0107	521.79	47.1	320.3	152.7	425.9	105.6	0.0418
10	0.0133	0.0049	5.58	0.1278	0.0107	521.79	47.7	320.9	155.7	428.9	108.0	0.0408
11	0.0133	0.0049	5.58	0.1278	0.0107	521.79	48.8	322.0	158.4	431.6	109.6	0.0402
12	0.0133	0.0049	5.58	0.1278	0.0107	521.79	49.4	322.6	160.6	433.8	111.2	0.0397
13	0.0133	0.0049	5.58	0.1278	0.0107	521.79	49.5	322.7	162.4	435.6	112.9	0.0391
14	0.0133	0.0049	5.58	0.1278	0.0107	521.79	50.1	323.3	163.7	436.9	113.6	0.0388
15	0.0133	0.0049	5.58	0.1278	0.0107	521.79	51.1	324.3	164.9	438.1	113.8	0.0387

Table 13. 15-Minute Experiments: Putty - Summary of Data

Time (mins.)	R2 (m)	R1 (m)	Power (W)	Length (m)	Area (m^2)	Heat Flux (W/m^2)	T2 (°C)	T2 (K)	T1 (°C)	T1 (K)	DeltaT (K)	K (W/m*K)
0	0.0133	0.0049	5.70	0.1278	0.0107	533.30	28.3	301.5	26.5	299.7	-1.8	-2.5035
1	0.0133	0.0049	5.70	0.1278	0.0107	533.30	30.2	303.4	29.7	302.9	-0.5	-9.0128
2	0.0133	0.0049	5.70	0.1278	0.0107	533.30	32.2	305.4	32.4	305.6	0.2	22.5319
3	0.0133	0.0049	5.70	0.1278	0.0107	533.30	33.7	306.9	33.9	307.1	0.2	22.5319
4	0.0133	0.0049	5.70	0.1278	0.0107	533.30	35.2	308.4	35.5	308.7	0.3	15.0213
5	0.0133	0.0049	5.70	0.1278	0.0107	533.30	36.0	309.2	36.7	309.9	0.7	6.4377
6	0.0133	0.0049	5.70	0.1278	0.0107	533.30	37.4	310.6	37.7	310.9	0.3	15.0213
7	0.0133	0.0049	5.70	0.1278	0.0107	533.30	38.4	311.6	38.9	312.1	0.5	9.0128
8	0.0133	0.0049	5.70	0.1278	0.0107	533.30	38.9	312.1	39.9	313.1	1.0	4.5064
9	0.0133	0.0049	5.70	0.1278	0.0107	533.30	39.9	313.1	40.7	313.9	0.8	5.6330
10	0.0133	0.0049	5.70	0.1278	0.0107	533.30	40.1	313.3	41.6	314.8	1.5	3.0043
11	0.0133	0.0049	5.70	0.1278	0.0107	533.30	42.0	315.2	42.1	315.3	0.1	45.0638
12	0.0133	0.0049	5.70	0.1278	0.0107	533.30	42.4	315.6	43.2	316.4	0.8	5.6330
13	0.0133	0.0049	5.70	0.1278	0.0107	533.30	42.5	315.7	43.9	317.1	1.4	3.2188
14	0.0133	0.0049	5.70	0.1278	0.0107	533.30	43.1	316.3	44.5	317.7	1.4	3.2188
15	0.0133	0.0049	5.70	0.1278	0.0107	533.30	43.4	316.6	45.2	318.4	1.8	2.5035

Table 14. 15-Minute Experiments: 70% AlN with 30% Putty – Summary of Data

Time (mins.)	R2 (m)	R1 (m)	Power (W)	Length (m)	Area (m^2)	Heat Flux (W/m^2)	T2 (°C)	T2 (K)	T1 (°C)	T1 (K)	DeltaT (K)	K (W/m*K)
0	0.0133	0.0049	5.41	0.1278	0.0107	506.44	25.6	298.8	25.0	298.2	-0.6	-7.1324
1	0.0133	0.0049	5.41	0.1278	0.0107	506.44	27.0	300.2	36.1	309.3	9.1	0.4703
2	0.0133	0.0049	5.41	0.1278	0.0107	506.44	30.2	303.4	45.0	318.2	14.8	0.2892
3	0.0133	0.0049	5.41	0.1278	0.0107	506.44	32.1	305.3	50.0	323.2	17.9	0.2391
4	0.0133	0.0049	5.41	0.1278	0.0107	506.44	35.2	308.4	54.4	327.6	19.2	0.2229
5	0.0133	0.0049	5.41	0.1278	0.0107	506.44	37.4	310.6	57.2	330.4	19.8	0.2161
6	0.0133	0.0049	5.41	0.1278	0.0107	506.44	39.3	312.5	59.4	332.6	20.1	0.2129
7	0.0133	0.0049	5.41	0.1278	0.0107	506.44	40.8	314.0	61.7	334.9	20.9	0.2048
8	0.0133	0.0049	5.41	0.1278	0.0107	506.44	42.1	315.3	63.3	336.5	21.2	0.2019
9	0.0133	0.0049	5.41	0.1278	0.0107	506.44	43.3	316.5	65.0	338.2	21.7	0.1972
10	0.0133	0.0049	5.41	0.1278	0.0107	506.44	44.4	317.6	66.1	339.3	21.7	0.1972
11	0.0133	0.0049	5.41	0.1278	0.0107	506.44	44.8	318.0	67.2	340.4	22.4	0.1910
12	0.0133	0.0049	5.41	0.1278	0.0107	506.44	45.1	318.3	68.3	341.5	23.2	0.1845
13	0.0133	0.0049	5.41	0.1278	0.0107	506.44	47.2	320.4	69.4	342.6	22.2	0.1928
14	0.0133	0.0049	5.41	0.1278	0.0107	506.44	47.8	321.0	70.6	343.8	22.8	0.1877
15	0.0133	0.0049	5.41	0.1278	0.0107	506.44	48.0	321.2	71.1	344.3	23.1	0.1853

Table 15. 15-Minute Experiments: 60% AlN with 40% Putty - Summary of Data

Time (mins.)	R2 (m)	R1 (m)	Power (W)	Length (m)	Area (m^2)	Heat Flux (W/m^2)	T2 (°C)	T2 (K)	T1 (°C)	T1 (K)	DeltaT (K)	K (W/m*K)
0	0.0133	0.0049	5.58	0.1278	0.0107	521.79	25.5	298.7	24.4	297.6	-1.1	-4.0083
1	0.0133	0.0049	5.58	0.1278	0.0107	521.79	25.8	299.0	37.2	310.4	11.4	0.3868
2	0.0133	0.0049	5.58	0.1278	0.0107	521.79	28.3	301.5	50.0	323.2	21.7	0.2032
3	0.0133	0.0049	5.58	0.1278	0.0107	521.79	31.0	304.2	58.3	331.5	27.3	0.1615
4	0.0133	0.0049	5.58	0.1278	0.0107	521.79	33.1	306.3	63.9	337.1	30.8	0.1432
5	0.0133	0.0049	5.58	0.1278	0.0107	521.79	35.7	308.9	67.2	340.4	31.5	0.1400
6	0.0133	0.0049	5.58	0.1278	0.0107	521.79	37.9	311.1	71.7	344.9	33.8	0.1304
7	0.0133	0.0049	5.58	0.1278	0.0107	521.79	39.9	313.1	74.4	347.6	34.5	0.1278
8	0.0133	0.0049	5.58	0.1278	0.0107	521.79	41.1	314.3	77.2	350.4	36.1	0.1221
9	0.0133	0.0049	5.58	0.1278	0.0107	521.79	42.7	315.9	79.4	352.6	36.7	0.1201
10	0.0133	0.0049	5.58	0.1278	0.0107	521.79	43.4	316.6	81.1	354.3	37.7	0.1170
11	0.0133	0.0049	5.58	0.1278	0.0107	521.79	45.2	318.4	82.8	356.0	37.6	0.1173
12	0.0133	0.0049	5.58	0.1278	0.0107	521.79	46.5	319.7	84.4	357.6	37.9	0.1163
13	0.0133	0.0049	5.58	0.1278	0.0107	521.79	47.0	320.2	85.6	358.8	38.6	0.1142
14	0.0133	0.0049	5.58	0.1278	0.0107	521.79	48.2	321.4	86.7	359.9	38.5	0.1145
15	0.0133	0.0049	5.58	0.1278	0.0107	521.79	49.0	322.2	87.8	361.0	38.8	0.1136

Table 16. 15-Minute Experiments: 50% AlN with 50% Putty - Summary of Data

Time (mins.)	R2 (m)	R1 (m)	Power (W)	Length (m)	Area (m^2)	Heat Flux (W/m^2)	T2 (°C)	T2 (K)	T1 (°C)	T1 (K)	DeltaT (K)	K (W/m*K)
0	0.0133	0.0049	5.62	0.1278	0.0107	525.63	25.5	298.7	25.0	298.2	-0.5	-8.8831
1	0.0133	0.0049	5.62	0.1278	0.0107	525.63	25.8	299.0	41.7	314.9	15.9	0.2793
2	0.0133	0.0049	5.62	0.1278	0.0107	525.63	28.3	301.5	57.8	331.0	29.5	0.1506
3	0.0133	0.0049	5.62	0.1278	0.0107	525.63	31.0	304.2	69.4	342.6	38.4	0.1157
4	0.0133	0.0049	5.62	0.1278	0.0107	525.63	33.1	306.3	78.3	351.5	45.2	0.0983
5	0.0133	0.0049	5.62	0.1278	0.0107	525.63	35.7	308.9	86.1	359.3	50.4	0.0881
6	0.0133	0.0049	5.62	0.1278	0.0107	525.63	37.9	311.1	89.4	362.6	51.5	0.0862
7	0.0133	0.0049	5.62	0.1278	0.0107	525.63	39.9	313.1	93.3	366.5	53.4	0.0832
8	0.0133	0.0049	5.62	0.1278	0.0107	525.63	41.1	314.3	95.6	368.8	54.5	0.0815
9	0.0133	0.0049	5.62	0.1278	0.0107	525.63	42.7	315.9	98.9	372.1	56.2	0.0790
10	0.0133	0.0049	5.62	0.1278	0.0107	525.63	43.4	316.6	101.1	374.3	57.7	0.0770
11	0.0133	0.0049	5.62	0.1278	0.0107	525.63	45.2	318.4	103.3	376.5	58.1	0.0764
12	0.0133	0.0049	5.62	0.1278	0.0107	525.63	46.5	319.7	105.0	378.2	58.5	0.0759
13	0.0133	0.0049	5.62	0.1278	0.0107	525.63	47.0	320.2	106.7	379.9	59.7	0.0744
14	0.0133	0.0049	5.62	0.1278	0.0107	525.63	48.2	321.4	108.3	381.5	60.1	0.0739
15	0.0133	0.0049	5.62	0.1278	0.0107	525.63	49.0	322.2	110.0	383.2	61.0	0.0728

Table 17. 15-Minute Experiments: 70% Putty with 30% AlN - Summary of Data

Time (mins.)	R2 (m)	R1 (m)	Power (W)	Length (m)	Area (m^2)	Heat Flux (W/m^2)	T2 (°C)	T2 (K)	T1 (°C)	T1 (K)	DeltaT (K)	K (W/m*K)
0	0.0133	0.0049	5.66	0.1278	0.0107	529.46	25.2	298.4	25.6	298.8	0.4	11.1849
1	0.0133	0.0049	5.66	0.1278	0.0107	529.46	36.6	309.8	44.4	317.6	7.8	0.5736
2	0.0133	0.0049	5.66	0.1278	0.0107	529.46	29.0	302.2	59.4	332.6	30.4	0.1472
3	0.0133	0.0049	5.66	0.1278	0.0107	529.46	32.0	305.2	68.9	342.1	36.9	0.1212
4	0.0133	0.0049	5.66	0.1278	0.0107	529.46	35.9	309.1	75.0	348.2	39.1	0.1144
5	0.0133	0.0049	5.66	0.1278	0.0107	529.46	38.9	312.1	80.0	353.2	41.1	0.1089
6	0.0133	0.0049	5.66	0.1278	0.0107	529.46	39.2	312.4	83.3	356.5	44.1	0.1015
7	0.0133	0.0049	5.66	0.1278	0.0107	529.46	41.8	315.0	86.1	359.3	44.3	0.1010
8	0.0133	0.0049	5.66	0.1278	0.0107	529.46	44.2	317.4	88.9	362.1	44.7	0.1001
9	0.0133	0.0049	5.66	0.1278	0.0107	529.46	44.6	317.8	91.1	364.3	46.5	0.0962
10	0.0133	0.0049	5.66	0.1278	0.0107	529.46	46.0	319.2	92.8	366.0	46.8	0.0956
11	0.0133	0.0049	5.66	0.1278	0.0107	529.46	48.5	321.7	94.4	367.6	45.9	0.0975
12	0.0133	0.0049	5.66	0.1278	0.0107	529.46	48.4	321.6	96.1	369.3	47.7	0.0938
13	0.0133	0.0049	5.66	0.1278	0.0107	529.46	49.0	322.2	96.7	369.9	47.7	0.0938
14	0.0133	0.0049	5.66	0.1278	0.0107	529.46	50.2	323.4	98.3	371.5	48.1	0.0930
15	0.0133	0.0049	5.66	0.1278	0.0107	529.46	51.1	324.3	99.4	372.6	48.3	0.0926

