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Matthew Schrenk
Central Washington University, schrenkma@cwu.edu

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By

Matthew Schrenk

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Currently, there are several ways in which thermal conductivity can be calculated or assessed on a given material. However, with each method of testing comes potential limitations such as size, material state, complexity, and time. The goal of this study was to develop a pulse heated thermistor that would reduce all four limitations, thus provide precise and timely results regardless of the material state and size. A thermistor is resistor which changes resistance in accordance to temperature. To achieve the design, heat transfer and electrical methods were applied. As with all resistors, heat is dissipated across the element and released into the surrounding environment. With this idea, the thermistor can be introduced with a large voltage, causing its resistive element to overheat and thus reduce its resistance. To manufacture such a device insulative material was added to prevent heat dissipation in the wrong direction. To achieve precise results, test specimens were required to be prepared to reduce the effects of ambient convective heat transfer. Measurement times after pulse were shown to have best results after seven seconds due to the thermistor achieving a steady decay of temperature back to equilibrium. Water was observed to have a thermal conductivity value of 0.613 W/m-K, within 5% of its accepted value. The results were obtained within five minutes, exceeding the fifteen-minute requirement. With the results obtained, it is conclusive that the device is functional and precise.

Keywords: <Thermistor>, <Conductivity>, <Pulse-Decay>

Contents

1. INTRODUCTION

a. Description

There currently exists a need for sensors and probes that accurately reports on the thermal conductivity of a material. Functionally, there are devices that preform this task however, they are less accurate and cannot be used on certain materials. Also, devices that report on thermal conductivity of bulk materials are few and far between. The devices that do exist require smaller amounts of substance to report on thermal conductivity.

b. Motivation

This project is motivated by the need for a device that is lightweight and can provide accurate temperature readings on all materials such as solids and liquids. There is a need for testing in more accessible sites that are not contained into a lab for testing. The intent of this device is to allow anyone to use it in a straightforward non-intrusive way and can be used in multiple settings. The device should be easily repaired by hand without the need to ship it back to a company and therefore uses easily obtainable and swappable parts.

c. Function Statement

The function of the device is to report on the thermal conductivity of any given material. The device measures the changes of temperature decaying over time to provide analog data to calculate thermal conductivity of bulk materials.

d. Requirements

The device has a handful of criteria that it must make in order to be functionally applicable device. The design is meant to have ease of access and portability for the user. The following requirements must be made to achieve this goal:

- The device must be under 20 pounds
- The circuitry used must be placed in a 18” × 13” × 10” box.
- The measuring probe will be easily located and replaceable, with spare probes located in a compartment in the box for ease of access.
- The power supply will be easily found and handled and must use AC 120V 60Hz outlets.
- The probe design must report directly or give enough information to calculate the thermal conductivity of a given material with 5% tolerance to known literature values.
- The probe must also provide information in under 15 minutes.
- Probe that houses thermistor must optimize surface area of the thermistor.

e. Engineering Merit

The design will functionally report accurate measurements in order to calculate the thermal conductivity of a given material. This means that there will be less room for error in calculations, providing real time insight into materials and their properties. The device will utilize electrical engineering aspects in circuit design. The thermistor probe will utilize static design elements for analysis of failure, and mechanical design parameters will be used for the success of the probes. Finally, heat transfer elements are utilized in the calculations of thermal conductivity as well as insulation used in the thermistor probe housing.

f. Scope of Effort

The device will only report on thermal conductivity and temperature.

g. Success Criteria

Success of the design depends upon the accuracy, precision, and accessibility of the probe and shape of the device. The probe will be successful if it meets the requirements listed in section "d."

2. DESIGN & ANALYSIS

a. Approach: Proposed Solution

The solution to the problem is to minimize circuitry and optimize circuitry. The housing of the circuitry is designed to be lightweight and easily accessible for repairs. The probe is designed to minimize interference of temperatures by insulating it with epoxy resin as well as protect the circuit from materials which may damage the circuit. The circuit itself is designed to be simple, outputting analog data for calculations. Housing the circuit is a simple box frame, providing modularity and mobility.

b. Design Description

The Pulse Decay thermistor is a thermistor connected to a power supply that delivers a set DC voltage to the circuit. The circuit is a Wheatstone bridge with a separated circuit delivering a heating voltage for 3 seconds and a measurement voltage for 20 seconds. The time is operated by a programmable relay switch.

As the thermistor experiences a self-heating scenario, it dissipates heat to the surrounding area. The design is intended to record this heat dissipation as a temperature with a function of time, and use the variables given to provide enough information to produce a resulting conductance value of a given material.

Collecting the data is an Arduino Uno R3 board which outputs the data for the reader to an LCD screen. Optionally, the Arduino can output the data to a computer with Arduino software.

c. Benchmark

There exist three benchmarks similar in design. One by *Ronald T. Atkins and Edmund A. Wright* which utilizes a heater current and a simple design. They were able to present data within 10% accuracy in some cases, but they needed an ample temperature difference of five degrees Celsius or more in some cases. Likewise, their probe required proper connection with the material that was being tested. The other benchmark is from *Nachiket M Kharalkar, et al*. Their design used complicated circuitry with analog data acquisition from LabView products. It proved to be highly reliable and produced results with experimental averages having a 5% or less error. Lastly, the other benchmark is from *Chen et al.* which delivered results within 2% of known values.

d. Performance Predictions

The design will produce a result within 5% tolerance of known conductance values. By the requirements, the probe will produce values for the given materials at +/- 5%:

- Water, 25 degrees Celsius: k = 0.607 Watts/meter-Kelvin
- Water, 0 degrees Celsius k = 0.561 Watts/meter-Kelvin
- Granny Smith Apple, 25 degrees Celsius: k = ???

The time to read such measurements will be around 15 to 20 seconds, corresponding with around a three second pulse and a 15 to 17 second measurement time, where time is recorded.

After measurements have been take, two more trials will take place. The thermistor must rest for a couple of minutes to reach an equilibrium. Overall time to finish trials will be around 12 minutes, giving three to four minutes of rest between trials.

e. Description of Analysis

Analysis one utilizes given inputs of analog data to be computed. The inputs were optimized to work with circuit components to provide a given output. The outputs designated in analysis one, located in Appendix A-1, were then used to finish other analyses. The power output at a given voltage is in Appendix A-1 and was used to calculate a radius of thermal insulating epoxy resin. While the radius is small, the calculation was necessary to reduce the error of interference in data collection, resulting in an error. In other analyses, weight was calculated in the housing of the device, in order to understand that the device will meet the weight and dimension requirements. To understand the issues which would result in inaccurate values, noise and tolerance levels of the circuitry was evaluated.

A separate FEA Analysis was conducted for the Pulse Decay Thermistor. The values are as expected and can be referenced in Appendix I. The purpose of this analysis was to utilize the heat generation of the thermistor in a basic material like water. The analysis shows that the bead heats up to a point in equilibrium, tapering off to steady state at a given time. Thus from the analysis, the thermistor will heat up the area around it, and the governing equations are applicable to this device.

f. Scope of Testing and Evaluation

The scope of testing is to ensure that the thermistor provides a precise decay of temperature in the medium it is testing. The precision must be within 5% of known literature values and the accuracy will be tested with multiple trials of the same material. As such, the evaluation will be determined on a pass/fail basis, with the resulting conductance values being averaged together and compared to known literature values. If the values are within a 5% tolerance, the test is considered a success and the device passes.

g. Analysis.

i. Analysis 1

As part of the design, a thermistor is placed in a heating mode to release a pulse of heat across it. The design must work without the thermistor failing under certain loads. First, the voltage source has a ripple or noise of 20mV which must be incorporated to the design. The calculations performed in the analysis were electricity functions and laws. Since the thermistor is a reactive resistor, the temperature of 25 degrees Celsius was assumed. This gave the nominal resistance from the data sheet. A design parameter around this resistance was incorporated to test the thermistor for failure. It succeeded in accordance to the data sheet provided by the manufacturer along with the testing voltages of 10V. Reference appendix A1 for schematics and mathematics.

ii. Analysis 2

Find and establish a minimum dimension to thermally insulate the thermistor in probe housing. Using resistance values, known thermistor radii, temperatures, and power output calculated in analysis 1, a radius of insulation was 1.22mm. This leaves a difference of 0.02mm outer ring to be filled with insulation in the probe housing.

iii. Analysis 3

Establish a tolerance value of a known material's thermal properties. In Analysis 3, the use of Ohm's law across the thermistor was to establish a power dissipation value. This power dissipation value was used in the Pulse Decay equation provided by Dr. Choi. The resistance of the thermistor at a delta temperature value was iterated using the data sheets on the thermistor and was evaluated at 2404 ohms. Secondly, a time constant after pulsation had ended was calculated using the actual thermal value of 0.607 W/m^2-K and became about 3.18 seconds. The next step was to use this time constant as a value of "t" to obtain an theoretical conductivity value "k" for water at 25 degrees Celsius. The error value was around 1%, which is within the required tolerance values.

iv. Analysis 4

Analysis four was used to determine a failure force for the epoxy resin which acts as an insulating glue for the thermistor. The next step of analysis four was to conclude a purchasing price for the volume of the thermistor housing. The combination of Analysis 2 and 4 resulted in a cylindrical housing for the thermistor which would insulate the thermistor as well as hold it in place for testing to be done on solid materials, as listed in the requirements. The failure force of the epoxy is around 30lbs.

v. Analysis 5

Analysis 5 determined the weight of the circuitry housing. It involved the use of variable densities of Balsa Wood, which is known for being very lightweight. The calculated weight is theoretical, but provides more room for heavier items, which will keep the weight of the entire device under twenty pounds, as per the requirements. The next step in analysis five was to determine the cost of the balsa wood and update the budget.

vi. Analysis 6

Analysis six consisted of determining a tolerance value for AISI 302 Stainless Steel. The theoretical tolerance value should be around 2%.

vii. Analysis 7

Analysis seven regarded breaking down the balance of a bridge in order to keep the bridge balanced. The Omega Thermistor has a nominal resistance of 3,000 ohms at 25 degrees Celsius, thus making the bridge potentiometers resistance 3,000 ohms respectively.

viii. Analysis 8

Analysis Eight broke the bridge circuit apart in order to calculate the power dissipated across the thermistor element. The power across the element is necessary for future calculations.

ix. Analysis 9

Analysis nine involved a reconstruction of mass with areas of the device housing with balsa wood being removed for ease of access to the internal components. This provides a weight savings and gives expected overall mass of the housing.

x. Analysis 10

Analysis ten involved a tolerance understanding of the ambient noise of the AC to DC power supply. The result was negligible with a new peak voltage therefore the error produced in measurement is minimal.

xi. Analysis 11

Analysis eleven involved more weight tolerancing with the cutouts in place as well as adding in the outsourced circuitry parts weights.

xii. Analysis 12

Analysis twelve involved a calculus approach and an understanding of the thermistor's resistance changes. The goal is to understand the temperatures decay with respect to time, and this can be associated with the thermistors resistance as the heating pulse was turned off.

xiii. Analysis 13

A revision on previous analyses were compiled involving the circuit. This analysis was used to provide power rating across the thermistor under pulsing and sensing loads. The power was used to calculate a heat generation per unit volume of the thermistor, and modeled in FEA. The analysis can be referenced in Appendix I, with the green sheet residing in A-13. This in effect revises Analysis one, two, and three.

h. Device: Parts, Shapes, and Conformation

The devices circuitry came into form via the analyses. As the circuit has been given life, the overall design has changed considerably. The most notable change came when the reference of *Chen 1981* was read for edification. The literature described a bridge circuit with a simple configuration. The success of Chen et al. and their device has influenced the progression of this project.

i. Device Assembly

The present circuit is a bridge circuit, which is known in the electrical world as a highly sensitive circuit. This involves four resistors that form a bridge. The bridge contains a thermistor which changes resistance in association to temperature. These changes will provide accurate results across the bridge. Other parts running across the circuitry such as a five-volt battery, a power supply, multimeter, and relay switch. Housing the parts will be a box of Balsa Wood. The device housing is connected via wood screws in some areas, and hinges in others.

j. Technical Risk Analysis

Associated risks the arise during the project consist of the construction and testing phases of the device. During the construction phase, material may be within short order. During the testing phase of the device, some circuitry may result in inaccurate measurements. To mitigate this, several trials per test must be conducted and averaged.

k. Failure Mode Analysis

Failure modes were addressed specifically in part #55-003. The thermistor is only rated for a specific heat dissipation value. As power goes across the thermistor, the resistance will change slightly as all resistors produce heat when under the influence of a current. If the voltage being introduced into the current is greater than the power dissipation value of the thermistor, the thermistor may overheat and fail.

l. Operation Limits and Safety

The most important aspect of the operation limits of the device is to not overload the circuit. The thermistor will fail if induced with too much current, with possibilities of catching on fire. Secondly, avoiding wet and damp areas when working with slightly exposed circuitry. Some minor pinch points are located around the hinges of the housing.

3. METHODS & CONSTRUCTION

a. Methods

The proposed project was provided by Dr. Choi, a professor of Mechanical Engineering and Technology at CWU. The device was analyzed and constructed in an apartment complex with limited access to resources. This is of course because of the COVID-19 epidemic of 2020. Within the constraints of space and proper machinery, the devices parts are to be outsourced to various companies. In this vein, circuitry parts included in Appendix C cannot be machined or manufactured and must be purchased outright. Other parts, however, will be made in house either at CWU or using common everyday house tools. These are outlined in Appendix C, but can be shown in a drawing in Appendix B. Other common parts such as hardware items will be outsourced to local Hardware stores in Ellensburg. Through analytical methods, hardware was chosen to produce a viable device which will provide the user the information adequate enough to understand the conductivity of a bulk material. Designs were made to minimize the effects of human and natural error. These errors are forced convection by ambient air as well as the user of the device not precisely monitoring time. To mitigate the risks of natural error, the probe is housed in insulating material, and the samples to be analyzed must be prepared correctly prior to testing. These are talked about in-depth in the testing section of this report. Secondly, to mitigate human error, automating the data acquisition was chosen without sacrificing portability and a modular design. Open sourced coding via Arduino's software is stored directly onto the chipset and can be used with either a computer or an LCD screen.

Due to the limitations of the manufacturing environment, wood and common wood tools were utilized in the building of this device. Likewise, the use of solder was not used in the building of this device, as it would hinder the ability to swap components out. This allows for quick troubleshooting of the circuit in case of misuse.

Of the components used, manors of safety were utilized in the construction of this device. Due to the use of power tools for the construction of the housing, proper ear and eye protection as well as clamps were used. In the case of the building of the probe, gloves and a mask were used to protect the skin and lungs from the noxious chemicals of epoxy resin.

In an effort to ease the access for future projects pertaining to the same build, the uses of materials were kept as modular as possible. Processes were kept simple for unskilled and novice users to replicate the device for future use. This can be seen from the use of breadboards, Arduinos, wood, and other pre-manufactured or easily manipulated materials.

i. Process Decisions

A handful of decisions had to be made for the parts that will be machined. The first decision had to be made on the material to be used that will house all the circuitry of the device. There are several types of wood that can be used so a decision matrix was implemented based on three criteria: Weight, Cost, and Durability. The winner of the matrix referenced in Appendix F was Balsa Wood, which is known for being incredibly lightweight. This allows a large amount of headway on the 20lb requirement for the circuitry and devices.

Updating a new process decision due to restraints on shipment times. The original source of Balsa wood was no longer needed as new ideas came into fruition. The project had run late on certain aspects and a new decision matrix was devised, located in Appendix F. Outsourcing to a Lumber Store in Ellensburg for the raw material was chosen due to its proximity and time constraints on the project. The items would still retain weight requirements as well as durability. The overall cost of the project has been reduced down, making the device itself under the estimated budget.

The second matrix used was to determine a circuit setup for the analog data acquisition. The circuit configurations were divided into three criteria: Accurate, Sensitive, and Minimalistic. The winner of the decision matrix was the bridge circuit which will provide excellent accuracy and sensitivity as per requirements. The convenience of minimal circuitry than the LabView configuration makes this an excellent choice. In an attempt to automate the analog data, an Arduino Uno was chosen for the code to output analog data can be monitored by either a computer of the user on a given LCD screen. In an effort to minimize the risk of disassembling the device in the event of failure, a modular design has been chosen. This means the circuitry can be removed easily be the user and replaced with a cache of spare components. In the event of a failure of the thermistor, a second probe is included, which can be used immediately.

b. Construction

i. Description

The construction of the device will be completely in-house except for one machined or made part which is 20-001. 20-001 is an ABS plastic print intended to house the thermistor for testing. 20-001 is used in Sub-Assembly “Thermistor Probe” (10-003) before final construction. The Thermistor Probe contains the Thermistor (55-003), which, has it’s leads taped with electrical tape, and Epoxy Resin (55-010) is placed around the thermistor, inside of 20-001. Jumper wires of a long length are connecting the probe assembly to the remainder of the circuitry.

The circuitry will be assembled in 10-002 with jumper wires, breadboards, and electrical tape around the potentiometer. The configuration of which is a Wheatstone bridge with the two 10k ohm resistors (55-005) above the potentiometer (55-004) and thermistor probe (10-003). The power supply and Arduino 5V pin feed power to the circuit. A timing relay which is programmed for 3 seconds on/20 seconds off relay, is connected to the power supply.

Housing the circuitry is a Plywood box (20-002 through 20-007) which is fastened with wood screws (50-001). Two hinges connect the front face of the device, allowing for ease of access. The circuitry (10-002) and 10-003, after being assembled and tested for results, was placed inside of the box assembly and fastened with wood screws. The breadboards (55-009) containing the Wheatstone bridge materials came with tape on the back of it which was fastened in any configuration on the plywood. The power supply is placed between two brackets and fastened with 2 bolts to avoid slippage. The long thermistor probe sub assembly (10-003) was fed through an opening and fastened outside of the box, for ease of access in the event of testing.

ii. Parts

Due to the COVID-19 epidemic of 2020, many parts will be purchased. Likewise, electrical components will be purchased to fit the needs of the device. 20-001, the thermistor probe housing is modeled and is 3-D printed. The device housing made of balsa wood is machined and fitted by hand as well. Fasteners are purchased to hold the device housing and the internal components safely inside. 40% of parts are machined and the remaining is purchased.

Parts 20-002 through 20-007 were purchased locally at Knudson Lumber Co. Through a process decision outlined in Appendix F, AC plywood was chosen as the wood to house the circuitry. The wood was weighed in its panel dimensions of 2ft. x 2ft. x 3/8ths in. and were well under the weight requirement, leaving headroom for the circuitry and bracket components. To process these components, first initial cuts of the panels were done using a jigsaw at the dimensions of the box as per the requirements. Then a secondary cut was performed on the side panels wrapping the box, to account for their 3/8th in. thickness. To cutout the sections which would display various electrical components, a 3/16ths in. drill bit and power drill was used to puncture holes large enough in the wood, so that a jigsaw blade could be fitted. After finishing all the cutouts, sanding with 220 grit sandpaper was used to smooth the surfaces damaged by the jig, as well as break edges.

Part 20-001 was a 3-D printed part, which in association with the process, PVA was applied. In order to remove the PVA, the part was submerged in lukewarm water over the course of 48 hours. The part is inherently small, which means it is fragile to forces such as bending. In an effort to remain safe with the PVA removal, a large time frame was utilized.

The use of Epoxy Resin on the probe in subassembly 10-003 required ample curing time. Scotch Cast Insulating Epoxy is a very fluid material which takes upwards to 12 hours to cure completely. Thus, the entire time to produce the subassembly was completed over the course of three days.

The use of coding is required for the device to function properly. This was done via the Arduino software. The simple code analyzes the voltage of the thermistor and potentiometer elements and computes the value internally for temperature. A reference to this is found in Appendix J.

iii. Manufacturing Issues

Long lead times are being considered for the electrical components. Due to COVID-19, manufacturers are having increased wait times on components to create the electrical equipment. This also trickles down into procurement issues as there is a demand and little supply. To mitigate these problems, the electrical parts will be purchased by November 27th, 2020.

"C" code has been developed which will output analog data for the user to interpret. The thermistor probe housing denoted in drawing 20-001 must be printed with the correct orientation to avoid sagging at the end which the thermistor will be placed.

20-001 was printed and a new design is chosen. Referenced in Appendix B, 20-001 now is a wider based cylinder on the back end, promoting easier resin pouring and a better path for the 3-D printer to follow.

An issue with the circuitry has arisen. The 5 Volt logic of the Arduino R3 is unable to reference a higher voltage, which causes issues in temperature readings. In order to mitigate this, the switch must be placed correctly without drawing current, to overvolt the system, then the Arduino can measure it properly.

Parts 20-002 through 20-007 were cut at an off angle with a jigsaw. This happened because the square that was being used was warped. The problem was mitigated as these were preliminary cuts, but they increased the time it took to finish the parts by several hours.

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iv. Discussion of Assembly

The first sub assembly to be completed will be the thermistor probe housing. This task is the most important to maintaining the strength and integrity of the thermistor prior to testing and calibration during the construction process. The probe sub-assembly will be electrically insulated with a resin compound. This further secures the thermistor to the probe for testing, while mitigating the risks of ambient air which drives forced convection. The leads need not be soldered as the connection with the jumper wires are designed to be unplugged. The second assembly is a circuit compilation, consisting of several electrical components. The power supply will have two outputs, one being a 5V DC supply to an Arduino Uno R3. The leads from the other output will connect to a timer switch which will be triggered for the duration of the pulse. The Arduino will output either to an LCD display screen or the serial monitor on Arduinos operating system. The components inside the assembly will be the wire leads extending from the thermistor, attached to the main aspects of the other circuitry. The thermistor bead will be held in place with epoxy to limit movement on testing of solid materials. Once the circuitry is assembled, it will be bracketed in place within the housing of wood, and the AC-DC power supply will be plugged into a 120V AC outlet. Now that power is connected, calibrate the potentiometer so that the bridge voltage on the circuit is balanced. From there turn the power supply on and begin testing. The device well report information sufficient enough for conductivity calculations within 30 seconds from power supply power up. The code currently written is used to analyze temperature decay, with the user paying close attention to the countdown timer on the timing relay.

The device can be used with either the Power supply located in the main assembly or by plugging in the Arduino’s USB interface into a computer. This is because the code on the Arduino initializes the serial monitor for the computer, as well as the LCD Screen on the device itself.

4. TESTING

a. Introduction

Thermal properties are essential to understand the interactions of materials with the world that surrounds them. All materials have a value of conductivity which is intrinsic. Currently, there are several ways to calculate and test thermal conductivity with several different devices, with certain limitations. A brief description of each common way to test thermal conductivity and their limitations will be discussed.

Steady state testing is a simple but effective way to test for thermal conductivity of a specimen. This typically involves the use of a hot plate and cold plate with the specimen positioned between the latter two. Simply be measuring the power being supplied to the hot plate, the temperature difference between the two plates, and knowing the thickness and area of the specimen, will deliver the thermal conductivity of the specimen. This method is straightforward with no significant variables to calculate. However, with simplicity comes limitations. The Steady State methods require ample amounts of time for the system to enter a steady state of heat transfer. Likewise, this method is limited to solid commonly shaped specimens. It is for this reason that Steady State approach was not selected for this project.

Transient Heat methods are numerous in testing procedures and devices. They range from the “Hot Wire Method”, “Hot Disk Method”, and “Laser Flash Method” (Yüksel). These methods mostly revolve around the testing of solid materials and had to be omitted from the use of this project. In a revision of the Hot Wire Method, *Chen et al.* use a thermistor instead of a thermocouple to test biological materials such as organs. This revision method also allows for the testing of liquid state specimens and the time between tests, allowing for more trials. This is the method that is chosen for the device and its construction.

b. Method/Approach

The thermistor pulse decay method is the approach to be conducted in this device. It requires understanding density and specific heat of the material prior to testing. The pulse decay method utilizes a thermistor placed in a probe. The thermistor is then introduced with a current that initiates a heating mode which causes the thermistors bead core to increase in temperature. This increase of temperature at the bead is proportional to the heat entering into the material it is testing, assuming the bead is uniformly distributing heat amongst its radius. It has been shown in *Chen et al.* (1981), that the current to cause heating in the thermistor must last around three to ten seconds. This is denoted as the pulse time. After the pulse is over, the thermistor is placed in a sensing mode, where the temperature of the bead is recorded for a time. These values are plugged into the following equation to solve for thermal conductivity:

$$T(0,t) = \frac{(\rho c)^{0.5} P}{8\pi^{1.5} k^{1.5}} [(t - t_p)^{-0.5} - t^{-0.5}]$$

Equation 1: Pulse Decay

Where:
T (0,t) = the temperature at a given time after pulse (K)
ρ = Density (kg/m^2)
c = Specific heat (J/kg-K)
P = Power measured across the thermistor (W)
k = Thermal Conductivity (W/m-K)
t = Time after pulse (s)
t_p = Time of the pulse (s)

One drawback from the use of this equation is that it assumes the use of an infinitesimally small probe size. This, however, is not the case when subjected to real world scenarios. To understand the accuracies or inaccuracies of Equation 1, the use of the following equation will be used as well, and the two will be compared.

$$k/(\rho c)^{1/3} = [P((t_m - t_p)^{-0.5} - t_m^{-0.5})/4T_o(t_m)]^{2/3}/\pi$$

Equation 2: Revised Pulse Decay

Where all variables are the same as Equation 1.

Power (P) is calculated by the assumption of a balanced bridge at t = 0 and the resistance at t = 0. By recording the resistance at t = 0, power across the thermistor element is a function of Ohm's law.

Temperature is calculated by knowing the resistance at a given time and applying the Steinhart equation with coefficients that are generally given by the manufacturer of the thermistor.

$$1/T = A + B\,[\mathrm{Ln}(R)] + C\,[\mathrm{Ln}(R)]^3$$

Equation 3: Steinhart Equation

Where:
A = 1.4052e -3
B = 2.3692e -4
C = 1.0125e – 7
R = Resistance at a given time

An addition of monitoring temperature decay over time is applied to the device. This ensures that the thermistor is properly working and functioning.

c. Test Procedure

Test procedures are broken into two phases, before and during testing. Prior to testing, the bridge circuit was balanced by adjusting the potentiometer. Next, constants must be established. The Density and Specific Heat of the specimen must be known before testing. Finally, establishing a pulse duration (t_p) and measurement time (t) will conclude the constants prior to testing. Power across the thermistor element must be calculated and thus the thermistor must be engaged in both heating and sensing mode. By measuring the current across the thermistor in heating mode, power delivered is calculated.

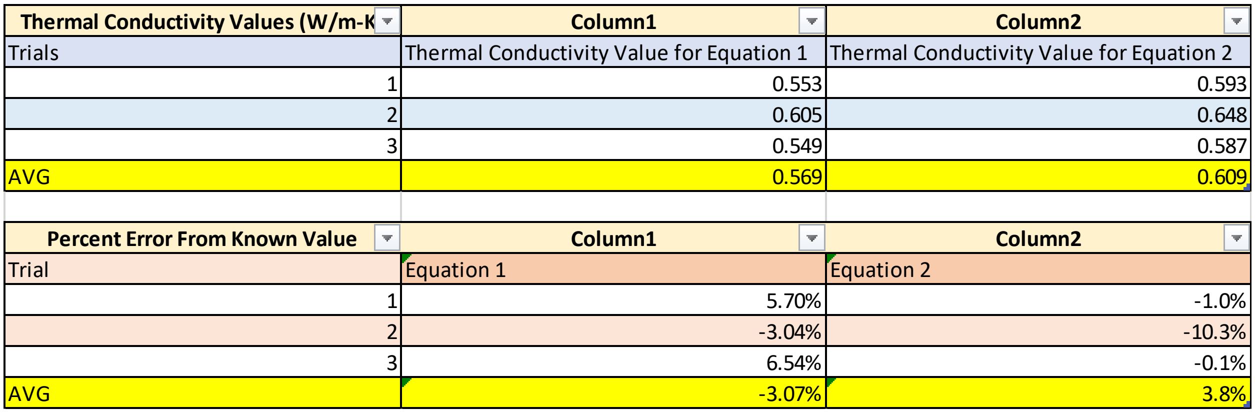
During testing, a current is induced across the thermistor that causes the thermistor to start a self-heating phase. During this phase, the thermistor received the current for three to five seconds and then a timing switch stops the current from flowing across the bridge. Once the current had ceased, the Arduino will power the bridge and the thermistor will begin sensing mode. During this phase, thermistor resistance and thus temperature was recorded for a period of ten to fifteen seconds, depending on the test.

To develop a clean graph of temperature decay with respect to time, the Arduino will export data to the software’s Serial Monitor. This data is then plotted against time to display a clear graph of decay. Initially there was an issue with data acquisition, as the circuitry was improperly positioned, thus the thermistor was not heating up. This effected the data as the Arduino was simply measuring the noise it gathered in what appeared to be the two voltages of pulsing and sensing competing with one another. This issue was fixed by splitting the circuits with two timers instead of the original one.

d. Deliverables

A successful test will result in a thermal conductivity measurement with +/-5% error of known values. If the results are out of that range, then the test is considered a failure. Likewise, a noticeable graph which outlines temperature over decay is required to emphasize that the device is functioning properly. If one of these parameters is missing, then the test is a failure.

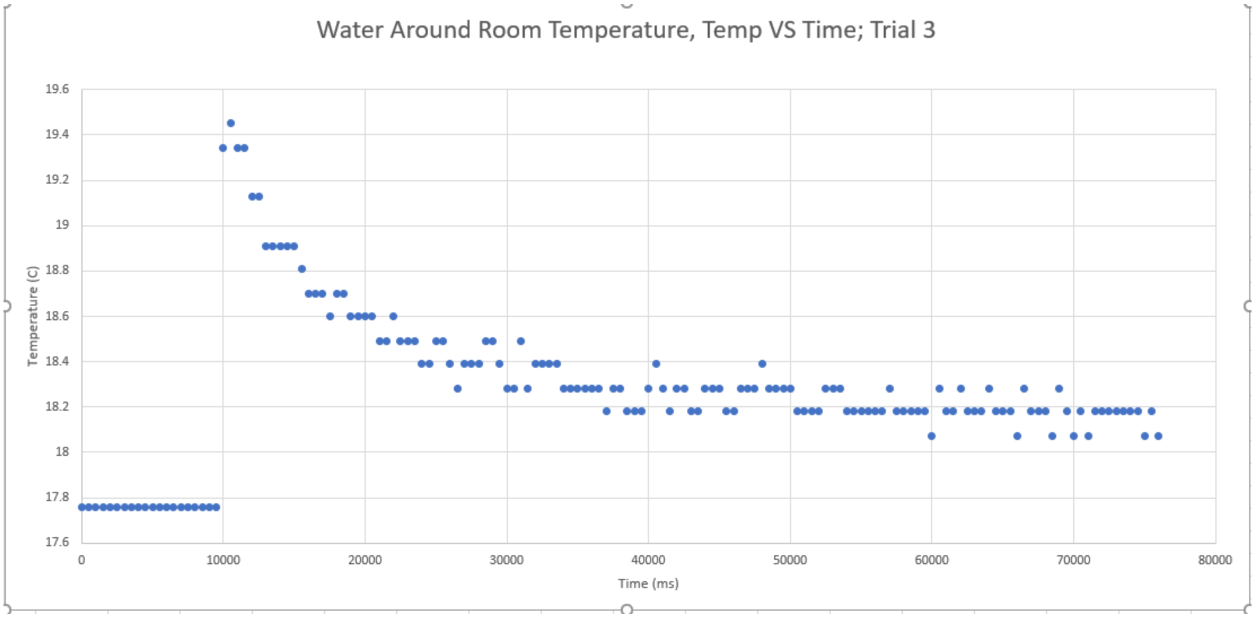
The measurements of “t” resulted in a parameter value for T (0,t), Amperage, Resistance that produced data for processing. The result of rearranging Equation One and Equation Two produces a value of thermal conductivity k in W/m-K. In the first test, the time it took to receive a value for thermal conductivity was ten minutes. This included using a multimeter to obtain the output amperage of the thermistor and various initial measurements. This time is also included in the linear interpolation and researching values of specific heat (J/kg-K), Density (kg/m^3), and Thermal Conductivity. The overall testing of temperature with the thermistor took less than two minutes, which is perfectly applicable to the requirements and predicted results. There was an issue in using the multimeter on the thermistor leads to obtain the amperage of a pulse. The leads used to receive the reading are extremely small, resulting in inaccurate or in some cases no readings. This was alleviated by moving further down the wires on the jumper cables. However, with using the jumper cables and mildly separating them to receive a reading would result in the thermistor getting disconnected at times. This is an issue in the testing procedures; however, it does not result in an inaccurate or imprecise test.



Thermal Conductivity Values (W/m-K	Column1	Column2
Trials	Thermal Conductivity Value for Equation 1	Thermal Conductivity Value for Equation 2
1	0.553	0.593
2	0.605	0.648
3	0.549	0.587
AVG	0.569	0.609

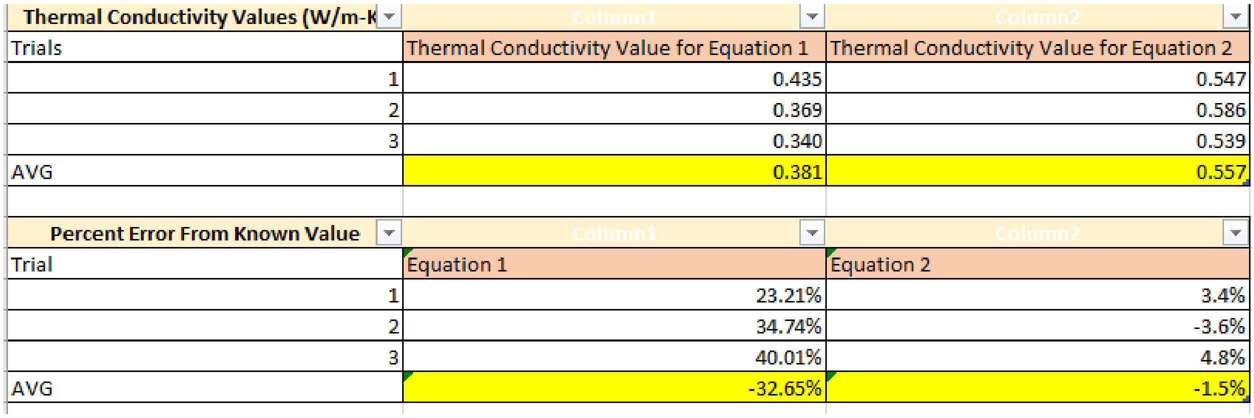
Percent Error From Known Value	Column1	Column2
Trial	Equation 1	Equation 2
1	5.70%	-1.0%
2	-3.04%	-10.3%
3	6.54%	-0.1%
AVG	-3.07%	3.8%

Table 1: Results for Water at 13.87 Degrees Celsius



Graph 1: Temperature Decay of Water Around Room Temperature

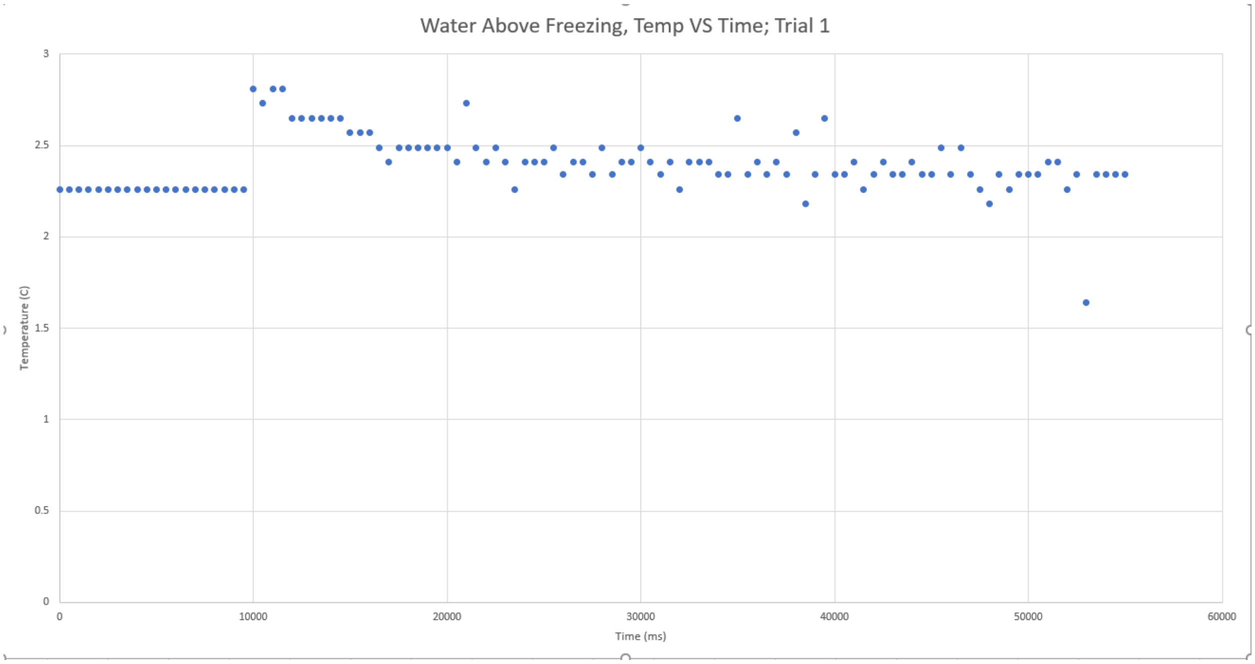
The results of the first test, water mixed with gelatin at around room temperature were as expected. The experiment produced a value of or 0.596 W/m-K for the first equation using a three second pulse time and a measurement time of six seconds. The second equation produced a thermal conductivity value of 0.609 W/m-K with a pulse time of 3 seconds and a measurement time of 8 seconds. Through interpolation a known value of conductivity for water at 13.87 degrees Celsius is 0.587 W/m-K and compared this with the experimental values. As stated per the requirements, the measurement had to be within +/- 5% error for the test to be successful. Thus, the device was designed and predicted to be within 5% error of known values. For equation one the averaged percent error was -3.07%. For equation two, the averaged thermal conductivity value had a 3.8% error. This value for the second equation may have been influenced by underlying issues with the test, as the first and third tests were less than 1% error, whereas the second test resulted in a 10% error in reading. To address this greater margin of error, another test is applicable to remove any outliers held within the data. Overall, test one was successful and both governing equations are accurate and precise in the results they produced. Regarding the two separate equations, there is no definitive conclusion to be made over which one is more accurate to use in the event of testing water at around room temperature.



Thermal Conductivity Values (W/m-K	Column1	Column2
Trials	Thermal Conductivity Value for Equation 1	Thermal Conductivity Value for Equation 2
1	0.435	0.547
2	0.369	0.586
3	0.340	0.539
AVG	0.381	0.557

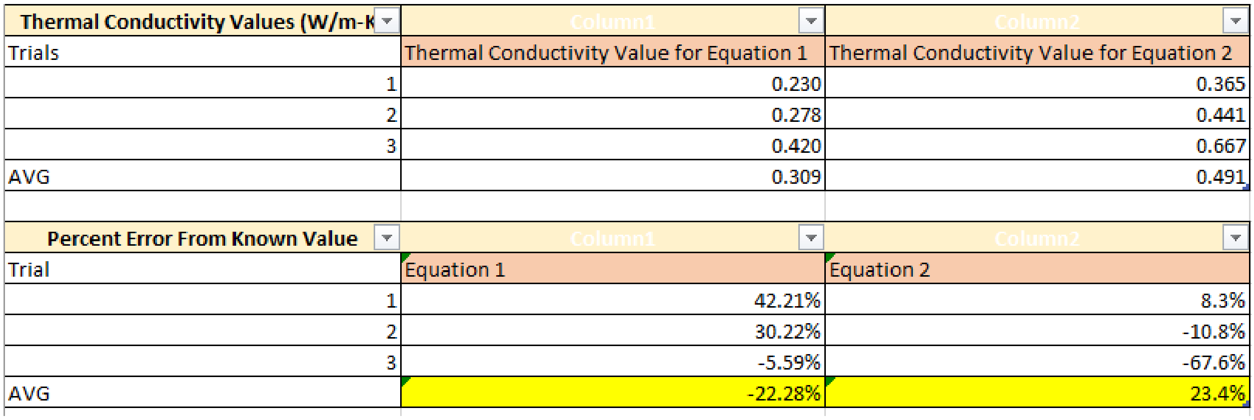
Percent Error From Known Value	Column1	Column2
Trial	Equation 1	Equation 2
1	23.21%	3.4%
2	34.74%	-3.6%
3	40.01%	4.8%
AVG	-32.65%	-1.5%

Table 2: Results for Water at 2.36 Degrees Celsius



Graph 2: Temperature Decay of Water Above Freezing

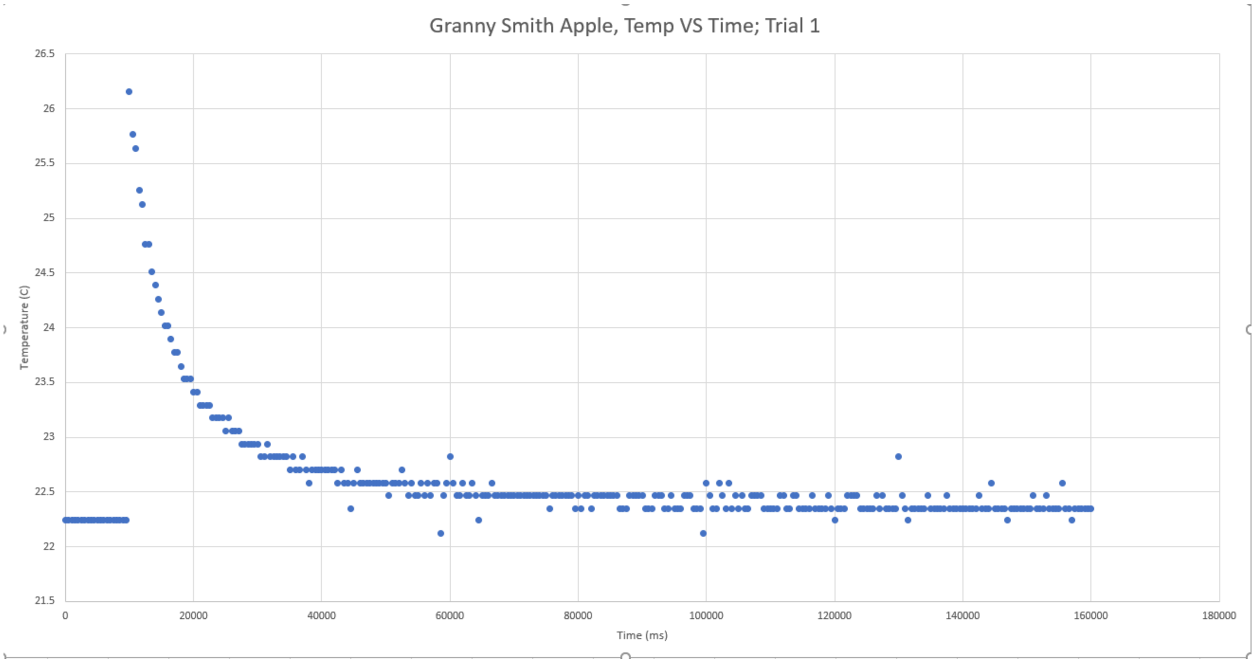
The second test was of water mixed with gelatin at slightly above freezing temperature. The experiment yielded a thermal conductivity value of 0.381 W/m-K and 0.557 W/m-K for Equations 1 and 2 respectively. The pulsing times consisted of a 15 second pulse per trial. Finding consolidation on *Graph 2*, the measurement times were 22 seconds, 22.5 seconds, and 25 seconds for trials one through 3. The results were averaged and a comparison to the known value of conductivity were evaluated. Equation 1 produced an error of -32.65% and Equation 2 produced an error of -1.5%. Equation One appears to require a closer time of measurement with respect to the pulse. This likely resides in the assumptions that Equation 1 governs upon and proves the thesis that Equation 2 will produce better results for finite probe methods.



Thermal Conductivity Values (W/m-K	Column1	Column2
Trials	Thermal Conductivity Value for Equation 1	Thermal Conductivity Value for Equation 2
1	0.230	0.365
2	0.278	0.441
3	0.420	0.667
AVG	0.309	0.491

Percent Error From Known Value	Column1	Column2
Trial	Equation 1	Equation 2
1	42.21%	8.3%
2	30.22%	-10.8%
3	-5.59%	-67.6%
AVG	-22.28%	23.4%

Table 3: Temperature Decay of Granny Smith Apple at Room Temperature



Graph 3: Temperature Decay of Granny Smith Apple at Room Temperature

The third test was of a Granny Smith Apple at around room temperature. The experiment produced a thermal conductivity value of 0.309 W/m-K and 0.491 W/m-K for Equations 1 and 2 respectively. These are the average of three trials conducted. The resulting errors consisted of -22.28% and 23.4%. The conductivity measurements were multiplied by a factor of 10, due to the time dependence on measurement or a false connection with the material being tested. This correction factor is likely due to the physical aspects of solid like materials, which starkly contrast the liquid materials studied in this experiment. Another source of error consists in lesser known values of thermal conductivity for Apples. There are little known sources of tabulated results for apples at varying degrees, which would produce greater margins of error. The graph cleanly shows a decay of temperature, which should indicate an amount of heat transfer being conducted.

5. BUDGET

a. Parts

There is a total of 15 parts needed for the construction of the device. Procurement of the most expensive parts, 55-001 and 20-002 through 20-007 will be purchased online. 55-001 is the Kaiweets DC power supply which will cost $100.00 via amazon and the Balsa wood paneling (20-002 through 20-007) will cost $71.00. Lead times on part 55-002 (Omega Thermistor) will be mitigated through early purchase, as available, ahead of schedule.

The part that heavily influenced the cost and decisions of device is the Thermistor Probe (20-001). This 3-D part minimizes cost and reduces risk of outsourcing this part to a premade syringe which would need to be cut to size. This minimizes cost and risk of human error. In contrast, the Arduino R3 was a revision to the overall design which influenced the design toward automation. It replaced the battery and other recorders like the mounted multimeter. This increased cost by another $38.00, but the decision is necessary for accuracy.

All parts were ordered on time except for the wood paneling for the device housing assembly. The intention with this is to understand and develop a working circuit prior to permanently placing it in an assembly. Due to this, the wood was ordered late into the construction process.

After a change in material for 20-002 through 20-007, the price of the wood paneling has decreased from an estimated $71.00 to $22.50. This has aided the bottom line of the device.

As of 3/10/2021, the overall cost of the device has totaled $306.37. The bulk of this cost has been in the electrical and sensing components of the device. Conveniently, some parts were delivered on discount, as compared to the original proposal. The overall cost has increased due to circuitry design changes. An additional $15.11 has been added due to an error in the construction of the circuitry. The Arduino R3's Atmega chipset has been overvolted in a trial error of the device. The actual cost is the overall cost as shipping/handling has been computed into the budget. To mitigate another risk of overvolting the Atmega chip on the new Arduino, a new switch is being considered as well as increased revisions of the circuit design.

The device is completed with a total cost of $306.37. The project is currently under the estimated budget, fulfilling only 75% of the projected $400 cost. Additional components such as a latch for the Assembly door is being considered, but the device is functional as of 3/10/2021.

As of 5/5/2021, additional parts were added to the device after careful reflection. The device required a new timing switch, bringing the total amount of switches to two. A group of additional, more modular potentiometers were added to the device to initiate different wirings of the Arduino as well as altering the pulse width when heating the device. These items were necessary to the completion of the project because the original design was merely measuring noise. These parts fixed that problem. This officially brings the completed device to $326.98, consuming 82% of the original budget. The device is under budget.

b. Outsourcing

Little to none of the items used in the creation of this device require outside processing. All components involved in the assembly can be purchased or machined to fit from the Machine/Wood Shops at CWU and from home. This is a good thing as it minimizes cost and coordination.

c. Labor

Projected labor costs are compiled using the median average for mechanical engineers and representing their salary as a dollar amount per hour, over the projected labor hours used on the project. The bls.gov projects that the median income of Mechanical Engineers to be $42.51/hour.

d. Estimated Total Project Cost

Estimated costs of parts for the project is $400.00 and labor is $6,887.00 bringing the total to $7,287.00.

e. Funding Source

Funding for the device will be internally provided. The entire cost of the project will be paid for out of pocket. Due to the lead engineer working on this project alone as well as the overall low cost of the project, there is no need to seek additional grants from companies familiar or interested in the field.