Table 18. 15-Minute Experiments: 60% Putty with 40% AlN - Summary of Data

Time (mins.)	R2 (m)	R1 (m)	Power (W)	Length (m)	Area (m^2)	Heat Flux (W/m^2)	T2 (°C)	T2 (K)	T1 (°C)	T1 (K)	DeltaT (K)	K (W/m*K)
0	0.0133	0.0049	5.66	0.1278	0.0107	529.46	27.5	300.7	25.6	298.8	-1.9	-2.3547
1	0.0133	0.0049	5.66	0.1278	0.0107	529.46	28.0	301.2	37.2	310.4	9.2	0.4863
2	0.0133	0.0049	5.66	0.1278	0.0107	529.46	30.0	303.2	47.2	320.4	17.2	0.2601
3	0.0133	0.0049	5.66	0.1278	0.0107	529.46	32.3	305.5	53.3	326.5	21.0	0.2130
4	0.0133	0.0049	5.66	0.1278	0.0107	529.46	34.6	307.8	57.8	331.0	23.2	0.1928
5	0.0133	0.0049	5.66	0.1278	0.0107	529.46	36.6	309.8	61.1	334.3	24.5	0.1826
6	0.0133	0.0049	5.66	0.1278	0.0107	529.46	37.8	311.0	63.9	337.1	26.1	0.1714
7	0.0133	0.0049	5.66	0.1278	0.0107	529.46	40.0	313.2	66.7	339.9	26.7	0.1676
8	0.0133	0.0049	5.66	0.1278	0.0107	529.46	41.6	314.8	68.3	341.5	26.7	0.1676
9	0.0133	0.0049	5.66	0.1278	0.0107	529.46	43.1	316.3	70.6	343.8	27.5	0.1627
10	0.0133	0.0049	5.66	0.1278	0.0107	529.46	44.2	317.4	72.2	345.4	28.0	0.1598
11	0.0133	0.0049	5.66	0.1278	0.0107	529.46	46.2	319.4	73.3	346.5	27.1	0.1651
12	0.0133	0.0049	5.66	0.1278	0.0107	529.46	47.0	320.2	75.0	348.2	28.0	0.1598
13	0.0133	0.0049	5.66	0.1278	0.0107	529.46	47.9	321.1	76.1	349.3	28.2	0.1587
14	0.0133	0.0049	5.66	0.1278	0.0107	529.46	48.7	321.9	72.2	345.4	23.5	0.1904
15	0.0133	0.0049	5.66	0.1278	0.0107	529.46	49.7	322.9	78.3	351.5	28.6	0.1564

Table 19. 15-Minute Experiments: 105g AlN with 50ml Silicone Oil - Summary of Data

Time (mins.)	R2 (m)	R1 (m)	Power (W)	Length (m)	Area (m^2)	Heat Flux (W/m^2)	T2 (ºC)	T2 (K)	T1 (ºC)	T1 (K)	DeltaT (K)	K (W/m*K)
0	0.0133	0.0049	5.66	0.1278	0.0107	529.46	27.2	300.4	25.6	298.8	-1.6	-2.7962
1	0.0133	0.0049	5.66	0.1278	0.0107	529.46	29.3	302.5	33.9	307.1	4.6	0.9726
2	0.0133	0.0049	5.66	0.1278	0.0107	529.46	32.0	305.2	40.6	313.8	8.6	0.5202
3	0.0133	0.0049	5.66	0.1278	0.0107	529.46	34.6	307.8	44.4	317.6	9.8	0.4565
4	0.0133	0.0049	5.66	0.1278	0.0107	529.46	36.5	309.7	47.8	321.0	11.3	0.3959
5	0.0133	0.0049	5.66	0.1278	0.0107	529.46	37.8	311.0	50.6	323.8	12.8	0.3495
6	0.0133	0.0049	5.66	0.1278	0.0107	529.46	39.7	312.9	52.8	326.0	13.1	0.3415
7	0.0133	0.0049	5.66	0.1278	0.0107	529.46	40.9	314.1	54.4	327.6	13.5	0.3314
8	0.0133	0.0049	5.66	0.1278	0.0107	529.46	42.2	315.4	56.1	329.3	13.9	0.3219
9	0.0133	0.0049	5.66	0.1278	0.0107	529.46	43.3	316.5	57.8	331.0	14.5	0.3085
10	0.0133	0.0049	5.66	0.1278	0.0107	529.46	44.6	317.8	58.9	332.1	14.3	0.3129
11	0.0133	0.0049	5.66	0.1278	0.0107	529.46	45.7	318.9	60.6	333.8	14.9	0.3003
12	0.0133	0.0049	5.66	0.1278	0.0107	529.46	46.4	319.6	61.7	334.9	15.3	0.2924
13	0.0133	0.0049	5.66	0.1278	0.0107	529.46	47.4	320.6	62.8	336.0	15.4	0.2905
14	0.0133	0.0049	5.66	0.1278	0.0107	529.46	48.1	321.3	63.3	336.5	15.2	0.2943
15	0.0133	0.0049	5.66	0.1278	0.0107	529.46	49.0	322.2	64.4	337.6	15.4	0.2905

Table 20. 15-Minute Experiments: 105g AlN with 30ml Silicone Oil - Summary of Data

Time (mins.)	R2 (m)	R1 (m)	Power (W)	Length (m)	Area (m^2)	Heat Flux (W/m^2)	T2 (ºC)	T2 (K)	T1 (ºC)	T1 (K)	DeltaT (K)	K (W/m*K)
0	0.0133	0.0049	5.94	0.1278	0.0107	555.85	24.5	297.7	25.0	298.2	0.5	9.3939
1	0.0133	0.0049	5.94	0.1278	0.0107	555.85	26.7	299.9	25.0	298.2	-1.7	-2.7629
2	0.0133	0.0049	5.94	0.1278	0.0107	555.85	28.4	301.6	26.7	299.9	-1.7	-2.7629
3	0.0133	0.0049	5.94	0.1278	0.0107	555.85	29.7	302.9	28.3	301.5	-1.4	-3.3550
4	0.0133	0.0049	5.94	0.1278	0.0107	555.85	32.4	305.6	30.0	303.2	-2.4	-1.9571
5	0.0133	0.0049	5.94	0.1278	0.0107	555.85	33.2	306.4	32.2	305.4	-1.0	-4.6969
6	0.0133	0.0049	5.94	0.1278	0.0107	555.85	35.6	308.8	33.9	307.1	-1.7	-2.7629
7	0.0133	0.0049	5.94	0.1278	0.0107	555.85	36.7	309.9	35.6	308.8	-1.1	-4.2700
8	0.0133	0.0049	5.94	0.1278	0.0107	555.85	36.9	310.1	37.8	311.0	0.9	5.2188
9	0.0133	0.0049	5.94	0.1278	0.0107	555.85	40.0	313.2	38.9	312.1	-1.1	-4.2700
10	0.0133	0.0049	5.94	0.1278	0.0107	555.85	41.4	314.6	40.6	313.8	-0.8	-5.8712
11	0.0133	0.0049	5.94	0.1278	0.0107	555.85	42.2	315.4	41.7	314.9	-0.5	-9.3939
12	0.0133	0.0049	5.94	0.1278	0.0107	555.85	43.3	316.5	42.8	316.0	-0.5	-9.3939
13	0.0133	0.0049	5.94	0.1278	0.0107	555.85	44.4	317.6	43.9	317.1	-0.5	-9.3939
14	0.0133	0.0049	5.94	0.1278	0.0107	555.85	45.2	318.4	45.0	318.2	-0.2	-23.4847
15	0.0133	0.0049	5.94	0.1278	0.0107	555.85	45.8	319.0	46.1	319.3	0.3	15.6565

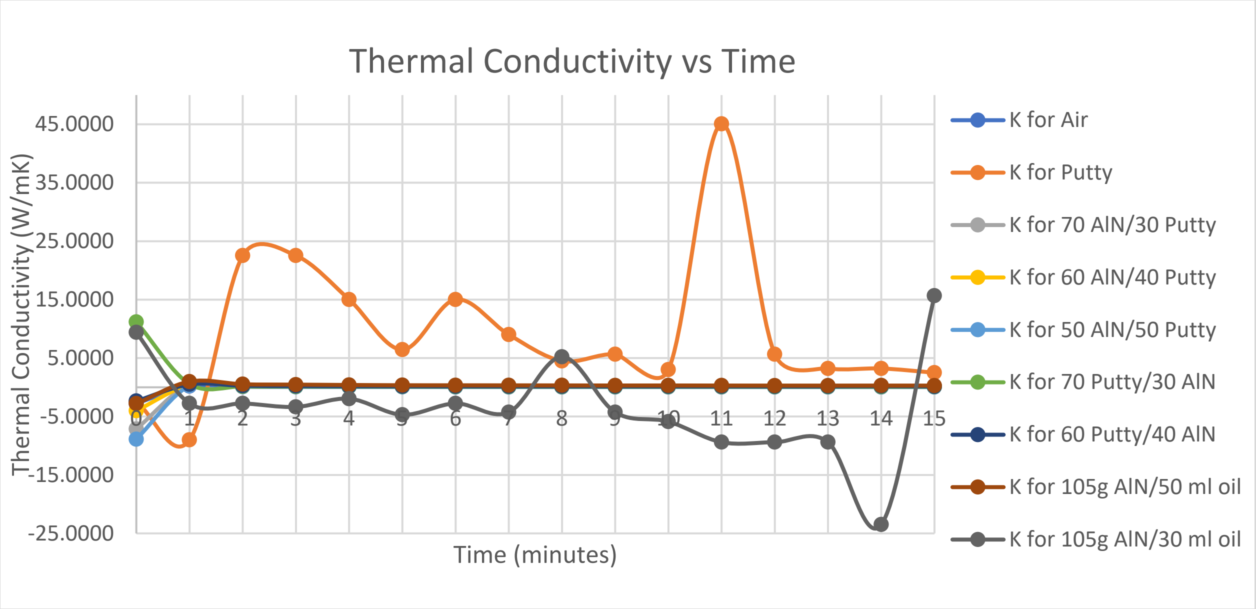

Figure 12. Thermal Conductivity vs Time Plot for the 15-Minute Experiments

Fig. 12 illustrates the calculated thermal conductivities up to 15 minutes. Some distortions can be observed since the thermal conductivities are not reaching steady-state values, and in some cases, the values are negative – obviously, incorrect since it is impossible for a material to have negative thermal conductivity. Therefore, 15-minute time is not suitable to get good results, so experiments lasting 30-minutes are done to evaluate the thermal conductivity results.

III.2.2 30-Minute Experiments

Tables 21 to 38 present the second round of experiments up to 30 minutes. Figs. 13 to 16 illustrate these results for better visualization and derivation of useful conclusions.

Table 21. 30-Minute Experiments: Air

Time (minutes)	Internal Temp of air (ºC)	External Temp of air (ºC)	Power of air (W)
0	23.9	24.2	5.56
1	52.8	25.2	5.56
2	82.8	27.8	5.56
3	106.1	31.5	5.56
4	125.6	36.4	5.56
5	141.1	38.7	5.56
6	153.9	40.0	5.56
7	163.3	41.4	5.56
8	168.9	43.5	5.56
9	173.3	46.3	5.56
10	177.2	47.7	5.56
11	181.1	48.9	5.56
12	183.3	49.7	5.56
13	185.0	50.2	5.56
14	186.1	51.6	5.56
15	186.7	52.8	5.56
16	187.8	52.7	5.56
17	188.3	52.2	5.56
18	188.9	54.0	5.56
19	189.4	53.7	5.56
20	189.4	54.8	5.56
21	190.0	55.0	5.56
22	190.0	55.2	5.56
23	188.3	54.6	5.56
24	187.8	54.8	5.56
25	187.8	54.7	5.56
26	187.8	55.6	5.56
27	187.2	55.6	5.56
28	187.2	55.6	5.56
29	187.2	55.7	5.56
30	187.2	55.0	5.56

The second experiment is only putty.