6. Schedule

a. Introduction

The Pulse Heated Thermistor must be completed by the last week of the third quarter at Central Washington University. Potential risks to prevent milestones from being completed on time are lead times on specific parts and loss of progress due to revisions. A Critical Design Report will be completed by the first week of January 2021 and parts are expected to arrive by Mid-December, paving the way for early construction of the device. The Final report and a presentation on the device and its functionality will be given by the first week of June 2021

b. Design

Few issues have been encountered as of 10/9/2020. Slight revisions have been made hindering forward progress of up to 3 hours of work. Revisions have been made to overall circuit design, incorporating a voltage divider for accurate measurements of voltage across the thermistor at given temperatures. Second revision was to swap out a silicone resin for an epoxy resin due to the material properties lining up with the intent of the design, as well as. Current up-to-date status of completed items is in Appendix E – Schedule. The finalized designs will be completed on Friday, November 20th, 2020.

Revision of Circuit schematic was completed on 2/3/2021. This updated the Arduino add on and removed the 5V battery.

Revisions to the Device Housing were done on 3/5/2021. This changed where certain cutouts were to better reflect the modularity of the circuit components inside. It also was updated to reflect the change in material.

A new FEA analysis was devised for the project and is in Appendix I. This data will be used and compared to the data done in testing. This project was completed with the help of Professor Pringle and fellow Engineer Lucas Hill.

c. Construction

Construction of the project will be completed by February 26th, 2021. Possible hinderances during this milestone will consist of lead time on specific parts and lack of access to specific tools. During the construction phase of the schedule, changes to overall design complicated the process. An Arduino R3 Uno was added to behave as an analog data converter as well as replace the 5V battery across the bridge circuit. The creation of a code that analyzes the voltage across the thermistor element and computes that as a power reading as well as a temperature reading has proven difficult.

Success came on 2/2/2021 when the proto type circuit showed that the temperature at the bead of the thermistor rose thirteen degrees Celsius under load, and climbed down in half second intervals, to equilibrium when the power supply was turned off by the switch. The code works but now must be tweaked to compute power dissipation across the thermistor element. The circuit design must also be tweaked as the Arduino was overloaded on the bootloader and wiped the code entirely out of the memory. Problems has arisen as the Arduino no longer can upload and compile code to be used. To mitigate this problem another Arduino must be used, circuit must be revised to prevent backwards potential, and the first Arduino may be fixed by another via the bootloader program. The leads connecting the potentiometer keep disrupting the system by disconnecting. Solder is being considered on the potentiometer to prevent the jumper leads from de-attaching themselves and creating an open circuit. The potentiometer calibration is straightforward and rests at 3,018 ohms. The Arduino connects to the thermistor by analyzing the output voltage on pin A_0. The switch connected to the power supply applies current for 3 seconds of pulse and is cutoff for twenty seconds before it loops. Programming the switch is straightforward however, a cancelation of the loop is being considered.

Certain tasks were required to move behind other tasks due to their complexity being misunderstood at the conception of the project. The circuitry took an exceedingly longer time to construct. The original estimated time frame to complete this aspect of the project was six hours when it took 13 hours. Due to the increase in time, certain aspects of the project were delayed, causing a delay in overall completion of the working device milestone.

As of 3/7/2021, the project has a functional working device. This is behind schedule on the estimated 2/26/2021 timeframe. The functional issues caused this delay, but the project was completed on time and ready for presentation on 3/10/2021. As of completion of the construction portion of the project, the total hours are 161. The completed project will go over estimated hours.

d. Testing

Initially, the projected completion of the testing portion of the design process for the Pulse Decay Thermal Conductivity Device was to be completed by April 17th, 2021. However, the completion for the testing portions of the design had to be delayed twice. Once on April 15th, where it became apparent that the circuitry was incorrectly utilized, and secondly on April 23rd due to a delay in shipment. Prior to the initial projection of April 17th, all testing materials had been tested for thermal conductivity using the device. When discussed with Dr. Choi over the results of the initial tests, there was a clarification that a usable graph of temperature decay is required to understand the mode of heat transfer between the probe assembly and the material. When this was quantified via changed procedures, it became apparent the device was measuring the noise signal between two competing voltage sources. Thus, the new procedures were written to understand the test, pushing the completion of testing further back.

A new switch was organized on the pin which the Arduino analyzes voltage changes where this switch operates in opposite time intervals with the pulsing voltage source. A new safety feature was added using an Arduino Uno’s Pulse Width Modulation pins as well. This consisted of utilizing a potentiometer to adjust the flow of current into the Wheatstone Bridge. This ensured the safety of the main processing areas of the Atmega processer which stores and analyzes the code it is written with. Another benefit of this configuration is that it reduces the noise associated with two competing sources of voltage as well as reduce the noise associated with the 5V pin which is variable depending on the USB interface which supplies power to the Arduino. When analyzed via the acquisition software, a clear graph of temperature decay with respect to time is established via importing the data over to a blank excel spreadsheet that is established in the Testing Report Appendices. This clearly indicated a mode of heat transfer between the testing material and the probe assembly. Now a pulse is associated with a heating temperature and consolidation of temperature near equilibrium is analyzed. These effects reduced the noise of the overall circuit, improved the safety of the device under higher pulsing loads, and allowed for improved data analyzation.

Once the circuitry was revised, preparations were taken to complete three trials of three materials. This consisted of water mixed with gelatin at varying degrees and an apple at room temperature. There became an evidence of the device operating a mode of heat transfer via conduction. The results were compiled and analyzed. The device had completed testing on May 5th, 2021. Completion of the project report are on track to be completed by the end of May 2021.

The project is completed on 6/3/2021. The predicted number of hours required to complete this project was estimated to be 165 hours. The actual amount of time spent to complete this project from start to finish was 195 hours as referenced in Appendix E. This includes all processes to succeed in completion of the project from design, to construction, to testing, and polishing of the final report on the device. Certain portions of the process were completed faster than expected while other tasks took considerably longer than originally realized. Most issues and setbacks in the schedule occurred during the construction and testing portions of the process. These were incurred by hardware issues as well as unforeseen problems that arose, however, they were mitigated swiftly and the project continued to completion.

7. Project Management

a. Introduction

This project will succeed due to the availability of technical expertise, resources, and time constraints. These areas encompass the least amount of risk for the duration of this project. Technical expertise or expert in the field is consistently available at CWU. The resources to construct and test the device are readily available. Time is the amplest because of the access to work-in-home due to COVID-19. Some areas of higher risk include budget and material acquisition.

b. Human Resources

The principal engineer will provide analyses in all aspects of the project, the construction, and the testing of the ending design and their resume is shown in Appendix H. Other human resources are Professors Charles Pringle and John Choi. Their expertise will aid in the completion and success of the project. Another resource is the other engineers Kyle Saafeld and Lucas Hill who are working on similar projects. With the resource sharing between engineers and the guidance of the Experts, the project will continue unhindered. Engineer Lucas Hill has been a great help in the finishing of the device. Both projects utilize Arduino data acquisition software and thus ideas on the code used to construct the device has been conversed about. Likewise, the conception of electrical circuit diagrams was shared, and problems were solved.

c. Physical Resources

Physical Resources are the processes and machines that will be utilized to complete the project. Among these resources, the most critical is the Makerbot 3-D printer that CWU will provide. This printer will create the thermistor housing which is necessary to produce a reasonably priced and tight tolerance housing for which the thermistor will reside and provide data for testing. Other minor resources will be the tools available at home. These include a jigsaw, screwdriver, hand drill, etc.

d. Soft Resources

Soft resources are limited to two types. Excel for data acquisition and analysis as well as Solidworks which is provided by CWU. Solidworks will provide drawings to be printed and modeled. Arduino's Programming Software will also be used. It is a free to download software. Autodesk Inventor Nastran was utilized for an FEA analysis of the project in a virtual sense as well, which aids the projection of testing.

e. Financial Resources

The project sponsor will be the principal engineer and provide monetary support to aid in the completion of the device. The equipment will also be provided by the principal engineer as well.

8. DISCUSSION

a. Design

The project initially began as a simple idea, consisting of a thermistor attached to a power supply and a resistor in series. During this first conceived idea, the device, and its evolution, were still in their infancy. By studying the thermistor and the properties associated with the thermistor, the initial idea was to introduce a heating current and measure the resistance of the thermistor when the current had ceased to flow at a high voltage. As time progressed and more research was conducted on the thermistor properties and the thermal properties of conductivity, it became more apparent the initial simple circuit would not work. This is where the first initial circuit became obsolete and was replaced by a bridge circuit acting similarly to a voltage divider. Through analyses and studying of *Chen* 1981, a new circuit which reflects the success of previous devices is to be used. This same circuit introduced modern parts which can be programmed for time, an important variable when testing for thermal conductivity. In these aspects, the project evolved to operate well in the tasks it is designed for. Another revision occurred to automize the circuitry. Using the same circuit diagram, an Arduino Uno R3 replaced the 5V battery and became the outbound data acquisition source. It will analyze the thermistors resistance and calculate the thermal conductivity of the material.

The other aspects of design, which became a problem, was the conception of the housing for which to thermistor would be housed. In previous designs, the thermistor was placed into a syringe and fastened with an insulating epoxy. The initial design concept was to place the thermistor into a syringe as well, however, the syringe must be cut radially to very tight tolerances for the bead to be accessible to the material it would be in contact with.

Another problem arose as well. The previous designs which were conceived before this device were designed to only test liquid or gelatinous materials. This is a problem in the design because as per the requirements, a solid metal material must be tested as well as liquid. Force must be delivered into the thermistor to optimize connection with the material to be tested, as well as reduction in ambient convection. After careful consideration, the concept was changed for this device to include a 3-D printed thermistor housing. This reduced waste by not purchasing large amounts of syringes, but also kept the tolerance of the radius of the housing lower. Lastly, the circuitry housing was conceived to allow access to the circuit for balancing. Initially, this was a wrong design. The housing was first conceived to be a closed box with minimal access to internal components. However, as new information began to be understood, the design had to be changed. The design encapsulated the idea that the internal circuit components must be balanced prior to use as well as replacement parts had to be accessed in case of failure. The final design became a housing of lightweight plywood with hinges that allow easy access to internal components.

Changes to the parts 20-002 through 20-007 have occurred. Certain limitations with the accessibility of tools have led to minor design changes that will not affect performance. The material changed to plywood to fit the budget while still being within acceptable weight parameters was chosen. The thickness of the plywood has been accounted for in the drawing by changing outside dimensions.

b. Construction

Construction has been successful with respect to the rigorous design process and minimal machining challenges. The circuitry is operating withing parameters and has been successful. The major setback with the construction process is with the programming of the Arduino. In order to work the Arduino, an understanding of the C coding language has too been applied. An initial code has been written and must be tweaked extensively prior to the final device turn in.

Another issue has arisen in the specification of the leads on the thermistor (55-003). The leads do not have the same gauge of wiring consistent with the jumper cables that were purchased. The voltage capacity of the gauge is unaffected by the amperage flowing through the wires; however, the connection is more of an issue. The thermistor leads have been positioned into the jumper cables and have established an adequate connection. The risk of the leads being removed is also mitigated in the sub-assembly of the thermistor housing.

In an effort to change the design, the material for the housing was swapped for a durable but lightweight plywood. The wood was economical, saving money in the budget and still fulfilled the weight requirement of 20lbs. Another revision in the design was altering the shape of 20-001. The small cylindrical shape caused difficulty in the pouring of insulating resin into the house. The change widened the cylinder at the end where the thermistor leads are placed. A deeper look into the revision can be referenced in Appendix B.

Parts 20-002 through 20-007 are almost at completion. Initially, a problem arose with cutting the boards out with a jigsaw. The square that was used was meant to keep the jigsaw straight while cutting, was warped after all pieces were cut. Fortunately, this problem was noticed quickly. Due to the thickness of the boards (3/8th in), the sides of parts 20-002 and 20-004 through 20-006, had to be trimmed down. The unparallel cuts were corrected and the boards were square. A problem did arise in the decision to use a circular cutout on 20-002. A three-inch cutout was chosen as it configured nicely with the tools at hand. A 1.5-inch cutout would stress the jigsaws blade. The circularity is uneven; however, the cutout is just a pathway for 20-001 to extend out and thus has little functionality. The continuation of the housing proceeded smoothly, with minor adjustments to the design to fit revisions.

Currently, the final part to truly be assembled is 20-001 and subassembly 10-003. The PVA glue that was used to print the probe takes extended time to break down in water at room temperature.

10-003 was completed without an issue and the remainder of the components were placed into the assembly. As of 3/7/2021, the device is working.

c. Testing

Testing of the device began in the first week of April. A procedure denoting the processes in which to operate the device was conceived. While writing the procedures there quickly came a realization a minor problem in the perceived notion of the modularity of the device. This issue was due to recording the output amperage traveling about the thermistor while under load. To remedy this situation, a multimeter was used to record the pulsing amps across the thermistor. The first iteration to the procedures consisted of touching the multimeter to the exposed leads on the thermistor. However, this proved troublesome. The leads on the thermistor are inherently small, resulting in poor contact between them and the multimeter. The second iteration fixed this problem. The probe was slightly disconnected at the jumper wires located down the probe assembly. This ensured that there was optimal connectivity of the device so that the circuit would not short out or redirect current to the other portion of the Wheatstone bridge. The leads on the jumper cables are large and sturdy enough to maintain optimal contact with the multimeter. However, the implication with this fix means poor user interface with the device. This issue should be addressed in later iterations of such a device.

The first test for thermal conductivity began with gelatin in water at around room temperature. The results were as expected with a mean value within parameters as per the requirements. One issue that was found is the resolution of the data. While conductivity is presented into the thousandths, the resolution for temperature is presented in the hundredths. This may impact future testing of the device.

The second test for thermal conductivity began with gelatin in water at above freezing but well below room temperature. There were issues with this test that needed addressed. First, the pulsing length of the thermistor was not as adequate as previously hoped. The resulting incremental temperature was about a quarter of a degree. Likewise, water is showing signs of being highly dependent on the value of t_m. To remedy this situation, the timer was adjusted to tenths of a second for resolution, an issue that was not anticipated. However, the implication here is there is more room for human error. With a new test conducted using calculated values of t_p and t_m that converged with the tenths of a second resolution. Adjusting these values resulted in adequate result. However, another implication of this test is that the thermistor behaves erratically at colder temperatures. This resulted in various spreads of thermal conductivity which directly influenced the average conductivity values.

The third test of thermal conductivity began with an apple at around room temperature. The first issue that arose was that apples, specifically Granny Smith Apples, have little to no tabulated thermally reliant values. These included specific heat, density, and thermal conductivity. There was no fix to this issue and the referenced values in the testing section are as is. Due to these errors, the final values of thermal conductivity are skewed. Another issue that arose in the testing of a Granny Smith Apple was the reliance of water with t_m. The initial estimates of pulse time and measurement time were not as previously thought in the Design Phase of the device. As with the second test, this issue was ratified with adjusting the time values and increasing the resolution of the timer. The implications remain the same as the second test.

As of 4/19/2021, a final material to test the device with has not been chosen. Due to recommendations from Dr. Choi, solid materials with high thermal conductivity values as located in *Cengal* are difficult to test as the thermistor has issues getting heated enough to dissipate heat into its environment. The decision is to use a fluid like oil for the final material. Research is underway on tabulated materials such as SAE 30W-15 Engine oil as well as simple olive oil.

An issue with the device concerning the resolution of the device was discovered. It is apparent that the Arduino board either cannot compute the resistance of the thermistor during pulsing or the thermistor does not undergo heating during pulse. This is seen while graphing the entire experiment after acquiring data via the serial monitor software on Arduino IDE.

While looking at the graph to notice any potential pulse decay, there is an extreme drop-off of temperature after pulsing. In a perfect experiment, the decay would take place over the time from of two to three seconds. While analyzing the graph it is apparent that noise is evident for the drop off temperature in the 50-millisecond range of data acquisition. Certain additions to the device were conducted to check if the thermistor is heating up properly. A 20V DC pulse was induced onto the thermistor and temperature was analyzed after the pulse. The thermistor gave no evidence that it had heated up during this experiment. The results of the first few experiments show evidence of thermal conductivity however there is no evidence of decay taking place with the device. An ADC was considered to combat the poor resolution of the Arduino, however, if there is no induced heating of the thermistor, the whole circuit will need to be reworked and examined. If no decay is apparent, the device is then to be considered obsolete as a decay in temperature is paramount to the laws governing the pulse-decay thermistor.

A potentiometer was added to the circuit. The placement is special because it regulates the Arduino's 5V DC supply and reorganizes it in a pulse width modulation (PWM) setup. A timing switch for the pin which measures the voltage logic across the thermistor was outfitted with a timing switch, acting opposite of the pulse. What was being explored earlier was an effort to acquire a steady decay of temperature over time. The original experiment plotted a version of noise being measured across the thermistor. The new configuration provides a detailed expression of temperature decay over time. Fortunately, the potentiometer was already included in the initial budget, so no additional costs were added for the function of the PWM circuit. The budget did receive an increase as a switch was purchased for the device to properly function.

The device operates as intended for liquid substances. The device can deliver a decaying temperature graph accurately and precisely. From that data the thermal conductivity is extrapolated and calculated. An issue did arrive while testing the water-like substance, The Granny Smith Apple. The Granny Smith Apple's thermal conductivity is under the known value's thermal conductivity by a factor of ten for both equations. This could be caused by the porous material of the Granny Smith Apple because the thermistor probe is unable to achieve proper connection with the specimen. Oddly, there is a clean graph of temperature decay with respect to time, thus there is a mode of heat transfer occurring within the material. In the event of improper connection between the probe and the material, it is likely to conclude that the thermistor dissipated heat into surrounding air, and not specifically the material. More testing is to understand if this is the case.

Additional trials for measuring the resistance of the thermistor were added to the experiment data sheets. This aids in understanding the power dissipated across the thermistor at several different resistances. One minor drawback is the interpolation of the thermal conductivity has yet to be added per each trial's respective initial temperature. Considering the thermistor does heat up and returns to a point where the temperature at the core of the thermistor is higher than it's initial, this is grounds to reestablish an interpolation per each trial. This is due to thermal conductivity being dependent on temperature, much like density and specific heat. Readjusting this will lead to more accurate data.

9. CONCLUSION

The purpose of the device is to successfully provide enough information to calculate the thermal conductivity of a given material. The success of this device is critically dependent on precise and repeatable results. To achieve these results, the design of the device was considerably analyzed. Aspects such as force of contact, avoidance of convection, imperfect circuit dynamics, and errors in measurement readings have all been analyzed. Other analyses were performed as well, the most important of these were the understanding of the circuitry and how it reacts. The last requirement to be analyzed was weight, considering the device itself must be under twenty pounds. The features of the device include an adjustable power supply, exchangeable parts, mechanically movable front panel for ease of access, and a reusable and repeatable thermistor. Through careful consideration and deliberate design intent, the device will be able to repeatably and reliably perform the task of providing analog data to calculate thermal conductivity within five percent of known values. In conclusion, the device is ready to be built.

The device is functioning and works as intended. The thermistor under pulsing voltage heats to a degree, then a decay of temperature to equilibrium is achieved. Despite minor inconveniences such as overloading the first Arduino and difficulty producing a circuit which delivers tangible results, the construction portion was completed on time for presentation. The addition of the LCD interfaces aids in a sleek but practical design. The device meets certain requirement such as a final size of 18in x 13in x 9.75 and a weight of 11.8lbs. Two probes were created, satisfying another requirement. In conclusion, the device is functional, meets specific requirements, and is ready to be tested.

The testing procedure was completed under 15 minutes for a given material, satisfying the time requirement of the device. Excluding material preparation, the overall time to complete a cycle of three trials per material is under 10 minutes. With the use of the automated excel worksheet held within Appendix G3 and G4, calculations take minutes to compute provided that the user has a reference for the thermal capacity and density of the material prior to or during the computation process.

To eliminate error two different equations regarding the pulse decay method were analyzed and complied. It is sufficient to conclude that Equation 2 produces more accurate results than Equation 1 in this study. Reasons for this being is that the thermistor used in this device has a large radius as compared to the original study conducted by Chen et al. More effective testing with varying thermistors and other materials is required to further compound upon this conclusion.

Originally, the device was predicted to measure thermal conductivity withing a +/- 5% accuracy range versus known values. After collecting the results for Water mixed with gelatin at room temperature and slightly above freezing as well as a Granny Smith Apple at room temperature, different conclusions about the effectiveness of the device are in question. For the gelatin mixtures, the range of values were effective and held within the 5% margin. The apple however maintained a large error margin well outside of the predicted value. This is likely due to the limitations of contact between the thermistor and more solid like materials.

A handful of improvements and further research to the device is needed to further establish the efficiency and scope of the device. Firstly, the thermistor probe is required. An improved design to the probe would aid in the processing of solid materials like the apple tested. Secondly, more trials conducted with the device on multiple different materials are needed as well. Improving and analyzing the issues with the Pulse Decay Method to compute thermal conductivity with solid materials that maintain high thermal conductivity values. Lastly, sleekness of design to improve portability. While the Arduino acquisition software is helpful to the design, being limited to a computer to analyze data is a hinderance. A suggestion to future designs is the exchanging of higher voltage batteries to power both the pulsing and sensing mechanisms would improve portability. For further research and continual improvement of the design, it is sufficient to suggest that once the issues regarding measuring thermal conductivity of highly conductive materials, further research into the conductivity of biological mediums such as skin and other organs is necessary.

Overall, the Pulse Decay Thermal Conductivity Device is a partial success. It satisfied most criteria excluding the thermal conductivity measurement in one experiment. It is function and precise in the testing of liquid state materials like water, while maintaining difficulty with solid state materials. In future research and processing of the device, it would be sufficient to conclude that a handful of changes to the project are needed to improve accuracy and design functionality.

10. ACKNOWLEDGEMENTS

The design engineer would personally like to thank Central Washington University for its helpfulness during the pressing times of 2020 and into 2021. They have paid for the Mechanical Engineering students to have access to all the virtual software needed to complete this project. Secondly, a huge thanks to the Faculty at Hogue, for their availability to access the facilities within the building have made the project progress without any setbacks. Lastly, a major thanks to Professors John Choi and Charles Pringle, who, without their guidance, this project would have been nigh impossible. Their support and insight to the real-world aspects of design, construction, and testing for engineers have left an everlasting impression.

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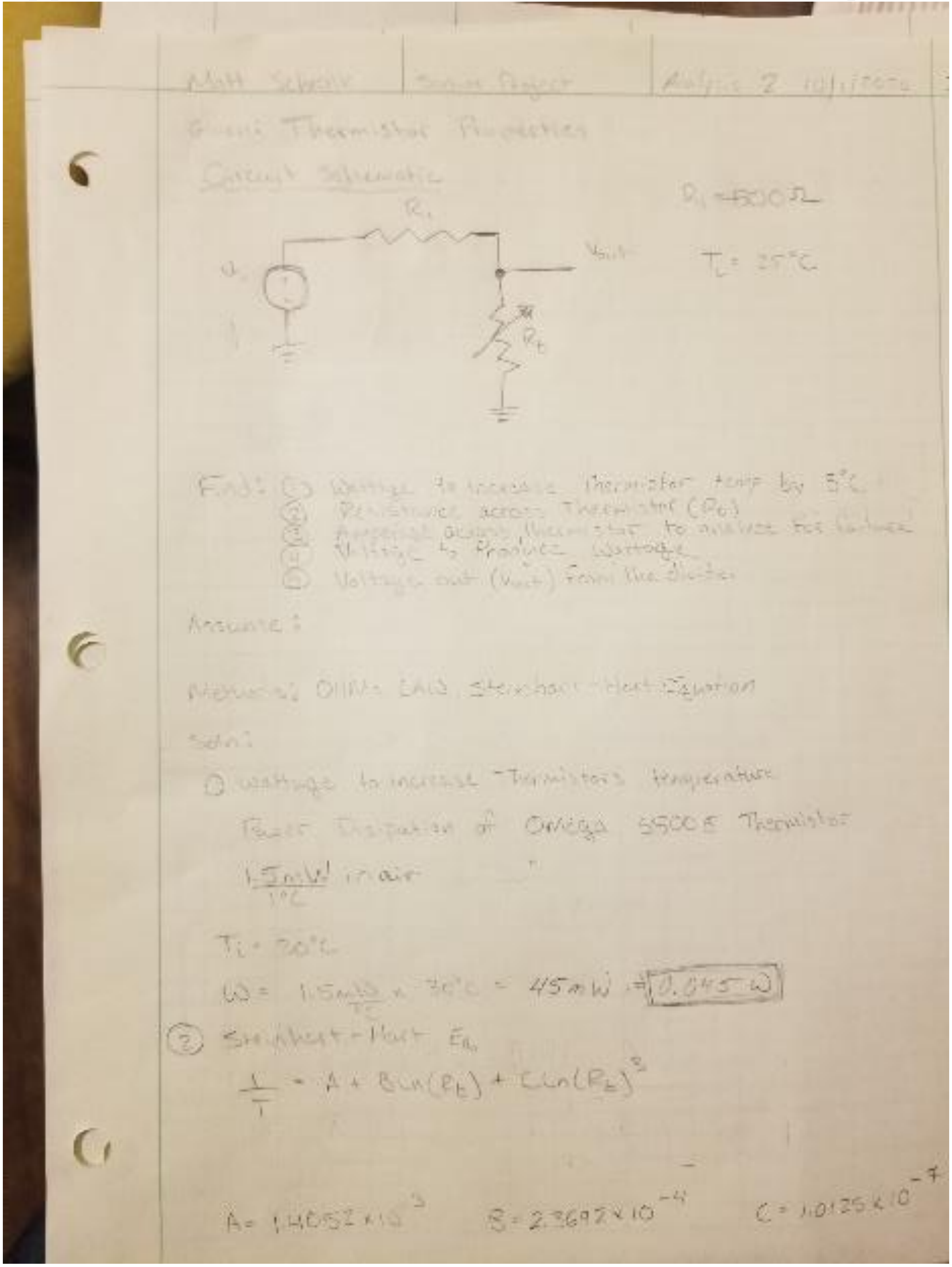
APPENDIX A - Analysis

Appendix A-1 – Circuit Schematic with Power Dissipated



Matt [illegible] | [illegible] Project | Analysis 2 [illegible]

Given: Thermistor Properties

Circuit Schematic

$R_1 = 4500\,\Omega$

$T_L = 25°C$

Find: ① Wattage to increase thermistor temp by 5°C
② Resistance across Thermistor (R_t)
③ Amperage across thermistor to achieve [illegible]
④ Voltage to Produce Wattage
⑤ Voltage out (V_{out}) from the divider

Assume:

Methods: Ohm's Law, Steinhart-Hart Equation

Soln:

① Wattage to increase Thermistor's temperature

Power Dissipation of Omega 5500E Thermistor

$\frac{1.5\,mW}{1°C}$ in air

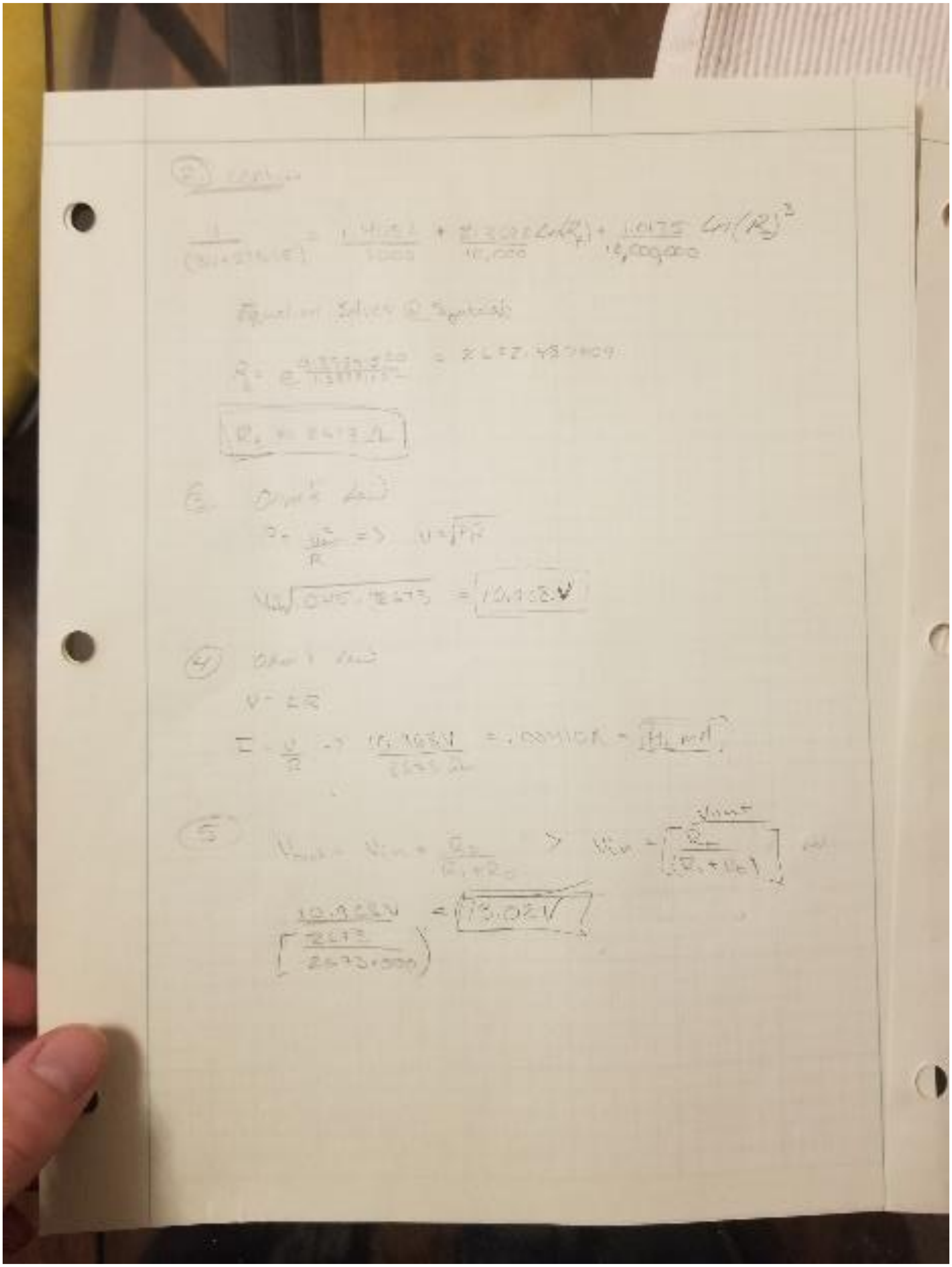
$T_i = 30°C$

$W = 1.5\frac{mW}{1°C} \times 30°C = 45\,mW \Rightarrow \boxed{0.045\ W}$

② Steinhart-Hart Eqn

$$\frac{1}{T} = A + B\ln(R_t) + C\ln(R_t)^3$$

$A = 1.4052 \times 10^{3}$ $B = 2.3692 \times 10^{-4}$ $C = 1.0125 \times 10^{-7}$



② [illegible]

$$\frac{1}{(31+273.15)} = \frac{1.4051}{1000} + \frac{2.3690\ln(R_T)}{10,000} + \frac{1.0175}{10,000,000}\ln(R_T)^3$$

Equation Solver @ Symbolab

$$R_T = e^{\frac{[illegible]}{[illegible]}} = 2672.4857409$$

$$\boxed{R_T \approx 2673\,\Omega}$$

③ Ohm's Law

$$P = \frac{V^2}{R} \Rightarrow V = \sqrt{PR}$$

$$V_{in} = \sqrt{.045 \cdot 2673} = \boxed{10.968V}$$

④ Ohm's Law

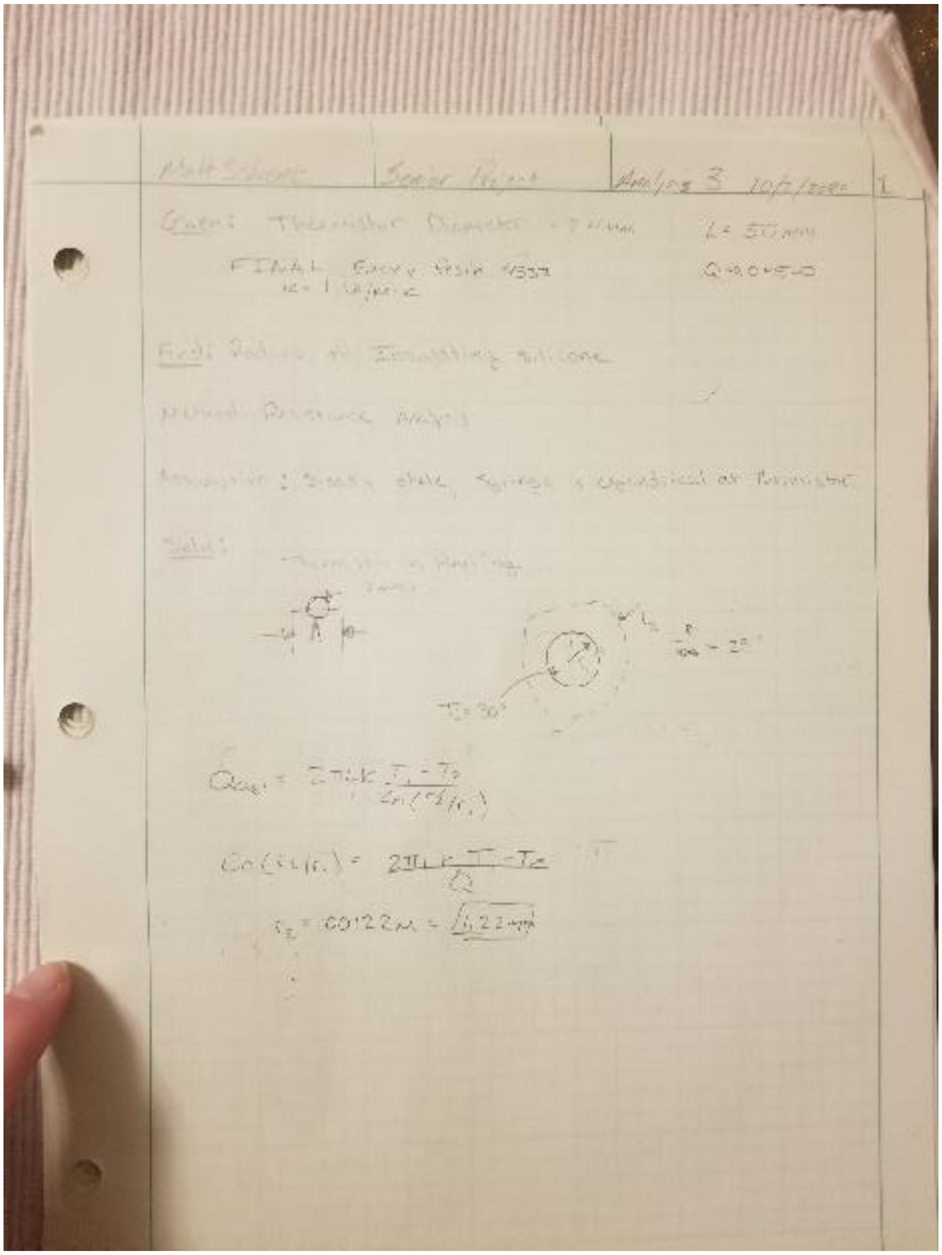
$$V = IR$$

$$I = \frac{V}{R} \Rightarrow \frac{10.968V}{2673\,\Omega} = .0041032 = \boxed{4.1mA}$$

⑤ $V_{out} = V_{in} \cdot \frac{R_2}{R_1+R_2}$ > $V_{in} = \left[\frac{V_{out}}{\frac{R_2}{R_1+R_2}}\right]$

$$\frac{10.968V}{\left(\frac{2673}{2673+500}\right)} = \boxed{13.02V}$$

Appendix A-2 – Radius of Insulation in Thermistor Housing



Matt Schaefer | Senior Project | Analysis 3 10/[illegible]/2020 | 1

Given: Thermistor Diameter = 2.4 mm   L = 50 mm

FINAL Epoxy Resin [illegible]   Q = [illegible]

k = 1 W/m·K

Find: Radius of Insulating silicone

Method: Resistance Analysis

Assumptions: Steady state, Syringe is cylindrical at thermistor

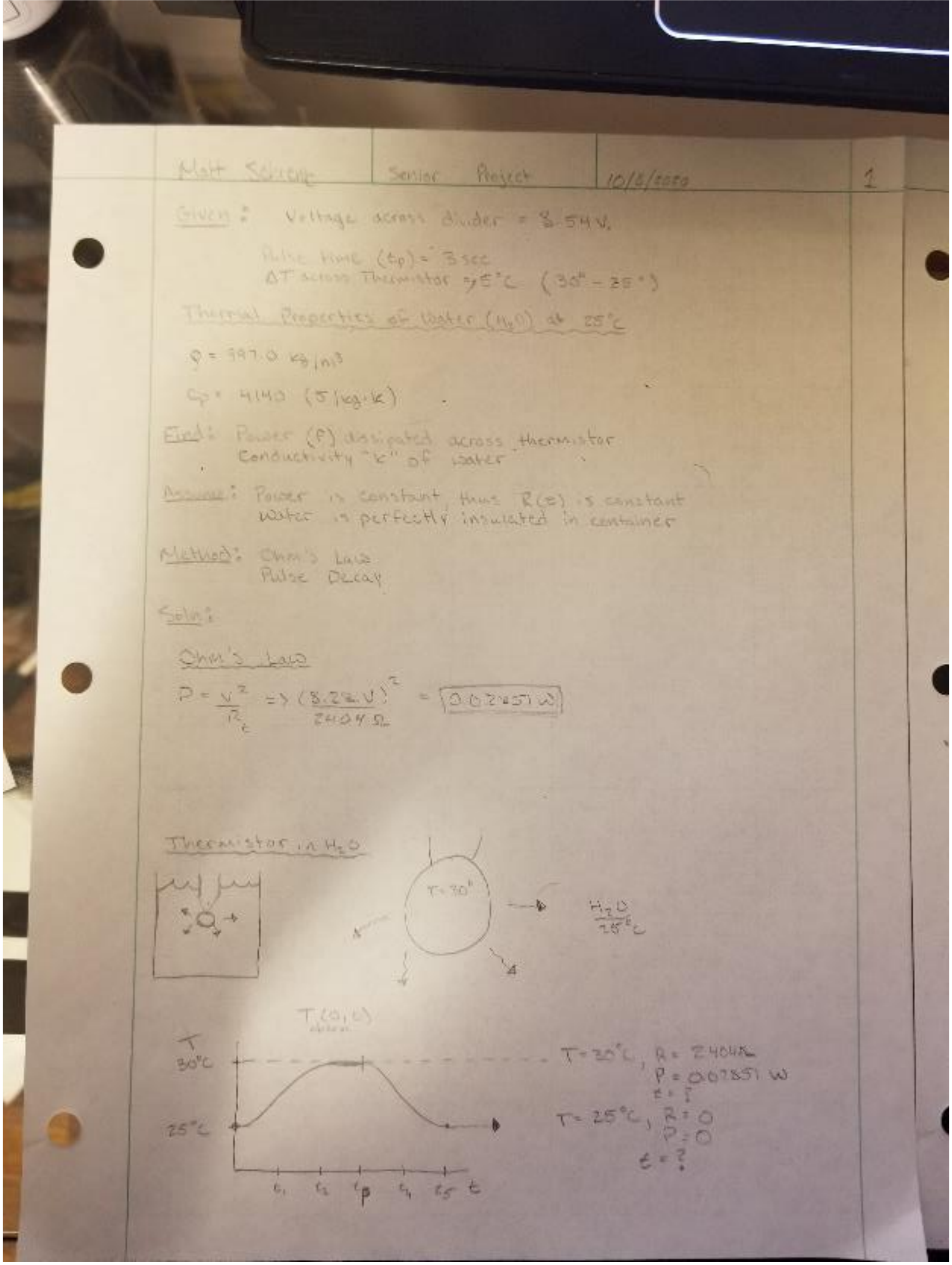
Solve:

$$Q_{cond} = 2\pi L k \frac{T_1 - T_2}{\ln(r_2/r_1)}$$

$$\ln(r_2/r_1) = \frac{2\pi L k (T_1 - T_2)}{Q}$$

$$r_2 = .00122\,m = \boxed{1.22\,mm}$$

Appendix A-3 – Tolerance



Matt Schrenk | Senior Project | 10/8/2020 | 1

Given: Voltage across divider = 8.54 V.

Pulse time (t_p) = 3 sec

ΔT across Thermistor ≈ 5°C (30° − 25°)

Thermal Properties of Water (H_2O) at 25°C

$\rho = 997.0\ kg/m^3$

$c_p = 4140\ (J/kg \cdot K)$

Find: Power (P) dissipated across thermistor

Conductivity "k" of water

Assume: Power is constant thus R(t) is constant

water is perfectly insulated in container

Method: Ohm's Law

Pulse Decay

Soln:

Ohm's Law

$$P = \frac{V^2}{R_t} \Rightarrow \frac{(8.22\ V)^2}{2404\ \Omega} = \boxed{0.02851\ W}$$

Thermistor in H_2O

T = 30°C, R = 2404Ω

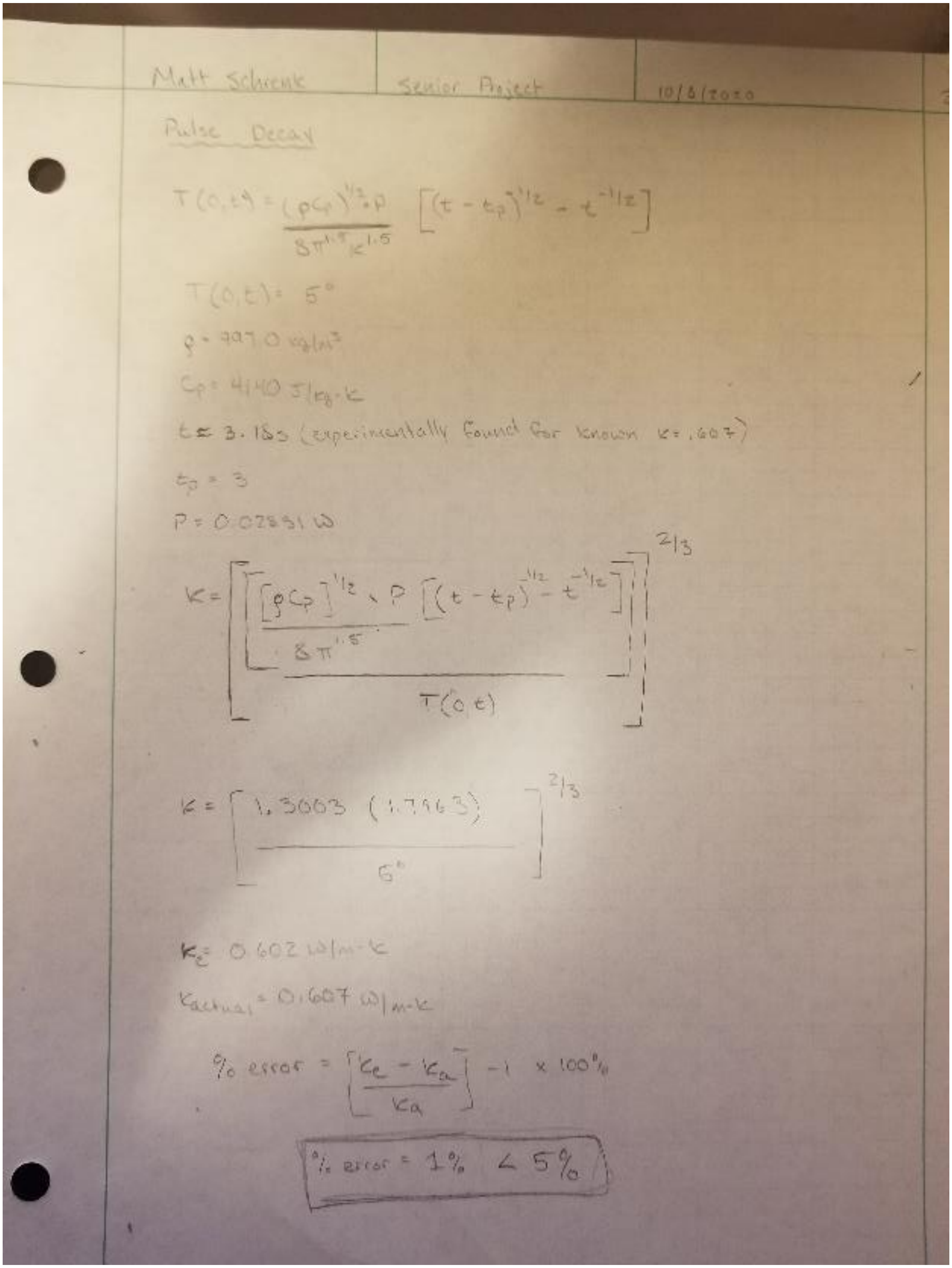
P = 0.02851 W

t = ?

T = 25°C, R = 0

P = 0

t = ?