Table 22. 30-Minute Experiments: Putty

Time (minutes)	Internal Temp of putty (ºC)	External Temp of putty (ºC)	Power of putty (W)
0	27.8	28.8	5.56
1	33.3	32.3	5.56
2	37.2	34.9	5.56
3	39.4	36.8	5.56
4	41.7	39.2	5.56
5	42.8	40.1	5.56
6	44.4	41.5	5.56
7	45.6	42.3	5.56
8	47.2	43.0	5.56
9	48.3	45.0	5.56
10	48.9	46.0	5.56
11	50.0	46.6	5.56
12	50.6	47.0	5.56
13	51.7	47.7	5.56
14	52.8	48.4	5.56
15	53.3	49.6	5.56
16	53.9	50.0	5.56
17	55.0	50.8	5.56
18	55.6	51.3	5.56
19	56.1	52.0	5.56
20	56.7	52.5	5.56
21	57.2	53.1	5.56
22	57.2	53.4	5.56
23	57.8	53.4	5.56
24	58.3	53.4	5.56
25	58.9	54.0	5.56
26	58.9	55.0	5.56
27	59.4	55.4	5.56
28	60.0	55.5	5.56
29	60.0	55.7	5.56
30	60.6	55.9	5.56

Table 23. 30-Minute Experiments: 70% AlN with 30% Putty

Time (minutes)	Internal Temp of 70% AlN and 30% putty (ºC)	External Temp of 70% AlN and 30% putty (ºC)	Power of 70% AlN and 30% putty (W)
0	25.6	27.2	5.56
1	36.1	27.8	5.56
2	45.0	29.9	5.56
3	50.6	33.2	5.56
4	55.0	35.8	5.56
5	58.3	38.3	5.56
6	61.1	39.7	5.56
7	63.3	41.3	5.56
8	65.0	42.9	5.56
9	66.7	43.8	5.56
10	68.3	46.3	5.56
11	69.4	47.0	5.56
12	70.6	48.3	5.56
13	71.7	49.2	5.56
14	72.8	50.5	5.56
15	73.3	51.1	5.56
16	74.4	51.9	5.56
17	75.0	52.3	5.56
18	75.6	52.9	5.56
19	76.1	53.2	5.56
20	76.7	53.5	5.56
21	77.2	54.8	5.56
22	77.8	55.2	5.56
23	78.3	55.5	5.56
24	78.9	55.9	5.56
25	78.9	56.5	5.56
26	79.4	56.9	5.56
27	79.4	56.9	5.56
28	80.0	57.3	5.56
29	80.0	57.6	5.56
30	80.6	58.2	5.56

Table 24. 30-Minute Experiments: 60% AlN with 40% Putty

Time (minutes)	Internal Temp of 60% AlN and 40% putty (ºC)	External Temp of 60% AlN and 40% putty (ºC)	Power of 60% AlN and 40% putty (W)
0	26.7	27.2	5.56
1	32.8	29.2	5.56
2	38.9	32.4	5.56
3	43.9	34.7	5.56
4	47.8	37.1	5.56
5	51.1	40.7	5.56
6	53.9	42.3	5.56
7	56.1	44.0	5.56
8	57.8	45.3	5.56
9	60.0	46.5	5.56
10	61.7	48.7	5.56
11	62.8	49.9	5.56
12	64.4	50.6	5.56
13	65.6	51.4	5.56
14	66.7	52.3	5.56
15	67.8	53.0	5.56
16	68.9	53.6	5.56
17	69.4	54.8	5.56
18	70.0	55.8	5.56
19	70.6	56.1	5.56
20	71.7	56.8	5.56
21	72.2	57.2	5.56
22	72.8	57.9	5.56
23	73.3	58.0	5.56
24	73.9	58.3	5.56
25	73.9	58.6	5.56
26	74.4	58.7	5.56
27	75.0	59.2	5.56
28	75.0	59.8	5.56
29	75.6	60.0	5.56
30	75.6	60.2	5.56

Table 25. 30-Minute Experiments: 50% AlN with 50% Putty

Time (minutes)	Internal Temp of 50% AlN and 50% putty (ºC)	External Temp of 50% AlN and 50% putty (ºC)	Power of 50% AlN and 50% putty (W)
0	27.8	28.9	5.56
1	44.4	30.4	5.56
2	55.0	33.3	5.56
3	61.1	36.2	5.56
4	65.6	38.3	5.56
5	68.9	41.4	5.56
6	71.7	42.9	5.56
7	73.9	44.3	5.56
8	76.1	45.1	5.56
9	77.8	46.6	5.56
10	79.4	48.2	5.56
11	80.6	49.6	5.56
12	82.2	50.4	5.56
13	83.3	51.0	5.56
14	84.4	51.7	5.56
15	85.0	52.2	5.56
16	86.1	53.6	5.56
17	87.2	54.4	5.56
18	87.8	54.8	5.56
19	88.3	55.0	5.56
20	88.9	55.8	5.56
21	89.4	56.7	5.56
22	90.0	56.9	5.56
23	90.6	57.1	5.56
24	91.1	57.3	5.56
25	91.7	57.5	5.56
26	92.2	58.1	5.56
27	92.2	58.7	5.56
28	92.2	58.7	5.56
29	92.8	58.9	5.56
30	92.8	59.1	5.56

Table 26. 30-Minute Experiments: 70% Putty with 30% AlN

Time (minutes)	Internal Temp of 70% putty and 30% AlN (ºC)	Internal Temp of 70% putty and 30% AlN (ºC)	Power of 70% putty and 30% AlN (W)
0	27.8	29.5	5.56
1	36.7	30.8	5.56
2	41.1	33.3	5.56
3	43.9	35.2	5.56
4	45.6	37.3	5.56
5	47.8	40.4	5.56
6	49.4	41.4	5.56
7	50.6	42.3	5.56
8	51.7	43.3	5.56
9	53.3	44.2	5.56
10	54.4	45.2	5.56
11	55.6	46.8	5.56
12	56.7	48.0	5.56
13	57.2	48.6	5.56
14	58.3	49.2	5.56
15	58.9	50.0	5.56
16	60.0	51.4	5.56
17	60.6	51.9	5.56
18	61.1	52.3	5.56
19	61.7	52.5	5.56
20	62.2	52.7	5.56
21	62.8	53.1	5.56
22	63.3	54.2	5.56
23	63.9	54.9	5.56
24	64.4	55.1	5.56
25	64.4	55.3	5.56
26	65.0	55.7	5.56
27	65.6	56.5	5.56
28	65.6	56.8	5.56
29	66.1	56.8	5.56
30	66.1	56.8	5.56

Table 27. 30-Minute Experiments: 60% Putty with 40% AlN

Time (minutes)	Internal Temp of 60% putty and 40% AlN (ºC)	External Temp of 60% putty and 40% AlN (ºC)	Power of 60% putty and 40% AlN (W)
0	28.3	29.3	5.56
1	44.4	30.8	5.56
2	53.3	33	5.56
3	57.8	35.1	5.56
4	60.6	37.5	5.56
5	63.3	40.4	5.56
6	65.6	41.6	5.56
7	67.2	42.8	5.56
8	68.9	43.8	5.56
9	70.0	44.8	5.56
10	71.1	46.2	5.56
11	72.8	47.1	5.56
12	73.9	48.0	5.56
13	74.4	49.1	5.56
14	75.6	51.3	5.56
15	76.7	51.4	5.56
16	77.2	51.8	5.56
17	78.3	52.4	5.56
18	78.9	52.5	5.56
19	79.4	52.6	5.56
20	80.0	52.8	5.56
21	80.6	54.3	5.56
22	81.1	54.7	5.56
23	81.7	55.1	5.56
24	82.2	55.4	5.56
25	82.2	56.1	5.56
26	82.8	56.4	5.56
27	83.3	56.6	5.56
28	83.3	56.8	5.56
29	83.9	56.8	5.56
30	83.9	56.9	5.56

Table 28. 30-Minute Experiments: 105g AlN with 50ml Silicone Oil

Time (minutes)	Int Temp of 105g AlN/50ml oil (ºC)	Ext Temp of 105g AlN/50ml oil (ºC)	Power of 105g AlN/50ml oil (W)
0	27.8	28.7	5.62
1	36.7	30.9	5.62
2	41.1	34.7	5.62
3	43.9	36.0	5.62
4	46.7	38.4	5.62
5	48.3	39.7	5.62
6	50.6	41.3	5.62
7	52.2	42.6	5.62
8	53.9	43.4	5.62
9	55.0	45.1	5.62
10	56.7	46.4	5.62
11	57.8	47.3	5.62
12	58.9	48.1	5.62
13	60.0	49.0	5.62
14	60.6	49.5	5.62
15	61.7	50.2	5.62
16	62.2	50.9	5.62
17	62.8	51.2	5.62
18	63.3	51.7	5.62
19	64.4	52.4	5.62
20	64.4	53.2	5.62
21	65.0	53.3	5.62
22	65.6	53.6	5.62
23	66.1	53.8	5.62
24	66.7	54.3	5.62
25	66.7	54.6	5.62
26	67.2	55.1	5.62
27	67.8	55.3	5.62
28	67.8	55.8	5.62
29	68.3	55.9	5.62
30	68.3	56.2	5.62

Table 29. 30-Minute Experiments: 105g AlN with 30ml Silicone Oil

Time (minutes)	Int Temp of 105g AlN/30ml oil (ºC)	Ext Temp of 105g AlN/30ml oil (ºC)	Power of 105g AlN/30ml oil (W)
0	26.7	27.2	5.62
1	37.2	28.4	5.62
2	43.9	31.3	5.62
3	47.8	33.3	5.62
4	51.1	35.8	5.62
5	53.9	37.5	5.62
6	56.7	39.9	5.62
7	58.9	41.8	5.62
8	60.6	43.0	5.62
9	62.2	44.1	5.62
10	63.9	45.1	5.62
11	65.0	46.0	5.62
12	66.1	47.5	5.62
13	67.2	48.3	5.62
14	68.3	48.9	5.62
15	69.4	49.6	5.62
16	70.0	50.9	5.62
17	70.6	51.6	5.62
18	71.1	51.9	5.62
19	72.2	52.4	5.62
20	72.2	52.7	5.62
21	72.8	52.8	5.62
22	73.3	52.8	5.62
23	73.9	54.1	5.62
24	74.4	54.4	5.62
25	74.4	54.7	5.62
26	74.4	54.7	5.62
27	75.0	54.9	5.62
28	75.6	55.8	5.62
29	75.6	55.8	5.62
30	75.6	55.8	5.62

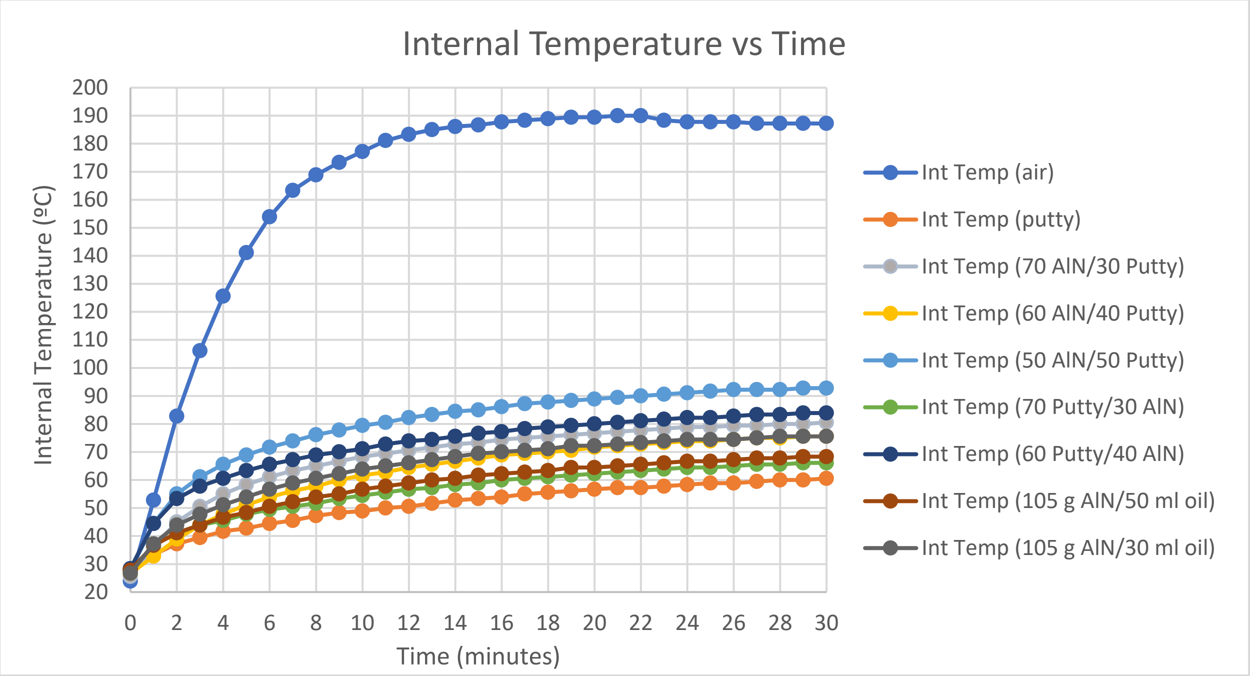

Figure 13. Internal Temperature vs Time Plot for the 30-Minute Experiments

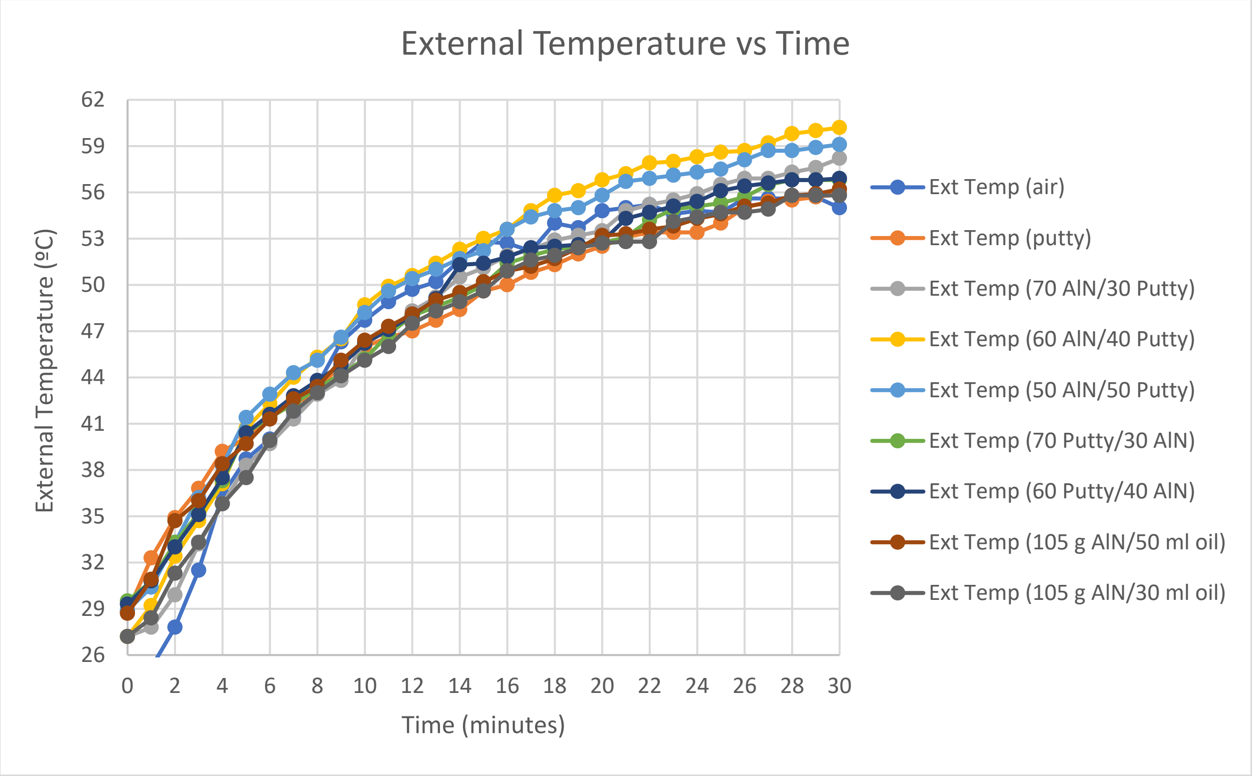

Figure 14. External Temperature vs Time Plot for the 30-Minute Experiments

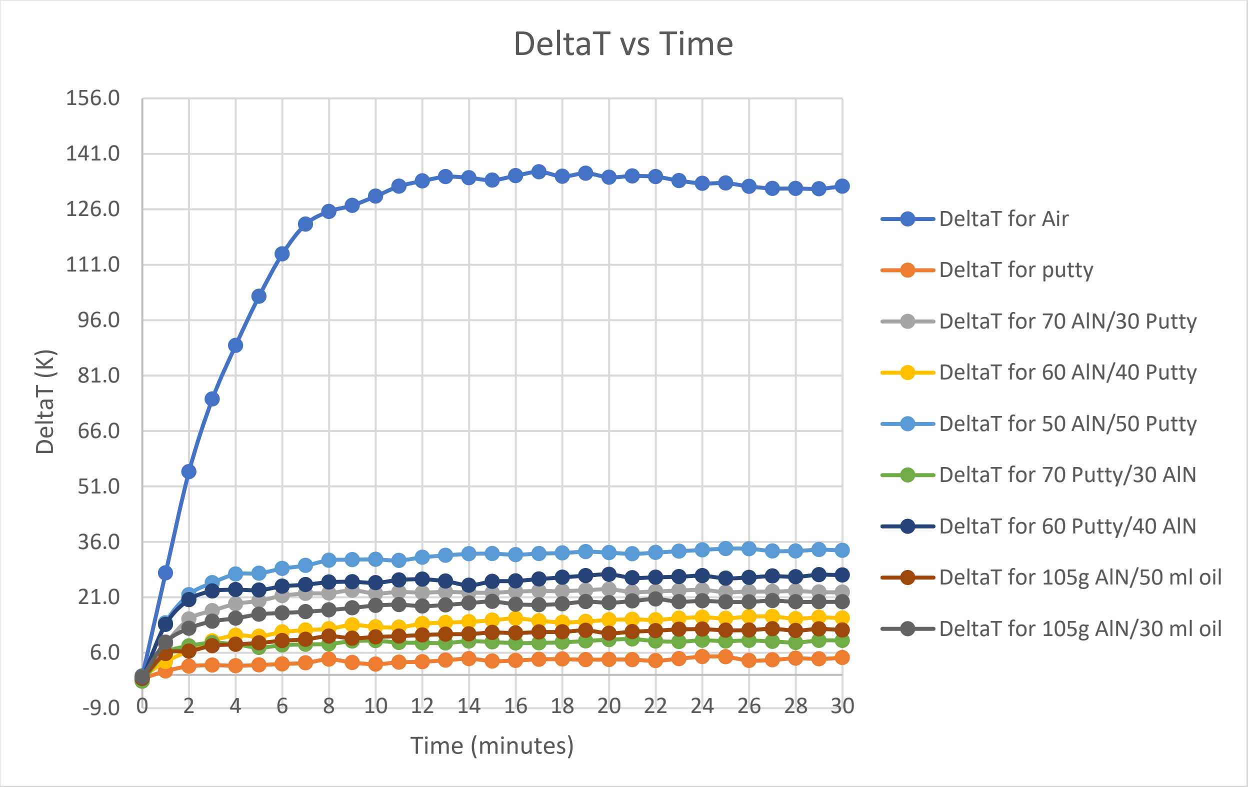

Figure 15. DeltaT vs Time Plot for the 30-Minute Experiments

Figs. 13-15 illustrate the temperatures approximating steady-state values for each experiment unlike the first round of experiments up to 15 minutes where steady-state values were not obtained. Fig. 15 clearly illustrates the advantage of using potting materials for fast removal of heat from inductors used in DC-DC converters.

Table 30. 30-Minute Experiments: Air - Summary of Data

Time (mins.)	R2 (m)	R1 (m)	Power (W)	Length (m)	Area (m^2)	Heat Flux (W/m^2)	T2 (°C)	T2 (K)	T1 (°C)	T1 (K)	DeltaT (K)	K (W/m*K)
0	0.0133	0.0045	5.56	0.1278	0.0107	520.20	24.2	297.4	23.9	297.0	-0.3	-14.723
1	0.0133	0.0045	5.56	0.1278	0.0107	520.20	25.2	298.4	52.8	325.9	27.6	0.1661
2	0.0133	0.0045	5.56	0.1278	0.0107	520.20	27.8	301.0	82.8	355.9	55.0	0.0833
3	0.0133	0.0045	5.56	0.1278	0.0107	520.20	31.5	304.7	106.1	379.3	74.6	0.0614
4	0.0133	0.0045	5.56	0.1278	0.0107	520.20	36.4	309.6	125.6	398.7	89.2	0.0514
5	0.0133	0.0045	5.56	0.1278	0.0107	520.20	38.7	311.9	141.1	414.3	102.4	0.0447
6	0.0133	0.0045	5.56	0.1278	0.0107	520.20	40.0	313.2	153.9	427.0	113.9	0.0402
7	0.0133	0.0045	5.56	0.1278	0.0107	520.20	41.4	314.6	163.3	436.5	121.9	0.0376
8	0.0133	0.0045	5.56	0.1278	0.0107	520.20	43.5	316.7	168.9	442.0	125.4	0.0365
9	0.0133	0.0045	5.56	0.1278	0.0107	520.20	46.3	319.5	173.3	446.5	127.0	0.0361
10	0.0133	0.0045	5.56	0.1278	0.0107	520.20	47.7	320.9	177.2	450.4	129.5	0.0354
11	0.0133	0.0045	5.56	0.1278	0.0107	520.20	48.9	322.1	181.1	454.3	132.2	0.0346
12	0.0133	0.0045	5.56	0.1278	0.0107	520.20	49.7	322.9	183.3	456.5	133.6	0.0343
13	0.0133	0.0045	5.56	0.1278	0.0107	520.20	50.2	323.4	185.0	458.2	134.8	0.0340
14	0.0133	0.0045	5.56	0.1278	0.0107	520.20	51.6	324.8	186.1	459.3	134.5	0.0341
15	0.0133	0.0045	5.56	0.1278	0.0107	520.20	52.8	326.0	186.7	459.8	133.9	0.0342
16	0.0133	0.0045	5.56	0.1278	0.0107	520.20	52.7	325.9	187.8	460.9	135.1	0.0339
17	0.0133	0.0045	5.56	0.1278	0.0107	520.20	52.2	325.4	188.3	461.5	136.1	0.0336
18	0.0133	0.0045	5.56	0.1278	0.0107	520.20	54.0	327.2	188.9	462.0	134.9	0.0340
19	0.0133	0.0045	5.56	0.1278	0.0107	520.20	53.7	326.9	189.4	462.6	135.7	0.0337
20	0.0133	0.0045	5.56	0.1278	0.0107	520.20	54.8	328.0	189.4	462.6	134.6	0.0340
21	0.0133	0.0045	5.56	0.1278	0.0107	520.20	55.0	328.2	190.0	463.2	135.0	0.0339
22	0.0133	0.0045	5.56	0.1278	0.0107	520.20	55.2	328.4	190.0	463.2	134.8	0.0340
23	0.0133	0.0045	5.56	0.1278	0.0107	520.20	54.6	327.8	188.3	461.5	133.7	0.0342
24	0.0133	0.0045	5.56	0.1278	0.0107	520.20	54.8	328.0	187.8	460.9	133.0	0.0344
25	0.0133	0.0045	5.56	0.1278	0.0107	520.20	54.7	327.9	187.8	460.9	133.1	0.0344
26	0.0133	0.0045	5.56	0.1278	0.0107	520.20	55.6	328.8	187.8	460.9	132.2	0.0347
27	0.0133	0.0045	5.56	0.1278	0.0107	520.20	55.6	328.8	187.2	460.4	131.6	0.0348
28	0.0133	0.0045	5.56	0.1278	0.0107	520.20	55.6	328.8	187.2	460.4	131.6	0.0348
29	0.0133	0.0045	5.56	0.1278	0.0107	520.20	55.7	328.9	187.2	460.4	131.5	0.0348
30	0.0133	0.0045	5.56	0.1278	0.0107	520.20	55.0	328.2	187.2	460.4	132.2	0.0346