Matt Schrenk

Senior Project

10/8/2020

Pulse Decay

$$T(0,t) = \frac{(\rho C_p)^{1/2} \cdot P}{8\pi^{1.5} k^{1.5}} \left[(t - t_p)^{-1/2} - t^{-1/2} \right]$$

$T(0,t) = 5°$

$\rho = 997.0 \ kg/m^3$

$C_p = 4140 \ J/kg \cdot K$

$t \approx 3.18s$ (experimentally found for known $k = .607$)

$t_p = 3$

$P = 0.02831 \ W$

$$k = \left[\frac{\left[\frac{[\rho C_p]^{1/2} \cdot P \left[(t - t_p)^{-1/2} - t^{-1/2} \right]}{8\pi^{1.5}} \right]}{T(0,t)} \right]^{2/3}$$

$$k = \left[\frac{1.3003 \ (1.7963)}{5°} \right]^{2/3}$$

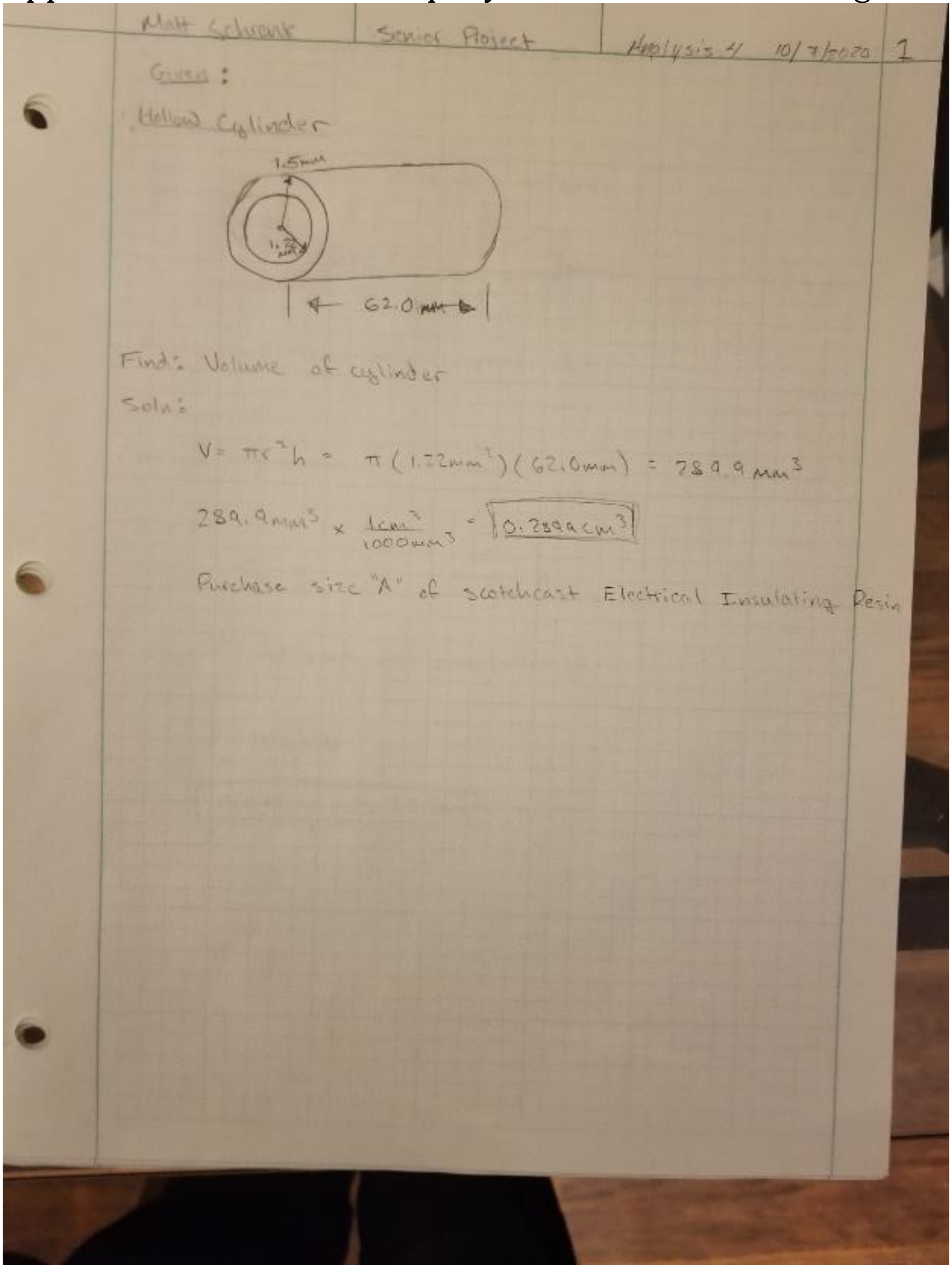
$k_e = 0.602 \ W/m \cdot K$

$k_{actual} = 0.607 \ W/m \cdot K$

$$\% \ error = \left[\frac{k_e - k_a}{k_a} \right] - 1 \times 100\%$$

$$\boxed{\% \ error = 1\% < 5\%}$$

Appendix A-4 – Failure of Epoxy on Thermistor Housing



Matt Schrank	Senior Project	Analysis 4 10/7/2020	1

Given :

Hollow Cylinder

1.5mm

1.22 mm

62.0 mm

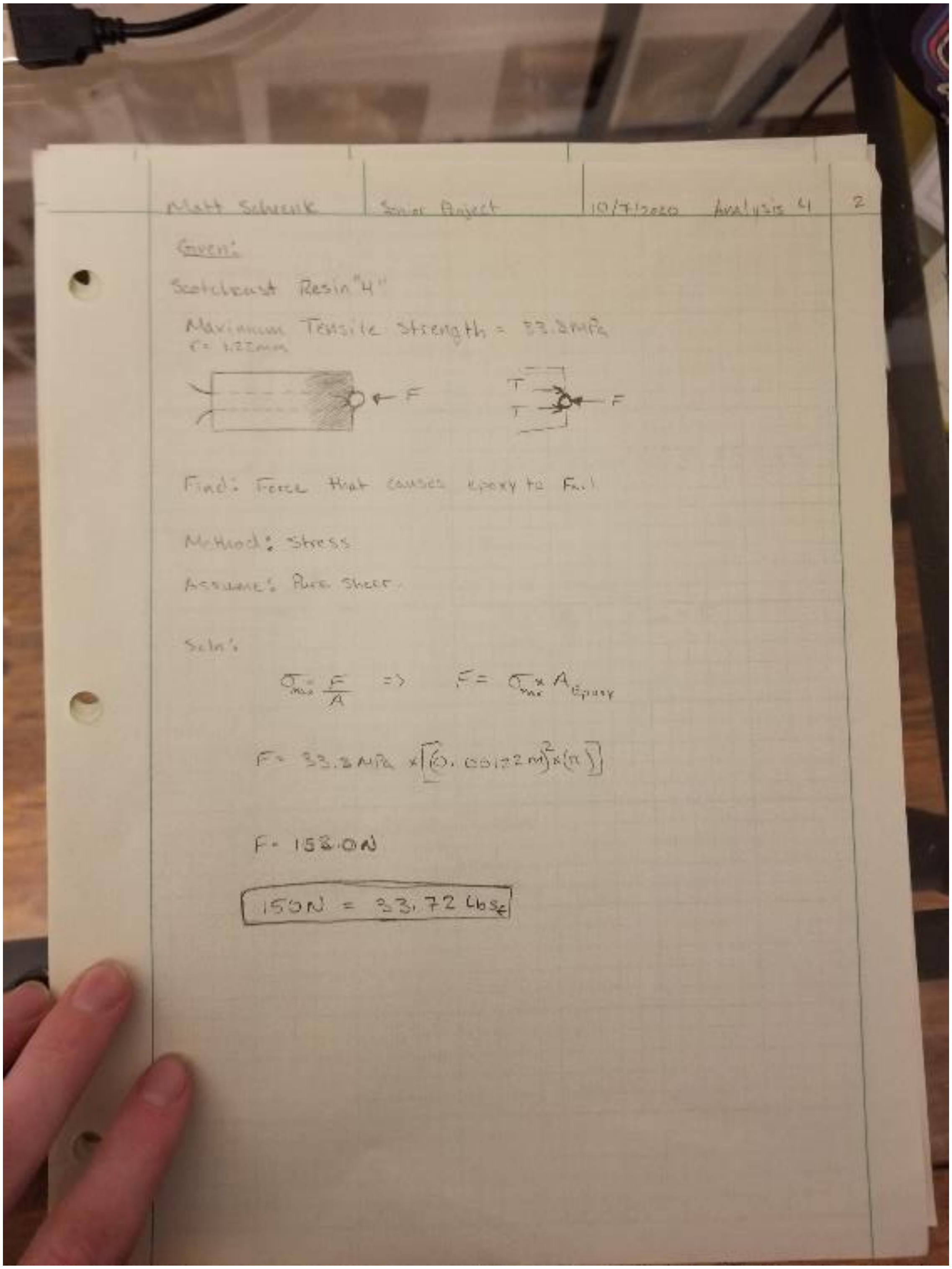
Find: Volume of cylinder

Soln:

$$V = \pi r^2 h = \pi (1.22mm^2)(62.0mm) = 289.9 mm^3$$

$$289.9mm^3 \times \frac{1cm^3}{1000mm^3} = \boxed{0.2899cm^3}$$

Purchase size "A" of scotchcast Electrical Insulating Resin



Matt Schwenk | Senior Project | 10/7/2020 Analysis 4 | 2

Given:

Scotchcast Resin "4"

Maximum Tensile Strength = 33.8MPa
$r = 1.22mm$

Find: Force that causes epoxy to Fail

Method: Stress

Assume: Pure Shear.

Soln:

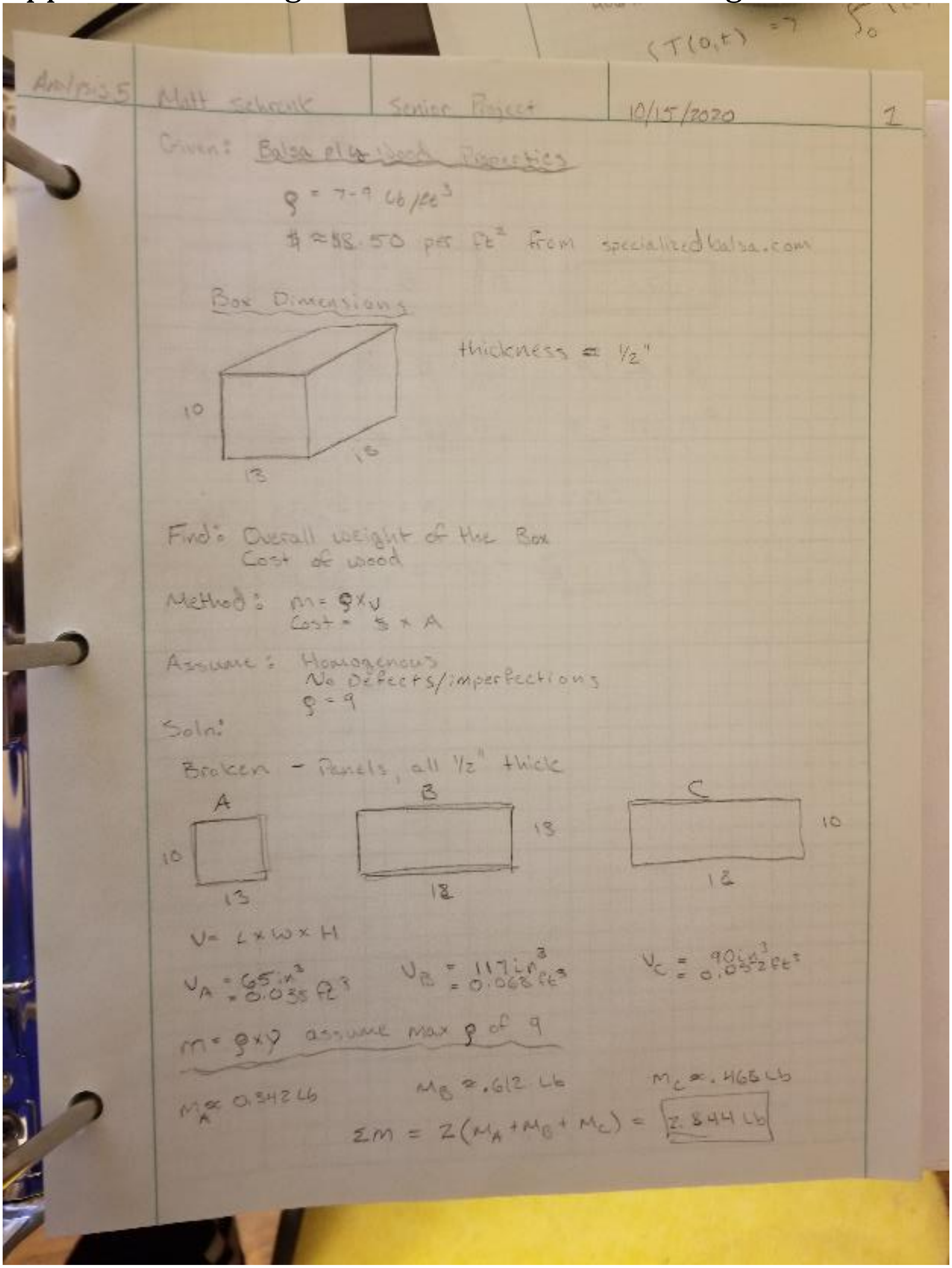
$$\sigma_{max} = \frac{F}{A} \Rightarrow F = \sigma_{max} \times A_{Epoxy}$$

$$F = 33.8MPa \times \left[(0.00122m)^2 \times (\pi)\right]$$

$$F = 158.0N$$

$$\boxed{150N = 33.72\ lbs_f}$$

Appendix A-5 Weight and Cost of Balsa Housing



Analysis 5 | Matt Schrunk | Senior Project | 10/15/2020 | 1

Given: Balsa ply wood Properties

ρ = 7-9 Lb/ft^3

\$ ≈ \$8.50 per ft^2 from specializedbalsa.com

Box Dimensions

thickness = ½"

10
13
18

Find: Overall weight of the Box
Cost of wood

Method: $m = \rho \times v$
Cost = \$ × A

Assume: Homogenous
No Defects/imperfections
$\rho = 9$

Soln:

Broken - Panels, all ½" thick

A
10
13

B
13
18

C
10
18

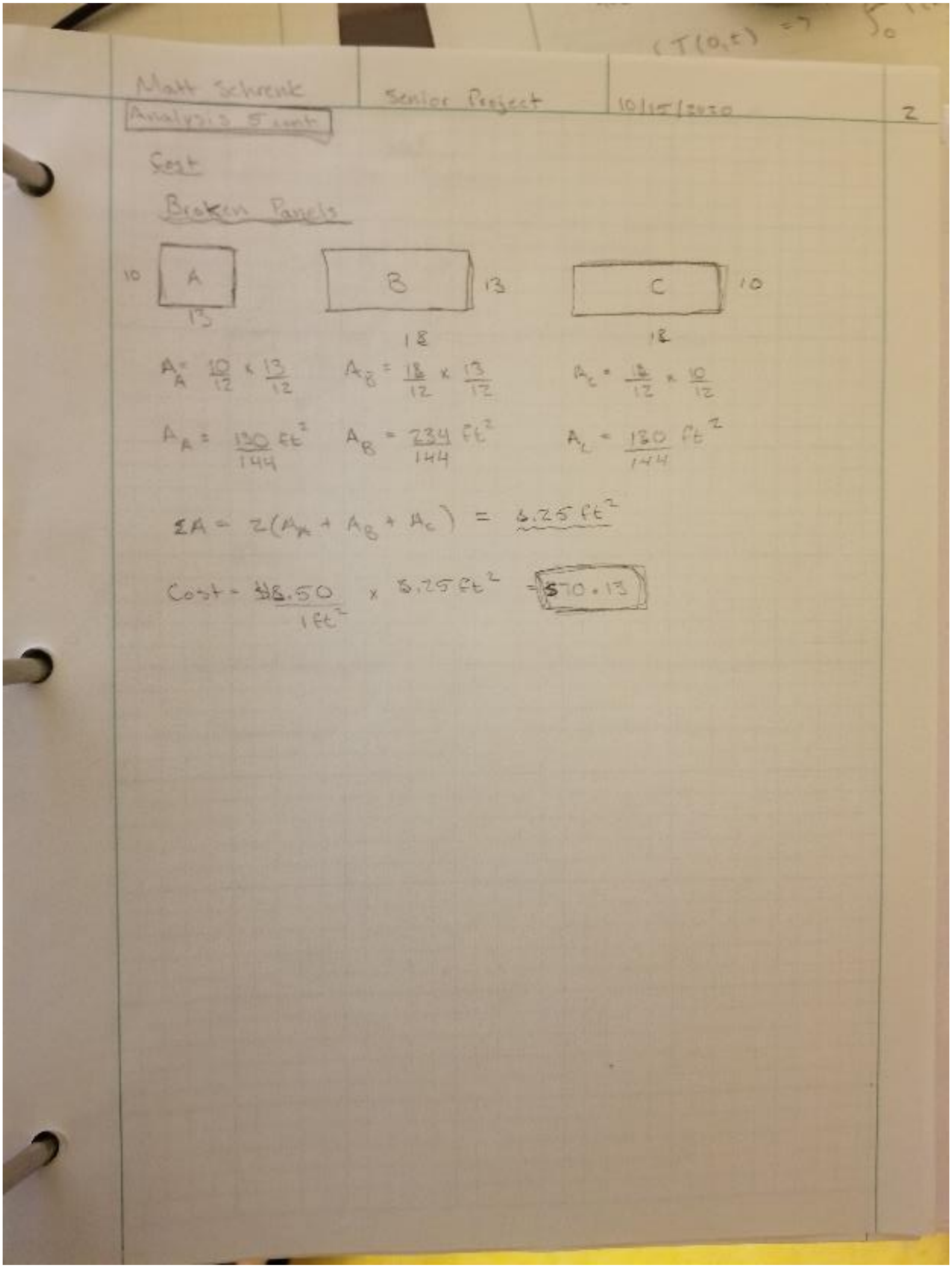
$V = L \times W \times H$

$V_A = 65 in^3 = 0.035 ft^3$ $V_B = 117 in^3 = 0.068 ft^3$ $V_C = 90 in^3 = 0.052 ft^3$

$m = \rho \times v$ assume max ρ of 9

$M_A \approx 0.342 Lb$ $M_B \approx .612 Lb$ $M_C \approx .465 Lb$

$$\Sigma m = 2(M_A + M_B + M_C) = \boxed{2.844 Lb}$$



Matt Schrenk | Senior Project | 10/15/2020 | 2

Analysis 5 cont

Cost

Broken Panels

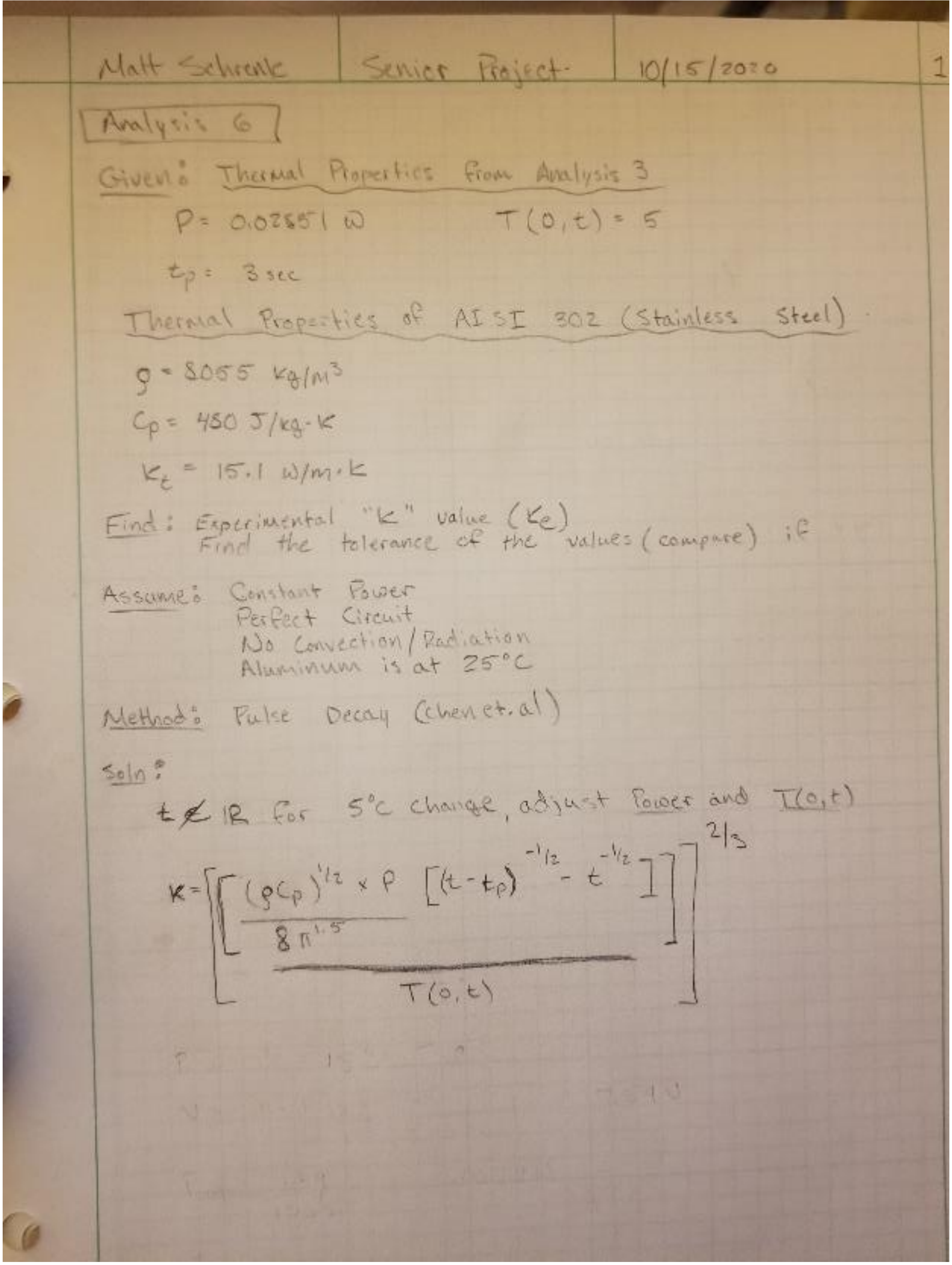
$A_A = \frac{10}{12} \times \frac{13}{12}$ $A_B = \frac{18}{12} \times \frac{13}{12}$ $A_C = \frac{18}{12} \times \frac{10}{12}$

$A_A = \frac{130}{144} ft^2$ $A_B = \frac{234}{144} ft^2$ $A_C = \frac{180}{144} ft^2$

$\Sigma A = 2(A_A + A_B + A_C) = 8.25 ft^2$

$Cost = \frac{\$8.50}{1 ft^2} \times 8.25 ft^2 = \boxed{\$70.13}$

Appendix A-6 Tolerance Value of AISI 302



Matt Schrenk | Senior Project | 10/15/2020 | 1

Analysis 6

Given: Thermal Properties from Analysis 3

$P = 0.02851\ W$ $\quad T(0,t) = 5$

$t_p = 3\ sec$

Thermal Properties of AISI 302 (Stainless Steel)

$\rho = 8055\ kg/m^3$

$C_p = 450\ J/kg\cdot K$

$k_t = 15.1\ W/m\cdot K$

Find: Experimental "k" value (k_e)
Find the tolerance of the values (compare) if

Assume: Constant Power
Perfect Circuit
No Convection/Radiation
Aluminum is at 25°C

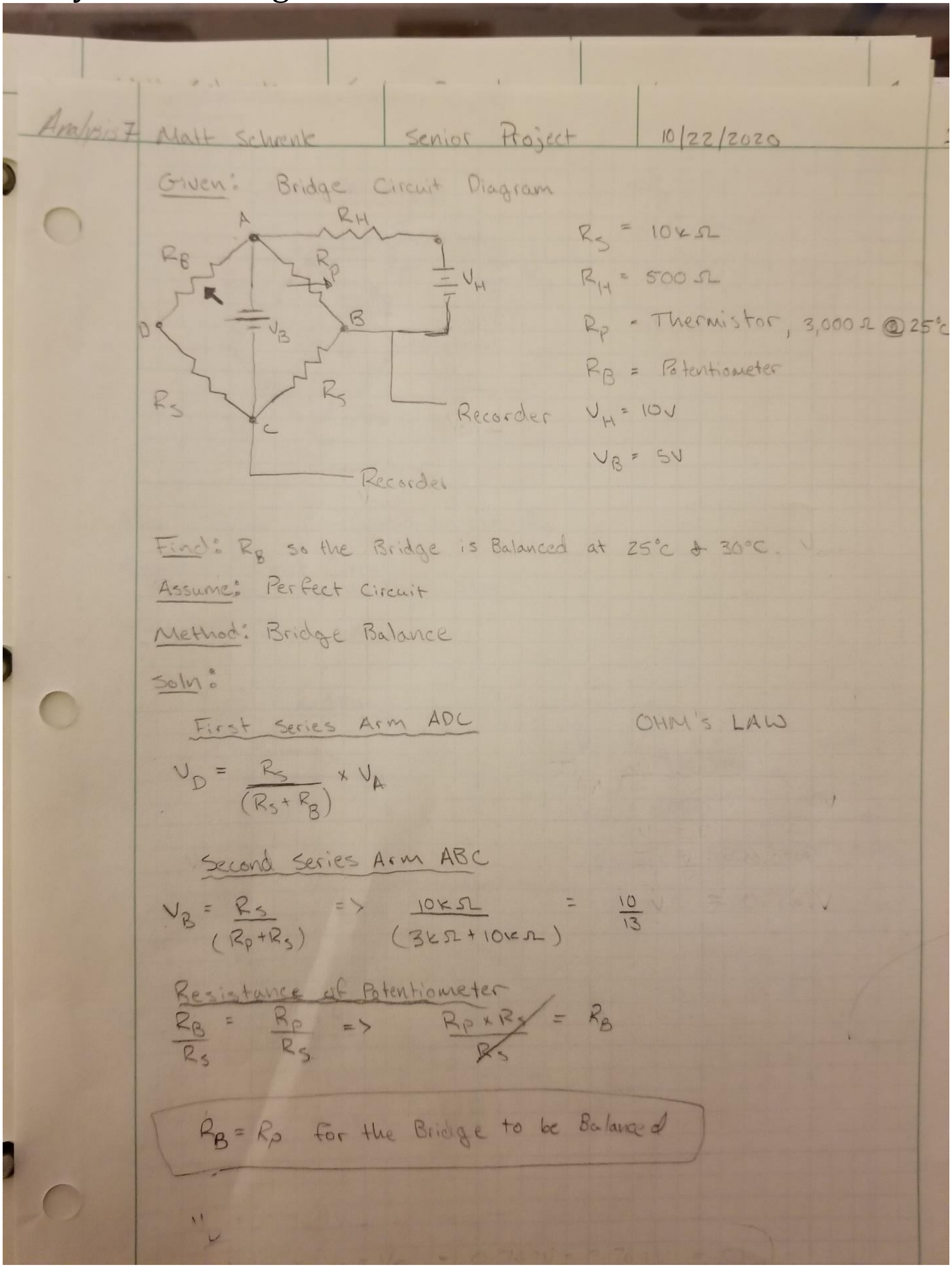
Method: Pulse Decay (chen et. al)

Soln:

$t \not\in \mathbb{R}$ for 5°C change, adjust Power and $T(0,t)$

$$k = \left[\frac{ \left[\frac{(\rho C_p)^{1/2} \times P}{8\pi^{1.5}} \left[(t-t_p)^{-1/2} - t^{-1/2} \right] \right] }{T(0,t)} \right]^{2/3}$$

Analysis A-7 Bridge Circuit Resistance



Analysis 7 Matt Schrenk | Senior Project | 10/22/2020

Given: Bridge Circuit Diagram

$R_s = 10k\Omega$

$R_H = 500\Omega$

R_p - Thermistor, $3{,}000\Omega$ @ 25°C

R_B = Potentiometer

$V_H = 10V$

$V_B = 5V$

Find: R_B so the Bridge is Balanced at 25°C & 30°C.

Assume: Perfect Circuit

Method: Bridge Balance

Soln:

First Series Arm ADC

OHM'S LAW

$$V_D = \frac{R_s}{(R_s + R_B)} \times V_A$$

Second Series Arm ABC

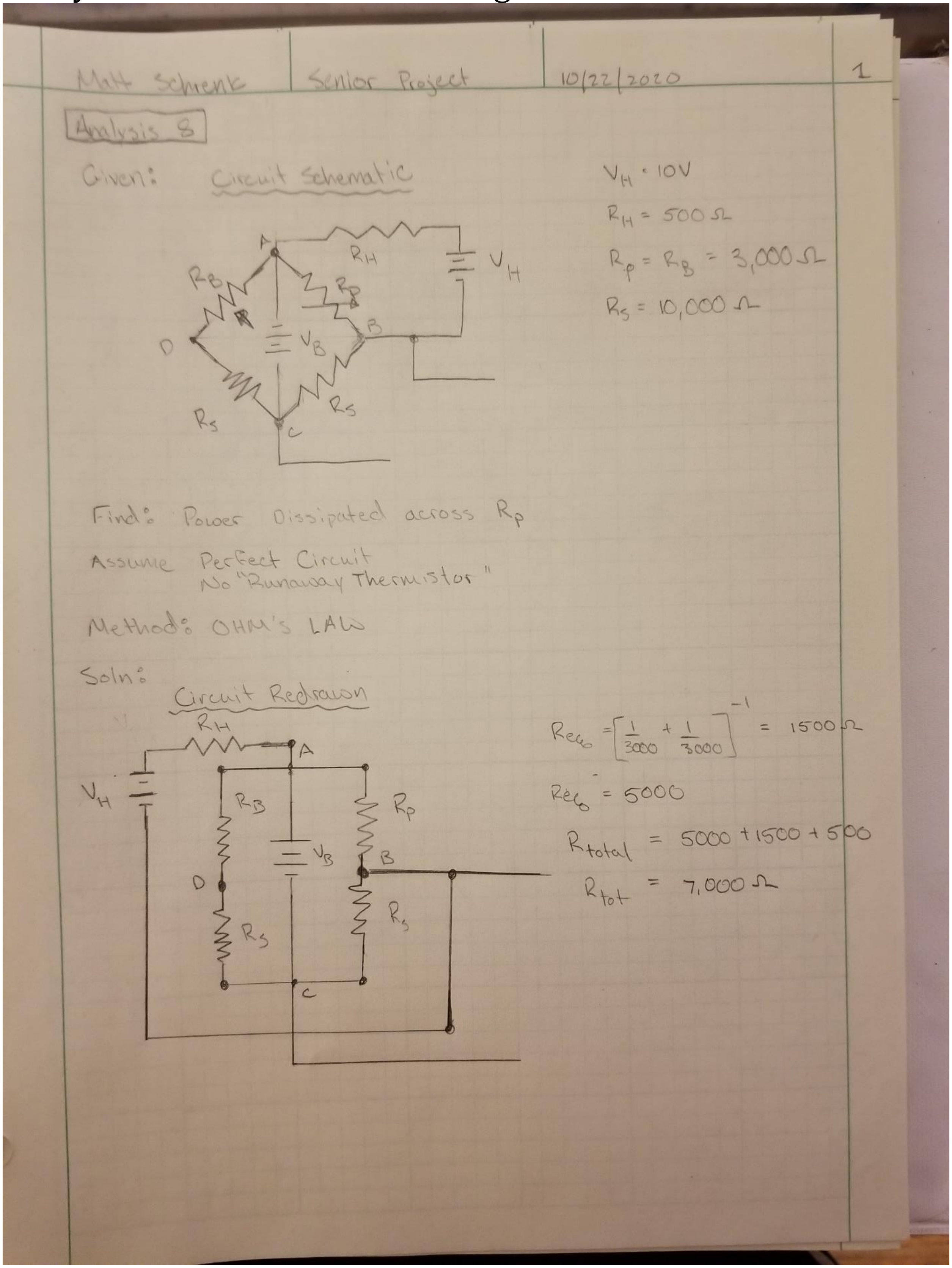
$$V_B = \frac{R_s}{(R_p + R_s)} \Rightarrow \frac{10k\Omega}{(3k\Omega + 10k\Omega)} = \frac{10}{13}$$

Resistance of Potentiometer

$$\frac{R_B}{R_s} = \frac{R_p}{R_s} \Rightarrow \frac{R_p \times \cancel{R_s}}{\cancel{R_s}} = R_B$$

$$\boxed{R_B = R_p \text{ for the Bridge to be Balanced}}$$

Analysis A-8 Power Across Bridge Circuit



Matt Schrenk | Senior Project | 10/22/2020 | 1

Analysis 8

Given: Circuit Schematic

$V_H \cdot 10V$

$R_H = 500\ \Omega$

$R_p = R_B = 3{,}000\ \Omega$

$R_S = 10{,}000\ \Omega$

Find: Power Dissipated across R_p

Assume Perfect Circuit
No "Runaway Thermistor"

Method: OHM'S LAW

Soln:

Circuit Redrawn

$$R_{eq} = \left[\frac{1}{3000} + \frac{1}{3000}\right]^{-1} = 1500\ \Omega$$

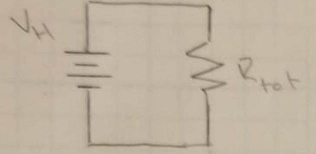
$$R_{eq} = 5000$$

$$R_{total} = 5000 + 1500 + 500$$

$$R_{tot} = 7{,}000\ \Omega$$

Analysis 8 cont

Circuit w/ R_{tot}



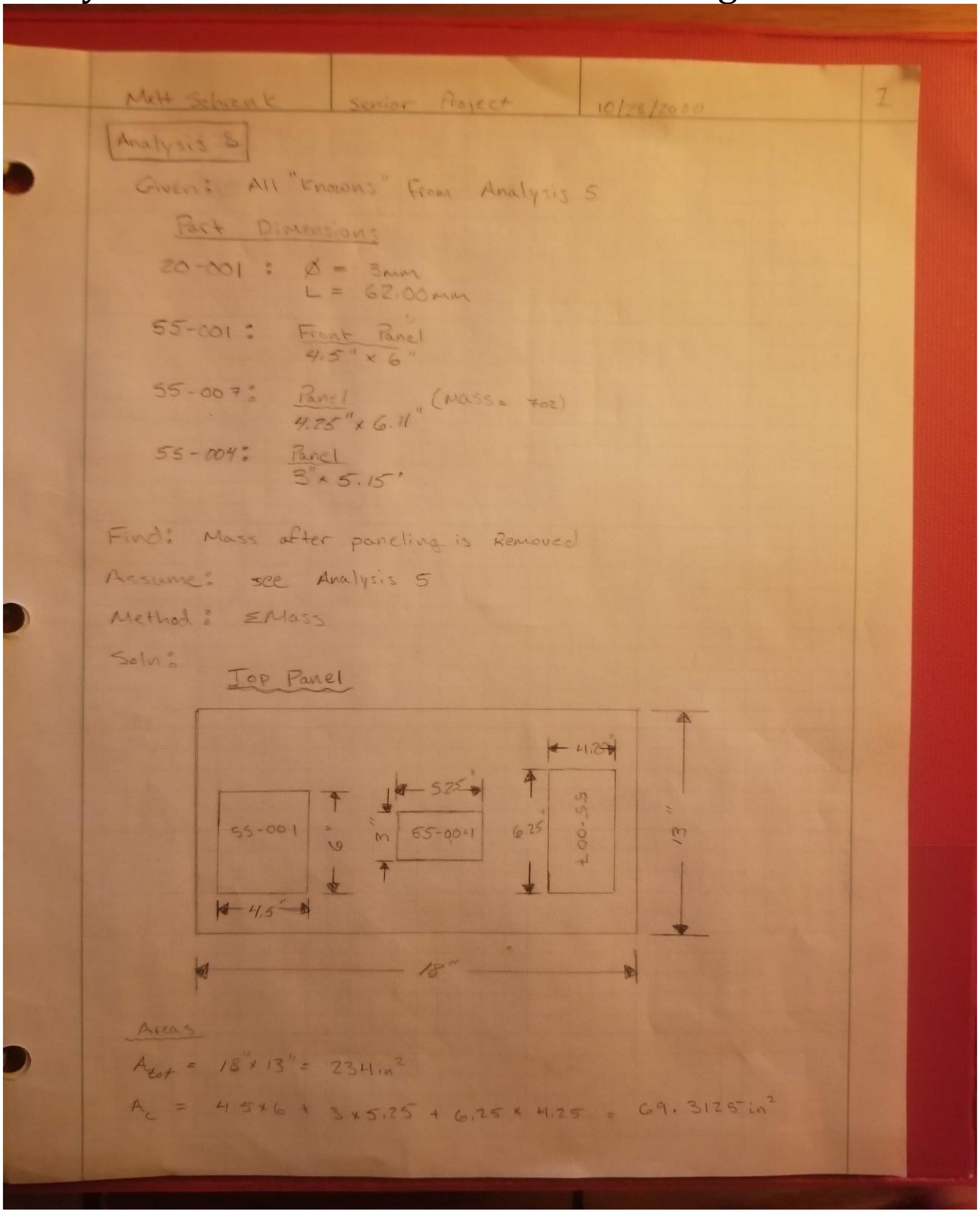
Ohm's Law

$$I'_{tot} = \frac{V_H}{R_{tot}} \Rightarrow \frac{10\,V}{7{,}000\,\Omega} = \underline{0.00143A}$$

$$I_p = \frac{R_p}{(R_p+R_B)} \times I_{tot} \Rightarrow \frac{3{,}000}{(6{,}000)} \times 0.00143 = 7.15\times10^{-4}A$$

$$\text{Power} = I^2R \Rightarrow \left[7.15\times10^{-4}A\right]^2 \times 3{,}000 = \boxed{0.00153W}$$

Analysis A-9: Mass with of Circuit Housing



Matt Schenk | Senior Project | 10/28/2020 | 1

Analysis 8

Given: All "Knowns" From Analysis 5

Part Dimensions

20-001 : $\varnothing$ = 3mm
L = 62.00mm

55-001 : Front Panel
4.5" x 6"

55-007 : Panel (Mass = 7oz)
4.25" x 6.11"

55-004 : Panel
3" x 5.15'

Find: Mass after paneling is Removed

Assume: see Analysis 5

Method : ΣMass

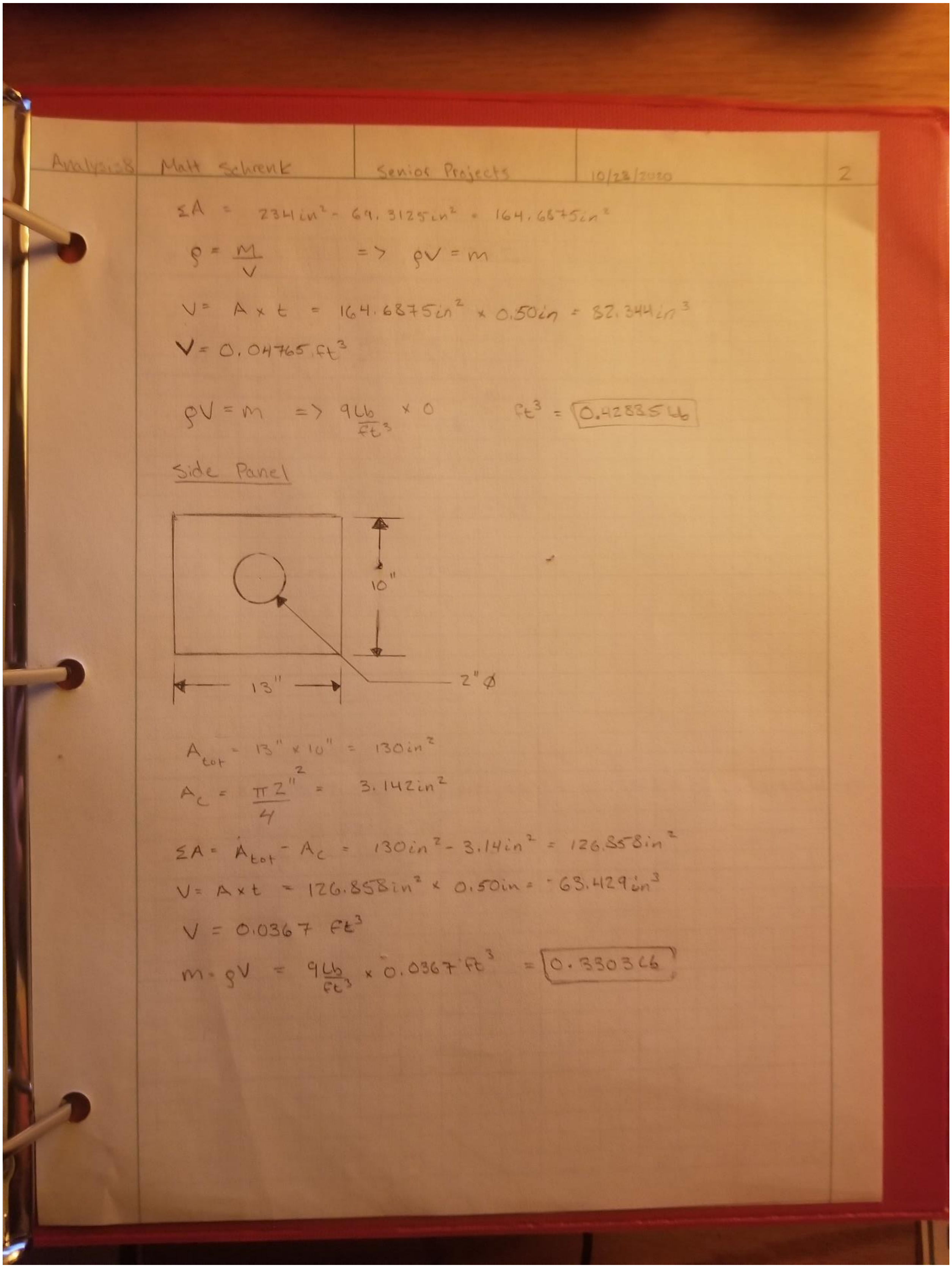
Soln :

Top Panel

Areas

A_{tot} = 18" x 13" = 234 in^2

A_c = 4.5x6 + 3x5.25 + 6.25 x 4.25 = 69.3125 in^2



Analysis 8 | Matt Schrenk | Senior Projects | 10/23/2020 | 2

$\Sigma A = 234in^2 - 69.3125in^2 = 164.6875in^2$

$\rho = \frac{M}{V} \Rightarrow \rho V = m$

$V = A \times t = 164.6875in^2 \times 0.50in = 82.344in^3$

$V = 0.04765 ft^3$

$\rho V = m \Rightarrow 9\frac{lb}{ft^3} \times 0 \quad ft^3 = \boxed{0.42835 lb}$

Side Panel

$A_{tot} = 13" \times 10" = 130in^2$

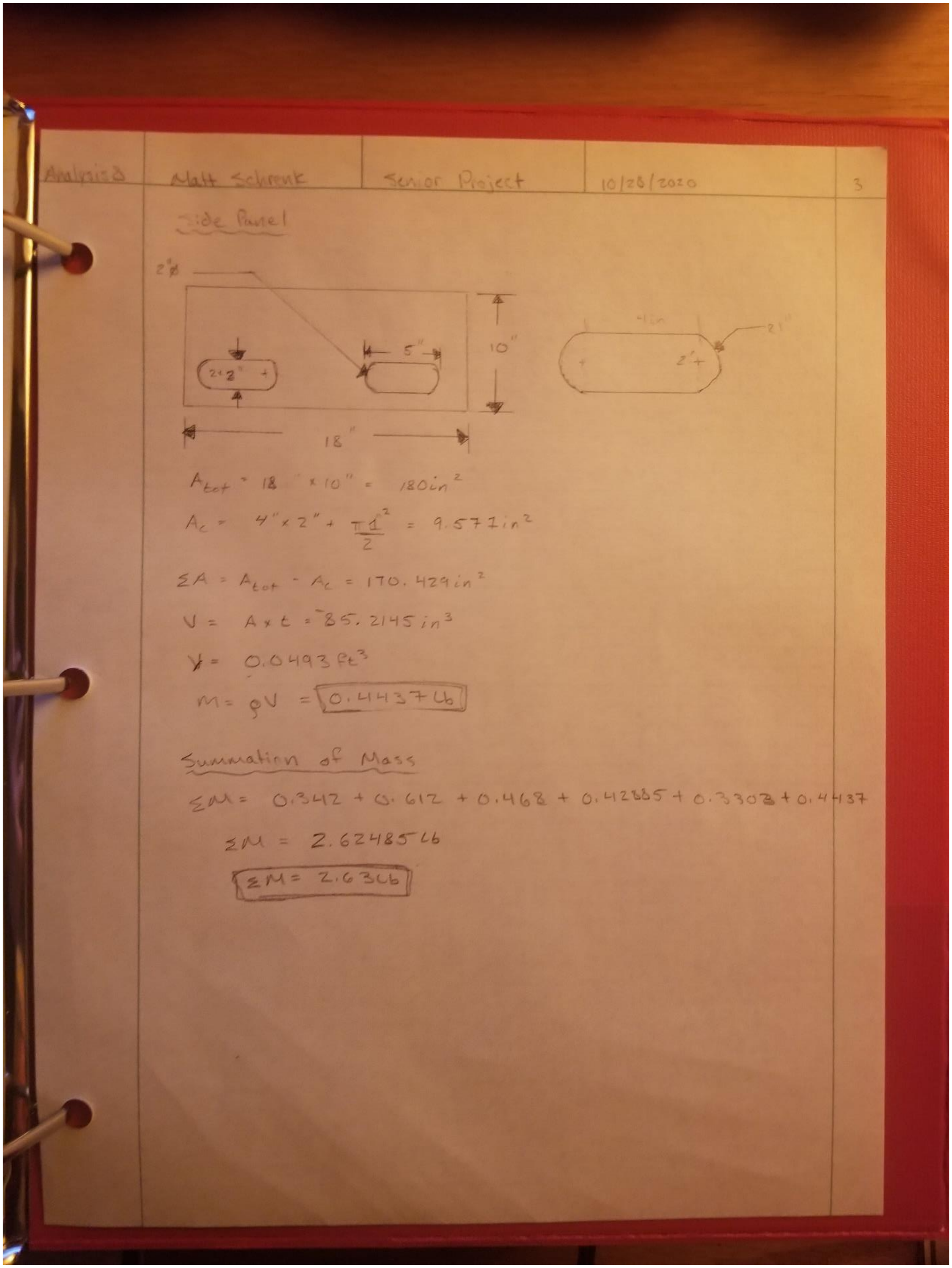
$A_c = \frac{\pi 2"^2}{4} = 3.142in^2$

$\Sigma A = A_{tot} - A_c = 130in^2 - 3.14in^2 = 126.858in^2$

$V = A \times t = 126.858in^2 \times 0.50in = 63.429in^3$

$V = 0.0367 ft^3$

$m = \rho V = 9\frac{lb}{ft^3} \times 0.0367 ft^3 = \boxed{0.3303 lb}$



Analysis 8	Matt Schrenk	Senior Project	10/28/2020	3

Side Panel

$A_{tot} = 18" \times 10" = 180 in^2$

$A_c = 4" \times 2" + \frac{\pi 1^2}{2} = 9.5717 in^2$

$\Sigma A = A_{tot} - A_c = 170.429 in^2$

$V = A \times t = \tilde{} 85.2145 in^3$

$V = 0.0493 ft^3$

$m = \rho V = \boxed{0.4437 lb}$

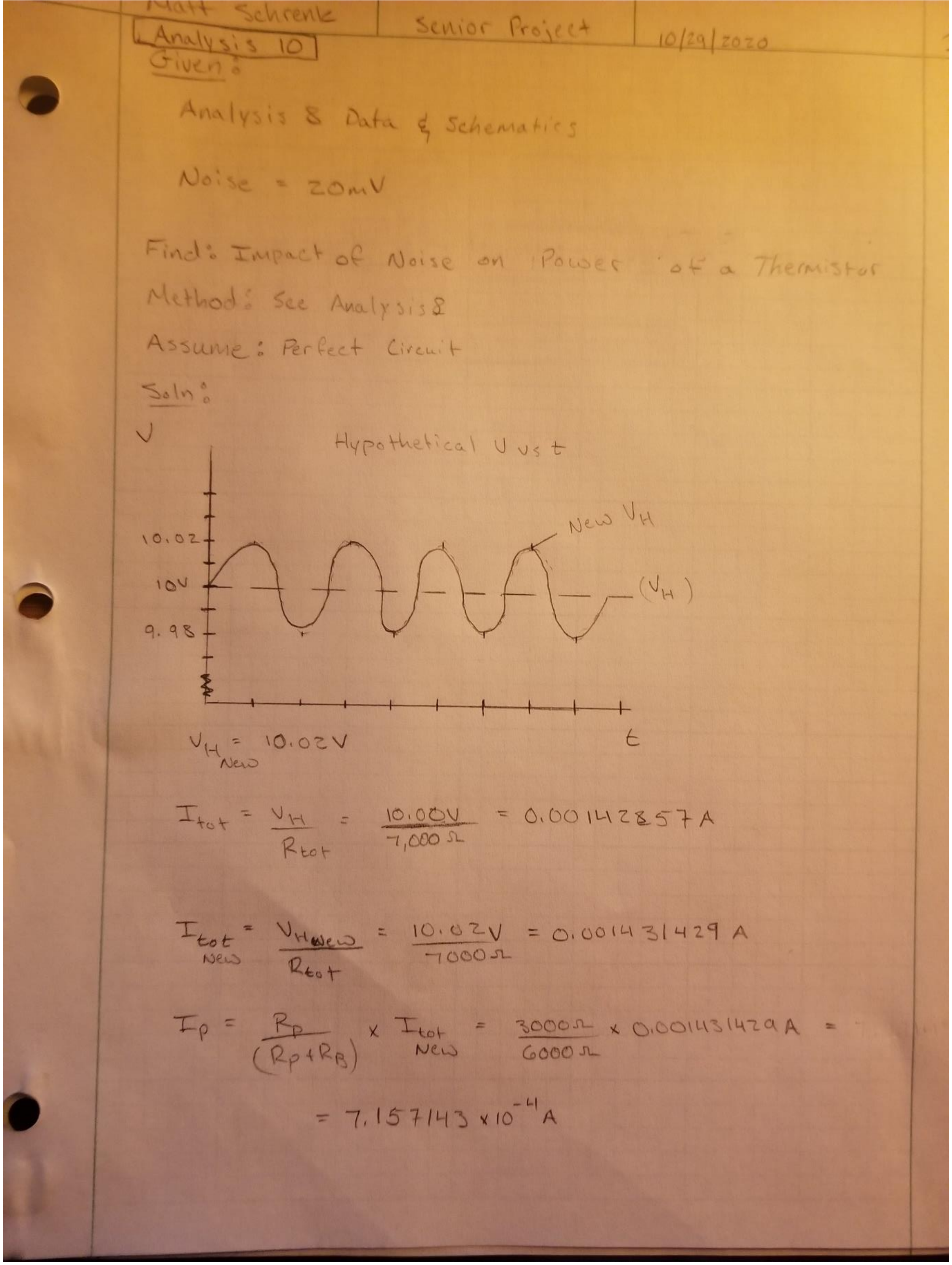
Summation of Mass

$\Sigma M = 0.342 + 0.612 + 0.468 + 0.42885 + 0.3303 + 0.4437$

$\Sigma M = 2.62485 lb$

$\boxed{\Sigma M = 2.63 lb}$

Analysis A-10: Noise Calibration



Matt Schrenk | Senior Project | 10/29/2020

Analysis 10

Given:

Analysis 8 Data & Schematics

Noise = 20mV

Find: Impact of Noise on Power of a Thermistor

Method: See Analysis 8

Assume: Perfect Circuit

Soln:

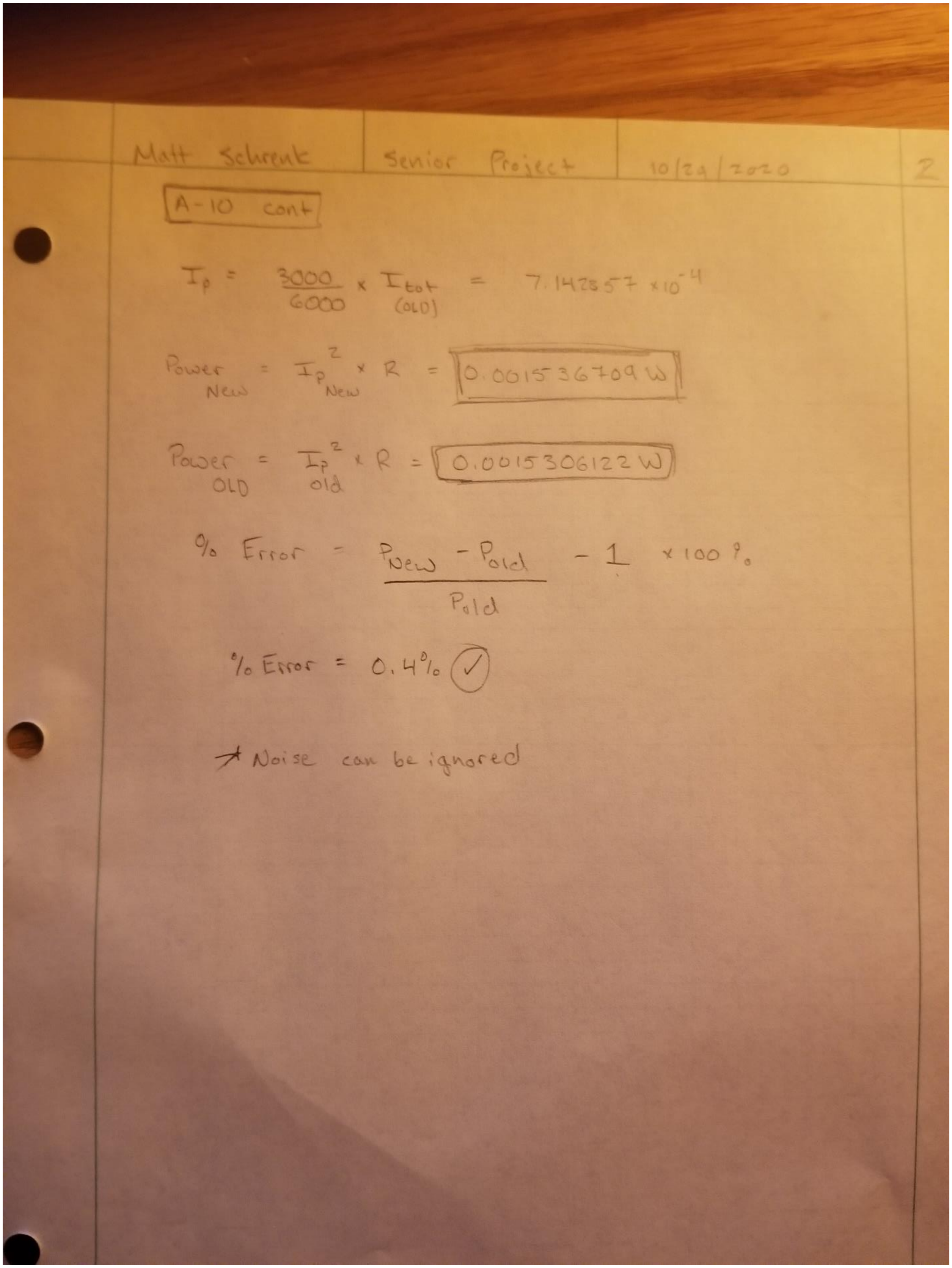
$V_{H_{New}} = 10.02V$

$$I_{tot} = \frac{V_H}{R_{tot}} = \frac{10.00V}{7{,}000\,\Omega} = 0.00142857A$$

$$I_{tot_{New}} = \frac{V_{H_{New}}}{R_{tot}} = \frac{10.02V}{7000\,\Omega} = 0.001431429\ A$$

$$I_p = \frac{R_p}{(R_p + R_B)} \times I_{tot_{New}} = \frac{3000\,\Omega}{6000\,\Omega} \times 0.001431429A =$$

$$= 7.157143 \times 10^{-4} A$$



Matt Schrenk | Senior Project | 10/24/2020 | 2

$\boxed{\text{A-10 cont}}$

$$I_p = \frac{3000}{6000} \times I_{tot_{(OLD)}} = 7.142857 \times 10^{-4}$$

$$Power_{New} = I_{p_{New}}^2 \times R = \boxed{0.001536709\,W}$$

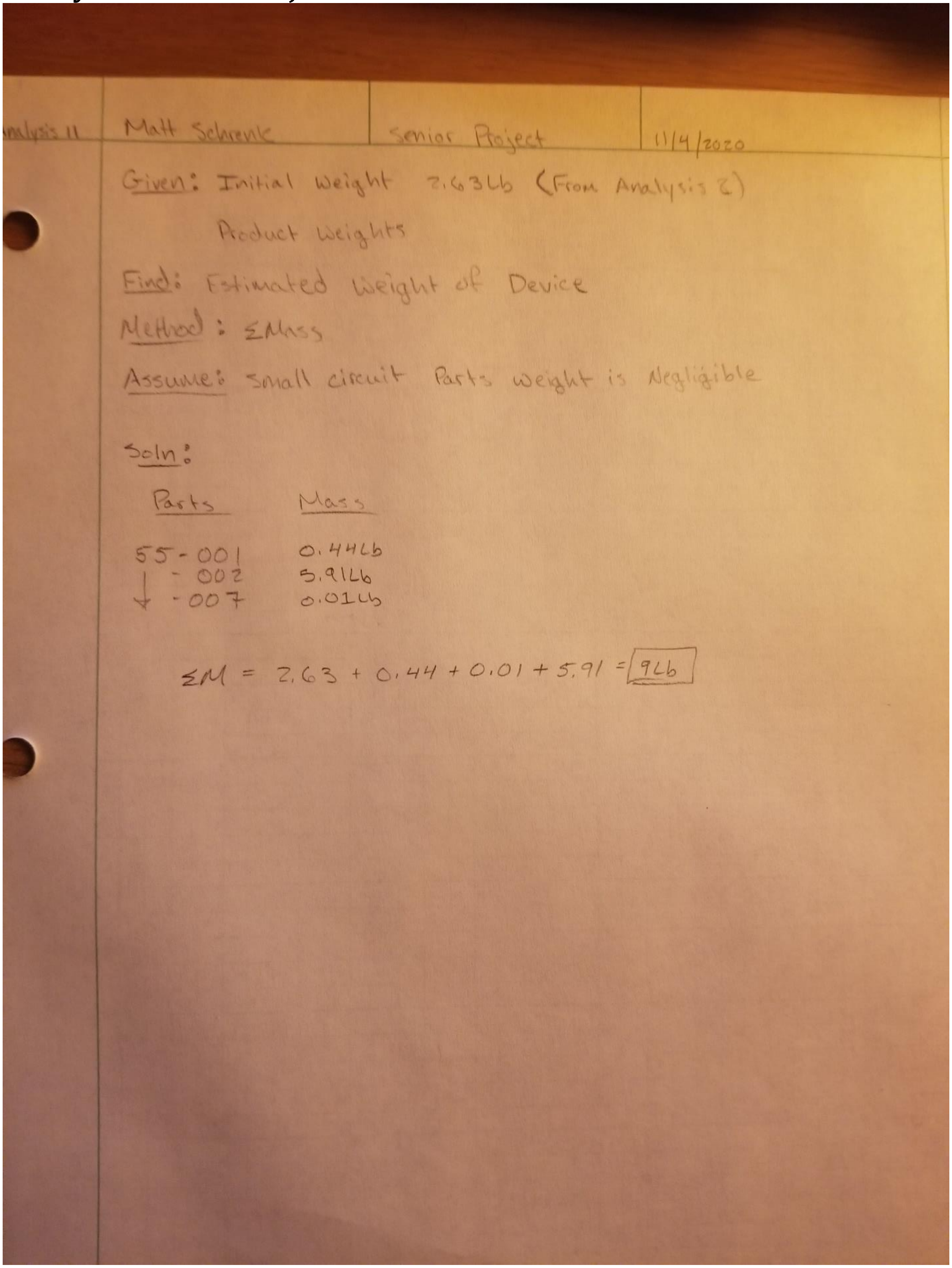
$$Power_{OLD} = I_{p_{old}}^2 \times R = \boxed{0.0015306122\,W}$$

$$\%\ Error = \frac{P_{New} - P_{old}}{P_{old}} - 1 \times 100\%$$

$$\%\ Error = 0.4\%$$ ✓

* Noise can be ignored

Analysis A-11: Projected Mass



nalysis 11 | Matt Schrenk | Senior Project | 11/4/2020

Given: Initial weight 2.63Lb (From Analysis 2)

Product Weights

Find: Estimated Weight of Device

Method: ΣMass

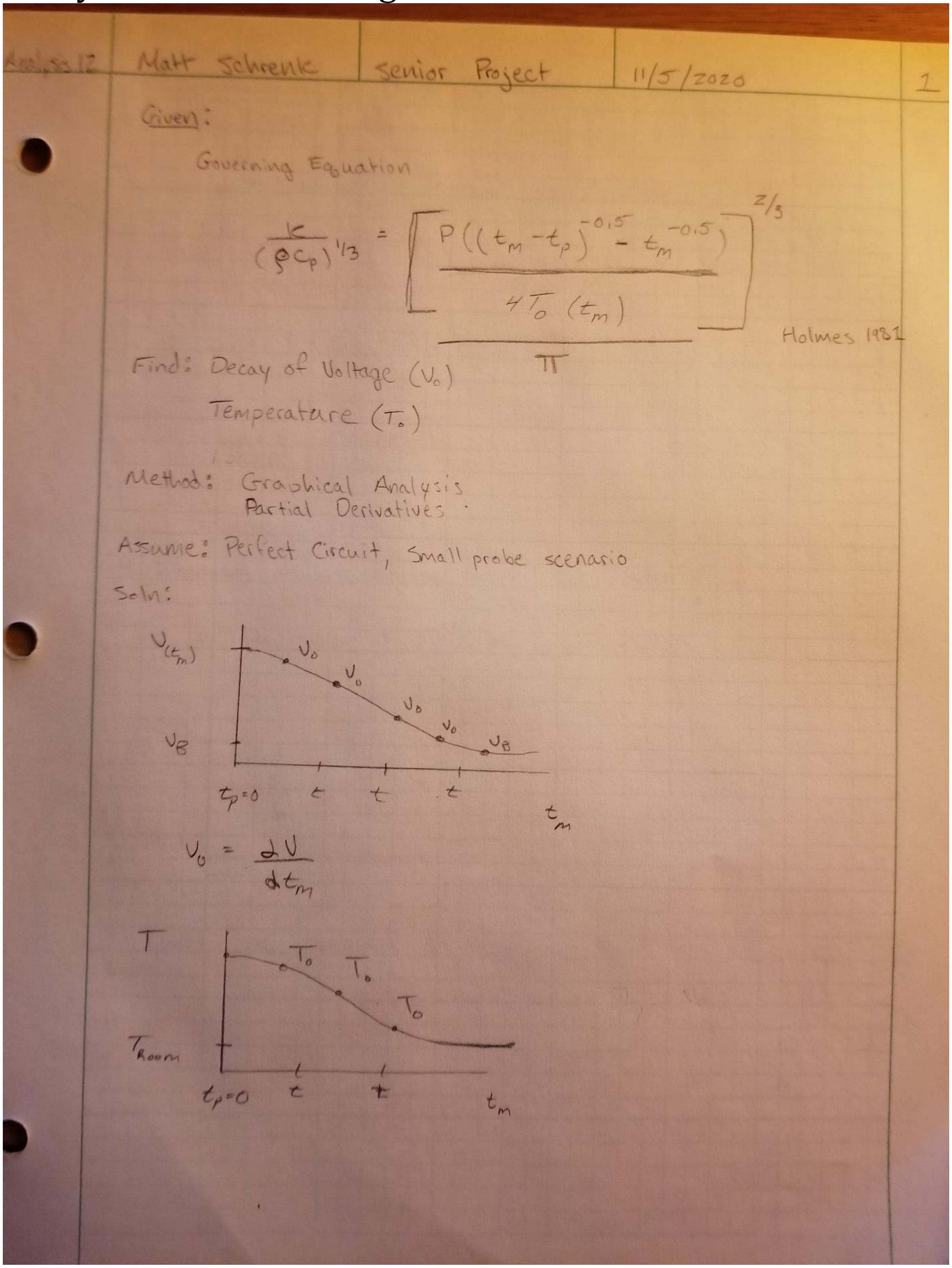
Assume: small circuit Parts weight is Negligible

Soln:

Parts	Mass
55-001	0.44Lb
↓ -002	5.91Lb
-007	0.01Lb

$$\Sigma M = 2.63 + 0.44 + 0.01 + 5.91 = \boxed{9Lb}$$

Analysis A-12 Obtaining Resistance as a Function of Time



Analysis 12 | Matt Schrenk | Senior Project | 11/5/2020 | 1

Given:

Governing Equation

$$\frac{k}{(\rho c_p)^{1/3}} = \left[\frac{\frac{P((t_m - t_p)^{-0.5} - t_m^{-0.5})}{4T_0(t_m)}}{\pi}\right]^{2/3}$$

Holmes 1981

Find: Decay of Voltage (V_0)

Temperature (T_0)

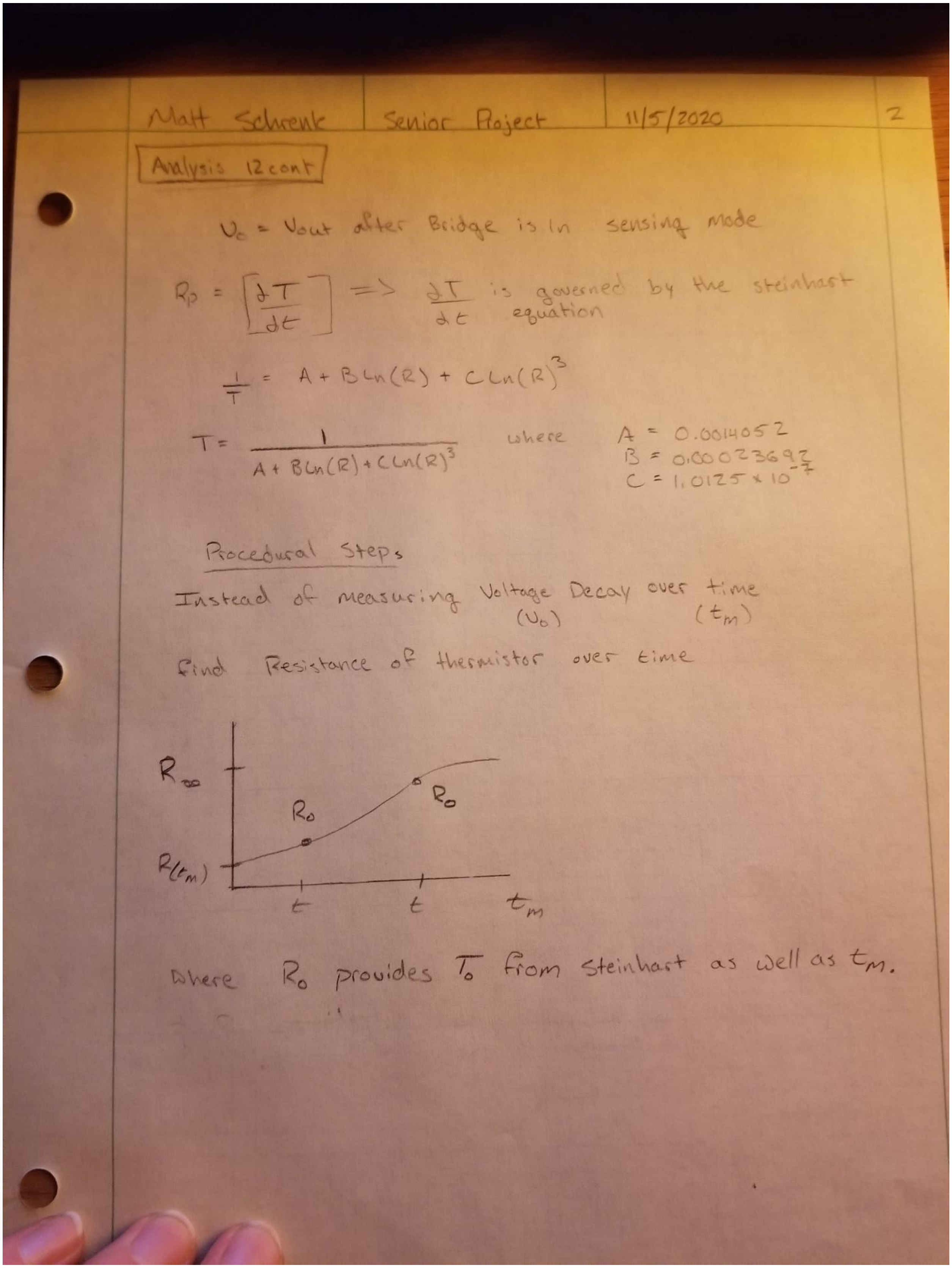
Method: Graphical Analysis

Partial Derivatives

Assume: Perfect Circuit, Small probe scenario

Soln:

$$V_0 = \frac{dV}{dt_m}$$



Matt Schrenk | Senior Project | 11/5/2020 | 2

Analysis 12 cont

V_o = V_{out} after Bridge is in sensing mode

$R_p = \left[\frac{\partial T}{\partial t}\right] \Rightarrow \frac{\partial T}{\partial t}$ is governed by the steinhart equation

$$\frac{1}{T} = A + B\ln(R) + C\ln(R)^3$$

$$T = \frac{1}{A + B\ln(R) + C\ln(R)^3}$$ where

$A = 0.0014052$
$B = 0.00023692$
$C = 1.0125 \times 10^{-7}$

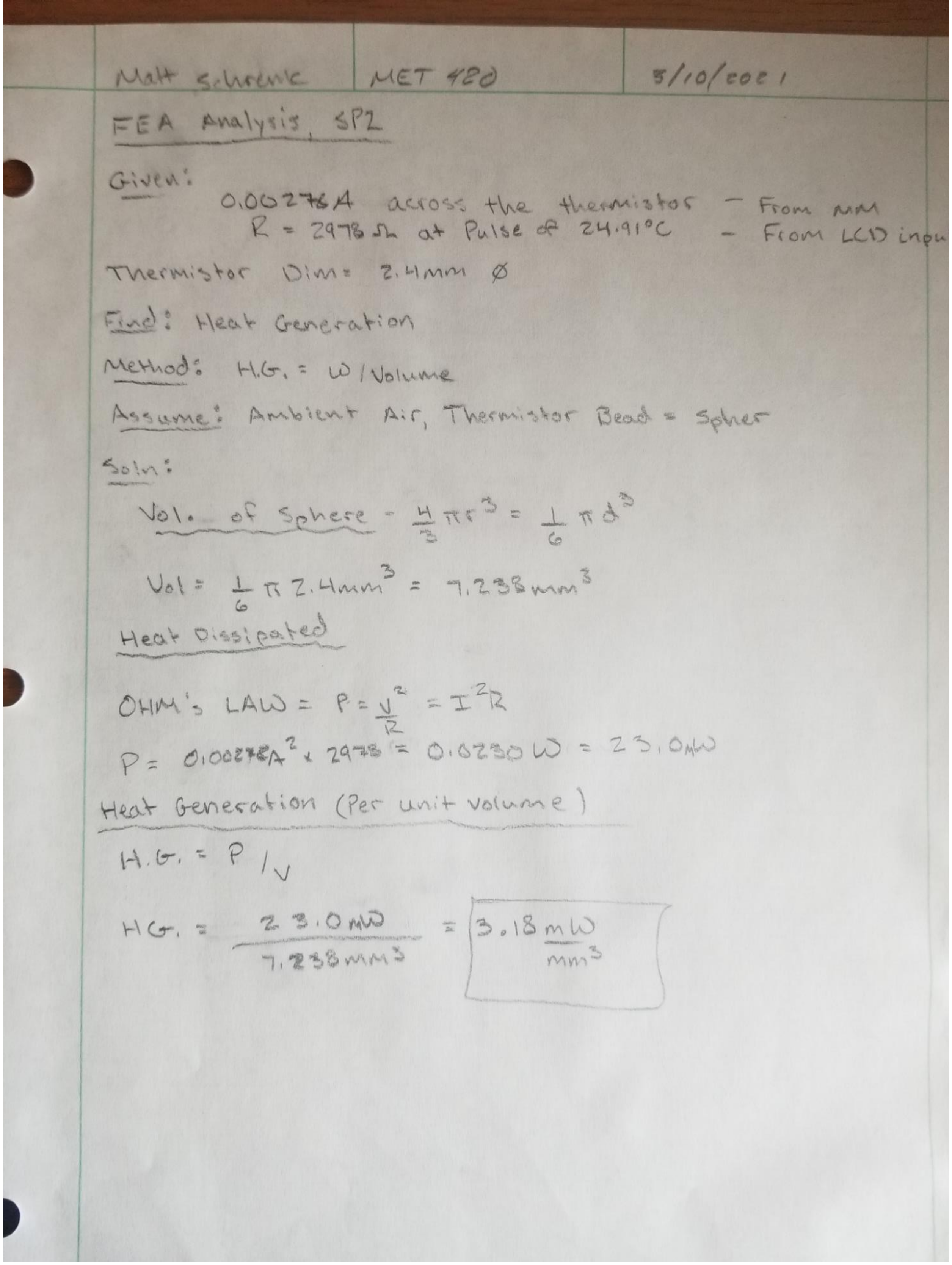
Procedural Steps

Instead of measuring Voltage Decay over time
(V_o) (t_m)

Find Resistance of thermistor over time

Where R_o provides T_o from Steinhart as well as t_m.

Appendix A13 – New Dissipation of Heat on Thermistor



Matt Schrenk | MET 420 | 3/10/2021

FEA Analysis, SP2

Given:

0.00278A across the thermistor – From MM
$R = 2978\,\Omega$ at Pulse of 24.91°C – From LCD inpu

Thermistor Dim = 2.4mm Ø

Find: Heat Generation

Method: H.G. = W / Volume

Assume: Ambient Air, Thermistor Bead = Spher

Soln:

Vol. of Sphere $= \frac{4}{3}\pi r^3 = \frac{1}{6}\pi d^3$

$$Vol = \frac{1}{6}\pi\, 2.4\text{mm}^3 = 7.238\,\text{mm}^3$$

Heat Dissipated

$$\text{OHM's LAW} = P = \frac{V^2}{R} = I^2R$$

$$P = 0.00278A^2 \times 2978 = 0.0230\,W = 23.0\,mW$$

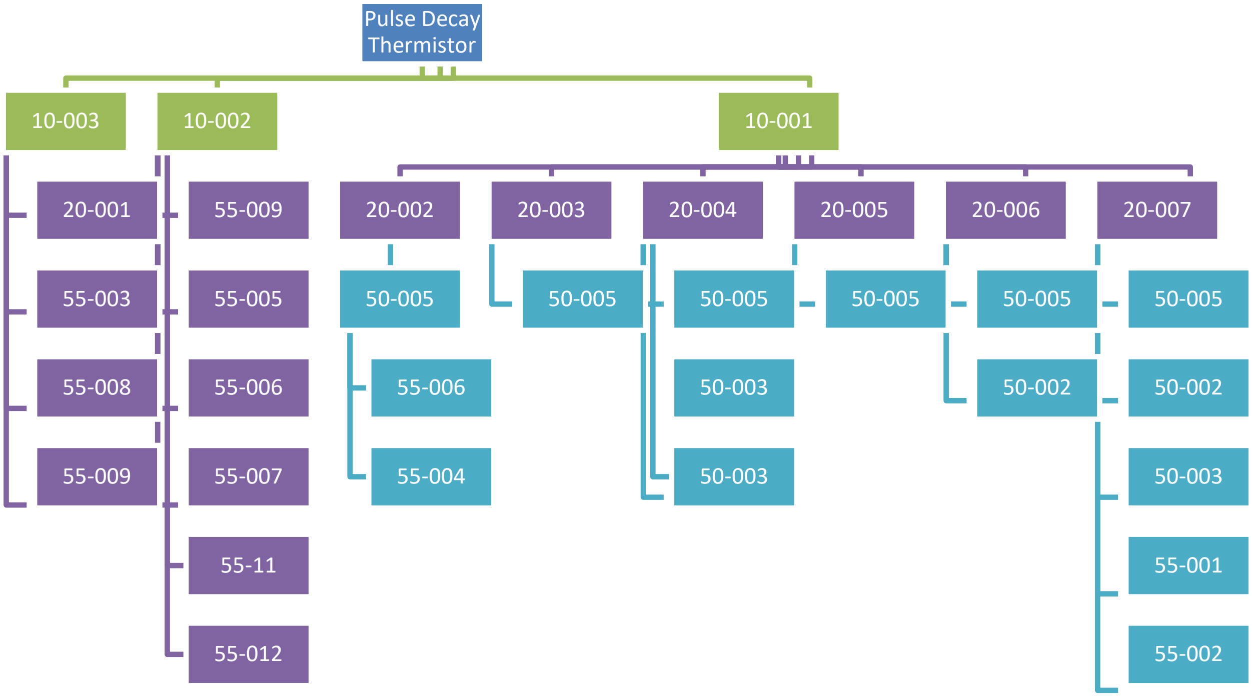
Heat Generation (Per unit volume)

$$H.G. = P/V$$

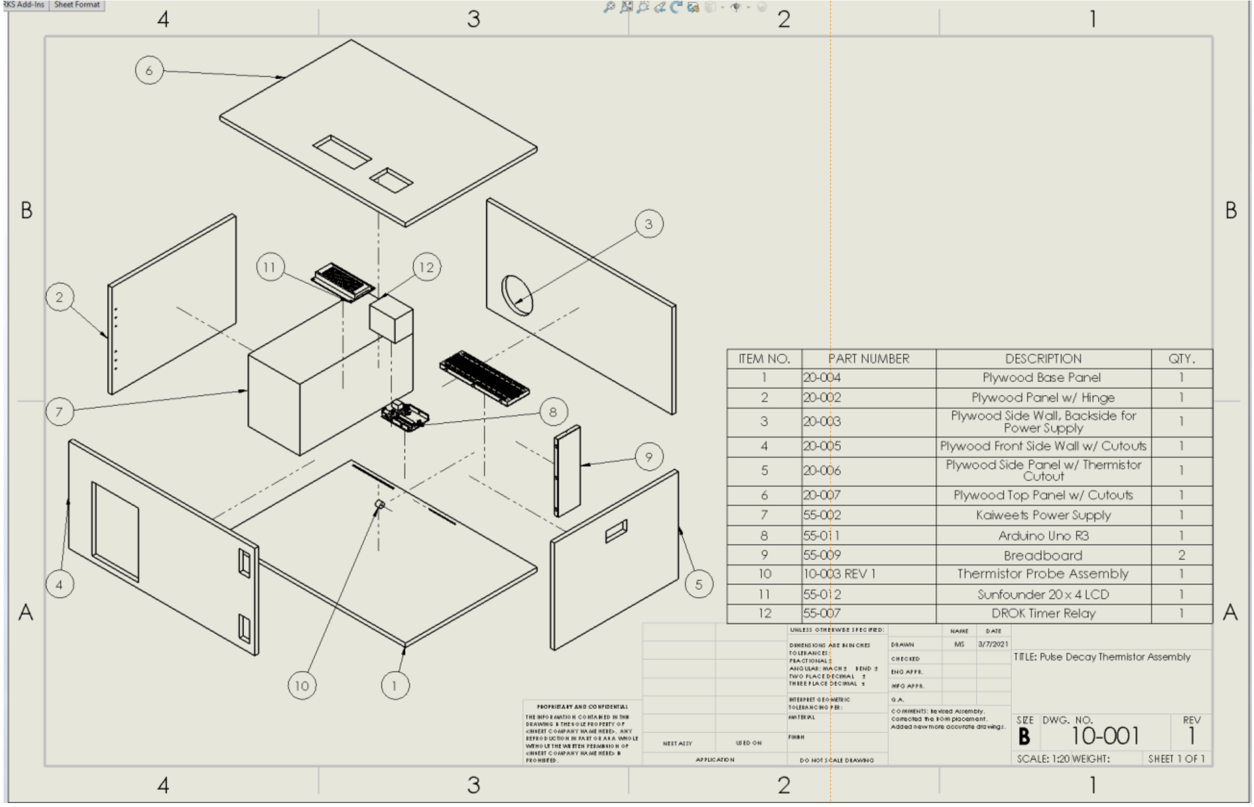
$$H.G. = \frac{23.0\,mW}{7.238\,mm^3} = \boxed{3.18\,\frac{mW}{mm^3}}$$

APPENDIX B – Drawings

Appendix B- Drawing Tree



Appendix B- 10-001



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	20-004	Plywood Base Panel	1
2	20-002	Plywood Panel w/ Hinge	1
3	20-003	Plywood Side Wall, Backside for Power Supply	1
4	20-005	Plywood Front Side Wall w/ Cutouts	1
5	20-006	Plywood Side Panel w/ Thermistor Cutout	1
6	20-007	Plywood Top Panel w/ Cutouts	1
7	55-002	Kaiweets Power Supply	1
8	55-011	Arduino Uno R3	1
9	55-009	Breadboard	2
10	10-003 REV 1	Thermistor Probe Assembly	1
11	55-012	Sunfounder 20 x 4 LCD	1
12	55-007	DROK Timer Relay	1

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NEXT ASSY
USED ON
APPLICATION

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

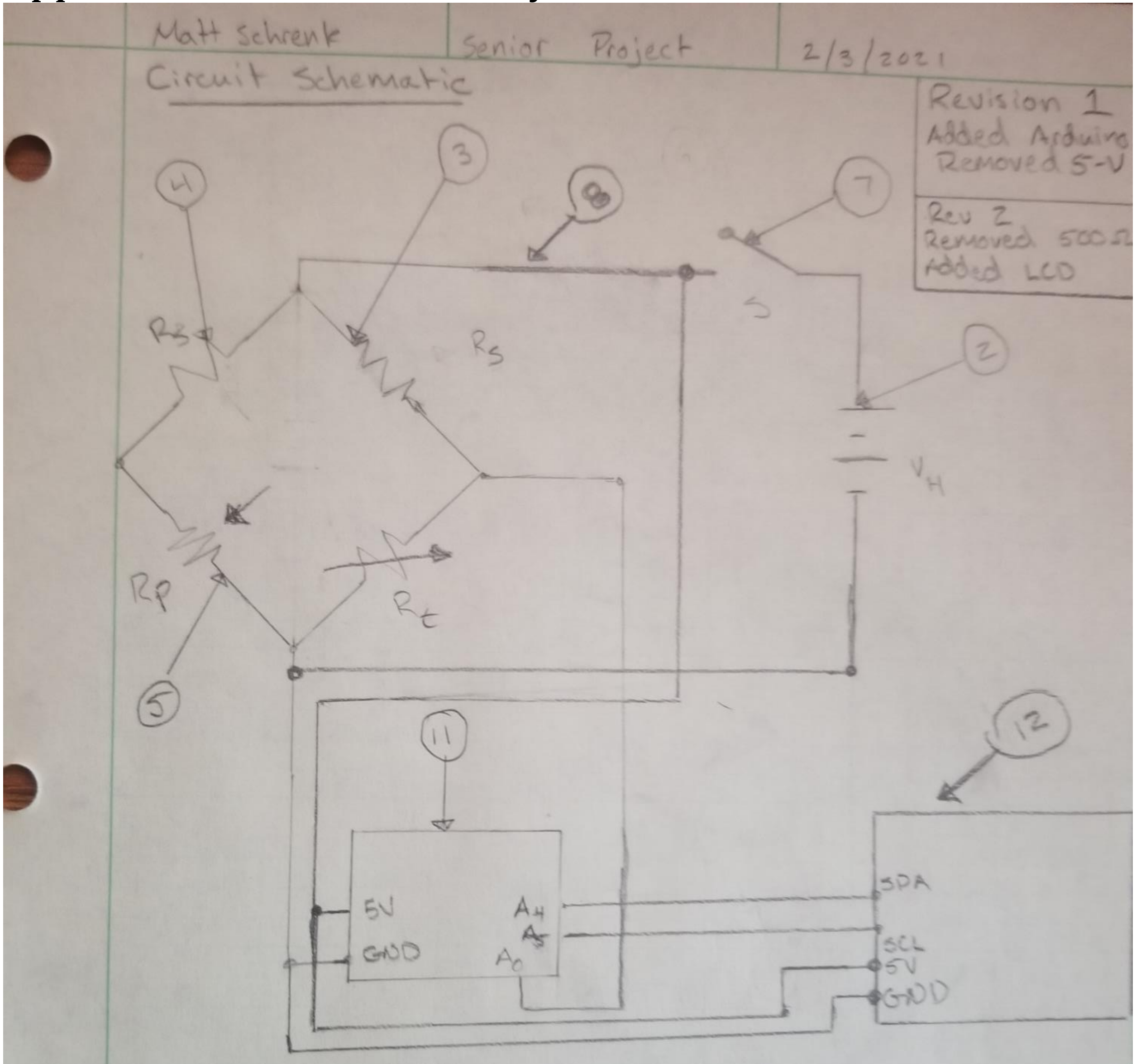
	NAME	DATE
DRAWN	MS	3/7/2021
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS: Revised Assembly. Corrected the BOM placement. Added new more accurate drawings.

TITLE: Pulse Decay Thermistor Assembly

SIZE B
DWG. NO. 10-001
REV 1
SCALE: 1:20 WEIGHT:
SHEET 1 OF 1

Appendix B: Circuit Assembly 10-002



Matt Schrenk | Senior Project | 2/3/2021

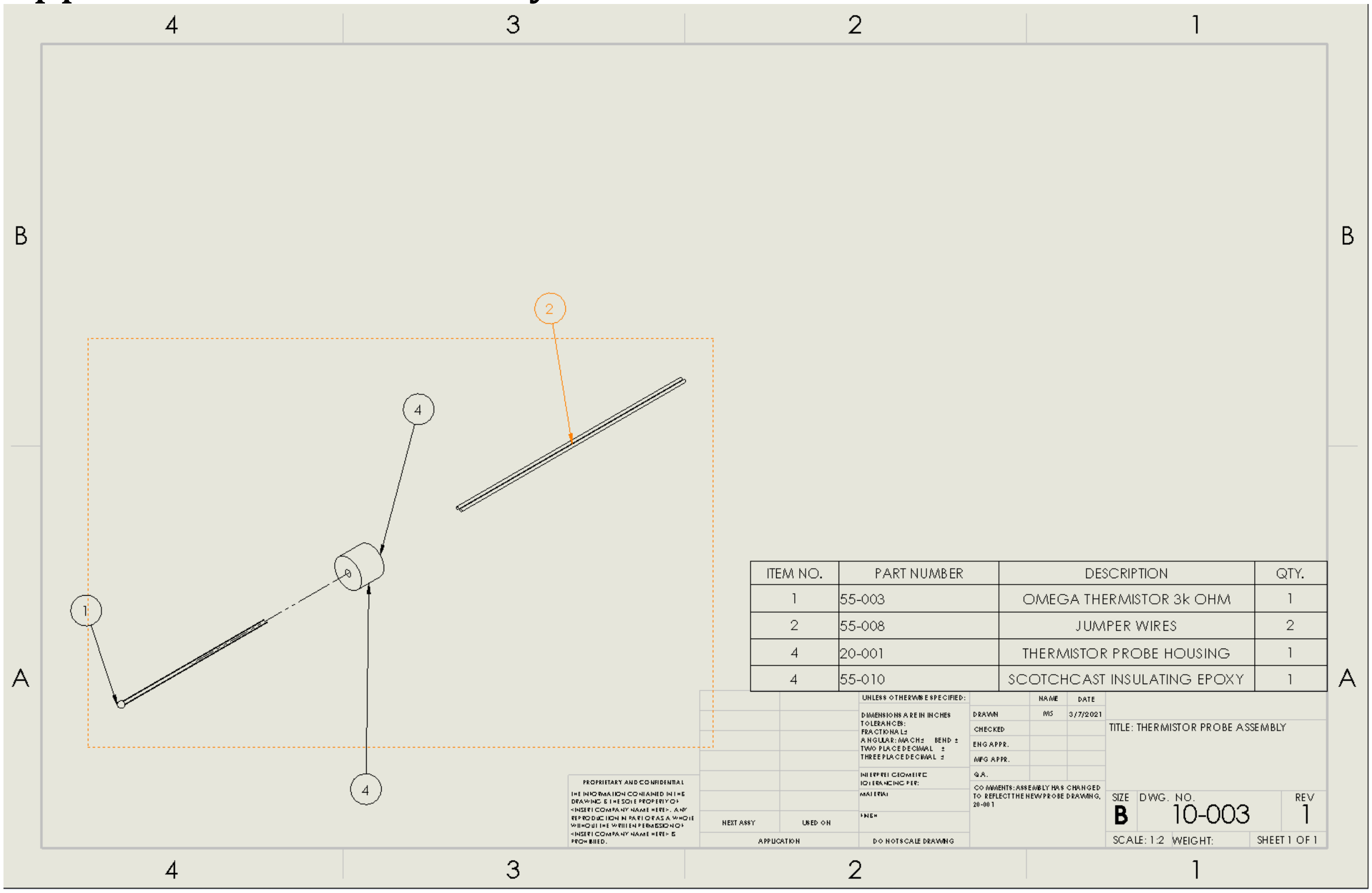
Circuit Schematic

Revision 1
Added Arduino
Removed 5-V

Rev 2
Removed 500Ω
Added LCD

Item #	Part	Description	Qty
2	55-002	Kaiweets PSU	1
3	55-003	Omega Thermister	1
4	55-004	3.5KΩ Potentiometer	1
5	55-005	10KΩ Resistor	2
12	55-012	LCD Module	1
7	55-007	Timer Switch	1
8	55-008	Jumper Wires	10
11	55-011	Arduino R3 Uno	1

Appendix B: Sub-Assembly 10-003



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	55-003	OMEGA THERMISTOR 3k OHM	1
2	55-008	JUMPER WIRES	2
4	20-001	THERMISTOR PROBE HOUSING	1
4	55-010	SCOTCHCAST INSULATING EPOXY	1

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NEXT ASSY
USED ON
APPLICATION

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

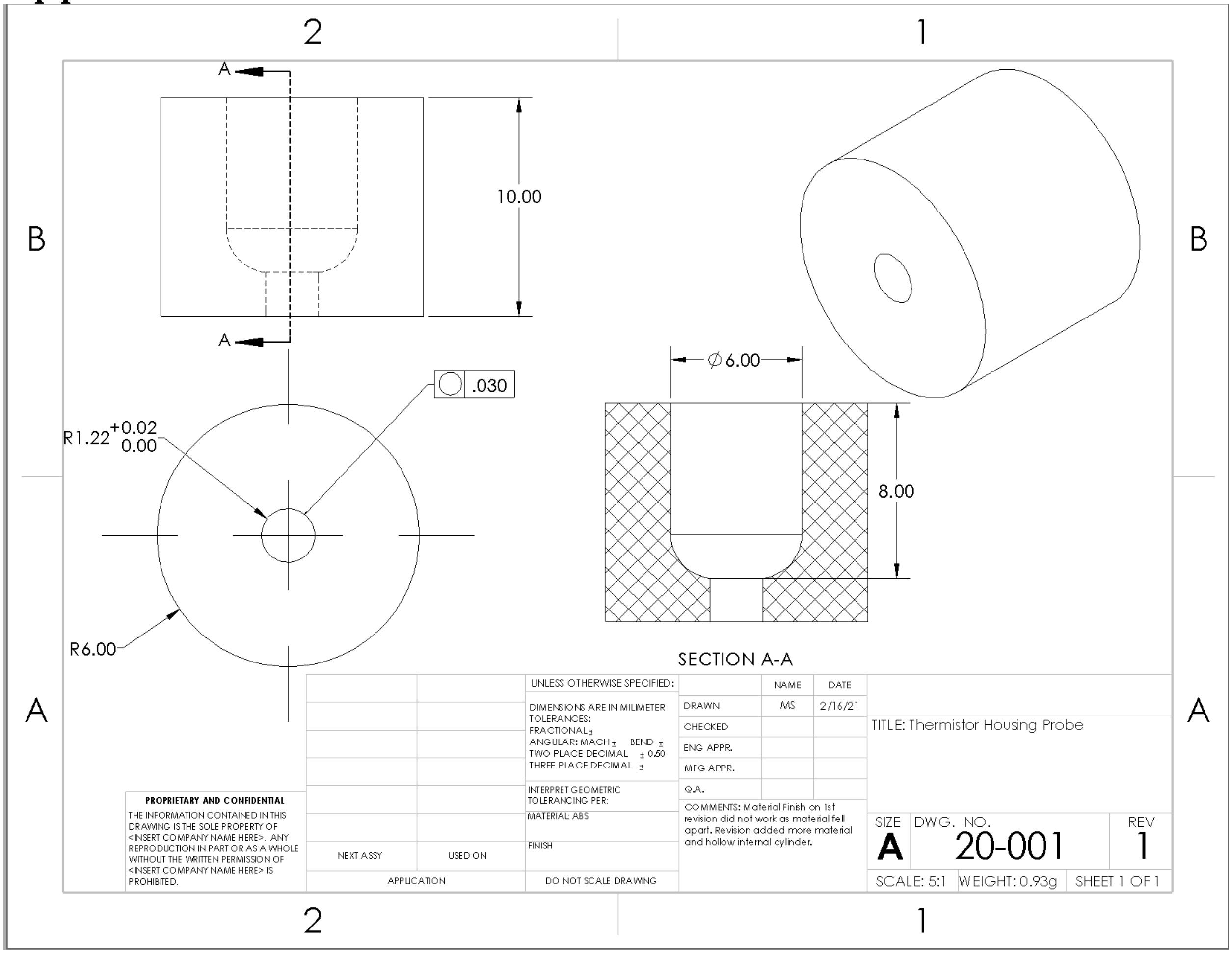
	NAME	DATE
DRAWN	MS	3/7/2021
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS: ASSEMBLY HAS CHANGED TO REFLECT THE NEW PROBE DRAWING, 20-001

TITLE: THERMISTOR PROBE ASSEMBLY

SIZE **B**
DWG. NO. 10-003
REV 1
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1

Appendix B – DWG 1: 20-001



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILIMETER
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ± 0.50
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL: ABS
FINISH
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	MS	2/16/21
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS: Material Finish on 1st revision did not work as material fell apart. Revision added more material and hollow internal cylinder.