Table 31. 30-Minute Experiments: Putty - Summary of Data

Time (mins.)	R2 (m)	R1 (m)	Power (W)	Length (m)	Area (m^2)	Heat Flux (W/m^2)	T2 (°C)	T2 (K)	T1 (°C)	T1 (K)	DeltaT (K)	K (W/m*K)
0	0.0133	0.0045	5.56	0.1278	0.0107	520.20	28.8	302.0	27.8	300.9	-1.0	-4.4808
1	0.0133	0.0045	5.56	0.1278	0.0107	520.20	32.3	305.5	33.3	306.5	1.0	4.4326
2	0.0133	0.0045	5.56	0.1278	0.0107	520.20	34.9	308.1	37.2	310.4	2.3	1.9724
3	0.0133	0.0045	5.56	0.1278	0.0107	520.20	36.8	310.0	39.4	312.6	2.6	1.7321
4	0.0133	0.0045	5.56	0.1278	0.0107	520.20	39.2	312.4	41.7	314.8	2.5	1.8569
5	0.0133	0.0045	5.56	0.1278	0.0107	520.20	40.1	313.3	42.8	315.9	2.7	1.7105
6	0.0133	0.0045	5.56	0.1278	0.0107	520.20	41.5	314.7	44.4	317.6	2.9	1.5556
7	0.0133	0.0045	5.56	0.1278	0.0107	520.20	42.3	315.5	45.6	318.7	3.3	1.4069
8	0.0133	0.0045	5.56	0.1278	0.0107	520.20	43.0	316.2	47.2	320.4	4.2	1.0848
9	0.0133	0.0045	5.56	0.1278	0.0107	520.20	45.0	318.2	48.3	321.5	3.3	1.3741
10	0.0133	0.0045	5.56	0.1278	0.0107	520.20	46.0	319.2	48.9	322.0	2.9	1.5855
11	0.0133	0.0045	5.56	0.1278	0.0107	520.20	46.6	319.8	50.0	323.2	3.4	1.3472
12	0.0133	0.0045	5.56	0.1278	0.0107	520.20	47.0	320.2	50.6	323.7	3.6	1.2882
13	0.0133	0.0045	5.56	0.1278	0.0107	520.20	47.7	320.9	51.7	324.8	4.0	1.1547
14	0.0133	0.0045	5.56	0.1278	0.0107	520.20	48.4	321.6	52.8	325.9	4.4	1.0463
15	0.0133	0.0045	5.56	0.1278	0.0107	520.20	49.6	322.8	53.3	326.5	3.7	1.2269
16	0.0133	0.0045	5.56	0.1278	0.0107	520.20	50.0	323.2	53.9	327.0	3.9	1.1778
17	0.0133	0.0045	5.56	0.1278	0.0107	520.20	50.8	324.0	55.0	328.2	4.2	1.0906
18	0.0133	0.0045	5.56	0.1278	0.0107	520.20	51.3	324.5	55.6	328.7	4.3	1.0763
19	0.0133	0.0045	5.56	0.1278	0.0107	520.20	52.0	325.2	56.1	329.3	4.1	1.1141
20	0.0133	0.0045	5.56	0.1278	0.0107	520.20	52.5	325.7	56.7	329.8	4.2	1.0993
21	0.0133	0.0045	5.56	0.1278	0.0107	520.20	53.1	326.3	57.2	330.4	4.1	1.1111
22	0.0133	0.0045	5.56	0.1278	0.0107	520.20	53.4	326.6	57.2	330.4	3.8	1.1983
23	0.0133	0.0045	5.56	0.1278	0.0107	520.20	53.4	326.6	57.8	330.9	4.4	1.0463
24	0.0133	0.0045	5.56	0.1278	0.0107	520.20	53.4	326.6	58.3	331.5	4.9	0.9284
25	0.0133	0.0045	5.56	0.1278	0.0107	520.20	54.0	327.2	58.9	332.0	4.9	0.9369
26	0.0133	0.0045	5.56	0.1278	0.0107	520.20	55.0	328.2	58.9	332.0	3.9	1.1778
27	0.0133	0.0045	5.56	0.1278	0.0107	520.20	55.4	328.6	59.4	332.6	4.0	1.1325
28	0.0133	0.0045	5.56	0.1278	0.0107	520.20	55.5	328.7	60.0	333.2	4.5	1.0179
29	0.0133	0.0045	5.56	0.1278	0.0107	520.20	55.7	328.9	60.0	333.2	4.3	1.0652
30	0.0133	0.0045	5.56	0.1278	0.0107	520.20	55.9	329.1	60.6	333.7	4.7	0.9838

Table 32. 30-Minute Experiments: 70% AlN with 30% Putty – Summary of Data

Time (mins.)	R2 (m)	R1 (m)	Power (W)	Length (m)	Area (m^2)	Heat Flux (W/m^2)	T2 (°C)	T2 (K)	T1 (°C)	T1 (K)	DeltaT (K)	K (W/m*K)
0	0.0133	0.0045	5.56	0.1278	0.0107	520.20	27.2	300.4	25.6	298.7	-1.6	-2.7853
1	0.0133	0.0045	5.56	0.1278	0.0107	520.20	27.8	301.0	36.1	309.3	8.3	0.5511
2	0.0133	0.0045	5.56	0.1278	0.0107	520.20	29.9	303.1	45.0	318.2	15.1	0.3033
3	0.0133	0.0045	5.56	0.1278	0.0107	520.20	33.2	306.4	50.6	323.7	17.4	0.2639
4	0.0133	0.0045	5.56	0.1278	0.0107	520.20	35.8	309.0	55.0	328.2	19.2	0.2386
5	0.0133	0.0045	5.56	0.1278	0.0107	520.20	38.3	311.5	58.3	331.5	20.0	0.2286
6	0.0133	0.0045	5.56	0.1278	0.0107	520.20	39.7	312.9	61.1	334.3	21.4	0.2139
7	0.0133	0.0045	5.56	0.1278	0.0107	520.20	41.3	314.5	63.3	336.5	22.0	0.2079
8	0.0133	0.0045	5.56	0.1278	0.0107	520.20	42.9	316.1	65.0	338.2	22.1	0.2073
9	0.0133	0.0045	5.56	0.1278	0.0107	520.20	43.8	317.0	66.7	339.8	22.9	0.2003
10	0.0133	0.0045	5.56	0.1278	0.0107	520.20	46.3	319.5	68.3	341.5	22.0	0.2079
11	0.0133	0.0045	5.56	0.1278	0.0107	520.20	47.0	320.2	69.4	342.6	22.4	0.2041
12	0.0133	0.0045	5.56	0.1278	0.0107	520.20	48.3	321.5	70.6	343.7	22.3	0.2058
13	0.0133	0.0045	5.56	0.1278	0.0107	520.20	49.2	322.4	71.7	344.8	22.5	0.2039
14	0.0133	0.0045	5.56	0.1278	0.0107	520.20	50.5	323.7	72.8	345.9	22.3	0.2056
15	0.0133	0.0045	5.56	0.1278	0.0107	520.20	51.1	324.3	73.3	346.5	22.2	0.2060
16	0.0133	0.0045	5.56	0.1278	0.0107	520.20	51.9	325.1	74.4	347.6	22.5	0.2032
17	0.0133	0.0045	5.56	0.1278	0.0107	520.20	52.3	325.5	75.0	348.2	22.7	0.2018
18	0.0133	0.0045	5.56	0.1278	0.0107	520.20	52.9	326.1	75.6	348.7	22.7	0.2022
19	0.0133	0.0045	5.56	0.1278	0.0107	520.20	53.2	326.4	76.1	349.3	22.9	0.1999
20	0.0133	0.0045	5.56	0.1278	0.0107	520.20	53.5	326.7	76.7	349.8	23.2	0.1977
21	0.0133	0.0045	5.56	0.1278	0.0107	520.20	54.8	328.0	77.2	350.4	22.4	0.2043
22	0.0133	0.0045	5.56	0.1278	0.0107	520.20	55.2	328.4	77.8	350.9	22.6	0.2029
23	0.0133	0.0045	5.56	0.1278	0.0107	520.20	55.5	328.7	78.3	351.5	22.8	0.2006
24	0.0133	0.0045	5.56	0.1278	0.0107	520.20	55.9	329.1	78.9	352.0	23.0	0.1992
25	0.0133	0.0045	5.56	0.1278	0.0107	520.20	56.5	329.7	78.9	352.0	22.4	0.2046
26	0.0133	0.0045	5.56	0.1278	0.0107	520.20	56.9	330.1	79.4	352.6	22.5	0.2032
27	0.0133	0.0045	5.56	0.1278	0.0107	520.20	56.9	330.1	79.4	352.6	22.5	0.2032
28	0.0133	0.0045	5.56	0.1278	0.0107	520.20	57.3	330.5	80.0	353.2	22.7	0.2018
29	0.0133	0.0045	5.56	0.1278	0.0107	520.20	57.6	330.8	80.0	353.2	22.4	0.2045
30	0.0133	0.0045	5.56	0.1278	0.0107	520.20	58.2	331.4	80.6	353.7	22.4	0.2049

Table 33. 30-Minute Experiments: 60% AlN with 40% Putty - Summary of Data

Time (mins.)	R2 (m)	R1 (m)	Power (W)	Length (m)	Area (m^2)	Heat Flux (W/m^2)	T2 (°C)	T2 (K)	T1 (°C)	T1 (K)	DeltaT (K)	K (W/m*K)
0	0.0133	0.0045	5.56	0.1278	0.0107	520.20	27.2	300.4	26.7	299.8	-0.5	-8.5882
1	0.0133	0.0045	5.56	0.1278	0.0107	520.20	29.2	302.4	32.8	305.9	3.6	1.2802
2	0.0133	0.0045	5.56	0.1278	0.0107	520.20	32.4	305.6	38.9	312.0	6.5	0.7059
3	0.0133	0.0045	5.56	0.1278	0.0107	520.20	34.7	307.9	43.9	317.0	9.2	0.4985
4	0.0133	0.0045	5.56	0.1278	0.0107	520.20	37.1	310.3	47.8	320.9	10.7	0.4290
5	0.0133	0.0045	5.56	0.1278	0.0107	520.20	40.7	313.9	51.1	324.3	10.4	0.4399
6	0.0133	0.0045	5.56	0.1278	0.0107	520.20	42.3	315.5	53.9	327.0	11.6	0.3952
7	0.0133	0.0045	5.56	0.1278	0.0107	520.20	44.0	317.2	56.1	329.3	12.1	0.3782
8	0.0133	0.0045	5.56	0.1278	0.0107	520.20	45.3	318.5	57.8	330.9	12.5	0.3671
9	0.0133	0.0045	5.56	0.1278	0.0107	520.20	46.5	319.7	60.0	333.2	13.5	0.3393
10	0.0133	0.0045	5.56	0.1278	0.0107	520.20	48.7	321.9	61.7	334.8	13.0	0.3532
11	0.0133	0.0045	5.56	0.1278	0.0107	520.20	49.9	323.1	62.8	335.9	12.9	0.3557
12	0.0133	0.0045	5.56	0.1278	0.0107	520.20	50.6	323.8	64.4	337.6	13.8	0.3308
13	0.0133	0.0045	5.56	0.1278	0.0107	520.20	51.4	324.6	65.6	338.7	14.2	0.3236
14	0.0133	0.0045	5.56	0.1278	0.0107	520.20	52.3	325.5	66.7	339.8	14.4	0.3188
15	0.0133	0.0045	5.56	0.1278	0.0107	520.20	53.0	326.2	67.8	340.9	14.8	0.3099
16	0.0133	0.0045	5.56	0.1278	0.0107	520.20	53.6	326.8	68.9	342.0	15.3	0.2996
17	0.0133	0.0045	5.56	0.1278	0.0107	520.20	54.8	328.0	69.4	342.6	14.6	0.3128
18	0.0133	0.0045	5.56	0.1278	0.0107	520.20	55.8	329.0	70.0	343.2	14.2	0.3226
19	0.0133	0.0045	5.56	0.1278	0.0107	520.20	56.1	329.3	70.6	343.7	14.5	0.3169
20	0.0133	0.0045	5.56	0.1278	0.0107	520.20	56.8	330.0	71.7	344.8	14.9	0.3081
21	0.0133	0.0045	5.56	0.1278	0.0107	520.20	57.2	330.4	72.2	345.4	15.0	0.3049
22	0.0133	0.0045	5.56	0.1278	0.0107	520.20	57.9	331.1	72.8	345.9	14.9	0.3079
23	0.0133	0.0045	5.56	0.1278	0.0107	520.20	58.0	331.2	73.3	346.5	15.3	0.2987
24	0.0133	0.0045	5.56	0.1278	0.0107	520.20	58.3	331.5	73.9	347.0	15.6	0.2938
25	0.0133	0.0045	5.56	0.1278	0.0107	520.20	58.6	331.8	73.9	347.0	15.3	0.2996
26	0.0133	0.0045	5.56	0.1278	0.0107	520.20	58.7	331.9	74.4	347.6	15.7	0.2909
27	0.0133	0.0045	5.56	0.1278	0.0107	520.20	59.2	332.4	75.0	348.2	15.8	0.2899
28	0.0133	0.0045	5.56	0.1278	0.0107	520.20	59.8	333.0	75.0	348.2	15.2	0.3013
29	0.0133	0.0045	5.56	0.1278	0.0107	520.20	60.0	333.2	75.6	348.7	15.6	0.2945
30	0.0133	0.0045	5.56	0.1278	0.0107	520.20	60.2	333.4	75.6	348.7	15.4	0.2983