TITLE: Thermistor Housing Probe

SIZE A
DWG. NO. 20-001
REV 1
SCALE: 5:1
WEIGHT: 0.93g
SHEET 1 OF 1

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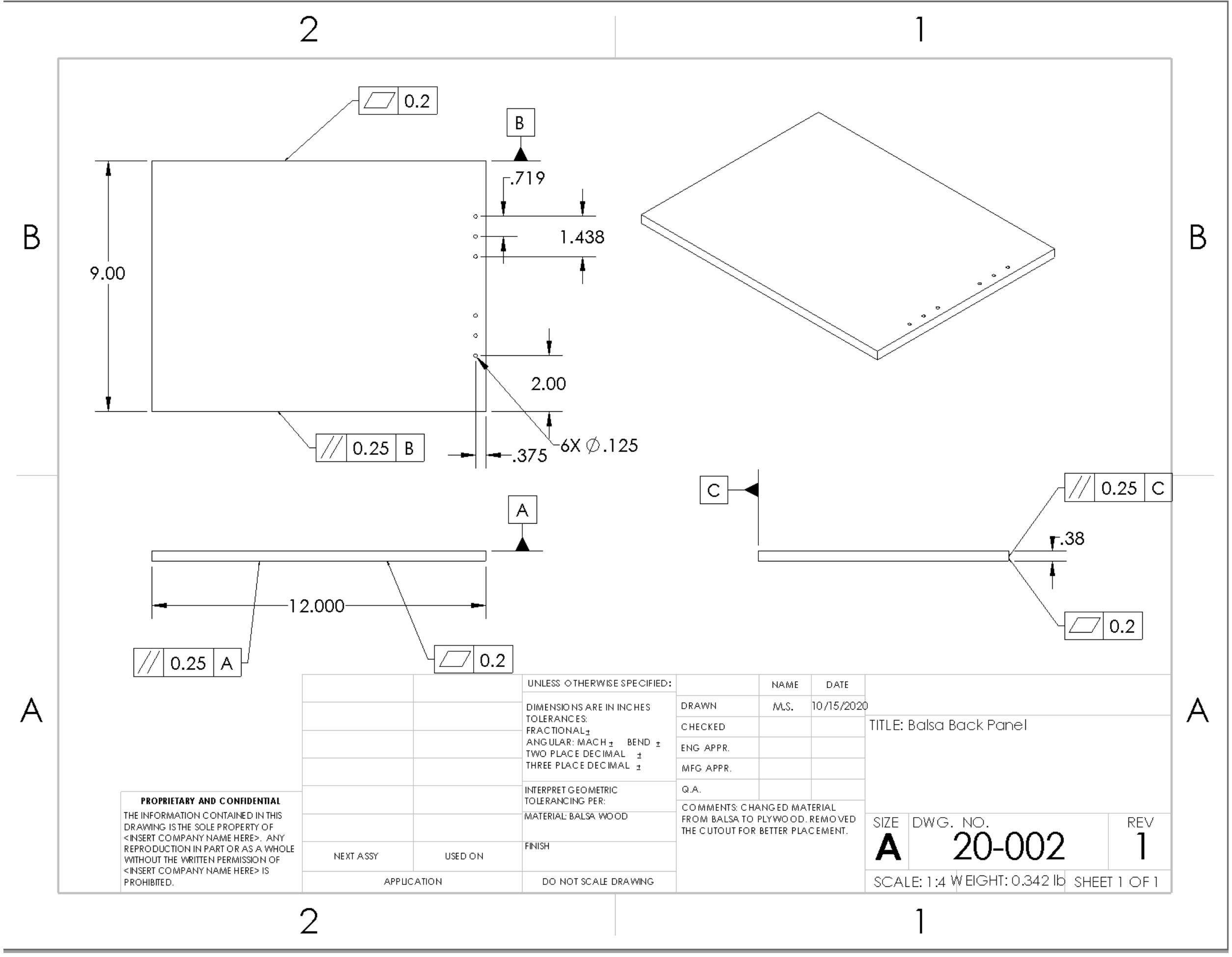
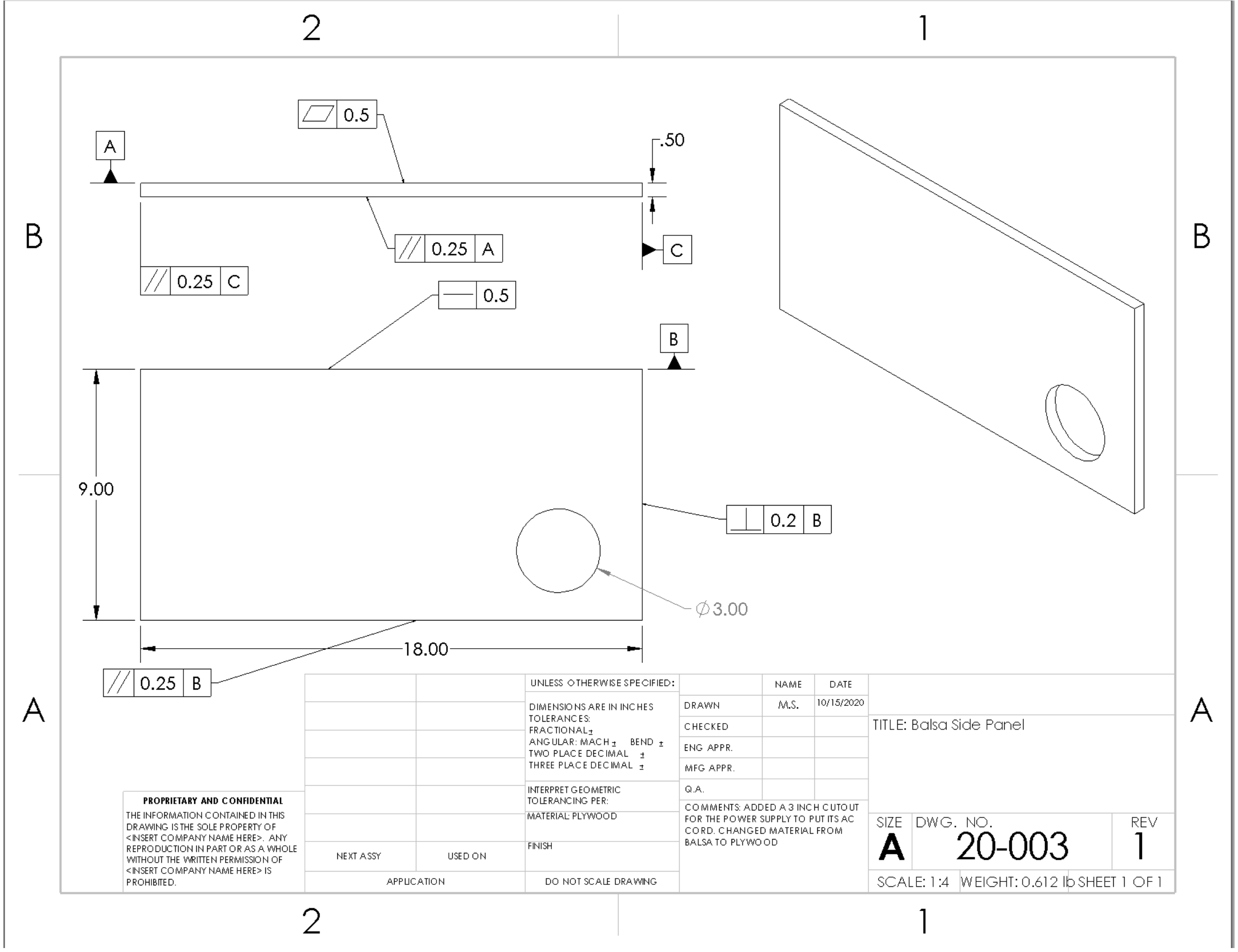
Appendix B – DWG 2: 20-002



Appendix B – DWG 3: 20-003



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NEXT ASSY | USED ON

APPLICATION

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL: PLYWOOD

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	M.S.	10/15/2020
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

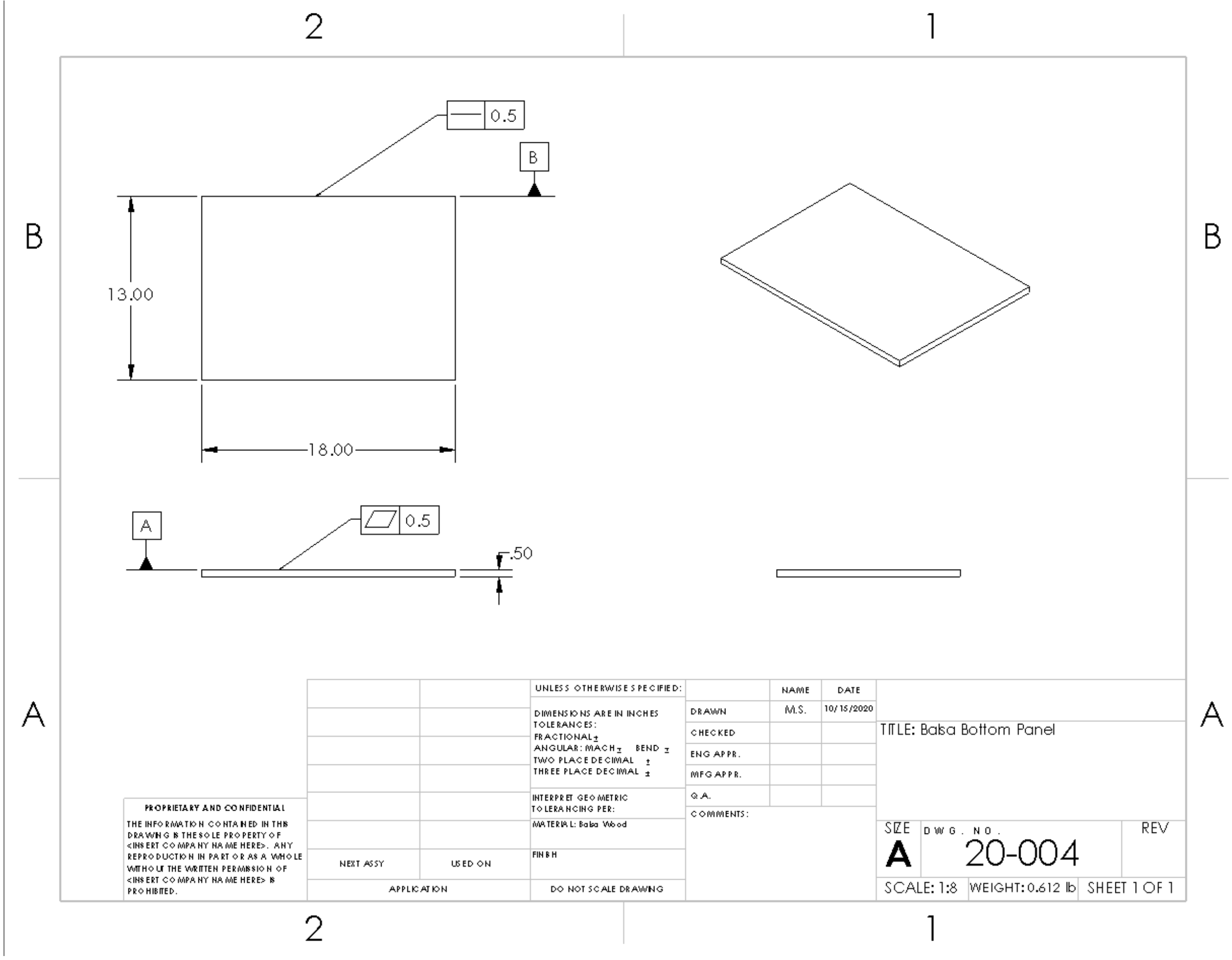
COMMENTS: ADDED A 3 INCH CUTOUT FOR THE POWER SUPPLY TO PUT ITS AC CORD. CHANGED MATERIAL FROM BALSA TO PLYWOOD

TITLE: Balsa Side Panel

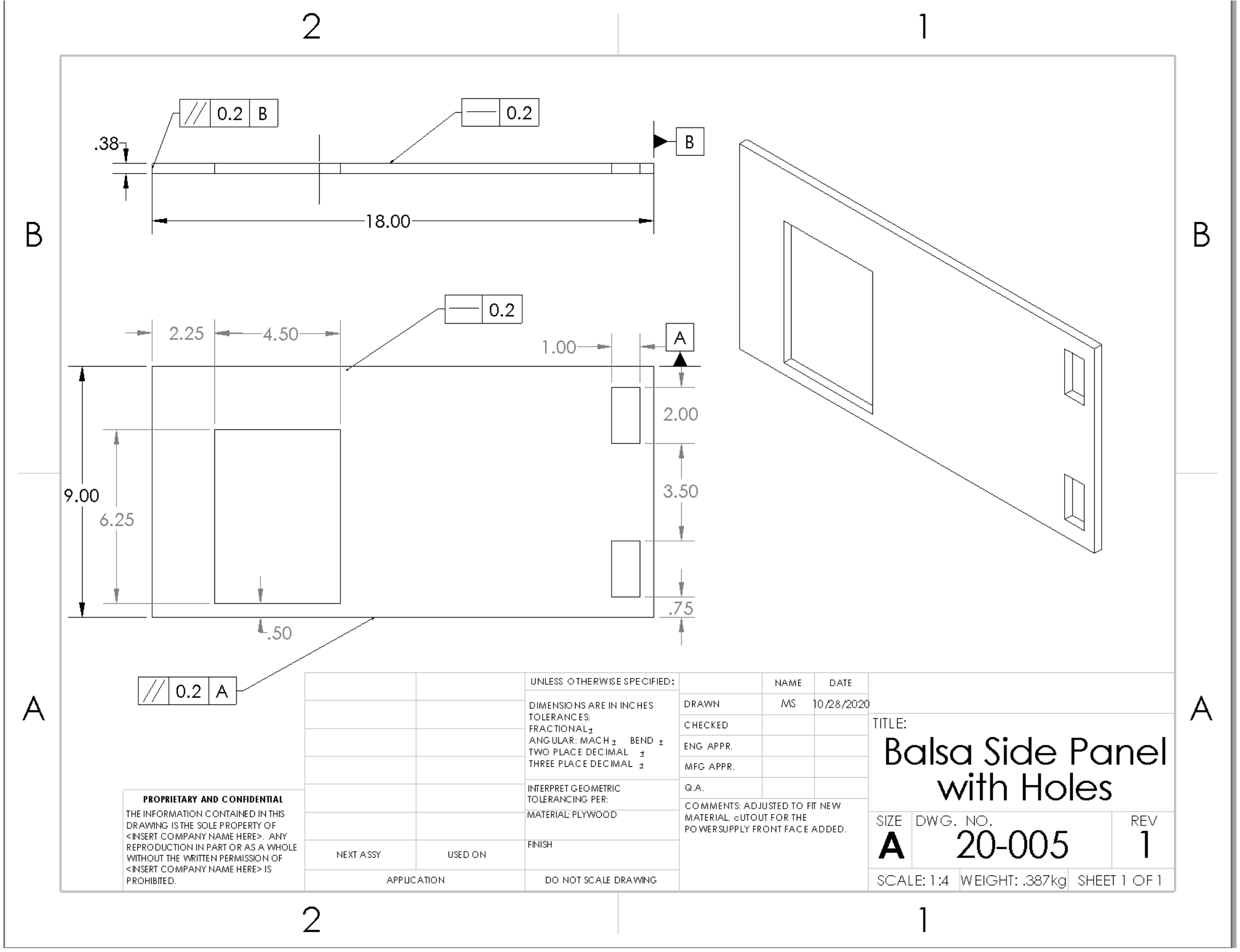
SIZE A
DWG. NO. 20-003
REV 1

SCALE: 1:4
WEIGHT: 0.612 lb
SHEET 1 OF 1

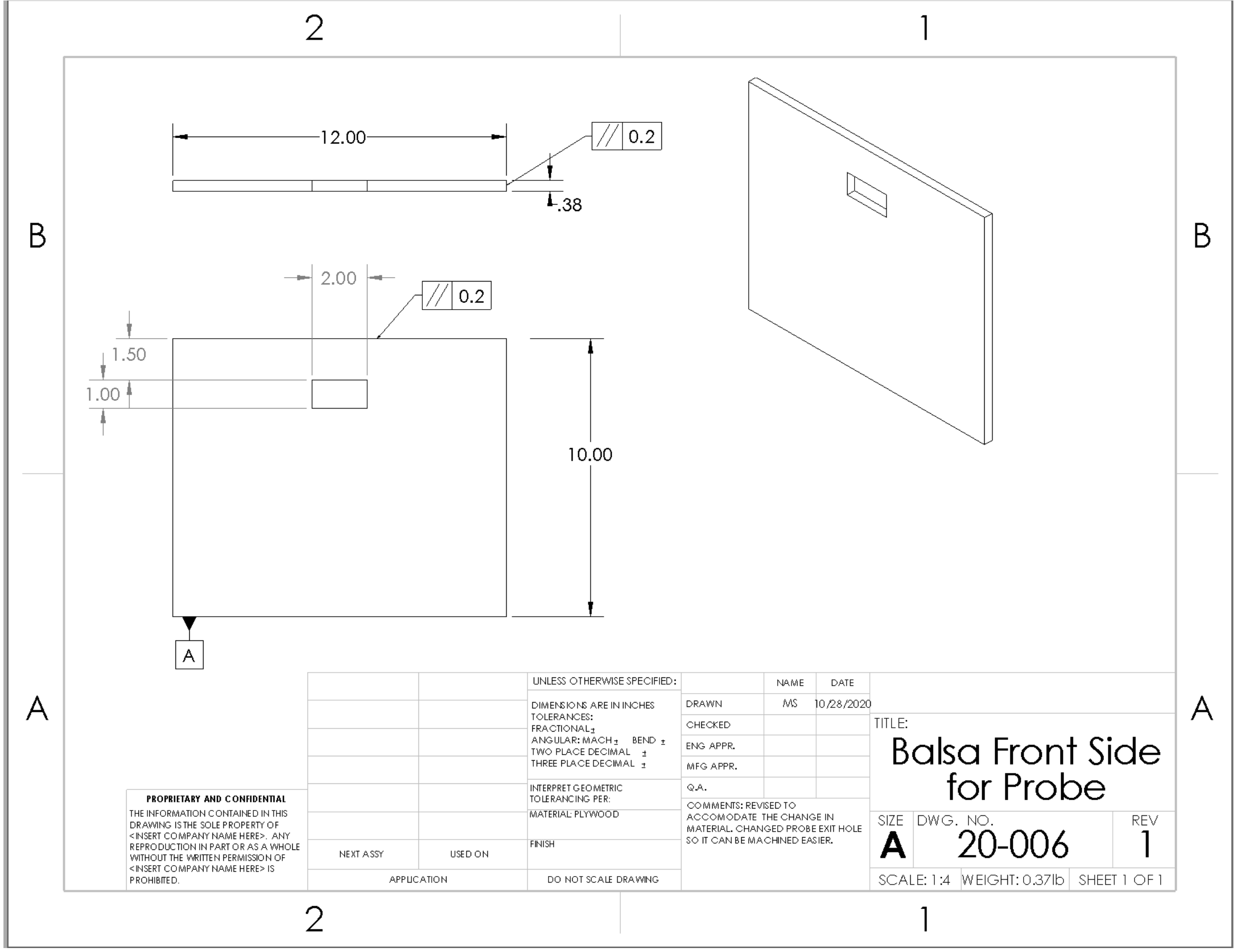
Appendix B – DWG 4: 20-004



Appendix B DWG 5: 20-005



Appendix B DWG 6: 20-006



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL: PLYWOOD
FINISH
DO NOT SCALE DRAWING

NEXT ASSY
USED ON
APPLICATION

	NAME	DATE
DRAWN	MS	10/28/2020
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

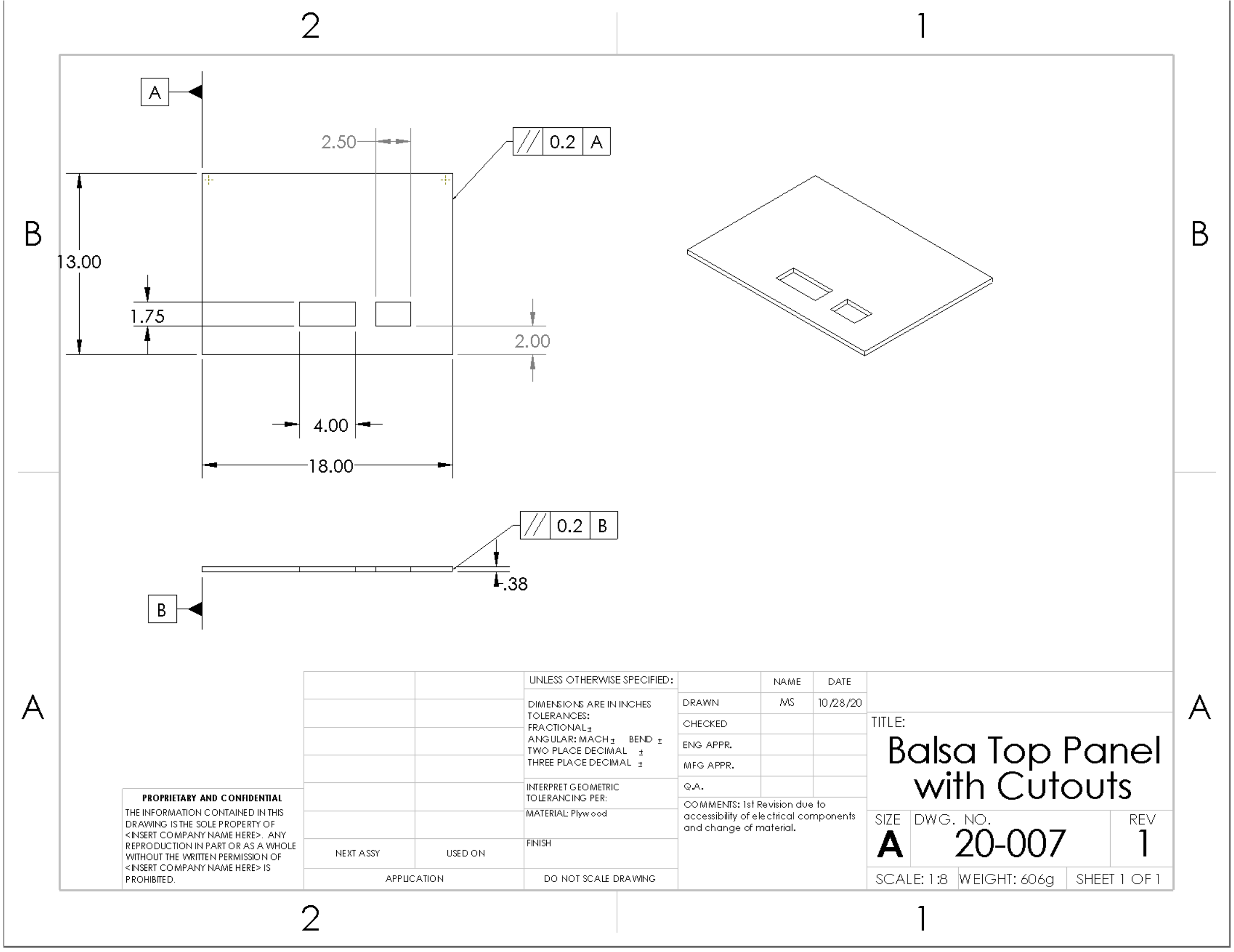
COMMENTS: REVISED TO ACCOMODATE THE CHANGE IN MATERIAL. CHANGED PROBE EXIT HOLE SO IT CAN BE MACHINED EASIER.

TITLE:
Balsa Front Side for Probe

SIZE A
DWG. NO. 20-006
REV 1
SCALE: 1:4
WEIGHT: 0.37lb
SHEET 1 OF 1

PROPRIETARY AND CONFIDENTIAL

Appendix B DWG 7: 20-007

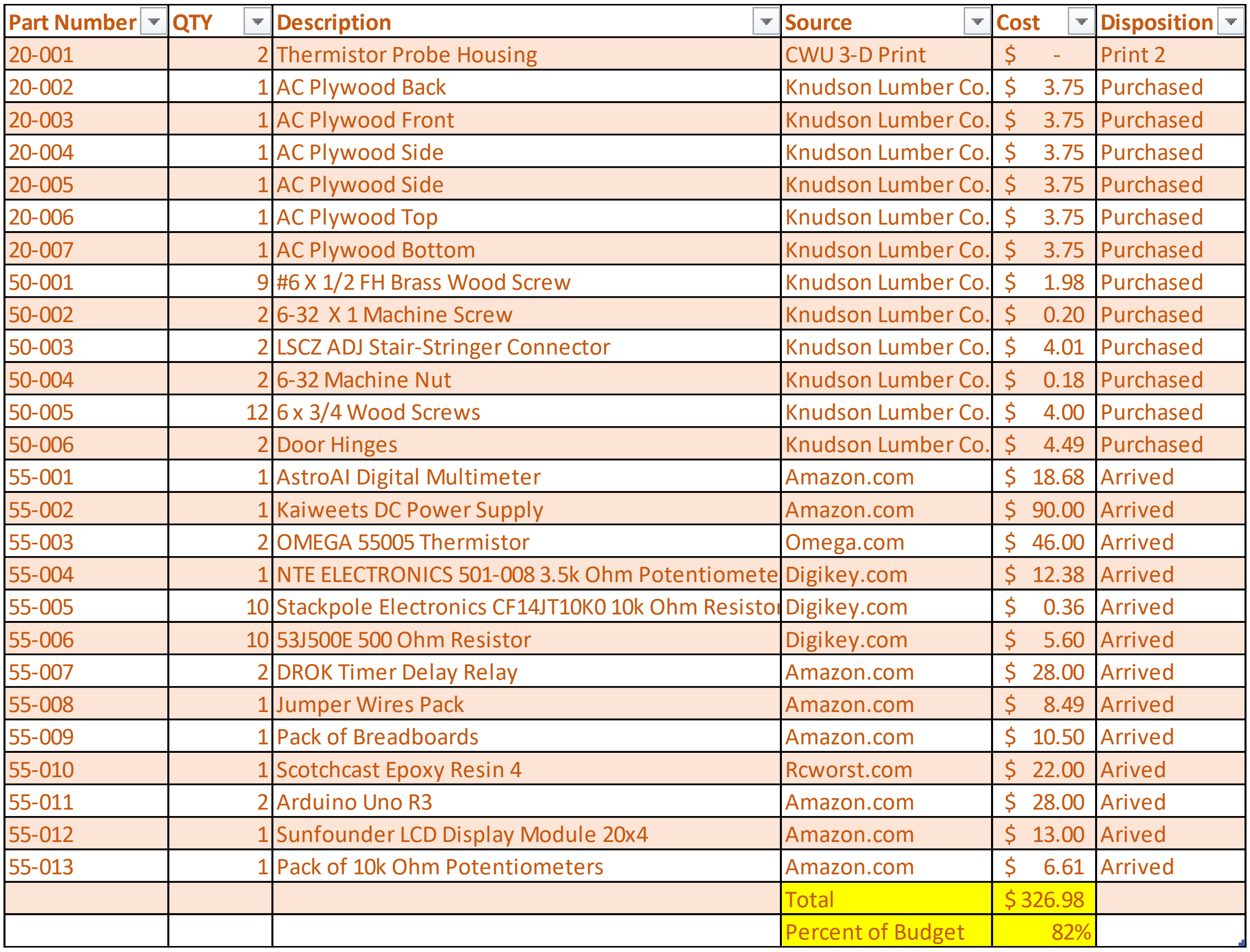


APPENDIX C – Parts List and Costs

Part Number	QTY	Description	Source	Cost
20-001	2	Thermistor Probe Housing	CWU 3-D Print	$ -
20-002	1	AC Plywood Back	Knudson Lumber Co.	$ 3.75
20-003	1	AC Plywood Front	Knudson Lumber Co.	$ 3.75
20-004	1	AC Plywood Side	Knudson Lumber Co.	$ 3.75
20-005	1	AC Plywood Side	Knudson Lumber Co.	$ 3.75
20-006	1	AC Plywood Top	Knudson Lumber Co.	$ 3.75
20-007	1	AC Plywood Bottom	Knudson Lumber Co.	$ 3.75
50-001	9	#6 X 1/2 FH Brass Wood Screw	Knudson Lumber Co.	$ 1.98
50-002	2	6-32 X 1 Machine Screw	Knudson Lumber Co.	$ 0.20
50-003	2	LSCZ ADJ Stair-Stringer Connector	Knudson Lumber Co.	$ 4.01
50-004	2	6-32 Machine Nut	Knudson Lumber Co.	$ 0.18
50-005	12	6 x 3/4 Wood Screws	Knudson Lumber Co.	$ 4.00
50-006	2	Door Hinges	Knudson Lumber Co.	$ 4.49
55-001	1	AstroAI Digital Multimeter	Amazon.com	$ 18.68
55-002	1	Kaiweets DC Power Supply	Amazon.com	$ 90.00
55-003	2	OMEGA 55005 Thermistor	Omega.com	$ 46.00
55-004	1	NTE ELECTRONICS 501-008 3.5k Ohm Potentiomete	Digikey.com	$ 12.38
55-005	10	Stackpole Electronics CF14JT10K0 10k Ohm Resistor	Digikey.com	$ 0.36
55-006	10	53J500E 500 Ohm Resistor	Digikey.com	$ 5.60
55-007	2	DROK Timer Delay Relay	Amazon.com	$ 28.00
55-008	1	Jumper Wires Pack	Amazon.com	$ 8.49
55-009	1	Pack of Breadboards	Amazon.com	$ 10.50
55-010	1	Scotchcast Epoxy Resin 4	Rcworst.com	$ 22.00
55-011	2	Arduino Uno R3	Amazon.com	$ 28.00
55-012	1	Sunfounder LCD Display Module 20x4	Amazon.com	$ 13.00
55-013	1	Pack of 10k Ohm Potentiometers	Amazon.com	$ 6.61
			Total	$ 326.98
			Percent of Budget	82%

APPENDIX D – Budget

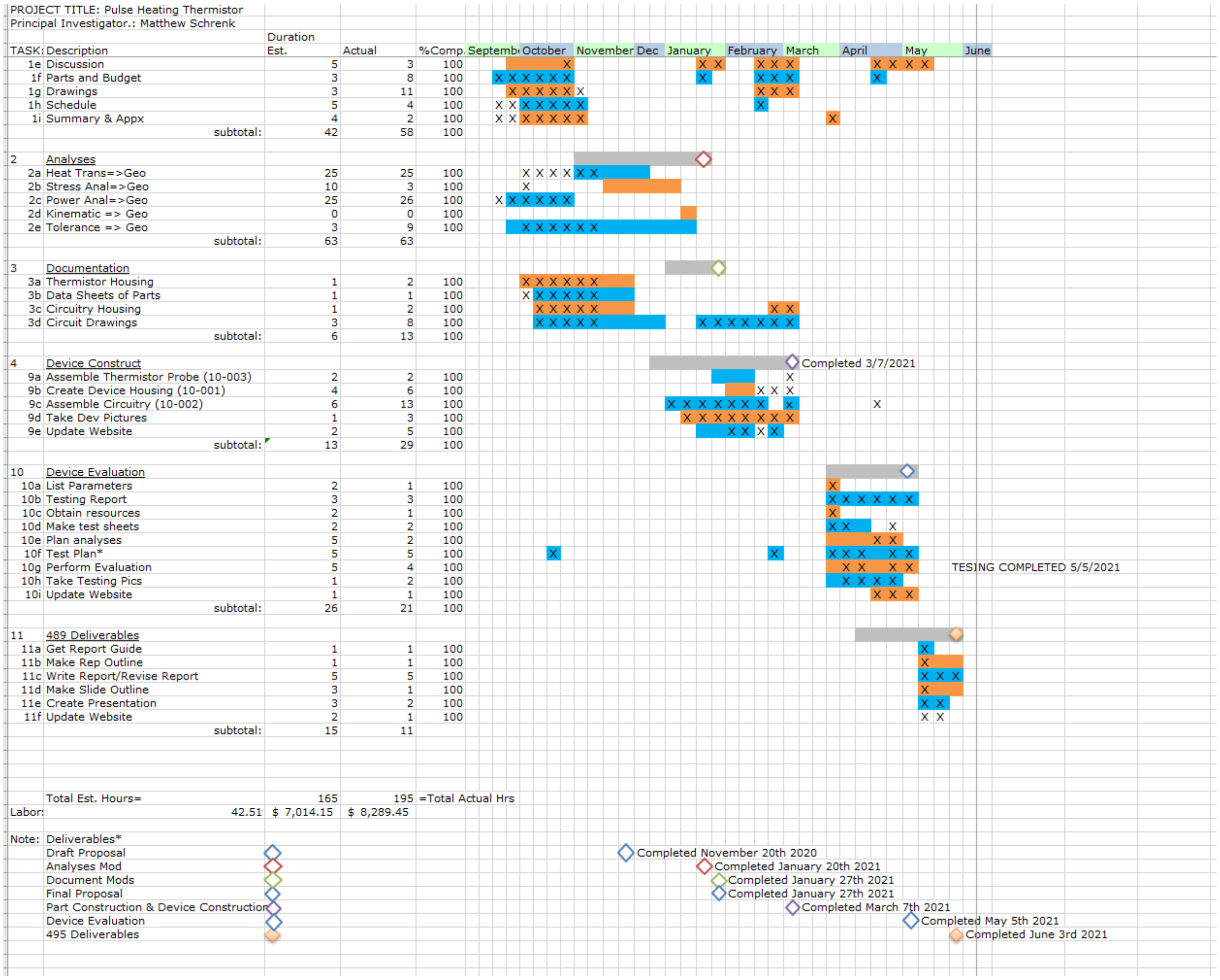
LINK HERE for Budget and Parts List File



Part Number	QTY	Description	Source	Cost	Disposition
20-001	2	Thermistor Probe Housing	CWU 3-D Print	$ -	Print 2
20-002	1	AC Plywood Back	Knudson Lumber Co.	$ 3.75	Purchased
20-003	1	AC Plywood Front	Knudson Lumber Co.	$ 3.75	Purchased
20-004	1	AC Plywood Side	Knudson Lumber Co.	$ 3.75	Purchased
20-005	1	AC Plywood Side	Knudson Lumber Co.	$ 3.75	Purchased
20-006	1	AC Plywood Top	Knudson Lumber Co.	$ 3.75	Purchased
20-007	1	AC Plywood Bottom	Knudson Lumber Co.	$ 3.75	Purchased
50-001	9	#6 X 1/2 FH Brass Wood Screw	Knudson Lumber Co.	$ 1.98	Purchased
50-002	2	6-32 X 1 Machine Screw	Knudson Lumber Co.	$ 0.20	Purchased
50-003	2	LSCZ ADJ Stair-Stringer Connector	Knudson Lumber Co.	$ 4.01	Purchased
50-004	2	6-32 Machine Nut	Knudson Lumber Co.	$ 0.18	Purchased
50-005	12	6 x 3/4 Wood Screws	Knudson Lumber Co.	$ 4.00	Purchased
50-006	2	Door Hinges	Knudson Lumber Co.	$ 4.49	Purchased
55-001	1	AstroAI Digital Multimeter	Amazon.com	$ 18.68	Arrived
55-002	1	Kaiweets DC Power Supply	Amazon.com	$ 90.00	Arrived
55-003	2	OMEGA 55005 Thermistor	Omega.com	$ 46.00	Arrived
55-004	1	NTE ELECTRONICS 501-008 3.5k Ohm Potentiomete	Digikey.com	$ 12.38	Arrived
55-005	10	Stackpole Electronics CF14JT10K0 10k Ohm Resistor	Digikey.com	$ 0.36	Arrived
55-006	10	53J500E 500 Ohm Resistor	Digikey.com	$ 5.60	Arrived
55-007	2	DROK Timer Delay Relay	Amazon.com	$ 28.00	Arrived
55-008	1	Jumper Wires Pack	Amazon.com	$ 8.49	Arrived
55-009	1	Pack of Breadboards	Amazon.com	$ 10.50	Arrived
55-010	1	Scotchcast Epoxy Resin 4	Rcworst.com	$ 22.00	Arived
55-011	2	Arduino Uno R3	Amazon.com	$ 28.00	Arived
55-012	1	Sunfounder LCD Display Module 20x4	Amazon.com	$ 13.00	Arived
55-013	1	Pack of 10k Ohm Potentiometers	Amazon.com	$ 6.61	Arrived
			Total	$ 326.98	
			Percent of Budget	82%	

APPENDIX E – Schedule

LINK HERE to Gantt Chart Excel File



PROJECT TITLE: Pulse Heating Thermistor
Principal Investigator.: Matthew Schrenk

TASK:	Description	Duration Est.	Actual	%Comp.
1e	Discussion	5	3	100
1f	Parts and Budget	3	8	100
1g	Drawings	3	11	100
1h	Schedule	5	4	100
1i	Summary & Appx	4	2	100
	subtotal:	42	58	100
2	Analyses			
2a	Heat Trans=>Geo	25	25	100
2b	Stress Anal=>Geo	10	3	100
2c	Power Anal=>Geo	25	26	100
2d	Kinematic => Geo	0	0	100
2e	Tolerance => Geo	3	9	100
	subtotal:	63	63	
3	Documentation			
3a	Thermistor Housing	1	2	100
3b	Data Sheets of Parts	1	1	100
3c	Circuitry Housing	1	2	100
3d	Circuit Drawings	3	8	100
	subtotal:	6	13	100
4	Device Construct			
9a	Assemble Thermistor Probe (10-003)	2	2	100
9b	Create Device Housing (10-001)	4	6	100
9c	Assemble Circuitry (10-002)	6	13	100
9d	Take Dev Pictures	1	3	100
9e	Update Website	2	5	100
	subtotal:	13	29	100
10	Device Evaluation			
10a	List Parameters	2	1	100
10b	Testing Report	3	3	100
10c	Obtain resources	2	1	100
10d	Make test sheets	2	2	100
10e	Plan analyses	5	2	100
10f	Test Plan*	5	5	100
10g	Perform Evaluation	5	4	100
10h	Take Testing Pics	1	2	100
10i	Update Website	1	1	100
	subtotal:	26	21	100
11	489 Deliverables			
11a	Get Report Guide	1	1	100
11b	Make Rep Outline	1	1	100
11c	Write Report/Revise Report	5	5	100
11d	Make Slide Outline	3	1	100
11e	Create Presentation	3	2	100
11f	Update Website	2	1	100
	subtotal:	15	11	
	Total Est. Hours=	165	195	=Total Actual Hrs
Labor:	42.51	$ 7,014.15	$ 8,289.45	

Completed 3/7/2021

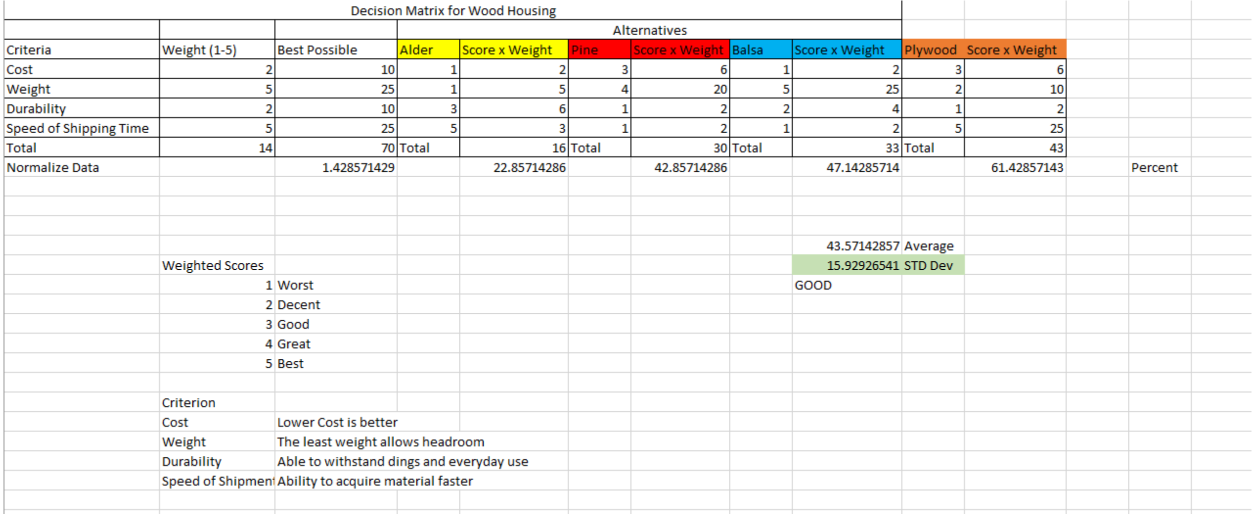
TESING COMPLETED 5/5/2021

Note: Deliverables*

Draft Proposal	◇	Completed November 20th 2020
Analyses Mod	◇	Completed January 20th 2021
Document Mods	◇	Completed January 27th 2021
Final Proposal	◇	Completed January 27th 2021
Part Construction & Device Construction	◇	Completed March 7th 2021
Device Evaluation	◇	Completed May 5th 2021
495 Deliverables	◆	Completed June 3rd 2021

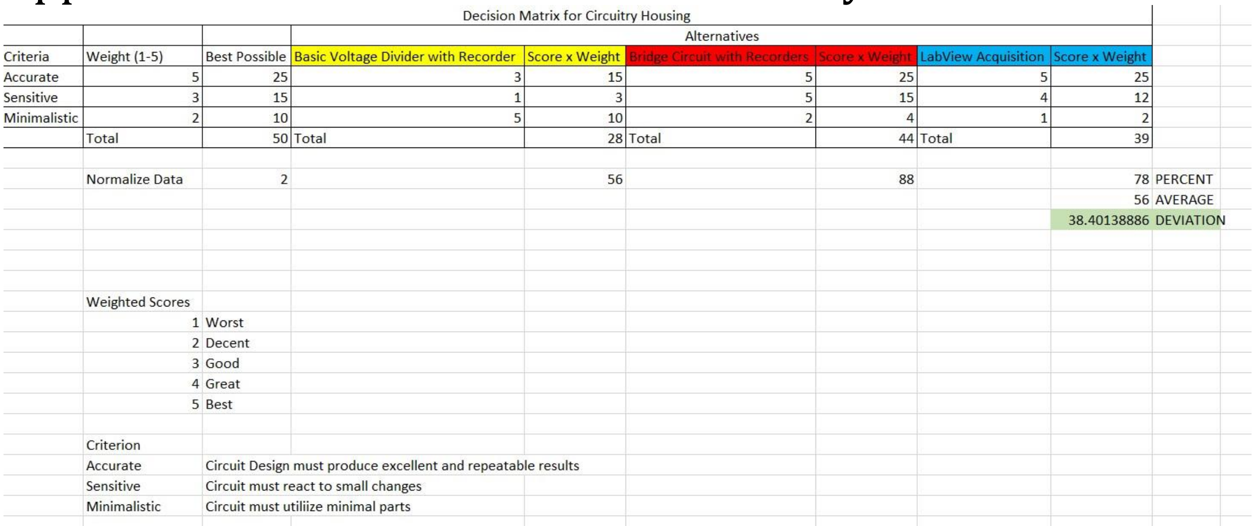
APPENDIX F – Expertise and Resources

Appendix F-1: Decision Matrix of Wood Choice



		Decision Matrix for Wood Housing										
						Alternatives						
Criteria	Weight (1-5)	Best Possible	Alder	Score x Weight	Pine	Score x Weight	Balsa	Score x Weight	Plywood	Score x Weight		
Cost	2	10	1	2	3	6	1	2	3	6		
Weight	5	25	1	5	4	20	5	25	2	10		
Durability	2	10	3	6	1	2	2	4	1	2		
Speed of Shipping Time	5	25	5	3	1	2	1	2	5	25		
Total	14	70	Total	16	Total	30	Total	33	Total	43		
Normalize Data		1.428571429		22.85714286		42.85714286		47.14285714		61.42857143		Percent
								43.57142857	Average			
	Weighted Scores							15.92926541	STD Dev			
	1	Worst						GOOD				
	2	Decent										
	3	Good										
	4	Great										
	5	Best										
	Criterion											
	Cost	Lower Cost is better										
	Weight	The least weight allows headroom										
	Durability	Able to withstand dings and everyday use										
	Speed of Shipment	Ability to acquire material faster										

Appendix F-2: Decision Matrix of Circuitry Choice



			Decision Matrix for Circuitry Housing						
					Alternatives				
Criteria	Weight (1-5)	Best Possible	Basic Voltage Divider with Recorder	Score x Weight	Bridge Circuit with Recorders	Score x Weight	LabView Acquisition	Score x Weight	
Accurate	5	25	3	15	5	25	5	25	
Sensitive	3	15	1	3	5	15	4	12	
Minimalistic	2	10	5	10	2	4	1	2	
	Total	50	Total	28	Total	44	Total	39	
	Normalize Data	2		56		88		78	PERCENT
								56	AVERAGE
								38.40138886	DEVIATION
	Weighted Scores								
	1	Worst							
	2	Decent							
	3	Good							
	4	Great							
	5	Best							
	Criterion								
	Accurate	Circuit Design must produce excellent and repeatable results							
	Sensitive	Circuit must react to small changes							
	Minimalistic	Circuit must utiliize minimal parts							

APPENDIX G – Testing Report

LINK HERE to Testing Report

Testing Report

Introduction:

This device was developed under the parameters assigned by Dr. Choi. The device must perform its measurements within 15 minutes and be within 5% of accepted literature values. Since the requirement is to perform measurements in 15 minutes, time is being considered for the whole process. To be within the tolerance of accepted literature values, two separate equations are being used to understand the integral difference between infinitely small probes and a generalized finitely small probe.

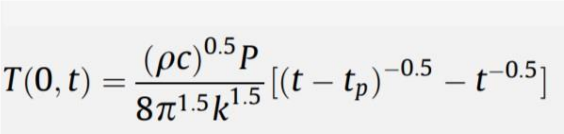
The device is predicted to provide enough data to calculate thermal conductivity within five minutes and 5% of accepted values. The thermistor under the assumption of being infinitely and finitely small distributes its heat and obtains equilibrium in a matter of seconds.

For the testing of the Pulse Heated Thermistor Device, the user must begin to measure a handful of variables. These variables are pulsing amperage across the thermistor during sensing mode and pulse mode, temperature before pulse, temperature during pulse, temperature after pulse, and time. To measure these variables, a multimeter is used to measure the amperage. The Arduino code is programmed to gather feedback from the thermistor’s resistor and output a temperature. The time is set to be measured at pre-set values gathered from various forms of literature. Once data is collected, applying it to various equations as denoted in the testing section and procedure appendices are used. These equations will output a thermal conductivity value in terms of Watts per meter Kelvin. These values will be compared to a preliminary finite element analysis and accepted literature values to determine precision.

The tests were taken place on April 2, 2021 through April 7, 2021. The materials tested were Water at below room temperature (10 degrees Celsius), water at room temperature (25 degrees Celsius), and a Granny Smith Apple at room temperature.

Method/Approach:

The thermistor pulse decay method is the approach to be conducted in this device. It requires understanding density and specific heat of the material prior to testing. The pulse decay method utilizes a thermistor placed in a probe. The thermistor is then introduced with a current that initiates a heating mode which causes the thermistors bead core to increase in temperature. This increase of temperature at the bead is proportional to the heat entering into the material it is testing, assuming the bead is uniformly distributing heat amongst its radius. It has been shown in *Chen et al.* (1981), that the current to cause heating in the thermistor must last around three to ten seconds. This is denoted as the pulse time. After the pulse is over, the thermistor is placed in a sensing mode, where the temperature of the bead is recorded for a time. These values are plugged into the following equation to solve for thermal conductivity:



$$T(0,t) = \frac{(\rho c)^{0.5} P}{8\pi^{1.5} k^{1.5}} [(t - t_p)^{-0.5} - t^{-0.5}]$$

Equation 1: Pulse Decay
Where:
T (0,t) = the temperature at a given time after pulse (K)
ρ = Density (kg/m^2)
c = Specific heat (J/kg-K)
P = Power measured across the thermistor (W)
k = Thermal Conductivity (W/m-K)
t = Time after pulse (s)
t_p = Time of the pulse (s)

One drawback from the use of this equation is that it assumes the use of an infinitesimally small probe size. This, however, is not the case when subjected to real world scenarios. To understand the accuracies or inaccuracies of Equation 1, the use of the following equation will be used as well, and the two will be compared.

$$k/(\rho c)^{1/3} = [P((t_m - t_p)^{-0.5} - t_m^{-0.5})/4T_o(t_m)]^{2/3}/\pi$$

Equation 2: Revised Pulse Decay

Where all variables are the same as Equation 1.

Power (P) is calculated by the assumption of a balanced bridge at t = 0 and the resistance at t = 0. By recording the resistance at t = 0, power across the thermistor element is a function of Ohm's law.
Temperature is calculated by knowing the resistance at a given time and applying the Steinhart equation with coefficients that are generally given by the manufacturer of the thermistor.

$$1/T = A + B\,[Ln(R)] + C\,[Ln(R)]^3$$

Equation 3: Steinhart Equation
Where:
A = 1.4052e -3
B = 2.3692e -4
C = 1.0125e – 7
R = Resistance at a given time

Programmed into the Arduino is Equation 3, which provides the user the absolute temperature of the specimen in degrees Kelvin. For an initial understanding of temperature decay, the LCD screen is used to monitor the temperature decay. The data is exported into the Serial Monitor on the Arduino IDE software on the computer. From there the temperature is exported into the excel spreadsheet in Appendix G4. and a visual graph of temperature decay is created. Likewise, Equations 1 and 2 are in Appendix G4, and the necessary values are plugged into their respective fields. The precision of the device prior to data manipulation will be in the hundredths of a volt change and the accuracy is a function of the calibration of the potentiometer. To improve accuracy, the user must edit the Arduino code and change the potentiometers resistance consecutively. The current code reflects a tuning of the device's potentiometer. This device cannot maintain a large enough temperature gradient to measure thermal conductivity of solid materials. This is due to the large amount of voltage required to pulse the thermistor to larger temperature gradients. Overvolting the system is a safety issue to both the user and the device.

Test Procedure:

Summary

This formal procedure is used for the acquisition of data involving the Pulse Heated Thermistor device and processing the results. This device was designed by a Mechanical Engineer and Technology student over the course of the academic year of 2020 through 2021. The device is designed to provide enough data for the user to compute the thermal conductivity of a bulk material. The following is the test information and procedure. This portion is split into three procedures for three different materials. Most of the testing procedure is inherently like the first.