Table 34. 30-Minute Experiments: 50% AlN with 50% Putty - Summary of Data

Time (mins.)	R2 (m)	R1 (m)	Power (W)	Length (m)	Area (m^2)	Heat Flux (W/m^2)	T2 (ºC)	T2 (K)	T1 (ºC)	T1 (K)	DeltaT (K)	K (W/m*K)
0	0.0133	0.0045	5.56	0.1278	0.0107	520.20	28.9	302.1	27.8	300.9	-1.1	-4.0815
1	0.0133	0.0045	5.56	0.1278	0.0107	520.20	30.4	303.6	44.4	317.6	14.0	0.3261
2	0.0133	0.0045	5.56	0.1278	0.0107	520.20	33.3	306.5	55.0	328.2	21.7	0.2111
3	0.0133	0.0045	5.56	0.1278	0.0107	520.20	36.2	309.4	61.1	334.3	24.9	0.1839
4	0.0133	0.0045	5.56	0.1278	0.0107	520.20	38.3	311.5	65.6	338.7	27.3	0.1681
5	0.0133	0.0045	5.56	0.1278	0.0107	520.20	41.4	314.6	68.9	342.0	27.5	0.1666
6	0.0133	0.0045	5.56	0.1278	0.0107	520.20	42.9	316.1	71.7	344.8	28.8	0.1592
7	0.0133	0.0045	5.56	0.1278	0.0107	520.20	44.3	317.5	73.9	347.0	29.6	0.1548
8	0.0133	0.0045	5.56	0.1278	0.0107	520.20	45.1	318.3	76.1	349.3	31.0	0.1477
9	0.0133	0.0045	5.56	0.1278	0.0107	520.20	46.6	319.8	77.8	350.9	31.2	0.1469
10	0.0133	0.0045	5.56	0.1278	0.0107	520.20	48.2	321.4	79.4	352.6	31.2	0.1466
11	0.0133	0.0045	5.56	0.1278	0.0107	520.20	49.6	322.8	80.6	353.7	31.0	0.1480
12	0.0133	0.0045	5.56	0.1278	0.0107	520.20	50.4	323.6	82.2	355.4	31.8	0.1439
13	0.0133	0.0045	5.56	0.1278	0.0107	520.20	51.0	324.2	83.3	356.5	32.3	0.1417
14	0.0133	0.0045	5.56	0.1278	0.0107	520.20	51.7	324.9	84.4	357.6	32.7	0.1399
15	0.0133	0.0045	5.56	0.1278	0.0107	520.20	52.2	325.4	85.0	358.2	32.8	0.1396
16	0.0133	0.0045	5.56	0.1278	0.0107	520.20	53.6	326.8	86.1	359.3	32.5	0.1409
17	0.0133	0.0045	5.56	0.1278	0.0107	520.20	54.4	327.6	87.2	360.4	32.8	0.1396
18	0.0133	0.0045	5.56	0.1278	0.0107	520.20	54.8	328.0	87.8	360.9	33.0	0.1389
19	0.0133	0.0045	5.56	0.1278	0.0107	520.20	55.0	328.2	88.3	361.5	33.3	0.1374
20	0.0133	0.0045	5.56	0.1278	0.0107	520.20	55.8	329.0	88.9	362.0	33.1	0.1384
21	0.0133	0.0045	5.56	0.1278	0.0107	520.20	56.7	329.9	89.4	362.6	32.7	0.1399
22	0.0133	0.0045	5.56	0.1278	0.0107	520.20	56.9	330.1	90.0	363.2	33.1	0.1384
23	0.0133	0.0045	5.56	0.1278	0.0107	520.20	57.1	330.3	90.6	363.7	33.5	0.1369
24	0.0133	0.0045	5.56	0.1278	0.0107	520.20	57.3	330.5	91.1	364.3	33.8	0.1355
25	0.0133	0.0045	5.56	0.1278	0.0107	520.20	57.5	330.7	91.7	364.8	34.2	0.1341
26	0.0133	0.0045	5.56	0.1278	0.0107	520.20	58.1	331.3	92.2	365.4	34.1	0.1342
27	0.0133	0.0045	5.56	0.1278	0.0107	520.20	58.7	331.9	92.2	365.4	33.5	0.1366
28	0.0133	0.0045	5.56	0.1278	0.0107	520.20	58.7	331.9	92.2	365.4	33.5	0.1366
29	0.0133	0.0045	5.56	0.1278	0.0107	520.20	58.9	332.1	92.8	365.9	33.9	0.1352
30	0.0133	0.0045	5.56	0.1278	0.0107	520.20	59.1	332.3	92.8	365.9	33.7	0.1360

Table 35. 30-Minute Experiments: 70% Putty with 30% AlN - Summary of Data

Time (mins.)	R2 (m)	R1 (m)	Power (W)	Length (m)	Area (m^2)	Heat Flux (W/m^2)	T2 (ºC)	T2(K)	T1 (ºC)	T1 (K)	DeltaT (K)	K (W/m*K)
0	0.0133	0.0045	5.56	0.1278	0.0107	520.20	29.5	302.7	27.8	300.9	-1.7	-2.6596
1	0.0133	0.0045	5.56	0.1278	0.0107	520.20	30.8	304.0	36.7	309.8	5.9	0.7807
2	0.0133	0.0045	5.56	0.1278	0.0107	520.20	33.3	306.5	41.1	314.3	7.8	0.5864
3	0.0133	0.0045	5.56	0.1278	0.0107	520.20	35.2	308.4	43.9	317.0	8.7	0.5272
4	0.0133	0.0045	5.56	0.1278	0.0107	520.20	37.3	310.5	45.6	318.7	8.3	0.5548
5	0.0133	0.0045	5.56	0.1278	0.0107	520.20	40.4	313.6	47.8	320.9	7.4	0.6208
6	0.0133	0.0045	5.56	0.1278	0.0107	520.20	41.4	314.6	49.4	322.6	8.0	0.5694
7	0.0133	0.0045	5.56	0.1278	0.0107	520.20	42.3	315.5	50.6	323.7	8.3	0.5548
8	0.0133	0.0045	5.56	0.1278	0.0107	520.20	43.3	316.5	51.7	324.8	8.4	0.5475
9	0.0133	0.0045	5.56	0.1278	0.0107	520.20	44.2	317.4	53.3	326.5	9.1	0.5015
10	0.0133	0.0045	5.56	0.1278	0.0107	520.20	45.2	318.4	54.4	327.6	9.2	0.4955
11	0.0133	0.0045	5.56	0.1278	0.0107	520.20	46.8	320.0	55.6	328.7	8.8	0.5231
12	0.0133	0.0045	5.56	0.1278	0.0107	520.20	48.0	321.2	56.7	329.8	8.7	0.5285
13	0.0133	0.0045	5.56	0.1278	0.0107	520.20	48.6	321.8	57.2	330.4	8.6	0.5312
14	0.0133	0.0045	5.56	0.1278	0.0107	520.20	49.2	322.4	58.3	331.5	9.1	0.5015
15	0.0133	0.0045	5.56	0.1278	0.0107	520.20	50.0	323.2	58.9	332.0	8.9	0.5153
16	0.0133	0.0045	5.56	0.1278	0.0107	520.20	51.4	324.6	60.0	333.2	8.6	0.5326
17	0.0133	0.0045	5.56	0.1278	0.0107	520.20	51.9	325.1	60.6	333.7	8.7	0.5292
18	0.0133	0.0045	5.56	0.1278	0.0107	520.20	52.3	325.5	61.1	334.3	8.8	0.5198
19	0.0133	0.0045	5.56	0.1278	0.0107	520.20	52.5	325.7	61.7	334.8	9.2	0.4997
20	0.0133	0.0045	5.56	0.1278	0.0107	520.20	52.7	325.9	62.2	335.4	9.5	0.4810
21	0.0133	0.0045	5.56	0.1278	0.0107	520.20	53.1	326.3	62.8	335.9	9.7	0.4733
22	0.0133	0.0045	5.56	0.1278	0.0107	520.20	54.2	327.4	63.3	336.5	9.1	0.5015
23	0.0133	0.0045	5.56	0.1278	0.0107	520.20	54.9	328.1	63.9	337.0	9.0	0.5096
24	0.0133	0.0045	5.56	0.1278	0.0107	520.20	55.1	328.3	64.4	337.6	9.3	0.4902
25	0.0133	0.0045	5.56	0.1278	0.0107	520.20	55.3	328.5	64.4	337.6	9.1	0.5009
26	0.0133	0.0045	5.56	0.1278	0.0107	520.20	55.7	328.9	65.0	338.2	9.3	0.4925
27	0.0133	0.0045	5.56	0.1278	0.0107	520.20	56.5	329.7	65.6	338.7	9.1	0.5058
28	0.0133	0.0045	5.56	0.1278	0.0107	520.20	56.8	330.0	65.6	338.7	8.8	0.5231
29	0.0133	0.0045	5.56	0.1278	0.0107	520.20	56.8	330.0	66.1	339.3	9.3	0.4919
30	0.0133	0.0045	5.56	0.1278	0.0107	520.20	56.8	330.0	66.1	339.3	9.3	0.4919

Table 36. 30-Minute Experiments: 60% Putty with 40% AlN - Summary of Data

Time (mins.)	R2 (m)	R1 (m)	Power (W)	Length (m)	Area (m^2)	Heat Flux (W/m^2)	T2 (°C)	T2 (K)	T1 (°C)	T1 (K)	DeltaT (K)	K (W/m*K)
0	0.0133	0.0045	5.56	0.1278	0.0107	520.20	29.3	302.5	28.3	301.5	-1.0	-4.7383
1	0.0133	0.0045	5.56	0.1278	0.0107	520.20	30.8	304.0	44.4	317.6	13.6	0.3357
2	0.0133	0.0045	5.56	0.1278	0.0107	520.20	33	306.2	53.3	326.5	20.3	0.2253
3	0.0133	0.0045	5.56	0.1278	0.0107	520.20	35.1	308.3	57.8	330.9	22.7	0.2020
4	0.0133	0.0045	5.56	0.1278	0.0107	520.20	37.5	310.7	60.6	333.7	23.1	0.1987
5	0.0133	0.0045	5.56	0.1278	0.0107	520.20	40.4	313.6	63.3	336.5	22.9	0.1997
6	0.0133	0.0045	5.56	0.1278	0.0107	520.20	41.6	314.8	65.6	338.7	24.0	0.1912
7	0.0133	0.0045	5.56	0.1278	0.0107	520.20	42.8	316.0	67.2	340.4	24.4	0.1875
8	0.0133	0.0045	5.56	0.1278	0.0107	520.20	43.8	317.0	68.9	342.0	25.1	0.1826
9	0.0133	0.0045	5.56	0.1278	0.0107	520.20	44.8	318.0	70.0	343.2	25.2	0.1818
10	0.0133	0.0045	5.56	0.1278	0.0107	520.20	46.2	319.4	71.1	344.3	24.9	0.1839
11	0.0133	0.0045	5.56	0.1278	0.0107	520.20	47.1	320.3	72.8	345.9	25.7	0.1784
12	0.0133	0.0045	5.56	0.1278	0.0107	520.20	48.0	321.2	73.9	347.0	25.9	0.1769
13	0.0133	0.0045	5.56	0.1278	0.0107	520.20	49.1	322.3	74.4	347.6	25.3	0.1807
14	0.0133	0.0045	5.56	0.1278	0.0107	520.20	51.3	324.5	75.6	348.7	24.3	0.1888
15	0.0133	0.0045	5.56	0.1278	0.0107	520.20	51.4	324.6	76.7	349.8	25.3	0.1813
16	0.0133	0.0045	5.56	0.1278	0.0107	520.20	51.8	325.0	77.2	350.4	25.4	0.1802
17	0.0133	0.0045	5.56	0.1278	0.0107	520.20	52.4	325.6	78.3	351.5	25.9	0.1766
18	0.0133	0.0045	5.56	0.1278	0.0107	520.20	52.5	325.7	78.9	352.0	26.4	0.1736
19	0.0133	0.0045	5.56	0.1278	0.0107	520.20	52.6	325.8	79.4	352.6	26.8	0.1706
20	0.0133	0.0045	5.56	0.1278	0.0107	520.20	52.8	326.0	80.0	353.2	27.2	0.1684
21	0.0133	0.0045	5.56	0.1278	0.0107	520.20	54.3	327.5	80.6	353.7	26.3	0.1745
22	0.0133	0.0045	5.56	0.1278	0.0107	520.20	54.7	327.9	81.1	354.3	26.4	0.1734
23	0.0133	0.0045	5.56	0.1278	0.0107	520.20	55.1	328.3	81.7	354.8	26.6	0.1724
24	0.0133	0.0045	5.56	0.1278	0.0107	520.20	55.4	328.6	82.2	355.4	26.8	0.1708
25	0.0133	0.0045	5.56	0.1278	0.0107	520.20	56.1	329.3	82.2	355.4	26.1	0.1753
26	0.0133	0.0045	5.56	0.1278	0.0107	520.20	56.4	329.6	82.8	355.9	26.4	0.1736
27	0.0133	0.0045	5.56	0.1278	0.0107	520.20	56.6	329.8	83.3	356.5	26.7	0.1713
28	0.0133	0.0045	5.56	0.1278	0.0107	520.20	56.8	330.0	83.3	356.5	26.5	0.1726
29	0.0133	0.0045	5.56	0.1278	0.0107	520.20	56.8	330.0	83.9	357.0	27.1	0.1691
30	0.0133	0.0045	5.56	0.1278	0.0107	520.20	56.9	330.1	83.9	357.0	27.0	0.1697

Table 37. 30-Minute Experiments: 105g AlN with 50ml Silicone Oil - Summary of Data

Time (mins.)	R2 (m)	R1 (m)	Power (W)	Length (m)	Area (m^2)	Heat Flux (W/m^2)	T2 (°C)	T2 (K)	T1 (°C)	T1(K)	DeltaT (K)	K (W/m*K)
0	0.0133	0.0045	5.62	0.1278	0.0107	525.72	28.7	301.9	27.8	300.9	-0.9	-5.0193
1	0.0133	0.0045	5.62	0.1278	0.0107	525.72	30.9	304.1	36.7	309.8	5.8	0.8027
2	0.0133	0.0045	5.62	0.1278	0.0107	525.72	34.7	307.9	41.1	314.3	6.4	0.7220
3	0.0133	0.0045	5.62	0.1278	0.0107	525.72	36.0	309.2	43.9	317.0	7.9	0.5868
4	0.0133	0.0045	5.62	0.1278	0.0107	525.72	38.4	311.6	46.7	319.8	8.3	0.5600
5	0.0133	0.0045	5.62	0.1278	0.0107	525.72	39.7	312.9	48.3	321.5	8.6	0.5362
6	0.0133	0.0045	5.62	0.1278	0.0107	525.72	41.3	314.5	50.6	323.7	9.3	0.5001
7	0.0133	0.0045	5.62	0.1278	0.0107	525.72	42.6	315.8	52.2	325.4	9.6	0.4811
8	0.0133	0.0045	5.62	0.1278	0.0107	525.72	43.4	316.6	53.9	327.0	10.5	0.4413
9	0.0133	0.0045	5.62	0.1278	0.0107	525.72	45.1	318.3	55.0	328.2	9.9	0.4676
10	0.0133	0.0045	5.62	0.1278	0.0107	525.72	46.4	319.6	56.7	329.8	10.3	0.4509
11	0.0133	0.0045	5.62	0.1278	0.0107	525.72	47.3	320.5	57.8	330.9	10.5	0.4418
12	0.0133	0.0045	5.62	0.1278	0.0107	525.72	48.1	321.3	58.9	332.0	10.8	0.4290
13	0.0133	0.0045	5.62	0.1278	0.0107	525.72	49.0	322.2	60.0	333.2	11.0	0.4208
14	0.0133	0.0045	5.62	0.1278	0.0107	525.72	49.5	322.7	60.6	333.7	11.1	0.4187
15	0.0133	0.0045	5.62	0.1278	0.0107	525.72	50.2	323.4	61.7	334.8	11.5	0.4037
16	0.0133	0.0045	5.62	0.1278	0.0107	525.72	50.9	324.1	62.2	335.4	11.3	0.4088
17	0.0133	0.0045	5.62	0.1278	0.0107	525.72	51.2	324.4	62.8	335.9	11.6	0.3998
18	0.0133	0.0045	5.62	0.1278	0.0107	525.72	51.7	324.9	63.3	336.5	11.6	0.3979
19	0.0133	0.0045	5.62	0.1278	0.0107	525.72	52.4	325.6	64.4	337.6	12.0	0.3843
20	0.0133	0.0045	5.62	0.1278	0.0107	525.72	53.2	326.4	64.4	337.6	11.2	0.4117
21	0.0133	0.0045	5.62	0.1278	0.0107	525.72	53.3	326.5	65.0	338.2	11.7	0.3956
22	0.0133	0.0045	5.62	0.1278	0.0107	525.72	53.6	326.8	65.6	338.7	12.0	0.3872
23	0.0133	0.0045	5.62	0.1278	0.0107	525.72	53.8	327.0	66.1	339.3	12.3	0.3760
24	0.0133	0.0045	5.62	0.1278	0.0107	525.72	54.3	327.5	66.7	339.8	12.4	0.3743
25	0.0133	0.0045	5.62	0.1278	0.0107	525.72	54.6	327.8	66.7	339.8	12.1	0.3836
26	0.0133	0.0045	5.62	0.1278	0.0107	525.72	55.1	328.3	67.2	340.4	12.1	0.3819
27	0.0133	0.0045	5.62	0.1278	0.0107	525.72	55.3	328.5	67.8	340.9	12.5	0.3710
28	0.0133	0.0045	5.62	0.1278	0.0107	525.72	55.8	329.0	67.8	340.9	12.0	0.3865
29	0.0133	0.0045	5.62	0.1278	0.0107	525.72	55.9	329.1	68.3	341.5	12.4	0.3723
30	0.0133	0.0045	5.62	0.1278	0.0107	525.72	56.2	329.4	68.3	341.5	12.1	0.3815

Table 38. 30-Minute Experiments: 105g AlN with 30ml Silicone Oil - Summary of Data

Time (mins.)	R2 (m)	R1 (m)	Power (W)	Length (m)	Area (m^2)	Heat Flux (W/m^2)	T2 (ºC)	T2 (K)	T1 (ºC)	T1 (K)	DeltaT (K)	K (W/m*K)
0	0.0133	0.0045	5.62	0.1278	0.0107	525.72	27.2	300.4	26.7	299.8	-0.5	-8.6793
1	0.0133	0.0045	5.62	0.1278	0.0107	525.72	28.4	301.6	37.2	310.4	8.8	0.5247
2	0.0133	0.0045	5.62	0.1278	0.0107	525.72	31.3	304.5	43.9	317.0	12.6	0.3677
3	0.0133	0.0045	5.62	0.1278	0.0107	525.72	33.3	306.5	47.8	320.9	14.5	0.3197
4	0.0133	0.0045	5.62	0.1278	0.0107	525.72	35.8	309.0	51.1	324.3	15.3	0.3023
5	0.0133	0.0045	5.62	0.1278	0.0107	525.72	37.5	310.7	53.9	327.0	16.4	0.2824
6	0.0133	0.0045	5.62	0.1278	0.0107	525.72	39.9	313.1	56.7	329.8	16.8	0.2761
7	0.0133	0.0045	5.62	0.1278	0.0107	525.72	41.8	315.0	58.9	332.0	17.1	0.2709
8	0.0133	0.0045	5.62	0.1278	0.0107	525.72	43.0	316.2	60.6	333.7	17.6	0.2637
9	0.0133	0.0045	5.62	0.1278	0.0107	525.72	44.1	317.3	62.2	335.4	18.1	0.2554
10	0.0133	0.0045	5.62	0.1278	0.0107	525.72	45.1	318.3	63.9	337.0	18.8	0.2464
11	0.0133	0.0045	5.62	0.1278	0.0107	525.72	46.0	319.2	65.0	338.2	19.0	0.2436
12	0.0133	0.0045	5.62	0.1278	0.0107	525.72	47.5	320.7	66.1	339.3	18.6	0.2487
13	0.0133	0.0045	5.62	0.1278	0.0107	525.72	48.3	321.5	67.2	340.4	18.9	0.2446
14	0.0133	0.0045	5.62	0.1278	0.0107	525.72	48.9	322.1	68.3	341.5	19.4	0.2382
15	0.0133	0.0045	5.62	0.1278	0.0107	525.72	49.6	322.8	69.4	342.6	19.8	0.2333
16	0.0133	0.0045	5.62	0.1278	0.0107	525.72	50.9	324.1	70.0	343.2	19.1	0.2424
17	0.0133	0.0045	5.62	0.1278	0.0107	525.72	51.6	324.8	70.6	343.7	19.0	0.2442
18	0.0133	0.0045	5.62	0.1278	0.0107	525.72	51.9	325.1	71.1	344.3	19.2	0.2410
19	0.0133	0.0045	5.62	0.1278	0.0107	525.72	52.4	325.6	72.2	345.4	19.8	0.2335
20	0.0133	0.0045	5.62	0.1278	0.0107	525.72	52.7	325.9	72.2	345.4	19.5	0.2371
21	0.0133	0.0045	5.62	0.1278	0.0107	525.72	52.8	326.0	72.8	345.9	20.0	0.2317
22	0.0133	0.0045	5.62	0.1278	0.0107	525.72	52.8	326.0	73.3	346.5	20.5	0.2254
23	0.0133	0.0045	5.62	0.1278	0.0107	525.72	54.1	327.3	73.9	347.0	19.8	0.2339
24	0.0133	0.0045	5.62	0.1278	0.0107	525.72	54.4	327.6	74.4	347.6	20.0	0.2309
25	0.0133	0.0045	5.62	0.1278	0.0107	525.72	54.7	327.9	74.4	347.6	19.7	0.2344
26	0.0133	0.0045	5.62	0.1278	0.0107	525.72	54.7	327.9	74.4	347.6	19.7	0.2344
27	0.0133	0.0045	5.62	0.1278	0.0107	525.72	54.9	328.1	75.0	348.2	20.1	0.2303
28	0.0133	0.0045	5.62	0.1278	0.0107	525.72	55.8	329.0	75.6	348.7	19.8	0.2343
29	0.0133	0.0045	5.62	0.1278	0.0107	525.72	55.8	329.0	75.6	348.7	19.8	0.2343
30	0.0133	0.0045	5.62	0.1278	0.0107	525.72	55.8	329.0	75.6	348.7	19.8	0.2343

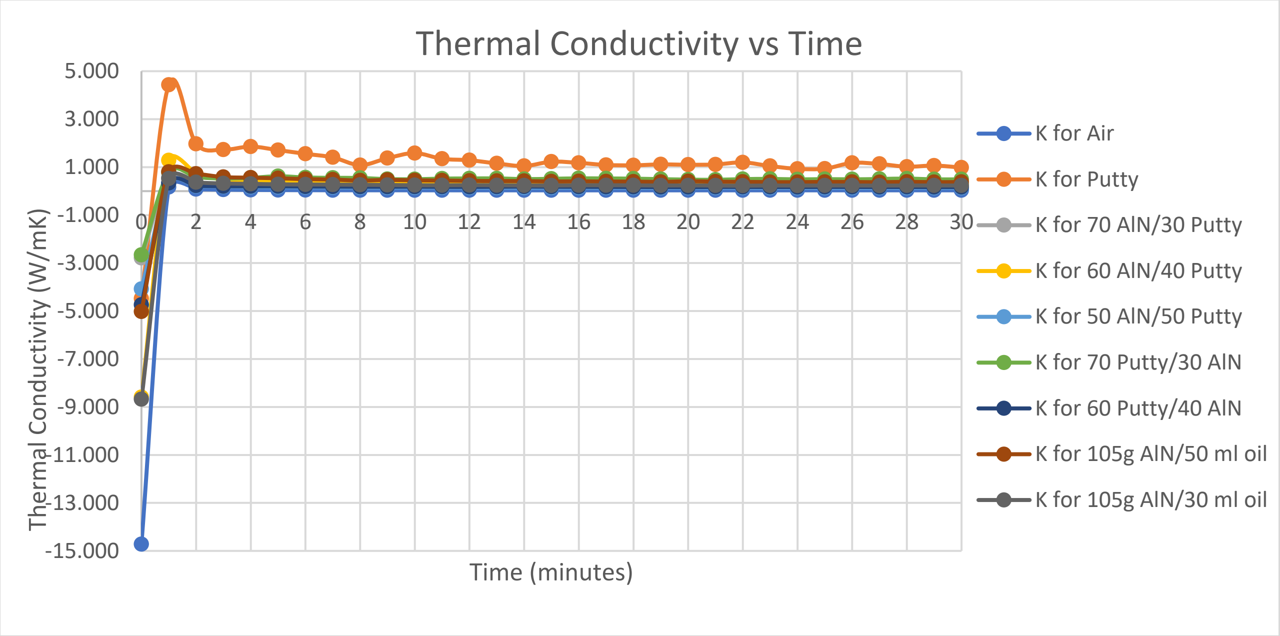

Figure 16. Thermal Conductivity vs Time Plot for the 30-Minute Experiments

Fig. 16 illustrates the plot for the thermal conductivity versus time from 0 to 30 minutes. From that plot, it can be observed that the value for the thermal conductivity in each experimental material is negative for the initial time which does not make sense since it is impossible for a material to have a negative thermal conductivity. However, the thermal conductivities obtained from 3 to 30 minutes converge to steady-state values demonstrating that this time duration should produce correct results.