Test Procedure for Water at Room Temperature:

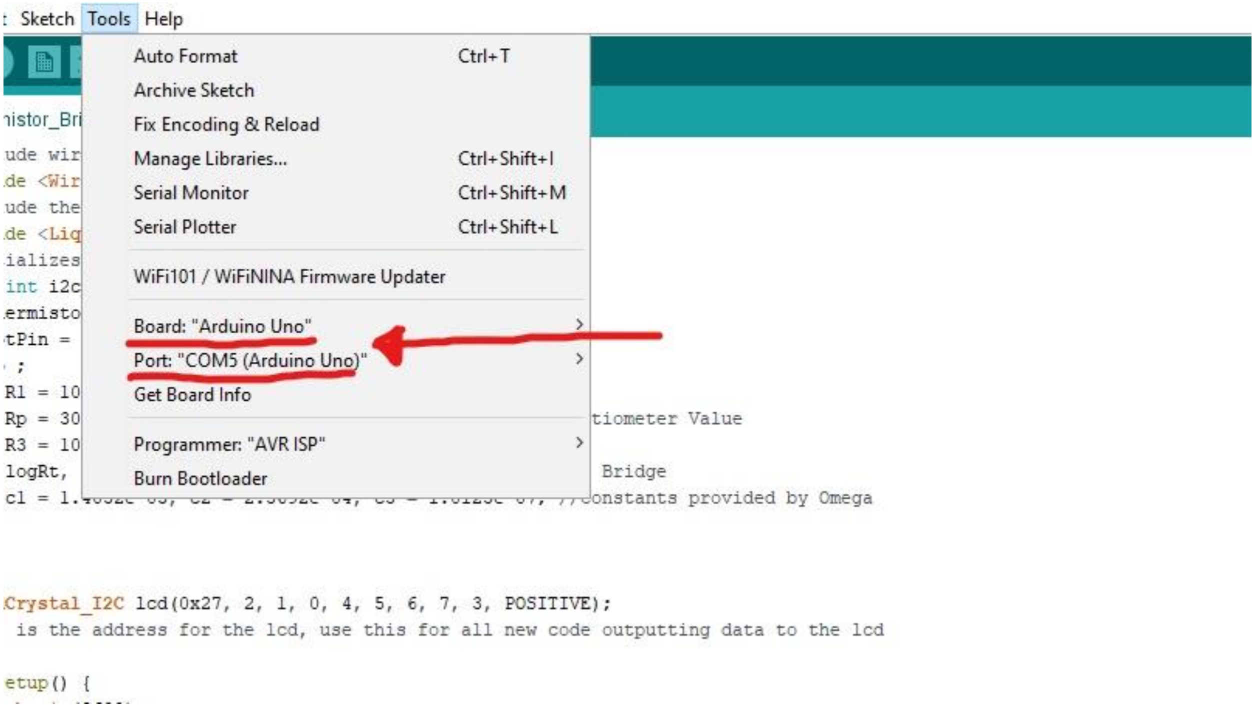
Time: 8:05 AM, 5/7/2021
Place: Apartment
Required Equipment:

- Computer with 5V USB and Arduino IDE software.
- Phone or Recording Device
- Thermometer or Temperature Sensing Mode of Device
- Multimeter
- Water mixed with gelatin which has been resting in ambient room temperature for at least 2 hours
- Table
- Writing implement
- Data Sheet

Risk: This test cannot be conducted without electrical power supplied from a wall outlet. All equipment must be collected ahead of time. Test Specimens must be ready prior to use of the device as per the requirements. When adjusting the power supply, if it is not currently at 10V, carefully adjust the nobs slightly. If the power supply is adjusted to 10V to roughly, it will overvolt the system and the Arduino will need replaced.

The test procedure is as follows:

1) Collect Equipment
    a. Room Temperature gelatin is left out. Cold temperature gelatin is held within a freezer until time to test. The potato is left out at room temperature as well as the stainless steel. Leave cold material in the freezer until time to test.
    b. Obtain a copy of Appendix G2 or access have access to excel spreadsheet in Appendix G4.
2) Turn computer on and navigate to Arduinos IDE Software.
3) Navigate to the Tools section on the bar and ensure that the computer and Arduino are communicating.



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de <Lig
ializes
int i2c
ermisto
tPin =
 ;
R1 = 10
Rp = 30                                    tiometer Value
R3 = 10
logRt,                                      Bridge
c1 = 1.                                    onstants provided by Omega


Crystal_I2C lcd(0x27, 2, 1, 0, 4, 5, 6, 7, 3, POSITIVE);
 is the address for the lcd, use this for all new code outputting data to the lcd

etup() {
```

Figure 01 Computer and Arduino Communication

4) Place device onto table and plug in the Power Supply and 5V USB into a Computer. Ensure that the power supply is left off. This ensures that the device is left into temperature sensing mode.

5) Turn the power supply on and adjust the nobs to make the output 10V.

Figure 02 Power Supply Adjustment

   a. Power off the supply when adjusted.

6) Obtain the first material to be tested and measure the current temperature with the thermistor probe.
   a. Leave the probe in the material.
   b. Record current temperature of the material.
   c. Record the reported resistance of the thermistor as displayed on the LCD screen.

```
Temp = 60.24 F
Temp = 15.69 C
Rt = 4566.14 ohms
Va = 1.16 Vb = 1.57
```

Figure 02, Where data is displayed

7) With the probe still in the material, obtain the multimeter.
8) Using the multimeter, measure the resistance of the potentiometer.

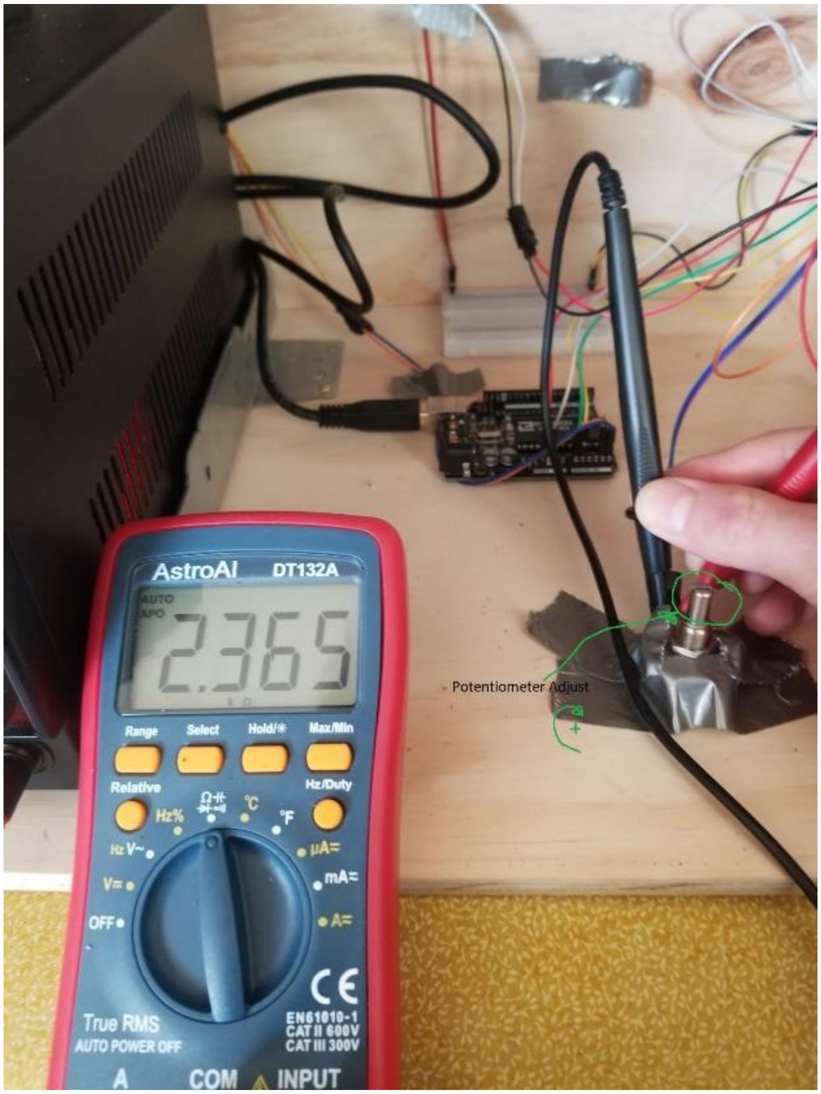


Figure 02 Potentiometer and Adjustments

   a. Carefully adjust the potentiometer to equal the resistance of the recorded thermistor resistance.

9) Remove multimeter from the potentiometer.
10) Using the multimeter, place the probes onto the leads of the thermistor and set the dial to measure amperage.
    a. Record sensing amperage across the thermistor on the data sheet
11) Turn on the power supply with the multimeter in place on the thermistor.

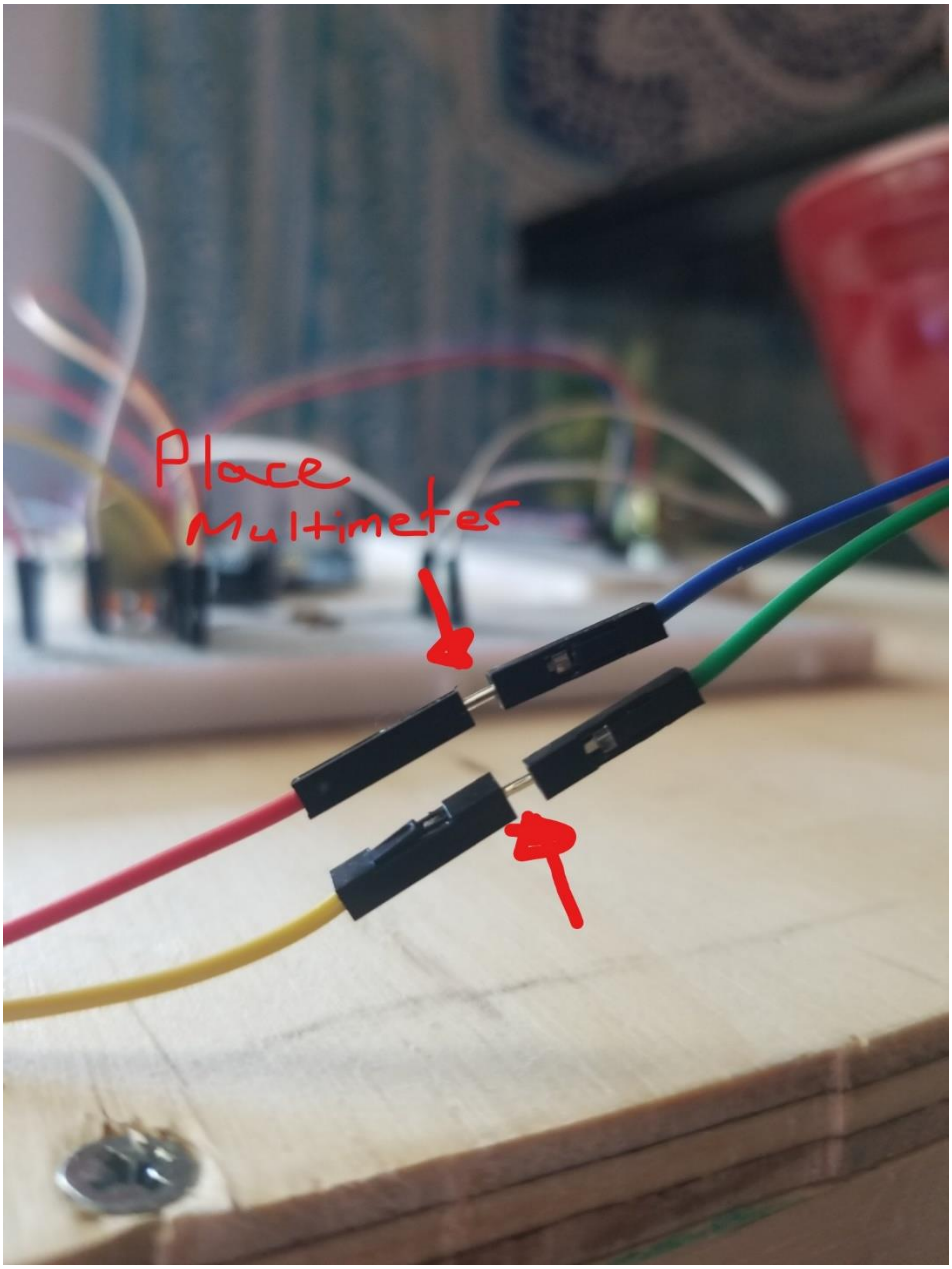


Figure 03: Where to Position Multimeter

   a. Record the pulsing amperage on to the data sheet.

12) Turn power supply off.
13) Remove Multimeter from Thermistor and set aside.
14) Navigate to the Computer
    a. On the Tools Header there is a tab that navigates to the Serial Monitor. If lost, reference Figure 01.
    b. Ensure that the baud is at “9600” for the Arduino to Export Data

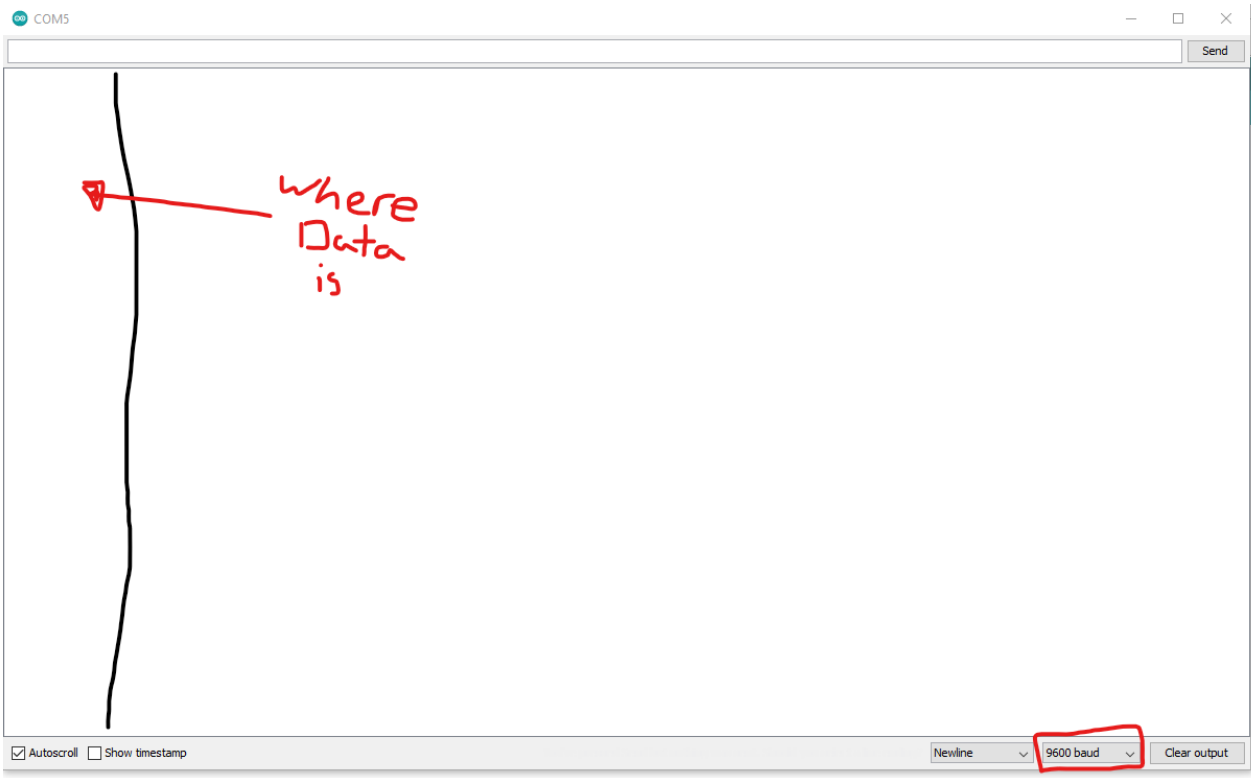
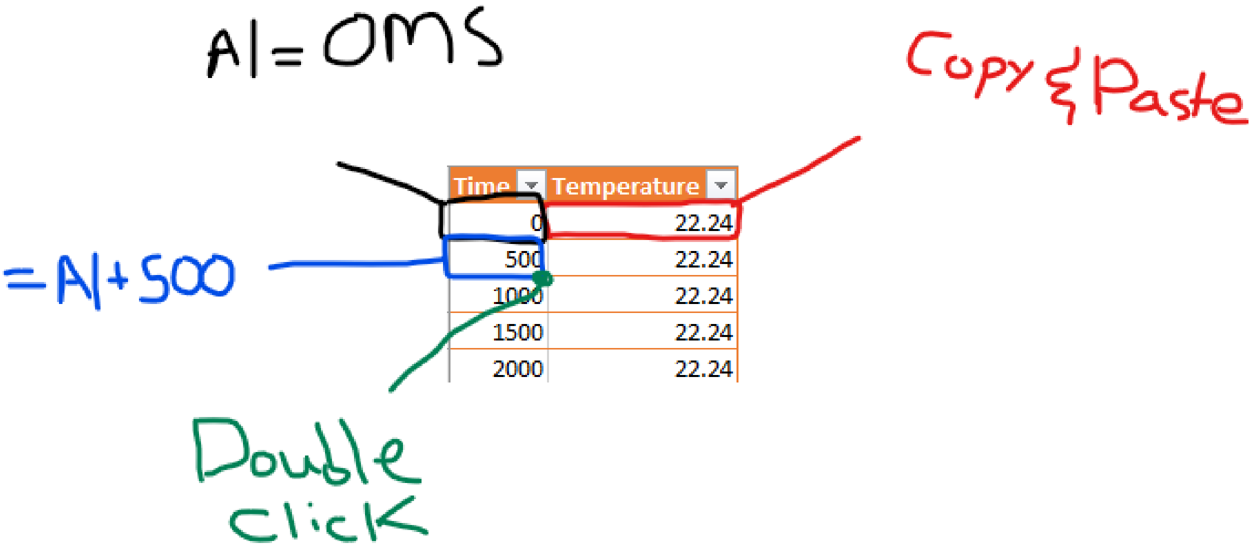


Figure 04 Serial Monitor Intro

  c. Start the Arduino's Serial Monitor. Temperature will begin recording immediately.

15) Power on the power supply, the Arduino Thermistor Probe will now begin the Pulsing Mode for 15 Seconds.
16) Turn on the switch when the pulsing has finished
17) The device will now loop and begin Sensing Mode for 25 seconds
18) Power off the supply when the 25 seconds of Sensing Mode is finished.
19) Remove the 5V USB from the Computer to completely power down the device.
20) Remove probe from material and put away.
21) Return to the Serial Monitor and Press Crtl+A or highlight data with the mouse
22) Copy it and Paste it into Appendix G4 in Cell A1 of the respective sheet for the given material.
23) In cell A1, write 0. This will be denoted as time in milliseconds
    a. The Arduino is programmed to gather data every 500 milliseconds
24) In cell B2, write “ = A1+500 “



Time	Temperature
0	22.24
500	22.24
1000	22.24
1500	22.24
2000	22.24

Figure 05: Making the Graph of Temperature Over Time in Appendix G4

a. This will add the previous cell with 50 milliseconds per each cell
b. Click the bottom of the cell to drag the data to the bottom of you gathered data

25) Insert and create a graph of Temperature over Time

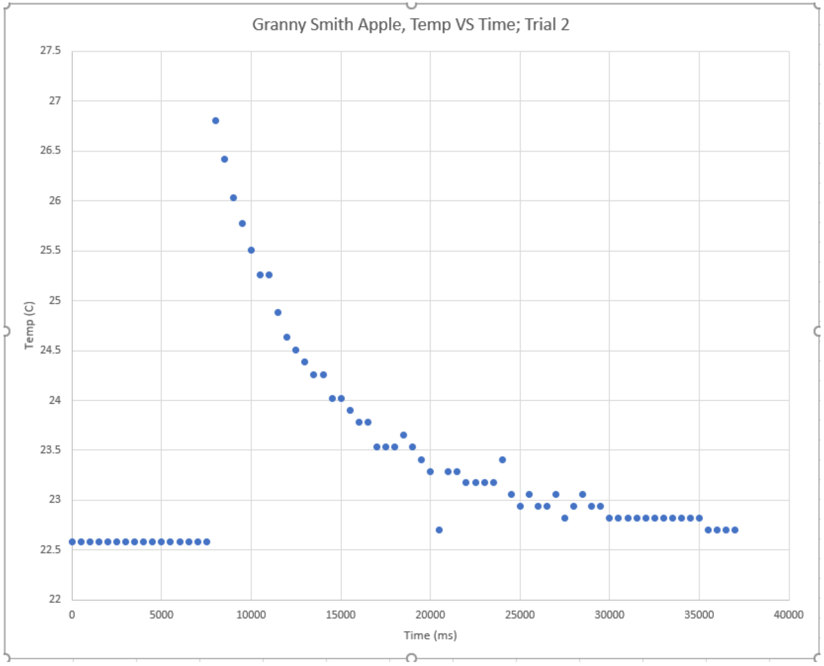


Figure 06: Graph of Decay

26) With data sheet containing the graph from Step 24 in Appendix G4, begin calculating the thermal conductivity of the materials.

a. Use Ohm's Law to calculate the power of the pulse in the material.
b. Lookup density and specific heat of given materials, these are denoted as Rho and c.
c. Specify a time of measurement where the data looks consolidated on the graph.
    i. Record the time of measurement
    ii. Record the temperature at that specific time

d. Time of pulse is predetermined at 3 seconds

$$T(0,t) = \frac{(\rho c)^{0.5}P}{8\pi^{1.5}k^{1.5}}[(t - t_p)^{-0.5} - t^{-0.5}]$$

Equation 01: Rearrange and solve for “k”

e. Use Equation 01 to Calculate the thermal conductivity assuming an infinitely small probe.

$$k/(\rho c)^{1/3} = [P((t_m - t_p)^{-0.5} - t_m^{-0.5})/4T_o(t_m)]^{2/3}/\pi$$

Equation 02: Rearrange and solve for “k”

f. Use Equation 2 to calculate the thermal conductivity assuming small probe.
g. Compare values of Equation 1 and 2 too known values of thermal conductivity.

27) Repeat Steps 15-25 for three more trials on the same material
28) Average results of the three trials and compute final comparison between experimental thermal conductivity and known thermal conductivity

Test Procedure for Water Around Freezing:

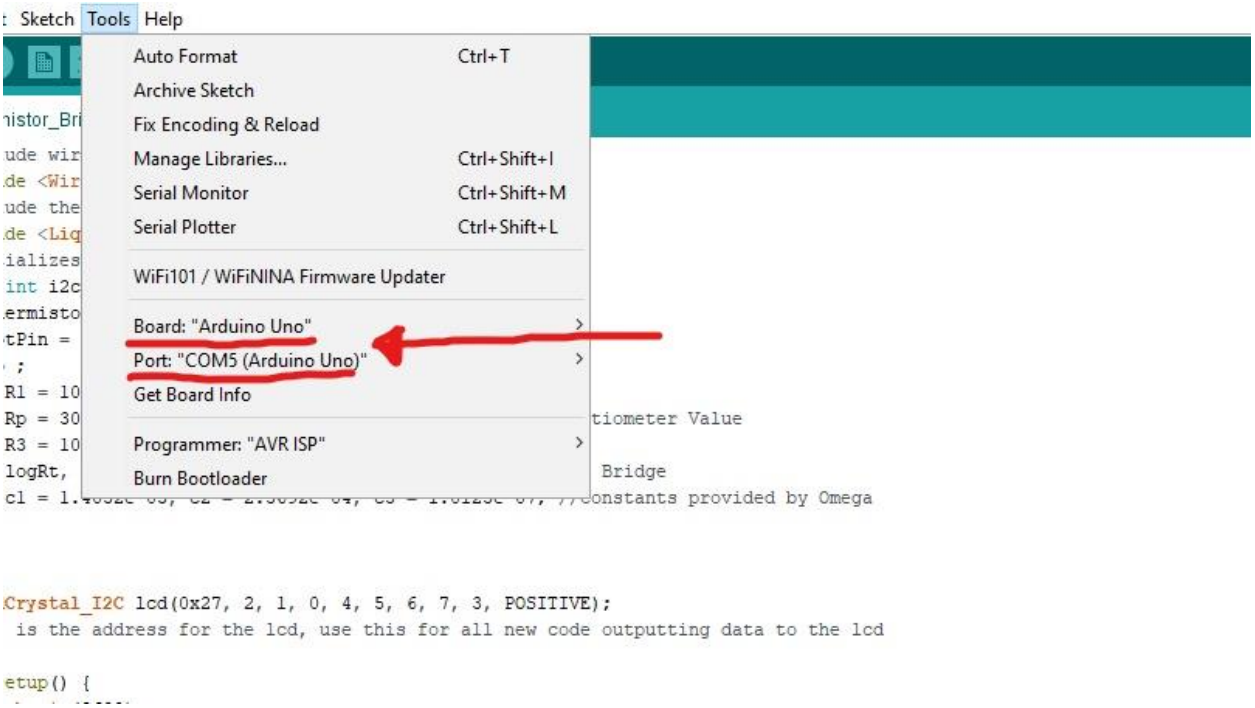
Time: 8:05 AM, 4/30/2021
Place: Apartment
Required Equipment:

- Computer with 5V USB and Arduino IDE software.
- Phone or Recording Device
- Thermometer or Temperature Sensing Mode of Device
- Multimeter
- Water Mixed with Gelatin which has been refrigerated for at least 2 hours
- Table
- Writing implement
- Data Sheet

Risk: This test cannot be conducted without electrical power supplied from a wall outlet. All equipment must be collected ahead of time. Test Specimens must be ready prior to use of the device as per the requirements. When adjusting the power supply, if it is not currently at 10V, carefully adjust the nobs slightly. If the power supply is adjusted to 10V to roughly, it will overvolt the system and the Arduino will need replaced.

The test procedure is as follows:

1) Collect Equipment
    a. Room Temperature gelatin is left out. Cold temperature gelatin is held within a freezer until time to test. The potato is left out at room temperature as well as the stainless steel. Leave cold material in the freezer until time to test.
    b. Obtain a copy of Appendix G2 or access have access to excel spreadsheet in Appendix G4.
2) Turn computer on and navigate to Arduinos IDE Software.
3) Navigate to the Tools section on the bar and ensure that the computer and Arduino are communicating.



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ializes
int i2c
ermisto
tPin =
 ;
R1 = 10
Rp = 30                                  tiometer Value
R3 = 10
logRt,                                    Bridge
cl = 1.                                 onstants provided by Omega


Crystal_I2C lcd(0x27, 2, 1, 0, 4, 5, 6, 7, 3, POSITIVE);
 is the address for the lcd, use this for all new code outputting data to the lcd

etup() {
```

Figure 01 Computer and Arduino Communication

4) Place device onto table and plug in the Power Supply and 5V USB into a Computer. Ensure that the power supply is left off. This ensures that the device is left into temperature sensing mode.

5) Turn the power supply on and adjust the nobs to make the output 10V.

Figure 02 Power Supply Adjustment

   a. Power off the supply when adjusted.

6) Obtain the first material to be tested and measure the current temperature with the thermistor probe.
   a. Leave the probe in the material.
   b. Record current temperature of the material.
   c. Record the reported resistance of the thermistor as displayed on the LCD screen.

Figure 02, Where data is displayed

7) With the probe still in the material, obtain the multimeter.
8) Using the multimeter, measure the resistance of the potentiometer.

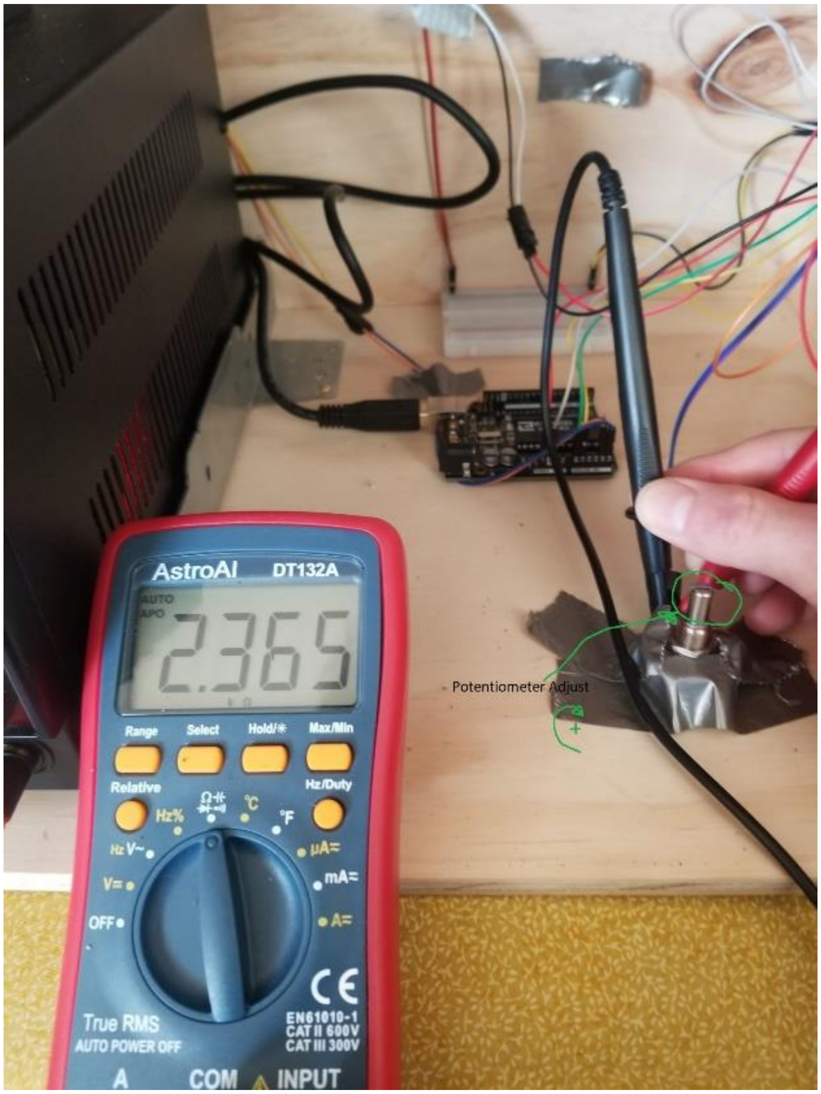


Figure 02 Potentiometer and Adjustments

   a. Carefully adjust the potentiometer to equal the resistance of the recorded thermistor resistance.

9) Remove multimeter from the potentiometer.
10) Using the multimeter, place the probes onto the leads of the thermistor and set the dial to measure amperage.
    a. Record sensing amperage across the thermistor on the data sheet
11) Turn on the power supply with the multimeter in place on the thermistor.

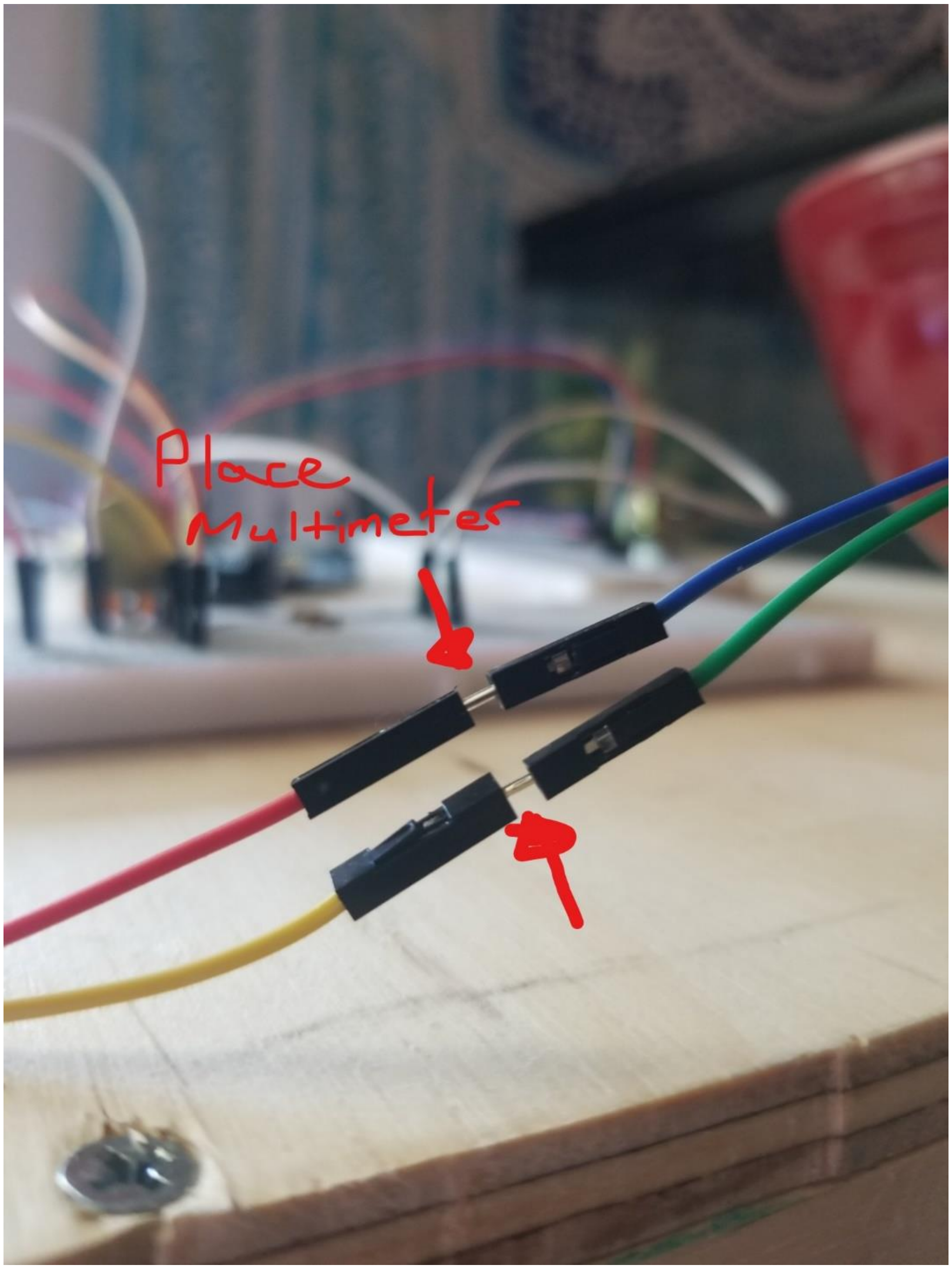
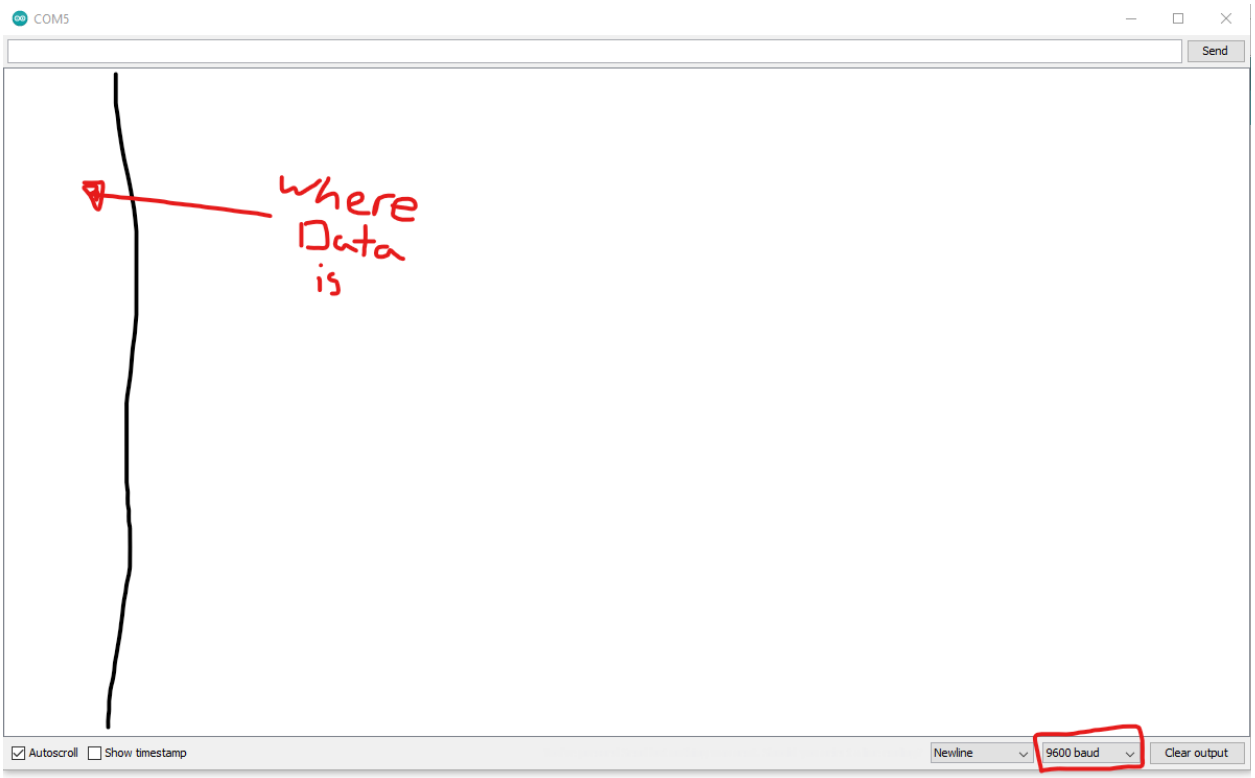


Figure 03: Where to Position Multimeter

   a. Record the pulsing amperage on to the data sheet.

12) Turn power supply off.
13) Remove Multimeter from Thermistor and set aside.
14) Navigate to the Computer
    a. On the Tools Header there is a tab that navigates to the Serial Monitor. If lost, reference Figure 01.
    b. Ensure that the baud is at “9600” for the Arduino to Export Data

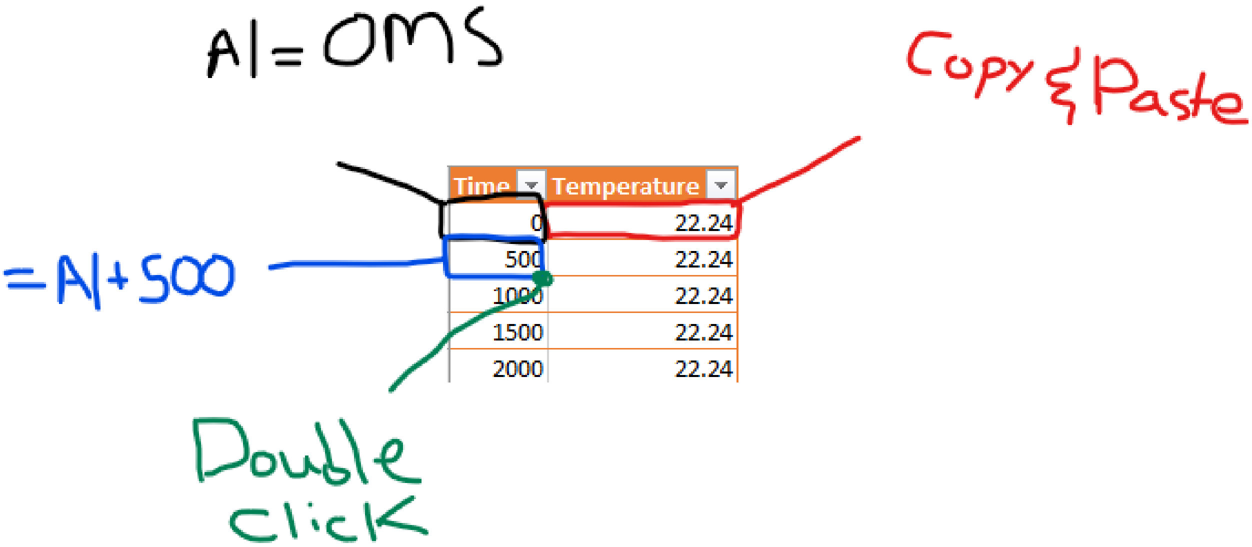


where Data is

Figure 04 Serial Monitor Intro

   c. Start the Arduino’s Serial Monitor. Temperature will begin recording immediately.

15) Power on the power supply, the Arduino Thermistor Probe will now begin the Pulsing Mode for 15 Seconds.
16) Turn on the switch when the pulsing has finished
17) The device will now loop and begin Sensing Mode for 25 seconds
18) Power off the supply when the 25 seconds of Sensing Mode is finished.
19) Remove the 5V USB from the Computer to completely power down the device.
20) Remove probe from material and put away.
21) Return to the Serial Monitor and Press Crtl+A or highlight data with the mouse
22) Copy it and Paste it into Appendix G4 in Cell A1 of the respective sheet for the given material.
23) In cell A1, write 0. This will be denoted as time in milliseconds
    a. The Arduino is programmed to gather data every 500 milliseconds
24) In cell B2, write “ = A1+500 “



Time	Temperature
0	22.24
500	22.24
1000	22.24
1500	22.24
2000	22.24

Figure 05: Making the Graph of Temperature Over Time in Appendix G4

a. This will add the previous cell with 50 milliseconds per each cell
b. Click the bottom of the cell to drag the data to the bottom of you gathered data

25) Insert and create a graph of Temperature over Time

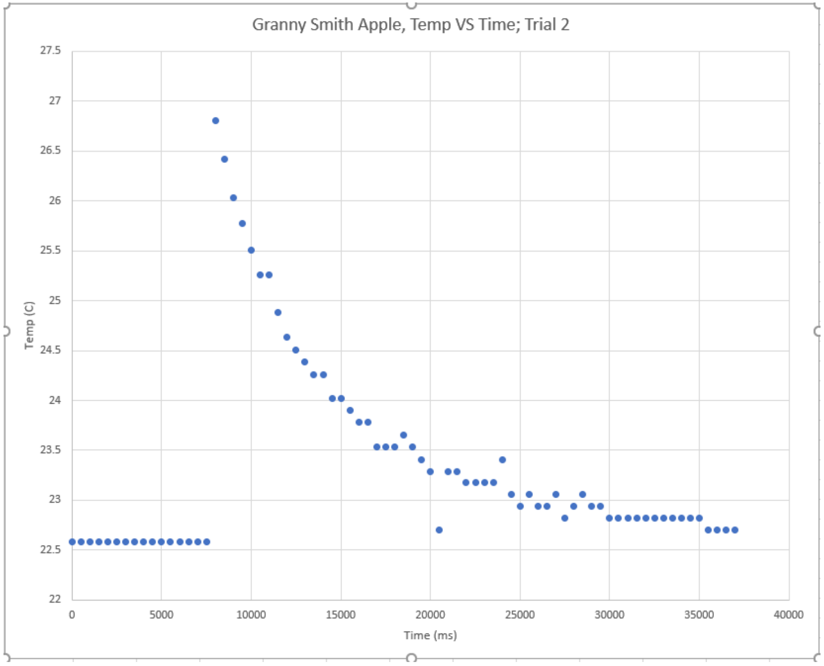


Figure 06: Graph of Decay

26) With data sheet containing the graph from Step 24 in Appendix G4, begin calculating the thermal conductivity of the materials.

a. Use Ohm's Law to calculate the power of the pulse in the material.
b. Lookup density and specific heat of given materials, these are denoted as Rho and c.
c. Specify a time of measurement where the data looks consolidated on the graph.
    i. Record the time of measurement
    ii. Record the temperature at that specific time

    d. Time of pulse is predetermined at 3 seconds

$$T(0,t) = \frac{(\rho c)^{0.5} P}{8\pi^{1.5} k^{1.5}} [(t - t_p)^{-0.5} - t^{-0.5}]$$

Equation 01: Rearrange and solve for “k”

    e. Use Equation 01 to Calculate the thermal conductivity assuming an infinitely small probe.

$$k / (\rho c)^{1/3} = [P((t_m - t_p)^{-0.5} - t_m^{-0.5}) / 4T_o (t_m)]^{2/3} / \pi$$

Equation 02: Rearrange and solve for “k”

    f. Use Equation 2 to calculate the thermal conductivity assuming small probe.
    g. Compare values of Equation 1 and 2 too known values of thermal conductivity.

27) Repeat Steps 15-25 for three more trials on the same material
28) Average results of the three trials and compute final comparison between experimental thermal conductivity and known thermal conductivity

Test Procedure for Granny Smith Apple at Room Temperature:

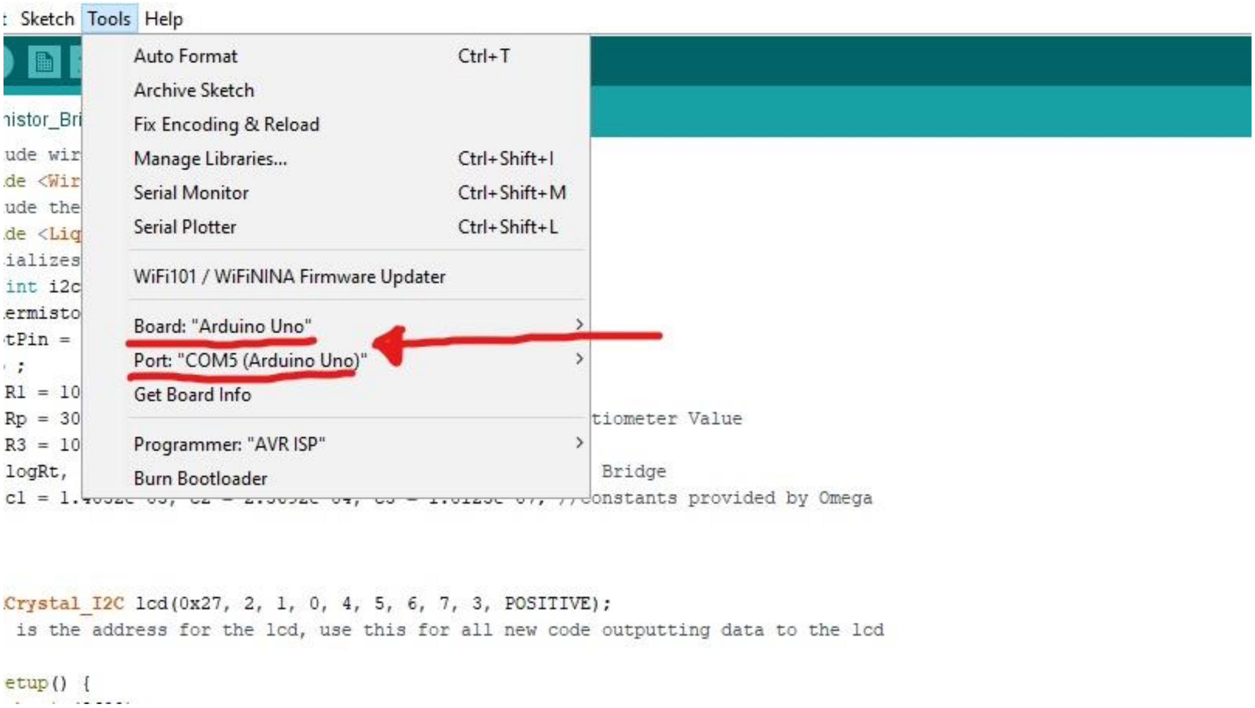
Time: 5:03 PM, 4/29/2021
Place: Apartment
Required Equipment:

- Computer with 5V USB and Arduino IDE software.
- Phone or Recording Device
- Thermometer or Temperature Sensing Mode of Device
- Multimeter
- Granny Smith Apple which has been left in ambient room temperature for at least 2 hours
- Table
- Writing implement
- Data Sheet

Risk: This test cannot be conducted without electrical power supplied from a wall outlet. All equipment must be collected ahead of time. Test Specimens must be ready prior to use of the device as per the requirements. When adjusting the power supply, if it is not currently at 10V, carefully adjust the nobs slightly. If the power supply is adjusted to 10V to roughly, it will overvolt the system and the Arduino will need replaced.

The test procedure is as follows:

1) Collect Equipment
    a. Room Temperature gelatin is left out. Cold temperature gelatin is held within a freezer until time to test. The potato is left out at room temperature as well as the stainless steel. Leave cold material in the freezer until time to test.
    b. Obtain a copy of Appendix G2 or access have access to excel spreadsheet in Appendix G4.
2) Turn computer on and navigate to Arduinos IDE Software.
3) Navigate to the Tools section on the bar and ensure that the computer and Arduino are communicating.