Table 39. Average of the Thermal Conductivities Obtained from 3-30 Minutes

Potting Material	Average Thermal Conductivity, K (W/mK)
Air	0.0367
Putty	1.2331
70 AlN/30 Putty	0.2081
60 AlN/40 Putty	0.3350
50 AlN/50 Putty	0.1445
70 Putty/30 AlN	0.5184
60 Putty/40 AlN	0.1795
105g AlN/50 ml oil	0.4268
105g AlN/30 ml oil	0.2481

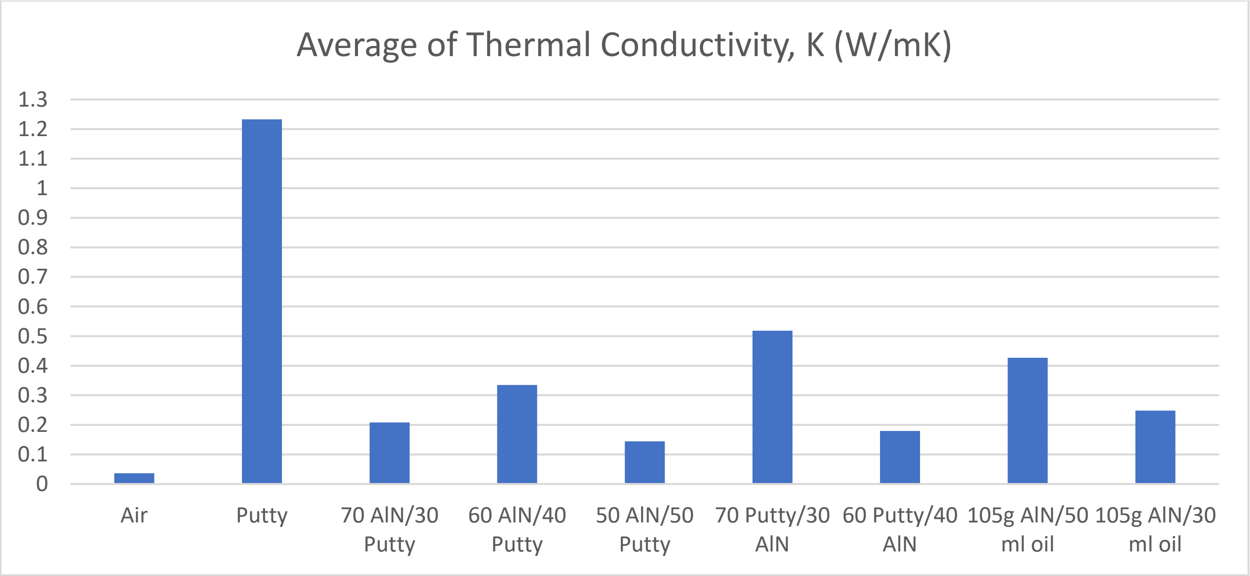

Figure 17. Conclusive Values for K

III.2.3 Comparison of the Results

A 2.7-Ω load resistor was used in the first round of experiments up to 15 minutes while a 20-Ω resistor was used in the second round of experiments up to 30 minutes with a power rating of approximately 15 W. The reason behind the change of resistor is that if the resistor of 2.7 Ω would have been used for a longer time (i.e., 30 minutes), it would cause thermal run away; in other words, the resistor would burn out because it would approach the thermal limit of the resistor. Therefore, another resistor with more resistance and power rating was used for the experiments of longer time. The power applied to the system was almost conserved so that it would not affect the comparison between the experiments. Another difference in the resistors is their radius. One is 0.0049 m and the other is 0.0045 m for the 15 and 30 minutes, respectively. The purpose to make a second round of experiments was because the 15-minute time was not suitable as some errors are obtained and a steady-state temperature is never reached. Hence, the time was doubled to 30 minutes to determine good thermal conductivity results.

The two plots for the internal and external temperatures as well as the DeltaT over time plot up to 15 minutes (i.e., Figs. 9 through 11) show that the curve is still increasing and never reach a steady-state. Therefore, an analysis cannot be drawn from those plots. However, the two plots for the internal and external temperatures and the DeltaT plot up 30 minutes (i.e., Figs. 13 through 15) show that the curve is approximating a steady-state. Hence, the influence of the time does determine the steady-state temperature and good results.

The calculated thermal conductivities for all 9 cases in the first round of experiments show that there are some distortions for some values. The thermal conductivities of the 15-minute experiment results are incorrect due to negative values being obtained. This suggests that the temperature outside of the can (i.e., external temperature) was not taken properly. On the other hand, the calculated thermal conductivities for all 9 cases in the second round of experiments show that the values reach almost a constant value taking into account that the thermal conductivity value for the initial time is ignored for all the cases as the value is negative.

Table 40. Steady-State Values of the Thermal Conductivities at 15 and 30 Minutes

Experimental Cases	Thermal Conductivity Average, K (W/mK)	
	at 15 minutes	Average from 3-30 minutes
Air	0.0387	0.0367
Putty	2.5035	1.2331
70 AlN/30 Putty	0.1853	0.2081
60 AlN/40 Putty	0.1136	0.3350
50 AlN/50 Putty	0.0728	0.1445
70 Putty/30 AlN	0.0926	0.5184
60 Putty/40 AlN	0.1564	0.1795
105g AlN/50 ml oil	0.2905	0.4268
105g AlN/30 ml oil	15.6565	0.2481

The “more -accurate” results of the thermal conductivities are the ones calculated at 15 and 30 minutes, respectively. However, for the “30-minute” values, an average from 3-30 minutes is taken for all the cases. Table 39 presents those steady-state values of the thermal conductivities for each conducted experimental cases. The “30-minute” experiments resulted in a better time-frame to determine steady-state values as presented in Figs. 13 through 15. Therefore, the average of the thermal conductivities calculated from 0 to 30 minutes will be taken as exact values and the thermal conductivities calculated at 15 minutes will be the approximate values in order to calculate the “percentage error”, which is all about comparing an estimate to an exact value as a percentage of the exact value. It should be emphasized that these percentage errors might be high since there were distortions in the “approximate” values.

"Percentage Error Equation":

$$\frac{|\text{Approximate Value} - \text{Exact Value}|}{|\text{Exact Value}|} \times 100\% \qquad (2)$$

Percentage Error for K of air:

$$\frac{|0.0387\ \text{W/mK} - 0.0367\ \text{W/mK}|}{|0.0367\ \text{W/mK}|} \times 100\% = 5.45\ \%$$

Percentage Error for K of putty:

$$\frac{|2.5035\ \text{W/mK} - 1.2331\ \text{W/mK}|}{|1.2331\ \text{W/mK}|} \times 100\% = 103.02\ \%$$

Percentage Error for K of 70 AlN/30 putty:

$$\frac{|0.1853 \text{ W/mK} - 0.2081 \text{ W/mK}|}{|0.2081 \text{ W/mK}|} \times 100\% = 10.96\ \%$$

Percentage Error for K of 60 AlN/40 putty:

$$\frac{|0.1136 \text{ W/mK} - 0.3350 \text{ W/mK}|}{|0.3350 \text{ W/mK}|} \times 100\% = 66.09\ \%$$

Percentage Error for K of 50 AlN/50 putty:

$$\frac{|0.0728 \text{ W/mK} - 0.1445 \text{ W/mK}|}{|0.1445 \text{ W/mK}|} \times 100\% = 49.62\ \%$$

Percentage Error for K of 70 putty/30 AlN:

$$\frac{|0.0926 \text{ W/mK} - 0.5184 \text{ W/mK}|}{|0.5184 \text{ W/mK}|} \times 100\% = 82.14\ \%$$

Percentage Error for K of 60 putty/40 AlN:

$$\frac{|0.1564 \text{ W/mK} - 0.1795 \text{ W/mK}|}{|0.1795 \text{ W/mK}|} \times 100\% = 12.87\ \%$$

Percentage Error for K of 105g AlN/50ml oil:

$$\frac{|0.2905 \text{ W/mK} - 0.4268 \text{ W/mK}|}{|0.4268 \text{ W/mK}|} \times 100\% = 31.94\ \%$$

Percentage Error for K of 105g AlN/30ml oil:

$$\frac{|15.6565 \text{ W/mK} - 0.2481 \text{ W/mK}|}{|0.2481 \text{ W/mK}|} \times 100\% = 6210.56\ \%$$

The largest thermal conductivity percentage error was 6210.56 % for 105g AlN/30 ml oil while the smallest percentage error was 5.45 % for air. The errors in the experiments can be classified as systematic errors because these kinds of errors are reproducible inaccuracies that are consistently in the same direction and can be eliminated. Overall, the differences between those steady-state values presented in Table 39 are large because of the above mentioned errors.

III.2.4 Experimental Conclusions

One objective in calculating the thermal conductivity is to determine the duration of the various experiments since they are time-consuming. Thus, the 15-minute experiment was run and after the analysis, some obvious errors are obtained. As a result, the time of the experiment is doubled and the results are evaluated again giving good results. Systematic errors might be of 4 kinds: instrumental, observational, environmental, and theoretical. One environmental with instrumental error could have been the external temperature readings during the experiments since the room temperature could have been altered because of people walking around the work station, doing other tests, and soldering in the same lab room. Therefore, the thermal conductivity values are deviated because the external temperatures were not taken properly and affected them resulting in negative thermal conductivity values which is impossible because a material can never have a negative thermal conductivity. Another potential reason for deviation in the thermal conductivity values might have been that the thermocouple was not being firmly placed on the resistor or weighting of the materials on the digital scale was not exact. These errors are considered to be instrumental and observational.

A conclusion from the experiments is that the time duration is important to get very good results and the 30-minute experiments resulted as the best approach to remove heat from potted inductors. Proper thermal management is fundamental for developing power electronics where volume reduction is involved, and that allows higher power density. Using the potting compounds for fast removal of the heat produced within inductors used in DC-DC converters for up to 30 minutes has demonstrated reductions in both maximum temperature rise and the time to reach a stable temperature, giving efficiency improvements, and thus enabling high-performance power electronics.

The average thermal conductivity for 100% putty was calculated to be 1.2331 W/mK. However, the quoted K for this material is 10 W/mK. The reason why the obtained value is very small is because the material itself has a very large thermal conductivity (i.e., 10 W/mK), but the material is not viscous at about 10,000,000 cps. Hence, when trying to put it into an enclosure, it cannot be guaranteed that all of the material is uniformly compacted such that all particles are touching each other and all air is expelled. Thus, manufacturers do not like potted inductors because of the air pockets formed in the putty compound which bring problems. Those are the disadvantages of using such a material.

In addition, the intrinsic value of K for AlN is 150 W/mK, but the mixtures with this material are under 1.0 W/mK. The reasons why the ratio of AlN varies in the experiments are because of three problems that need to be addressed regarding such a brittle material: decrease the viscosity of potting material, synthesize high thermal conductivity, and final material should not be brittle in order to withstand operating conditions, so by varying the ratio of AlN, the best solution can be synthesized. However, due to the low tessellation factor of the silicon oil/epoxy with AlN, heat is not transferred as easily across planes versus if a uniform AlN block was analyzed. A similar case is presented in a Conference Paper where AlN was added to resin in which similar results were obtained. Although the thermal conductivity of the resin was improved on the order of several magnitudes, the overall thermal conductivity is low as compared to the AlN [10]. Adding fillers to carrier fluid is a common practice in industry to improve thermal conductivity. However, it becomes a balancing act for all 3 considerations above.

IV. Conclusions and Future Work

IV.1 Thesis Summary

Through this thesis, a transient method called the "hot-wire" method was utilized to evaluate the thermal conductivity of specific thermally conductive potting materials such as AlN, putty, and silicone oil in order to enable volume reduction of inductors and thus increase the power density of converters. Chapter I presented the background and motivation for this thesis. In Chapter II, the thermal management formulation and the theory behind the "hot-wire" method were detailed. Finally, in Chapter III, the experimental results for both rounds of experiments, up to 15 and 30 minutes, respectively were presented, compared, and discussed. It can be concluded that the results obtained for the thermal conductivities using potting materials from the second round of experiments (i.e., up to 30 minutes) were good enough to show reductions in the temperature rise and time to reach a stable temperature.

IV.2 Future Work

Continuing with other different material testings will allow a better picture of the results. There are numerous thermal conductive potting compounds that can be tested to obtain a better volume reduction of inductors and an increase in power density. Thus, further tests should be performed to improve the efficiency and performance of power electronics.

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