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ude wir
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tPin =
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R1 = 10
Rp = 30                                          tiometer Value
R3 = 10
logRt,                                            Bridge
cl = 1.                                          onstants provided by Omega


Crystal_I2C lcd(0x27, 2, 1, 0, 4, 5, 6, 7, 3, POSITIVE);
 is the address for the lcd, use this for all new code outputting data to the lcd

etup() {
```

Figure 01 Computer and Arduino Communication

4) Place device onto table and plug in the Power Supply and 5V USB into a Computer. Ensure that the power supply is left off. This ensures that the device is left into temperature sensing mode.

5) Turn the power supply on and adjust the nobs to make the output 10V.

Figure 02 Power Supply Adjustment

    a. Power off the supply when adjusted.

6) Obtain the first material to be tested and measure the current temperature with the thermistor probe.
    a. Leave the probe in the material.
    b. Record current temperature of the material.
    c. Record the reported resistance of the thermistor as displayed on the LCD screen.

Figure 02, Where data is displayed

7) With the probe still in the material, obtain the multimeter.
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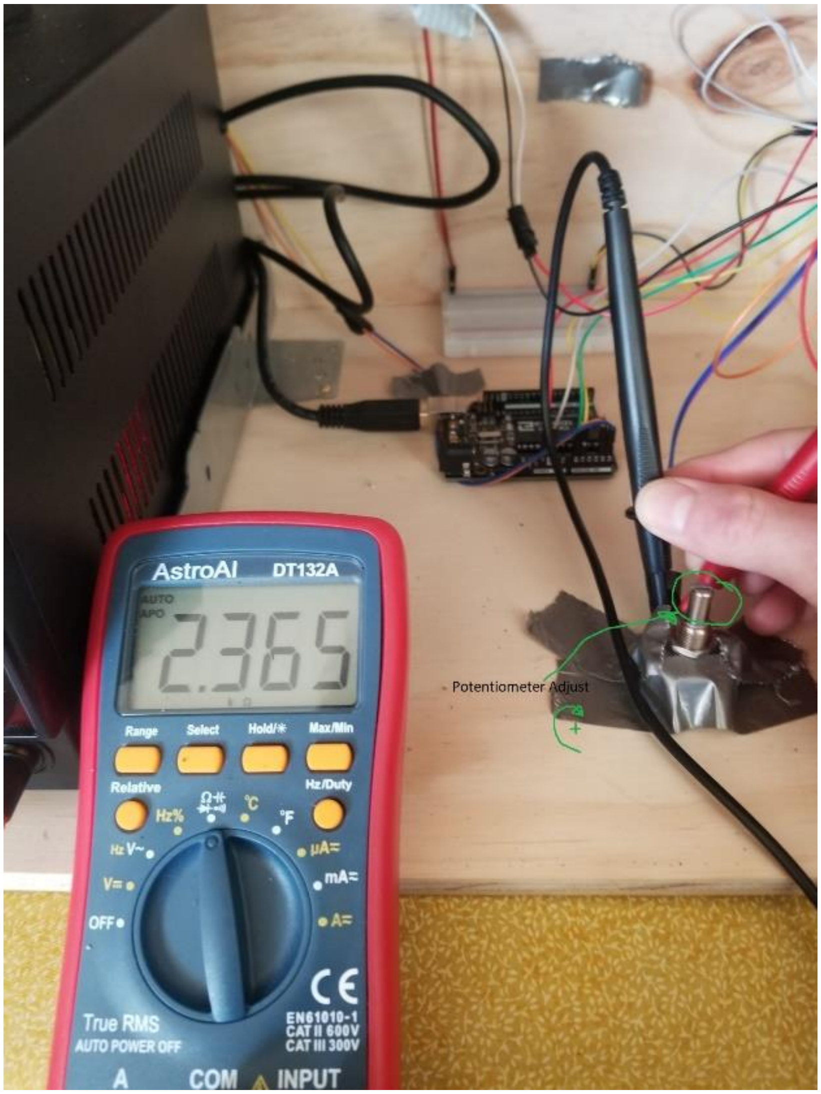

Figure 02 Potentiometer and Adjustments

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9) Remove multimeter from the potentiometer.
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    a. Record sensing amperage across the thermistor on the data sheet
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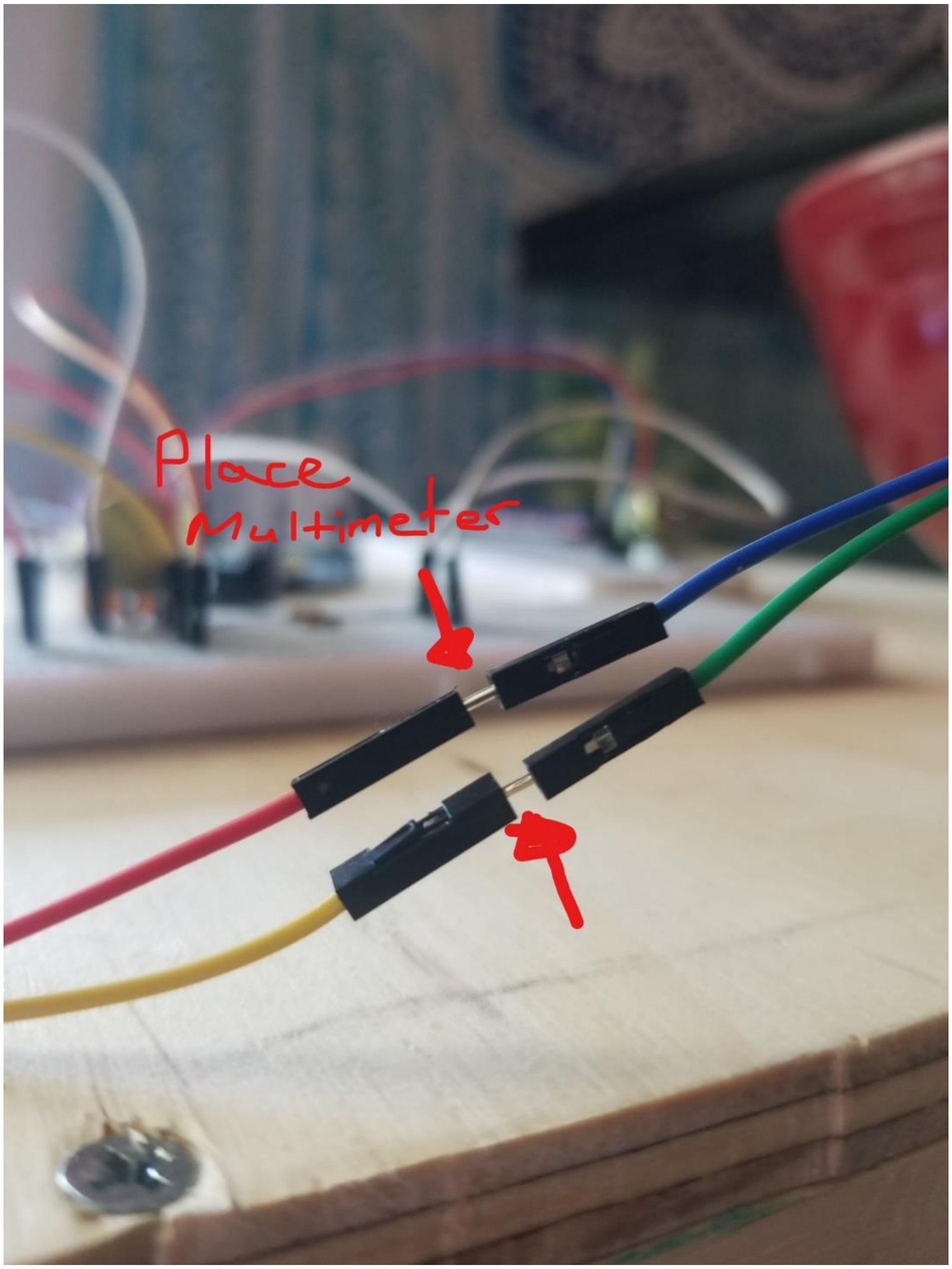

Figure 03: Where to Position Multimeter

   a. Record the pulsing amperage on to the data sheet.

12) Turn power supply off.
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    a. On the Tools Header there is a tab that navigates to the Serial Monitor. If lost, reference Figure 01.
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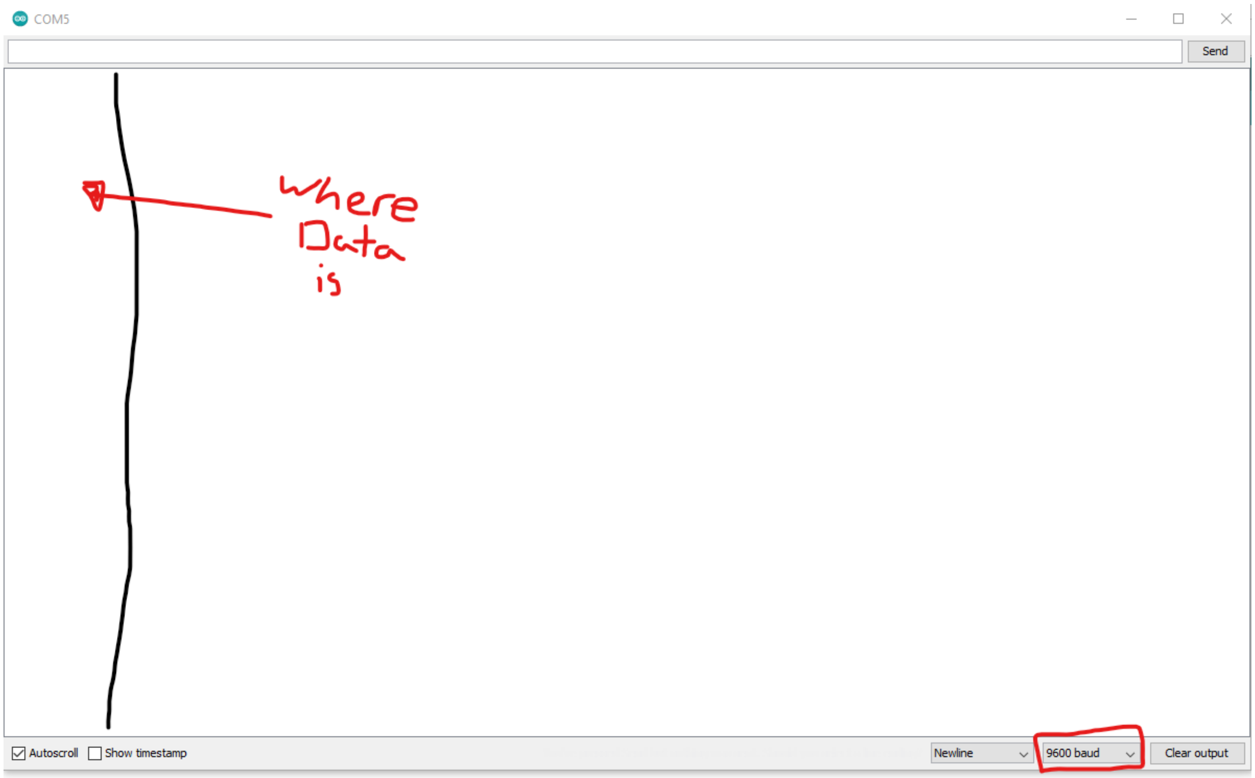

Figure 04 Serial Monitor Intro

    c. Start the Arduino’s Serial Monitor. Temperature will begin recording immediately.

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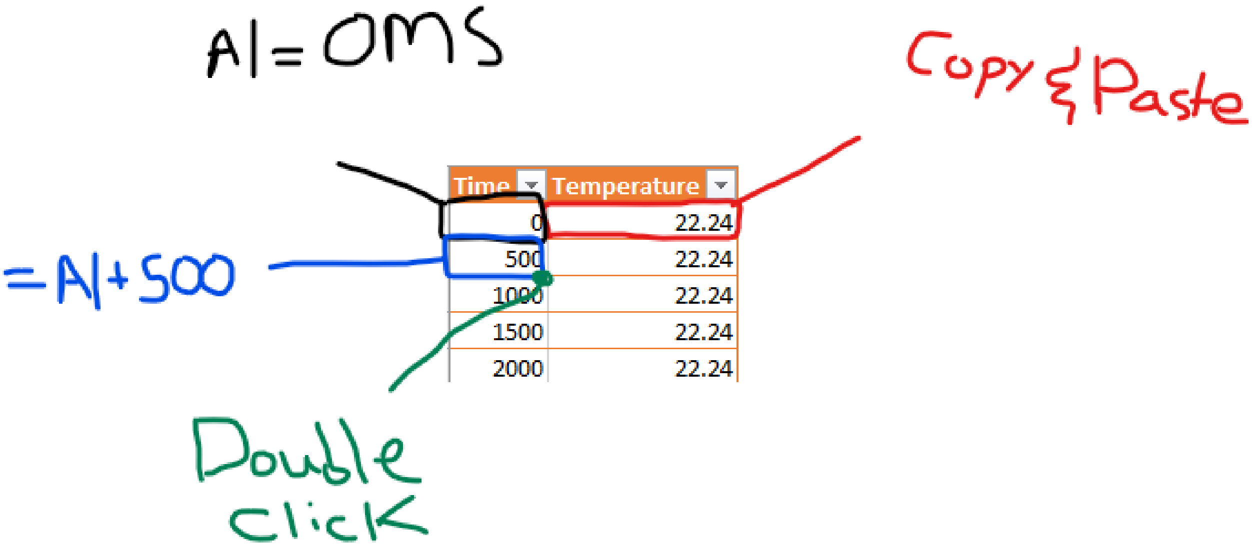
19) Remove the 5V USB from the Computer to completely power down the device.
20) Remove probe from material and put away.
21) Return to the Serial Monitor and Press Crtl+A or highlight data with the mouse
22) Copy it and Paste it into Appendix G4 in Cell A1 of the respective sheet for the given material.
23) In cell A1, write 0. This will be denoted as time in milliseconds
    a. The Arduino is programmed to gather data every 500 milliseconds
24) In cell B2, write “ = A1+500 “



Time	Temperature
0	22.24
500	22.24
1000	22.24
1500	22.24
2000	22.24

Figure 05: Making the Graph of Temperature Over Time in Appendix G4

a. This will add the previous cell with 50 milliseconds per each cell
b. Click the bottom of the cell to drag the data to the bottom of you gathered data

25) Insert and create a graph of Temperature over Time

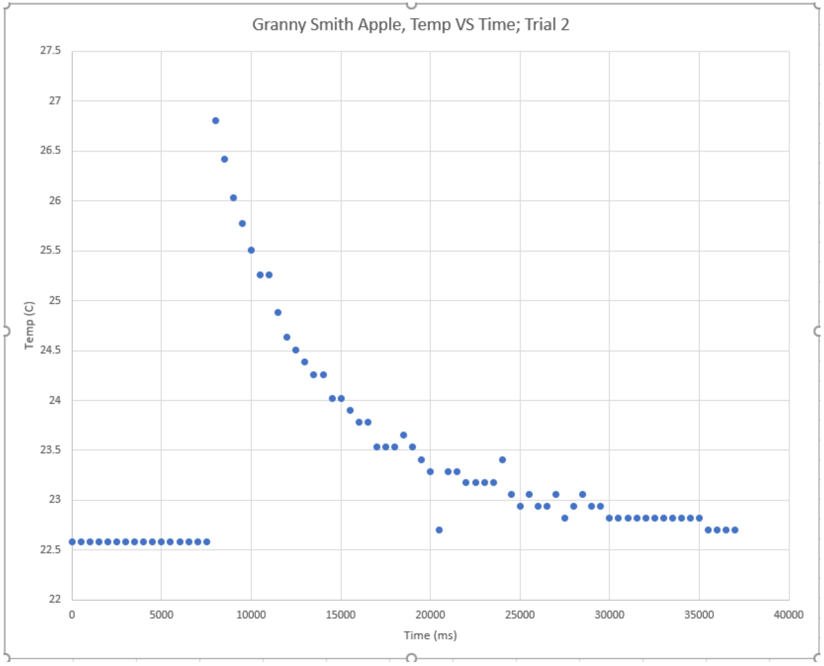


Figure 06: Graph of Decay

26) With data sheet containing the graph from Step 24 in Appendix G4, begin calculating the thermal conductivity of the materials.

a. Use Ohm's Law to calculate the power of the pulse in the material.
b. Lookup density and specific heat of given materials, these are denoted as Rho and c.
c. Specify a time of measurement where the data looks consolidated on the graph.
    i. Record the time of measurement
    ii. Record the temperature at that specific time

d. Time of pulse is predetermined at 3 seconds

$$T(0,t) = \frac{(\rho c)^{0.5} P}{8\pi^{1.5} k^{1.5}} [(t - t_p)^{-0.5} - t^{-0.5}]$$

Equation 01: Rearrange and solve for “k”

e. Use Equation 01 to Calculate the thermal conductivity assuming an infinitely small probe.

$$k / (\rho c)^{1/3} = [P((t_m - t_p)^{-0.5} - t_m^{-0.5})/4T_o(t_m)]^{2/3} / \pi$$

Equation 02: Rearrange and solve for “k”

f. Use Equation 2 to calculate the thermal conductivity assuming small probe.
g. Compare values of Equation 1 and 2 too known values of thermal conductivity.

27) Repeat Steps 15-25 for three more trials on the same material
28) Average results of the three trials and compute final comparison between experimental thermal conductivity and known thermal conductivity

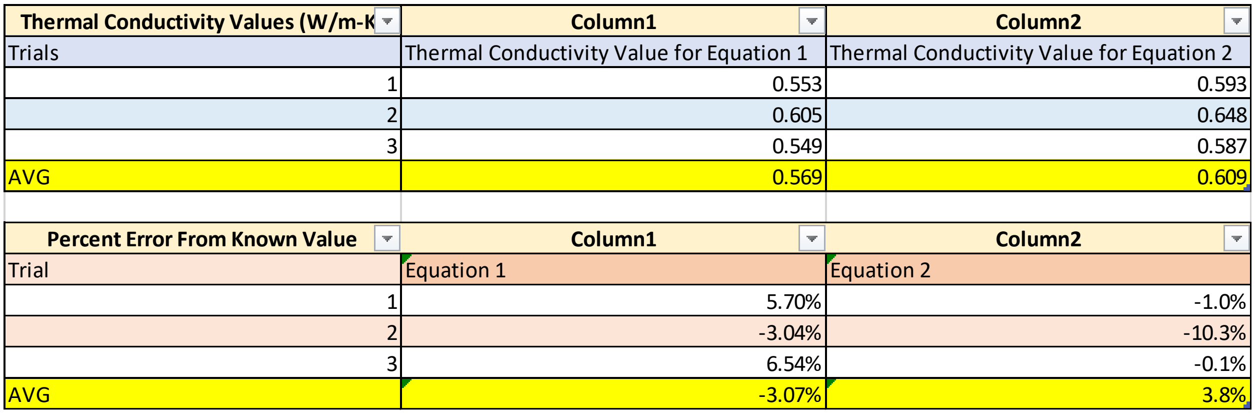
Discussion:

Testing went well with issues in recording the amperage output of the pulse as well as analyzing the graph. The variability in measurements will result in some human error if there is little prior knowledge to how the test should be conducted. The first issue arose with the thermistor not properly heating up during pulsing mode. This was fixed by separating the circuit with another timer.

Originally, the circuit was specifically measuring noise in what appeared to be the two voltage sources competing with one another. To remedy this situation, the Arduino was configured into a Pulse Width Module and the acquisition pin was given a switch to separate the circuit. This result was a good graph of temperature decay with respect to time.

Deliverables:

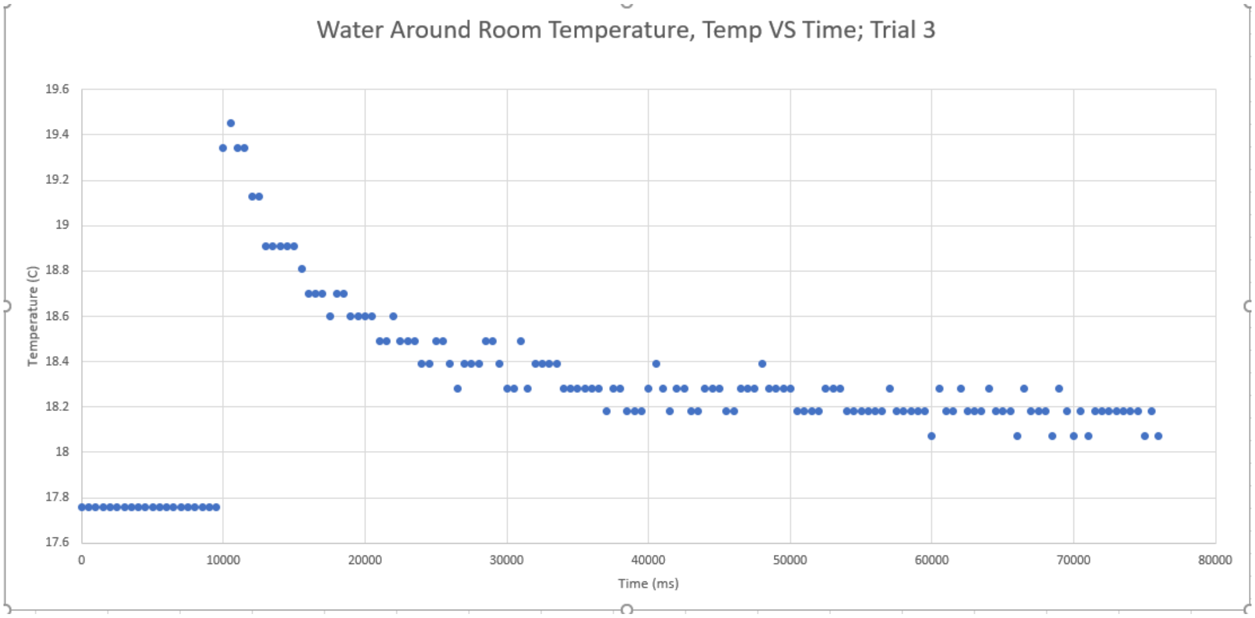
A successful test will result in a thermal conductivity measurement with +/-5% error of known values. If the results are out of that range, then the test is considered a failure. Likewise, a noticeable graph which outlines temperature over decay is required to emphasize that the device is functioning properly. If one of these parameters is missing, then the test is a failure. The measurements of “t” resulted in a parameter value for T (0,t), Amperage, Resistance that produced data for processing. The result of rearranging Equation One and Equation Two produces a value of thermal conductivity k in W/m-K. In the first test, the time it took to receive a value for thermal conductivity was ten minutes. This included using a multimeter to obtain the output amperage of the thermistor and various initial measurements. This time is also included in the linear interpolation and researching values of specific heat (J/kg-K), Density (kg/m^3), and Thermal Conductivity. The overall testing of temperature with the thermistor took less than two minutes, which is perfectly applicable to the requirements and predicted results. There was an issue in using the multimeter on the thermistor leads to obtain the amperage of a pulse. The leads used to receive the reading are extremely small, resulting in inaccurate or in some cases no readings. This was alleviated by moving further down the wires on the jumper cables. However, with using the jumper cables and mildly separating them to receive a reading would result in the thermistor getting disconnected at times. This is an issue in the testing procedures; however, it does not result in an inaccurate or imprecise test.



Thermal Conductivity Values (W/m-K	Column1	Column2
Trials	Thermal Conductivity Value for Equation 1	Thermal Conductivity Value for Equation 2
1	0.553	0.593
2	0.605	0.648
3	0.549	0.587
AVG	0.569	0.609

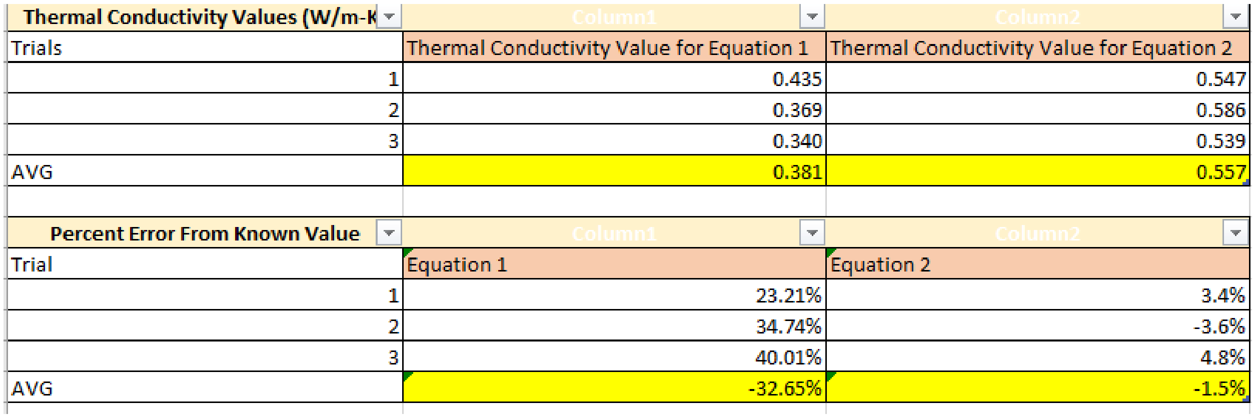
Percent Error From Known Value	Column1	Column2
Trial	Equation 1	Equation 2
1	5.70%	-1.0%
2	-3.04%	-10.3%
3	6.54%	-0.1%
AVG	-3.07%	3.8%

Table 1: Results for Water at 13.87 Degrees Celsius



Graph 1: Water at Room Temperature; Decay of Temperature with Respect to Time

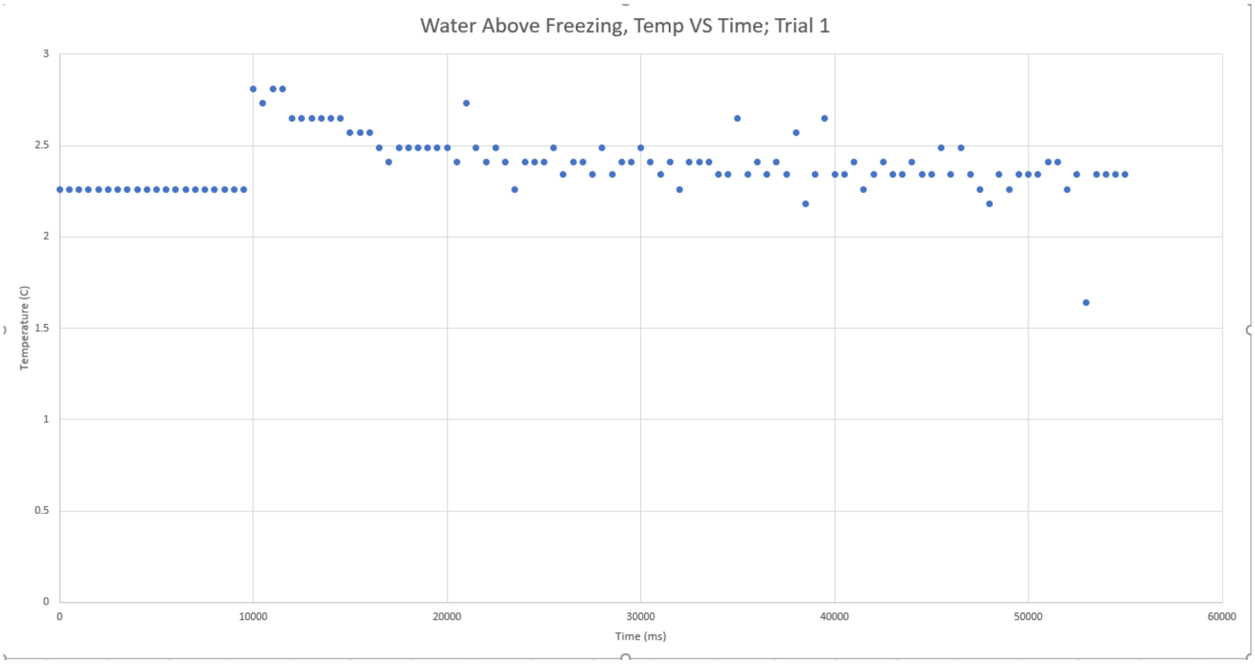
The results of the first test, water mixed with gelatin at around room temperature were as expected. The experiment produced a value of 0.596 W/m-K for the first equation using a three second pulse time and a measurement time of six seconds. The second equation produced a thermal conductivity value of 0.609 W/m-K with a pulse time of 15 seconds and a measurement time of 40 seconds. Through interpolation a known value of conductivity for water at 13.87 degrees Celsius is 0.587 W/m-K and compared this with the experimental values. As stated per the requirements, the measurement had to be within +/- 5% error for the test to be successful. Thus, the device was designed and predicted to be within 5% error of known values. For equation one the averaged percent error was -3.07%. For equation two, the averaged thermal conductivity value had a 3.8% error. This value for the second equation may have been influenced by underlying issues with the test, as the first and third tests were less than 1% error, whereas the second test resulted in a 10% error in reading. To address this greater margin of error, another test is applicable to remove any outliers held within the data. Overall, test one was successful and both governing equations are accurate and precise in the results they produced. Regarding the two separate equations, there is no definitive conclusion to be made over which one is more accurate to use in the event of testing water at around room temperature.



Thermal Conductivity Values (W/m-K	Column1	Column2
Trials	Thermal Conductivity Value for Equation 1	Thermal Conductivity Value for Equation 2
1	0.435	0.547
2	0.369	0.586
3	0.340	0.539
AVG	0.381	0.557

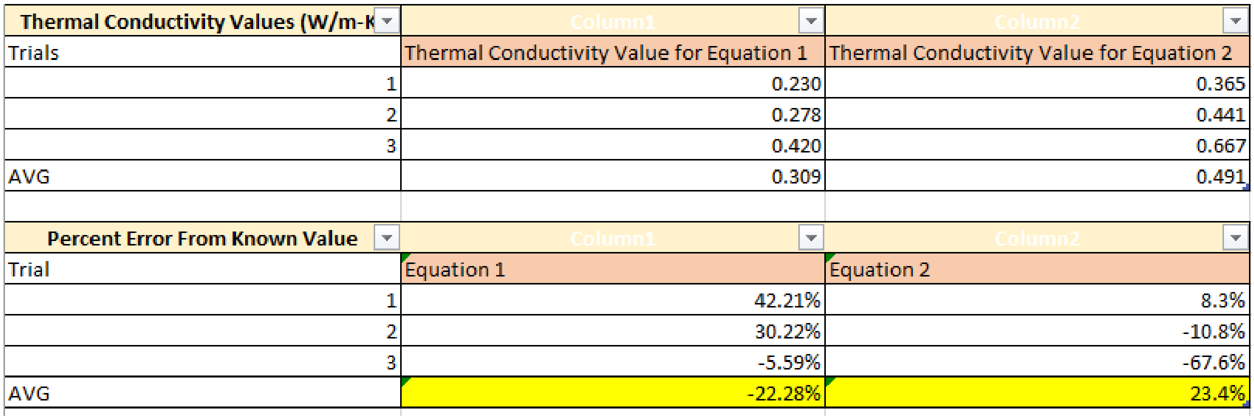
Percent Error From Known Value	Column1	Column2
Trial	Equation 1	Equation 2
1	23.21%	3.4%
2	34.74%	-3.6%
3	40.01%	4.8%
AVG	-32.65%	-1.5%

Table 2: Results for Water at 2.26 Degrees Celsius



Graph 2: Water above Freezing Temperature; Decay of Temperature with Respect to Time

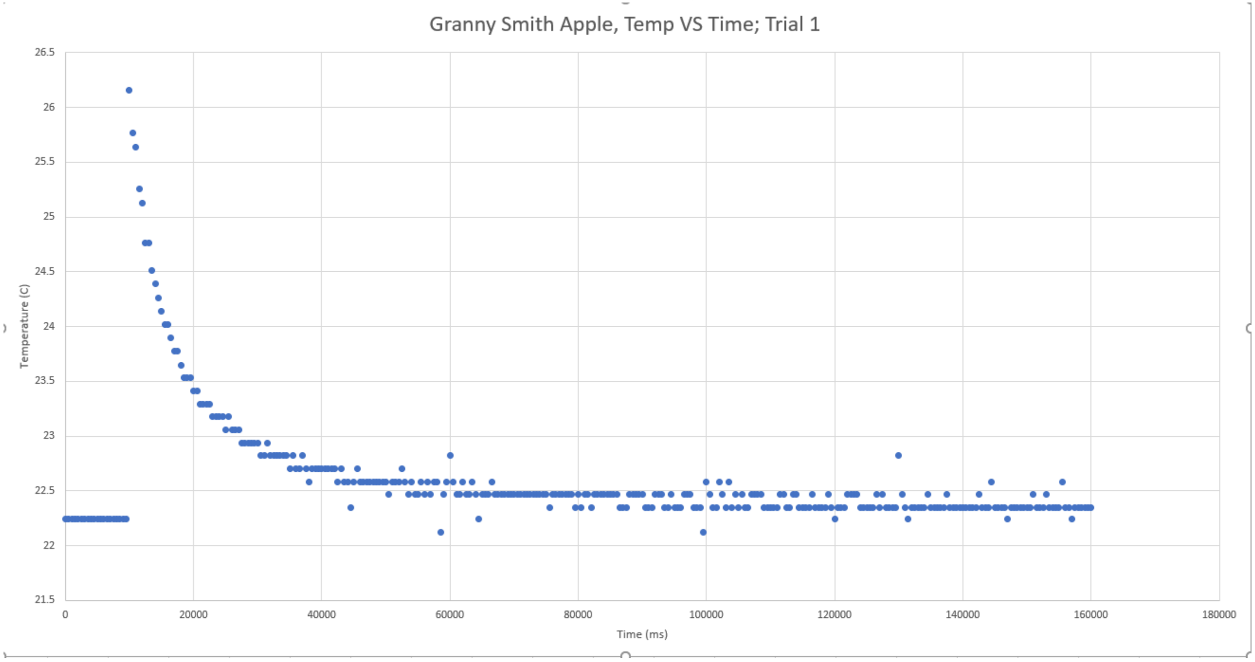
The second test was of water mixed with gelatin at slightly above freezing temperature. The experiment yielded a thermal conductivity value of 0.381 W/m-K and 0.557 W/m-K for Equations 1 and 2 respectively. The pulsing times consisted of a 15 second pulse per trial. Finding consolidation on *Graph 2*, the measurement times were 22 seconds, 22.5 seconds, and 25 seconds for trials one through 3. The results were averaged and a comparison to the known value of conductivity were evaluated. Equation 1 produced an error of -32.65% and Equation 2 produced an error of -1.5%. Equation One appears to require a closer time of measurement with respect to the pulse. This likely resides in the assumptions that Equation 1 governs upon and proves the thesis that Equation 2 will produce better results for finite probe methods.



Thermal Conductivity Values (W/m-K	Column1	Column2
Trials	Thermal Conductivity Value for Equation 1	Thermal Conductivity Value for Equation 2
1	0.230	0.365
2	0.278	0.441
3	0.420	0.667
AVG	0.309	0.491

Percent Error From Known Value	Column1	Column2
Trial	Equation 1	Equation 2
1	42.21%	8.3%
2	30.22%	-10.8%
3	-5.59%	-67.6%
AVG	-22.28%	23.4%

Table 3: Results for Granny Smith Apple at 22.24 Degrees Celsius



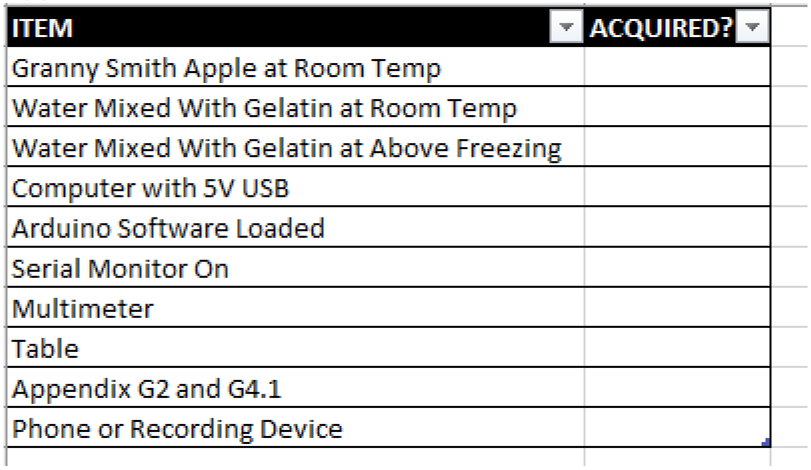
Graph 3: Granny Smith Apple at about Room Temperature; Decay of Temperature with Respect to Time

The third test was of a Granny Smith Apple at around room temperature. The experiment produced a thermal conductivity value of 0.309 W/m-K and 0.491 W/m-K for Equations 1 and 2 respectively. These are the average of three trials conducted. The resulting errors consisted of -22.28% and 23.4%. The conductivity measurements were multiplied by a factor of 10, due to the time dependence on measurement or a false connection with the material being tested. This correction factor is likely due to the physical aspects of solid like materials, which starkly contrast the liquid materials studied in this experiment. Another source of error consists in lesser known values of thermal conductivity for Apples. There are little known sources of tabulated results for apples at varying degrees, which would produce greater margins of error. The graph cleanly shows a decay of temperature, which should indicate an amount of heat transfer being conducted. More experiments in the thermal conductivity of apples should be conducted based off the results obtained.

In conclusion, the device can perform evaluations on liquid like materials with an accuracy within +/- 5% error. Issues with testing solid materials occurred and cannot be recommended for the current device. Thus, further research into this phenomenon is required. Also, the second equation developed by *Holmes* is more applicable for the design of the probe, as it proved to be more accurate than Equation one. There appears to be strong dependence on time for the parameters of this testing and thus should be chosen with caution when selecting a consolidation period provided by the graphs of temperature decay versus time. Overall, the device is successful in reporting thermal conductivity as there is a mode of heat transfer between the thermistor and the medium it is testing. Further research into the efficacy of the device is in order for further experiments.

Appendices

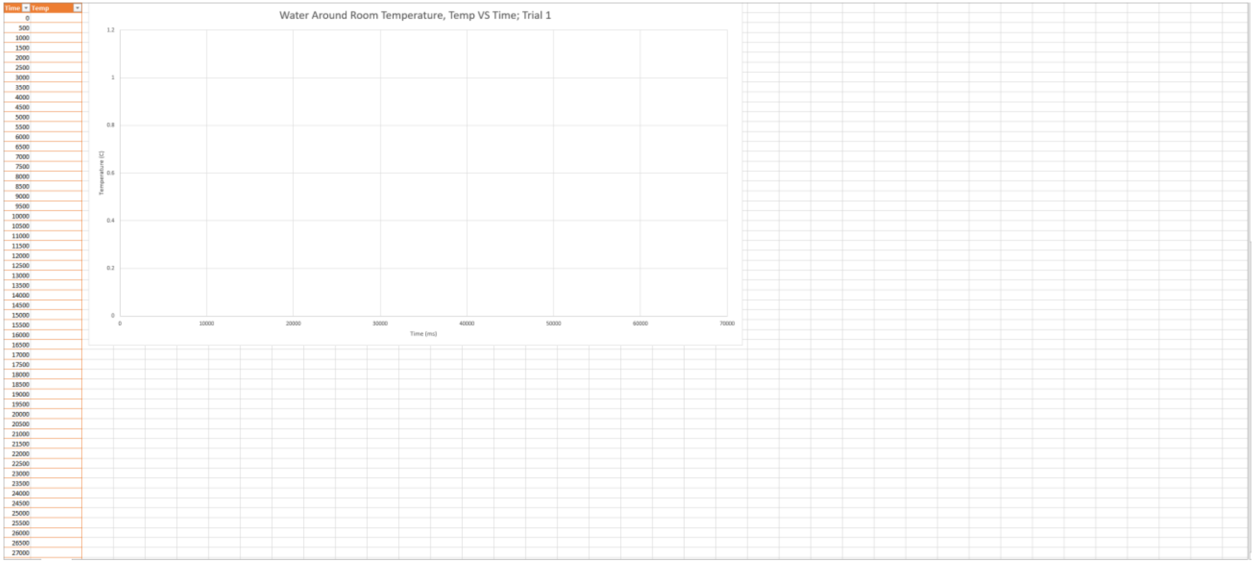
Appendix G1:



ITEM	ACQUIRED?
Granny Smith Apple at Room Temp	
Water Mixed With Gelatin at Room Temp	
Water Mixed With Gelatin at Above Freezing	
Computer with 5V USB	
Arduino Software Loaded	
Serial Monitor On	
Multimeter	
Table	
Appendix G2 and G4.1	
Phone or Recording Device	

Appendix G2:

Appendix G2.1 – Blank Form of Water at Room Temperature (LINK)

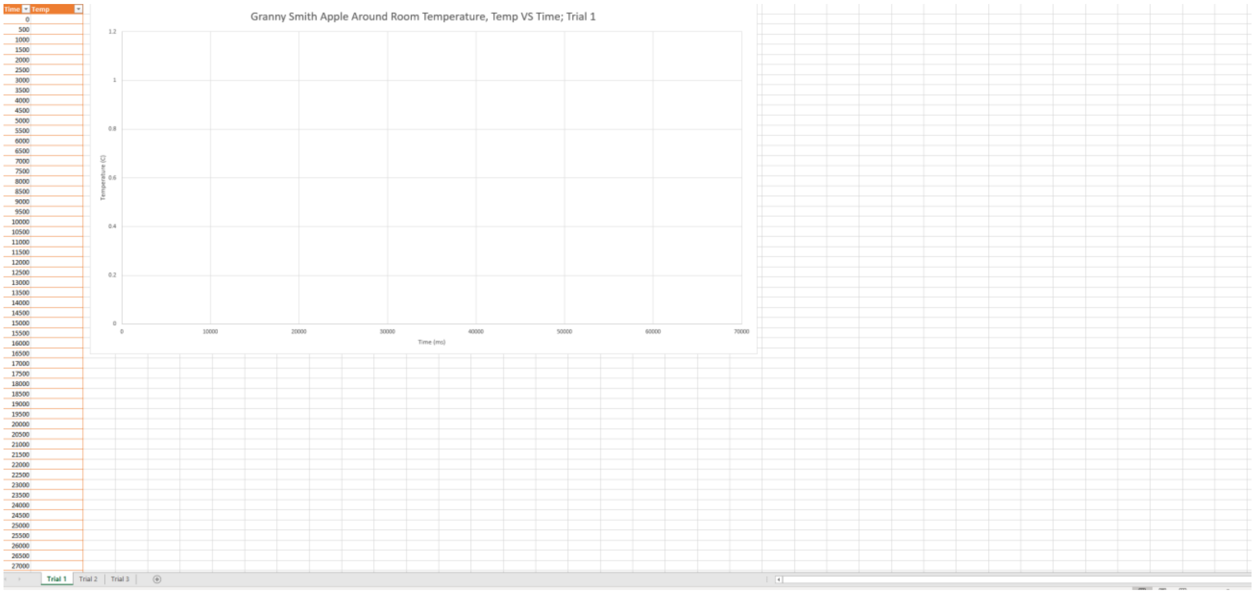


Time	Temp
0	
500	
1000	
1500	
2000	
2500	
3000	
3500	
4000	
4500	
5000	
5500	
6000	
6500	
7000	
7500	
8000	
8500	
9000	
9500	
10000	
10500	
11000	
11500	
12000	
12500	
13000	
13500	
14000	
14500	
15000	
15500	
16000	
16500	
17000	
17500	
18000	
18500	
19000	
19500	
20000	
20500	
21000	
21500	
22000	
22500	
23000	
23500	
24000	
24500	
25000	
25500	
26000	
26500	
27000	

Appendix G2.2 – Blank Form of Water Above Freezing (LINK)

Time	Temp
0	
500	
1000	
1500	
2000	
2500	
3000	
3500	
4000	
4500	
5000	
5500	
6000	
6500	
7000	
7500	
8000	
8500	
9000	
9500	
10000	
10500	
11000	
11500	
12000	
12500	
13000	
13500	
14000	
14500	
15000	
15500	
16000	
16500	
17000	
17500	
18000	
18500	
19000	
19500	
20000	
20500	
21000	
21500	
22000	
22500	
23000	
23500	
24000	
24500	
25000	
25500	
26000	
26500	
27000	

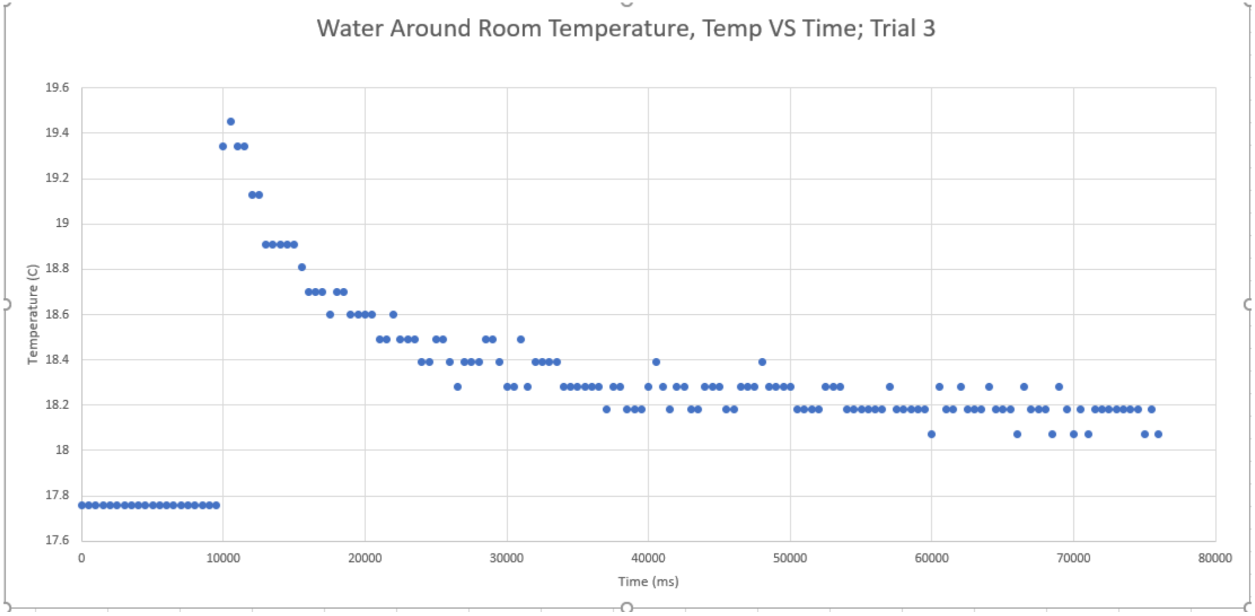
Appendix G2.3 – Blank Form of Granny Smith Apple at Room Temperature (LINK)



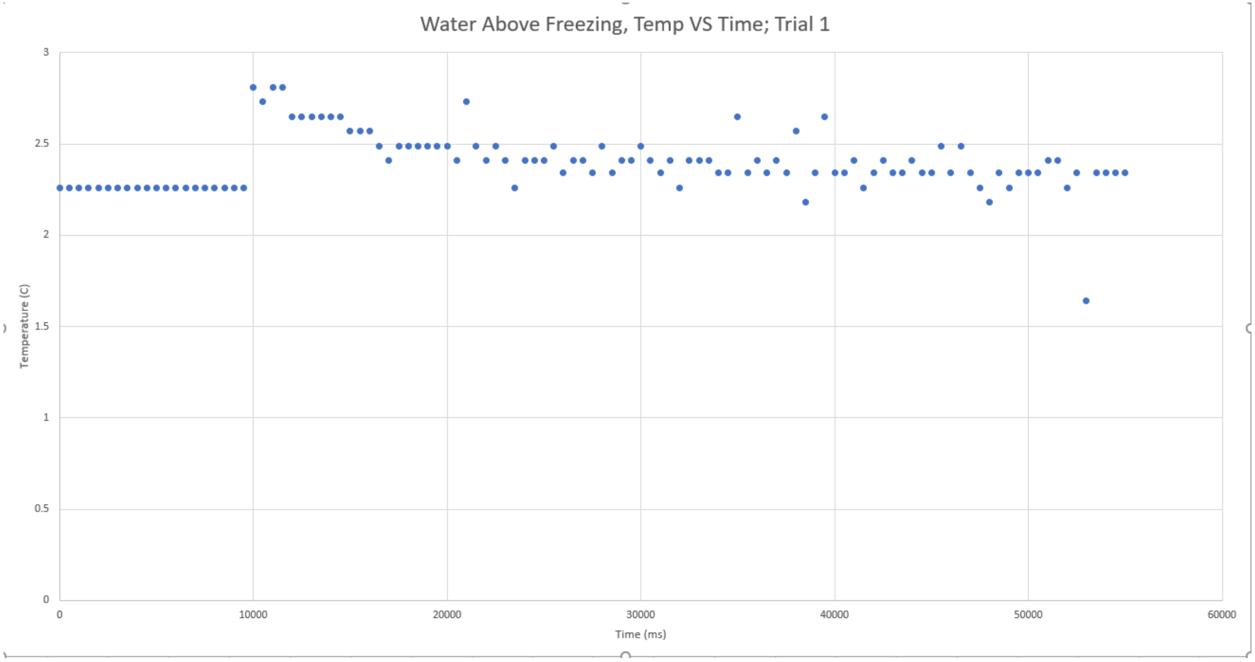
Time	Temp
0	
500	
1000	
1500	
2000	
2500	
3000	
3500	
4000	
4500	
5000	
5500	
6000	
6500	
7000	
7500	
8000	
8500	
9000	
9500	
10000	
10500	
11000	
11500	
12000	
12500	
13000	
13500	
14000	
14500	
15000	
15500	
16000	
16500	
17000	
17500	
18000	
18500	
19000	
19500	
20000	
20500	
21000	
21500	
22000	
22500	
23000	
23500	
24000	
24500	
25000	
25500	
26000	
26500	
27000	

Appendix G3:

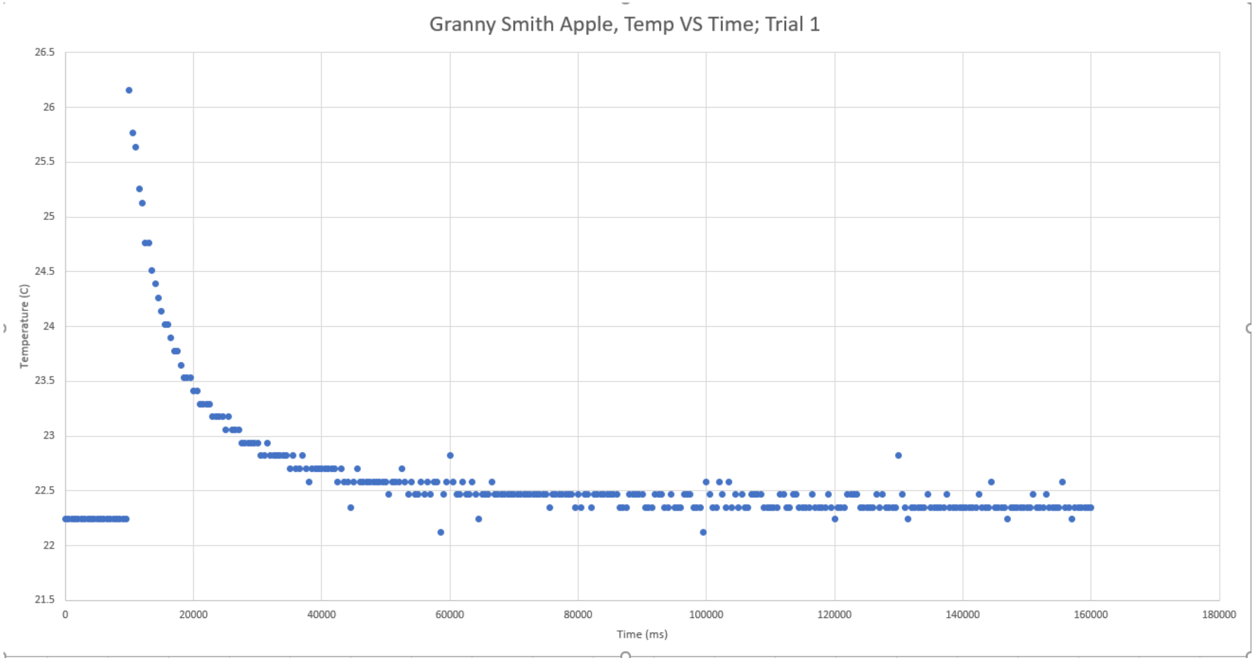
Appendix G3.1 – Completed Form of Water at Room Temperature



Appendix G3.2 – Completed Form of Water Above Freezing

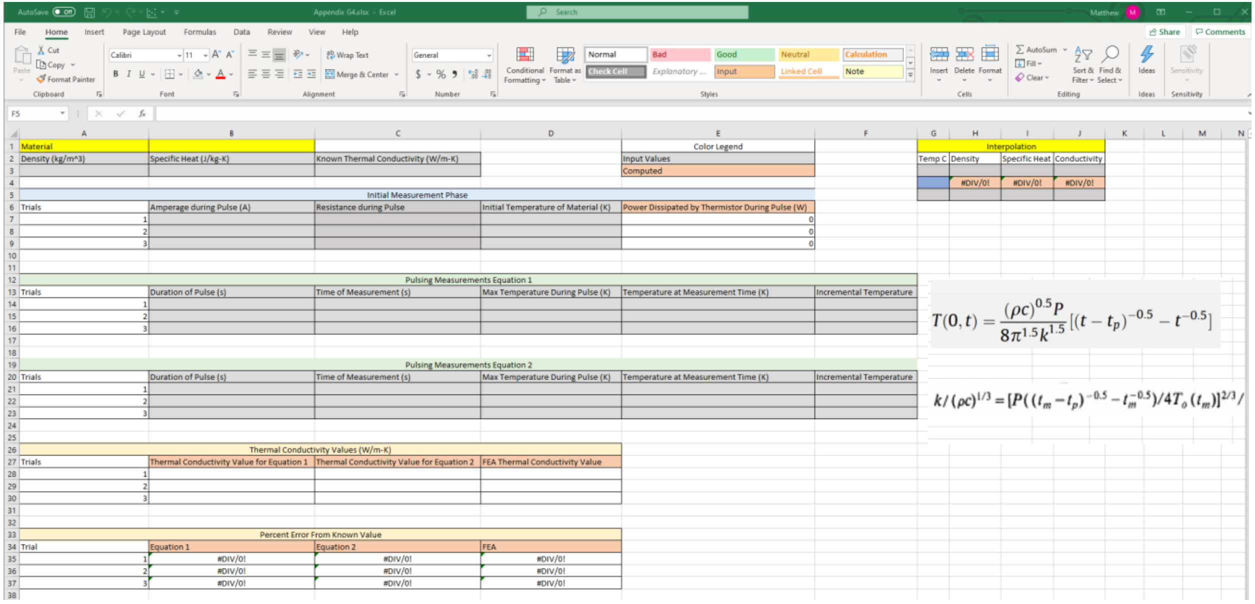


Appendix G3.3 – Completed Form of Granny Smith Apple at Room Temperature



Appendix G4:

Appendix G4.1 – Blank Computational Sheet (LINK)

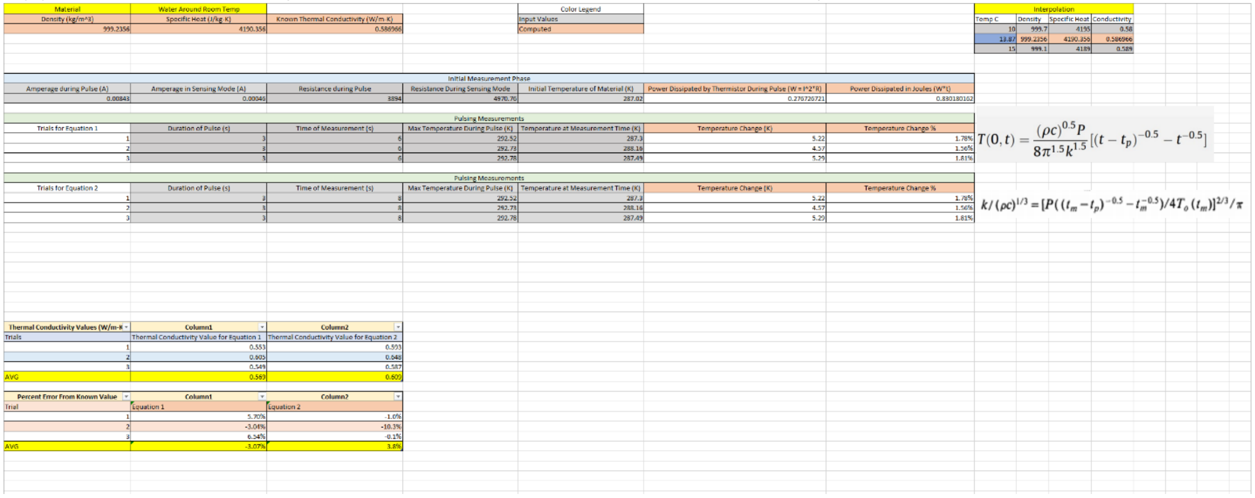


	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	Material				Color Legend		Interpolation							
2	Density (kg/m^3)	Specific Heat (J/kg-K)	Known Thermal Conductivity (W/m-K)		Input Values		Temp C	Density	Specific Heat	Conductivity				
3					Computed									
4								#DIV/0!	#DIV/0!	#DIV/0!				
5	Initial Measurement Phase													
6	Trials	Amperage during Pulse (A)	Resistance during Pulse	Initial Temperature of Material (K)	Power Dissipated by Thermistor During Pulse (W)									
7	1				0									
8	2				0									
9	3				0									
10														
11														
12	Pulsing Measurements Equation 1													
13	Trials	Duration of Pulse (s)	Time of Measurement (s)	Max Temperature During Pulse (K)	Temperature at Measurement Time (K)	Incremental Temperature								
14	1													
15	2													
16	3													
17														
18														
19	Pulsing Measurements Equation 2													
20	Trials	Duration of Pulse (s)	Time of Measurement (s)	Max Temperature During Pulse (K)	Temperature at Measurement Time (K)	Incremental Temperature								
21	1													
22	2													
23	3													
24														
25														
26	Thermal Conductivity Values (W/m-K)													
27	Trials	Thermal Conductivity Value for Equation 1	Thermal Conductivity Value for Equation 2	FEA Thermal Conductivity Value										
28	1													
29	2													
30	3													
31														
32														
33	Percent Error From Known Value													
34	Trial	Equation 1	Equation 2	FEA										
35	1	#DIV/0!	#DIV/0!	#DIV/0!										
36	2	#DIV/0!	#DIV/0!	#DIV/0!										
37	3	#DIV/0!	#DIV/0!	#DIV/0!										
38														

$$T(0,t) = \frac{(\rho c)^{0.5} P}{8\pi^{1.5} k^{1.5}} [(t - t_p)^{-0.5} - t^{-0.5}]$$

$$k/(\rho c)^{1/3} = [P((t_m - t_p)^{-0.5} - t_m^{-0.5})/4T_o(t_m)]^{2/3}/$$

Appendix G4.2 – Completed Evaluation of Water at Room Temperature



Material	Water Around Room Temp	
Density (kg/m^3)	Specific Heat (J/kg-K)	Known Thermal Conductivity (W/m-K)
999.2356	4190.356	0.586966

Color Legend
Input Values
Computed

Interpolation			
Temp C	Density	Specific Heat	Conductivity
10	999.7	4195	0.58
13.87	999.2356	4190.356	0.586966
15	999.1	4189	0.589

Initial Measurement Phase

Amperage during Pulse (A)	Amperage in Sensing Mode (A)	Resistance during Pulse	Resistance During Sensing Mode	Initial Temperature of Material (K)	Power Dissipated by Thermistor During Pulse (W = I^2*R)	Power Dissipated in Joules (W*t)
0.00843	0.00046	3894	4970.76	287.02	0.276726721	0.830180162

Pulsing Measurements

Trials for Equation 1	Duration of Pulse (s)	Time of Measurement (s)	Max Temperature During Pulse (K)	Temperature at Measurement Time (K)	Temperature Change (K)	Temperature Change %
1	3	6	292.52	287.3	5.22	1.78%
2	3	6	292.73	288.16	4.57	1.56%
3	3	6	292.78	287.49	5.29	1.81%

$$T(0,t) = \frac{(\rho c)^{0.5} P}{8\pi^{1.5} k^{1.5}} [(t - t_p)^{-0.5} - t^{-0.5}]$$

Pulsing Measurements

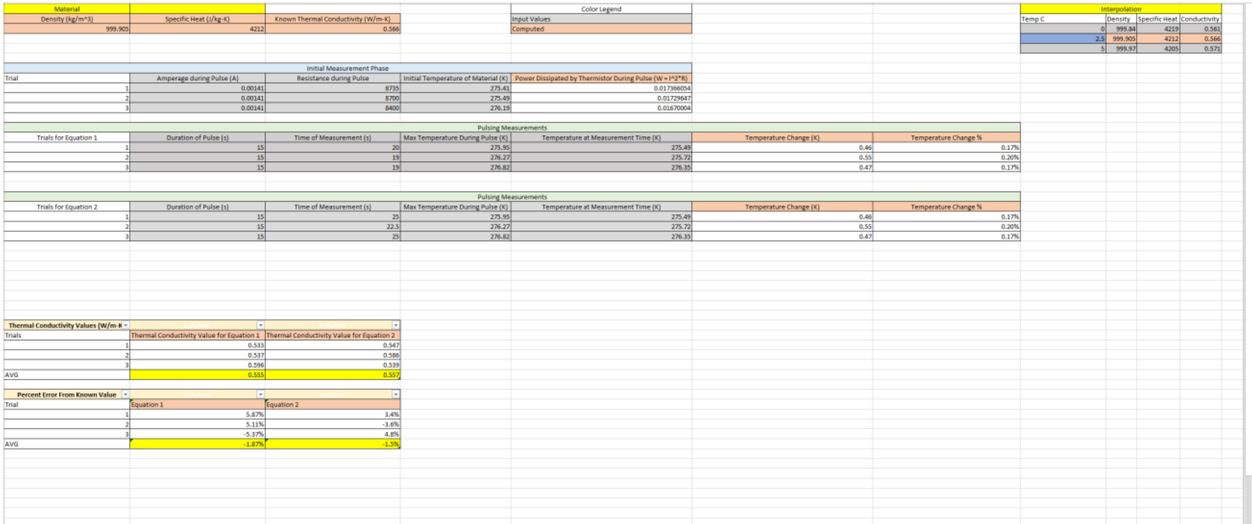
Trials for Equation 2	Duration of Pulse (s)	Time of Measurement (s)	Max Temperature During Pulse (K)	Temperature at Measurement Time (K)	Temperature Change (K)	Temperature Change %
1	3	8	292.52	287.3	5.22	1.78%
2	3	8	292.73	288.16	4.57	1.56%
3	3	8	292.78	287.49	5.29	1.81%

$$k/(\rho c)^{1/3} = [P((t_m - t_p)^{-0.5} - t_m^{-0.5})/4T_o(t_m)]^{2/3}/\pi$$

Thermal Conductivity Values (W/m-K	Column1	Column2
Trials	Thermal Conductivity Value for Equation 1	Thermal Conductivity Value for Equation 2
1	0.553	0.593
2	0.605	0.648
3	0.549	0.587
AVG	0.569	0.609

Percent Error From Known Value	Column1	Column2
Trial	Equation 1	Equation 2
1	5.70%	-1.0%
2	-3.04%	-10.3%
3	6.54%	-0.1%
AVG	-3.07%	3.8%

Appendix G4.3 – Completed Evaluation of Water Above Freezing



Material		
Density (kg/m^3)	Specific Heat (J/kg-K)	Known Thermal Conductivity (W/m-K)
999.905	4212	0.566

Color Legend
Input Values
Computed

Interpolation			
Temp C	Density	Specific Heat	Conductivity
0	999.84	4219	0.561
2.5	999.905	4212	0.566
5	999.97	4205	0.571

Initial Measurement Phase

Trial	Amperage during Pulse (A)	Resistance during Pulse	Initial Temperature of Material (K)	Power Dissipated by Thermistor During Pulse (W = I^2*R)
1	0.00141	8735	275.41	0.017366054
2	0.00141	8700	275.49	0.01729647
3	0.00141	8400	276.19	0.01670004

Pulsing Measurements

Trials for Equation 1	Duration of Pulse (s)	Time of Measurement (s)	Max Temperature During Pulse (K)	Temperature at Measurement Time (K)	Temperature Change (K)	Temperature Change %
1	15	20	275.95	275.49	0.46	0.17%
2	15	19	276.27	275.72	0.55	0.20%
3	15	19	276.82	276.35	0.47	0.17%

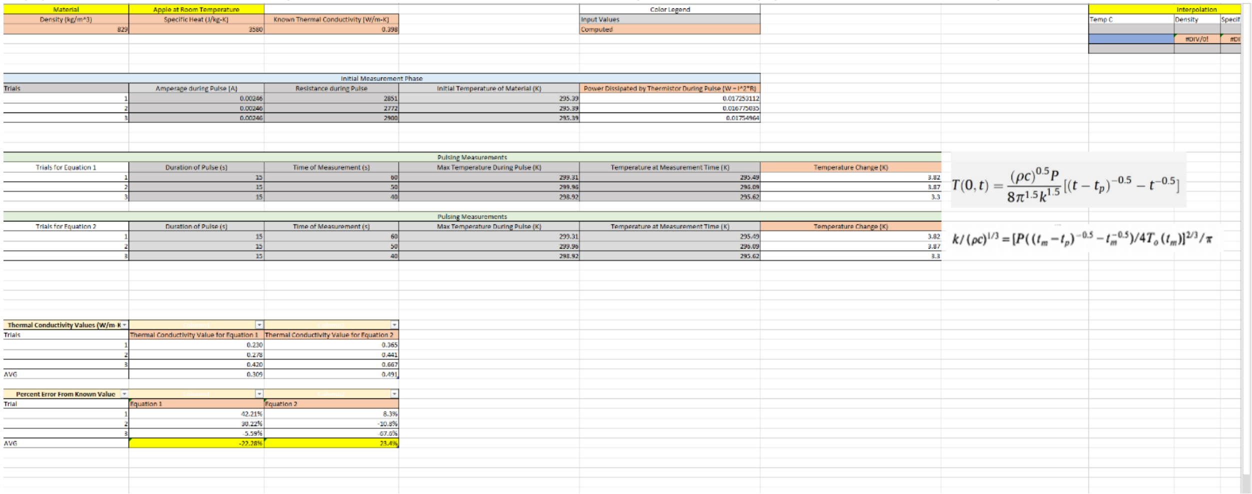
Pulsing Measurements

Trials for Equation 2	Duration of Pulse (s)	Time of Measurement (s)	Max Temperature During Pulse (K)	Temperature at Measurement Time (K)	Temperature Change (K)	Temperature Change %
1	15	25	275.95	275.49	0.46	0.17%
2	15	22.5	276.27	275.72	0.55	0.20%
3	15	25	276.82	276.35	0.47	0.17%

Thermal Conductivity Values (W/m-K	Column1	Column2
Trials	Thermal Conductivity Value for Equation 1	Thermal Conductivity Value for Equation 2
1	0.533	0.547
2	0.537	0.586
3	0.596	0.539
AVG	0.555	0.557

Percent Error From Known Value	Column1	Column2
Trial	Equation 1	Equation 2
1	5.87%	3.4%
2	5.11%	-3.6%
3	-5.37%	4.8%
AVG	-1.87%	-1.5%

Appendix G4.4 – Completed Evaluation of Granny Smith Apple at Room Temperature



Material	Apple at Room Temperature	
Density (kg/m^3)	Specific Heat (J/kg-K)	Known Thermal Conductivity (W/m-K)
829	3580	0.398

Color Legend
Input Values
Computed

Interpolation		
Temp C	Density	Specif
	#DIV/0!	#DI

Initial Measurement Phase

Trials	Amperage during Pulse (A)	Resistance during Pulse	Initial Temperature of Material (K)	Power Dissipated by Thermistor During Pulse (W = I^2*R)
1	0.00246	2851	295.39	0.017253112
2	0.00246	2772	295.39	0.016775035
3	0.00246	2900	295.39	0.01754964

Pulsing Measurements

Trials for Equation 1	Duration of Pulse (s)	Time of Measurement (s)	Max Temperature During Pulse (K)	Temperature at Measurement Time (K)	Temperature Change (K)
1	15	60	299.31	295.49	3.82
2	15	50	299.96	296.09	3.87
3	15	40	298.92	295.62	3.3

$$T(0,t) = \frac{(\rho c)^{0.5} P}{8\pi^{1.5} k^{1.5}} [(t - t_p)^{-0.5} - t^{-0.5}]$$

Pulsing Measurements

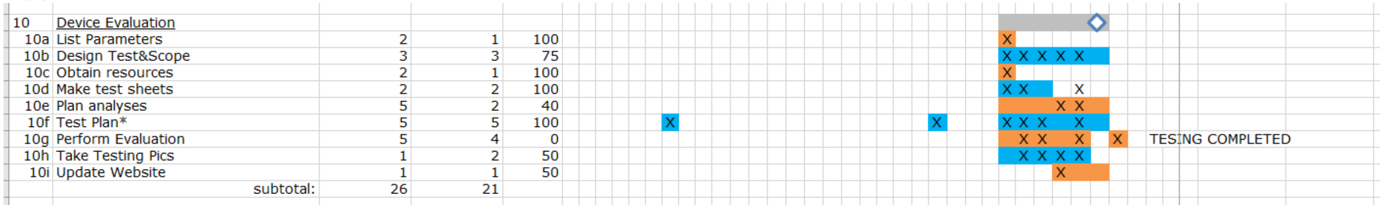
Trials for Equation 2	Duration of Pulse (s)	Time of Measurement (s)	Max Temperature During Pulse (K)	Temperature at Measurement Time (K)	Temperature Change (K)
1	15	60	299.31	295.49	3.82
2	15	50	299.96	296.09	3.87
3	15	40	298.92	295.62	3.3

$$k/(\rho c)^{1/3} = [P((t_m - t_p)^{-0.5} - t_m^{-0.5})/4T_o(t_m)]^{2/3}/\pi$$

Thermal Conductivity Values (W/m-K	Column1	Column2
Trials	Thermal Conductivity Value for Equation 1	Thermal Conductivity Value for Equation 2
1	0.230	0.365
2	0.278	0.441
3	0.420	0.667
AVG	0.309	0.491

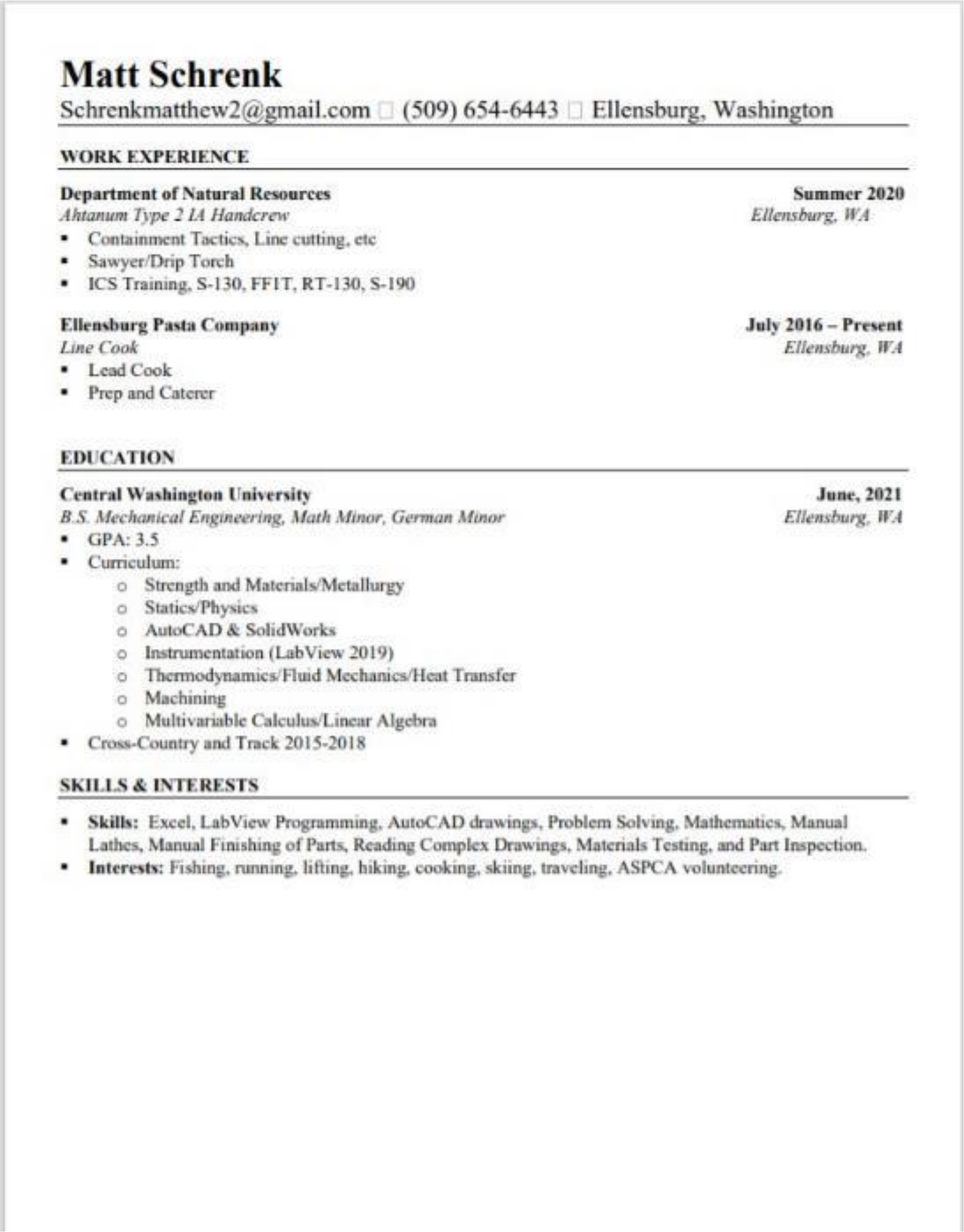
Percent Error From Known Value	Column1	Column2
Trial	Equation 1	Equation 2
1	42.21%	8.3%
2	30.22%	-10.8%
3	-5.59%	-67.6%
AVG	-22.28%	23.4%

Appendix G5:



10	Device Evaluation				
10a	List Parameters	2	1	100	
10b	Design Test&Scope	3	3	75	
10c	Obtain resources	2	1	100	
10d	Make test sheets	2	2	100	
10e	Plan analyses	5	2	40	
10f	Test Plan*	5	5	100	
10g	Perform Evaluation	5	4	0	TESING COMPLETED
10h	Take Testing Pics	1	2	50	
10i	Update Website	1	1	50	
	subtotal:	26	21		

APPENDIX H – Resume



Matt Schrenk

Schrenkmatthew2@gmail.com □ (509) 654-6443 □ Ellensburg, Washington

WORK EXPERIENCE

Department of Natural Resources **Summer 2020**
Ahtanum Type 2 IA Handcrew *Ellensburg, WA*

- Containment Tactics, Line cutting, etc
- Sawyer/Drip Torch
- ICS Training, S-130, FFIT, RT-130, S-190

Ellensburg Pasta Company **July 2016 – Present**
Line Cook *Ellensburg, WA*

- Lead Cook
- Prep and Caterer

EDUCATION

Central Washington University **June, 2021**
B.S. Mechanical Engineering, Math Minor, German Minor *Ellensburg, WA*

- GPA: 3.5
- Curriculum:
    - Strength and Materials/Metallurgy
    - Statics/Physics
    - AutoCAD & SolidWorks
    - Instrumentation (LabView 2019)
    - Thermodynamics/Fluid Mechanics/Heat Transfer
    - Machining
    - Multivariable Calculus/Linear Algebra
- Cross-Country and Track 2015-2018

SKILLS & INTERESTS

- **Skills:** Excel, LabView Programming, AutoCAD drawings, Problem Solving, Mathematics, Manual Lathes, Manual Finishing of Parts, Reading Complex Drawings, Materials Testing, and Part Inspection.
- **Interests:** Fishing, running, lifting, hiking, cooking, skiing, traveling, ASPCA volunteering.

APPENDIX I – FEA ANALYSIS

Introduction to the FEA Analysis

The following is a memo addressing an FEA analysis of a Pulse Heated Thermistor for Senior Project Design. The model is designed to simulate the effect of the thermistor under a pulsing voltage.

The analysis was conducted using a Nonlinear Transient Heat Analysis. The loading is Heat Generation, which is applied to the simulated thermistor bead. Calculated from previous analysis, the load is approximated to be 3.18 mW per unit volume. The second load is an initial condition, applied to the surface contact between the simulated thermistor and simulated container of water. In this simulation, the assumption is that the water is at 18 degrees Celsius, and the thermistor is at equilibrium with the material.

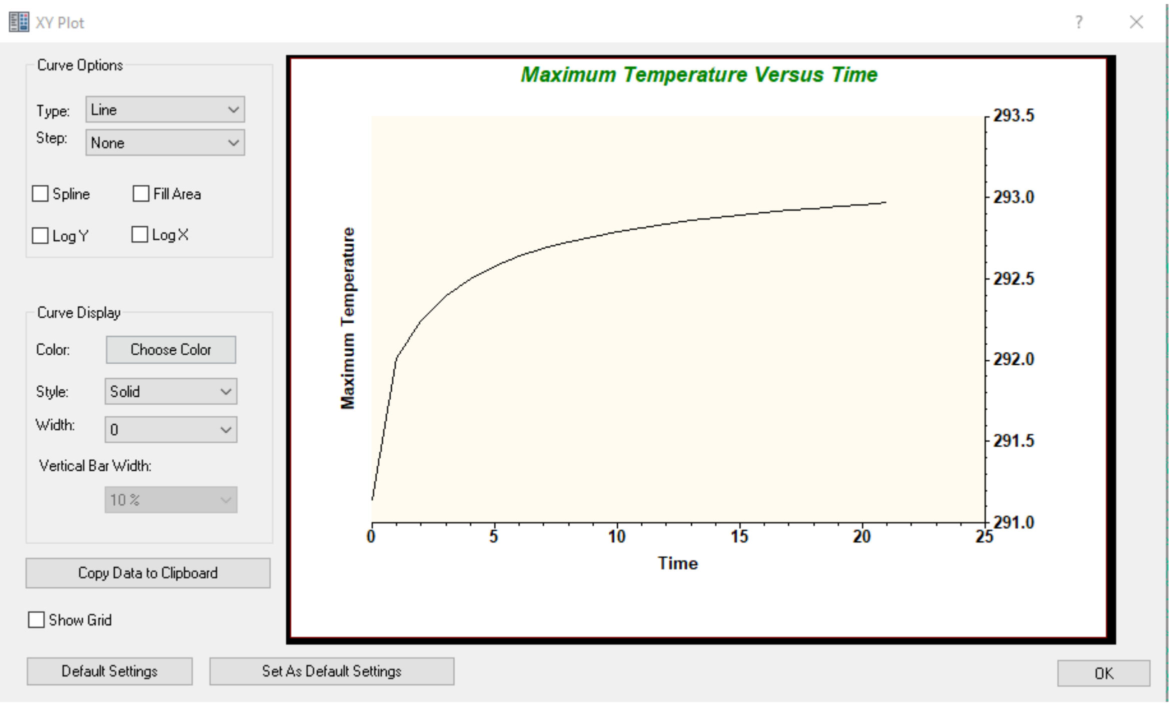
To simulate transient heat transfer, time steps were decided to be 200 steps of 0.1 seconds. This would simulate a pulsing heat of 20 seconds.

In the assembly, the material of the thermistor bead is assumed to be the Autodesk libraries for glass (Conductivity = 1.38mW/mm-K), and the Autodesk library for water (Conductivity = 0.58mW/mm-K).

The mesh size was 0.508mm operating under linear constraints. The number of elements was 935572 with 156934 Nodes.

Data from Nastran

The simulation was used to gather values of heat dissipation into the medium of water. After 3 Seconds, the temperature of the middle of the bead was 292.502 Degrees Kelvin. After 10 seconds of pulsing the temperature of the water was 292.789 Degrees Kelvin. After 20 seconds the heat the temperature was 292.985 degrees Kelvin. Referencing Plot 1 below, the thermistor bead and the surrounding medium reach an equilibrium point and steady state heat transfer occurs.



XY Plot

Curve Options

Type: Line

Step: None

☐ Spline ☐ Fill Area

☐ Log Y ☐ Log X

Curve Display

Style: Solid

Width: 0

Vertical Bar Width: 10 %

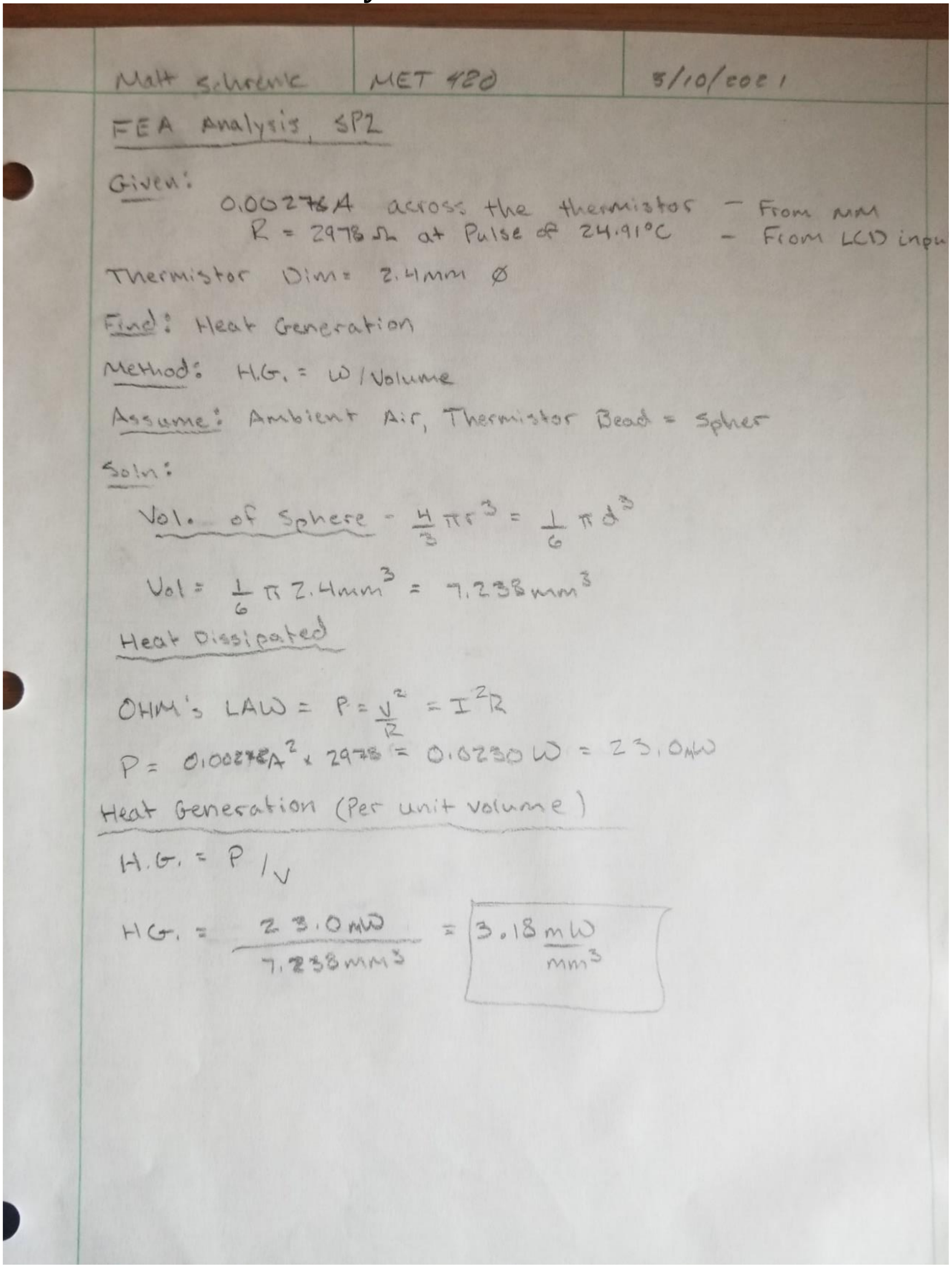
☐ Show Grid

Plot 1 – Maximum Temperature Versus Time

Conclusion

The use of the runaway thermistor effect can be modeled into FEA very well. The temperature of the bead rises to a point of equilibrium and dissipates into an infinite medium. Some limitations of this process assume uses the glass bead as a material of conductivity, whereas the experiment for Senior Project utilizes the idea that the bead is infinitely small, and thus has an infinite conductivity value. Further analysis of these values will aid the project in comparing tested values in the Spring of 2021, thus bolstering or damaging confidence in the Pulse Decay Thermistor Design.

Attached Photos of Analysis



Matt Schrenk | MET 420 | 3/10/2021

FEA Analysis, SP2

Given:

0.00276A across the thermistor – From MM

$R = 2978\,\Omega$ at Pulse of 24.91°C – From LCD inpu

Thermistor Dim = 2.4mm Ø

Find: Heat Generation

Method: H.G. = W / Volume

Assume: Ambient Air, Thermistor Bead = Spher

Soln:

Vol. of Sphere - $\frac{4}{3}\pi r^3 = \frac{1}{6}\pi d^3$

Vol = $\frac{1}{6}\pi\, 2.4\text{mm}^3 = 7.238\text{mm}^3$

Heat Dissipated

OHM's LAW = $P = \frac{V^2}{R} = I^2R$

$P = 0.00278\text{A}^2 \times 2978 = 0.0230\text{ W} = 23.0\text{mW}$

Heat Generation (Per unit volume)

H.G. = $P/_V$

HG. = $\frac{23.0\text{mW}}{7.238\text{mm}^3} = \boxed{3.18\frac{\text{mW}}{\text{mm}^3}}$

Image 1 - Green Sheet calculation of Heat Generation

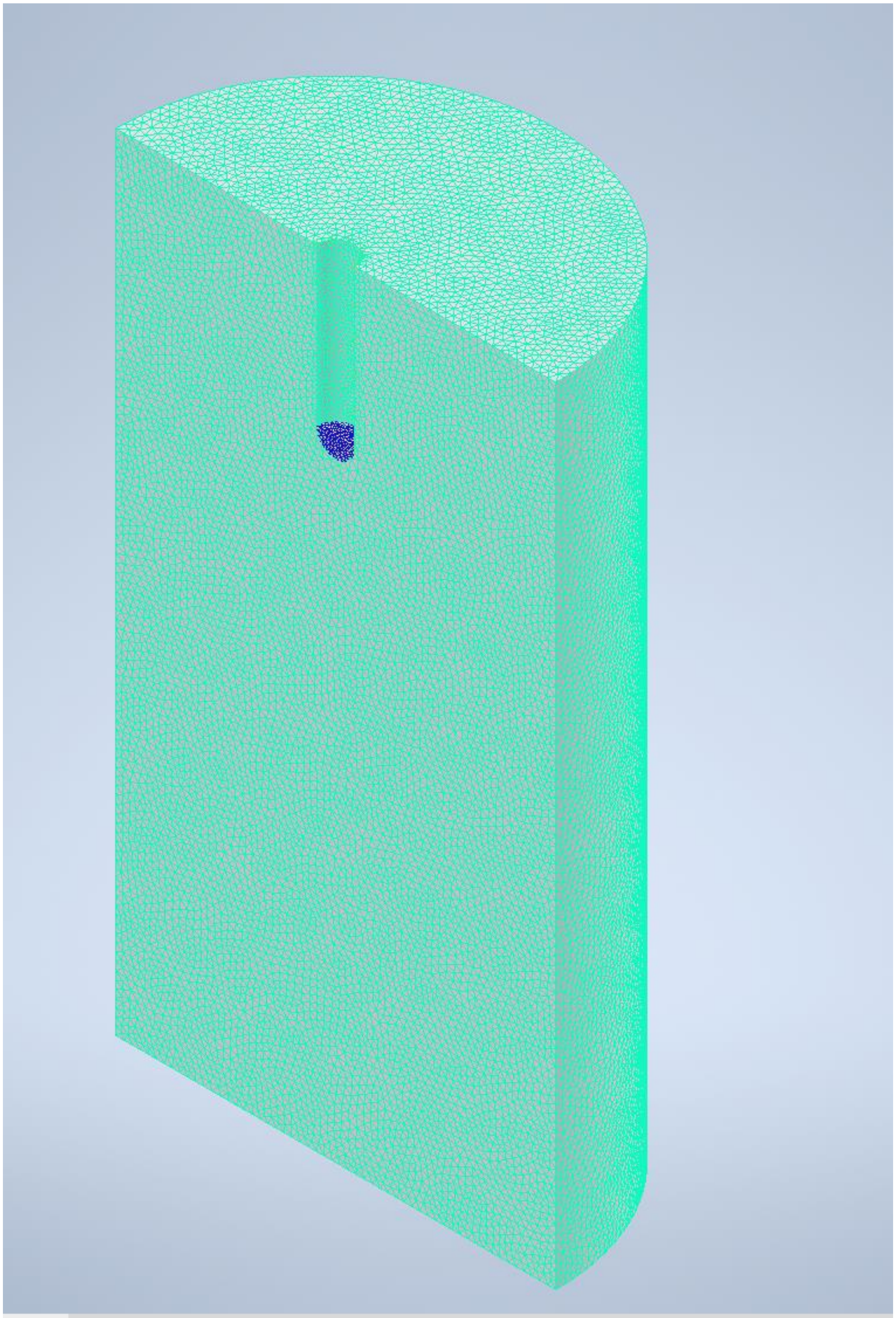
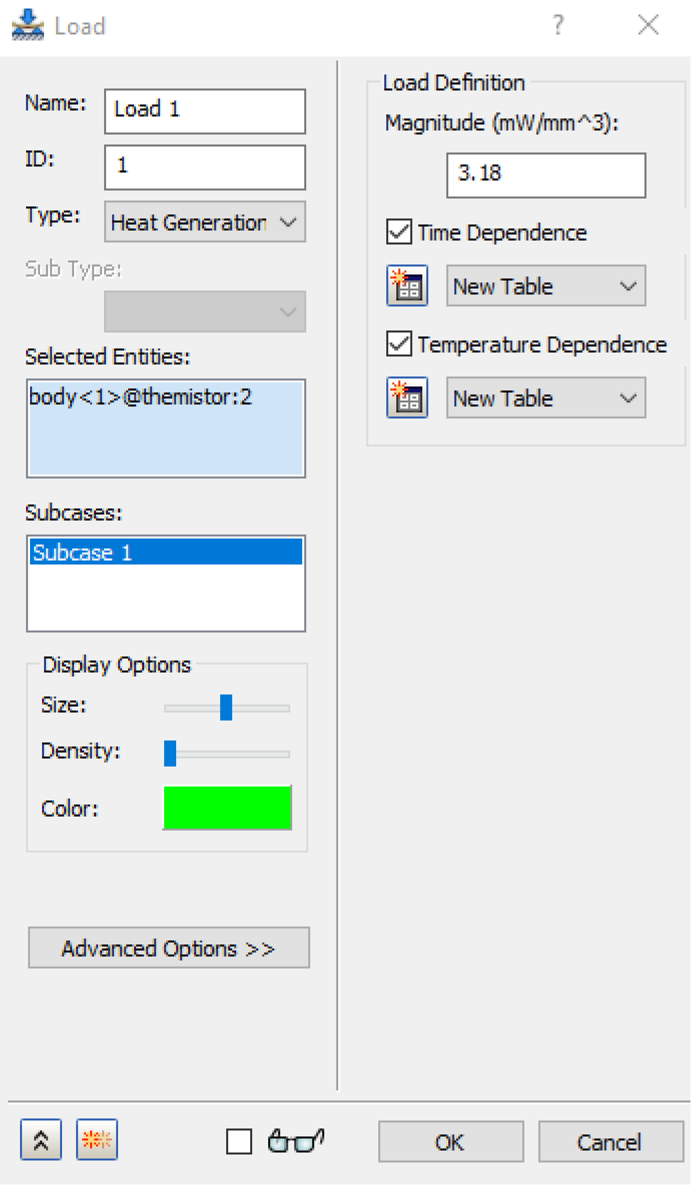


Image 2 – Assembly



Name: Load 1

ID: 1

Type: Heat Generation

Selected Entities: body<1>@themistor:2

Subcases: Subcase 1

Magnitude (mW/mm^3): 3.18

☑ Time Dependence: New Table

☑ Temperature Dependence: New Table

Image 3 – Loading Applied to the Assembly

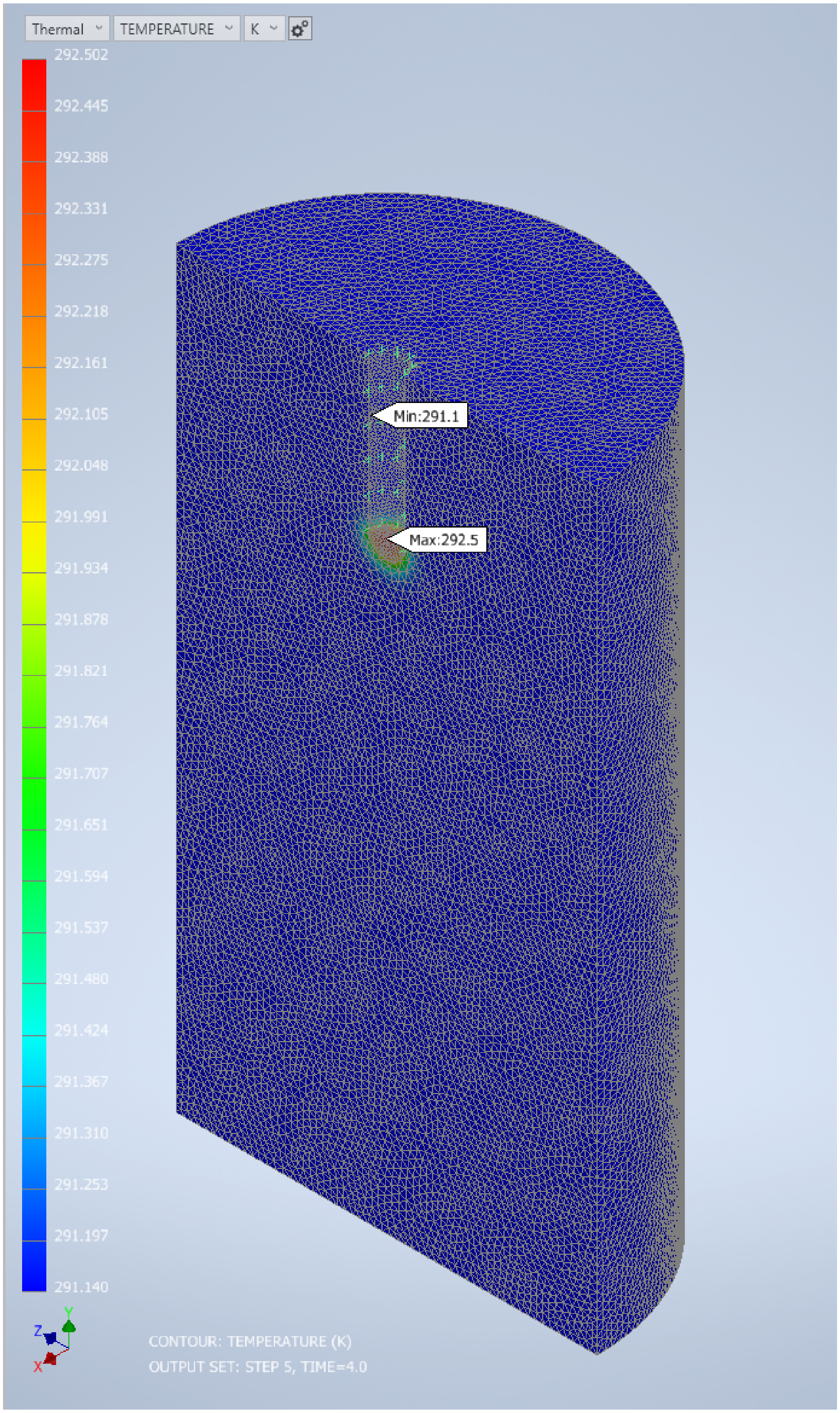


Image 4 – Heat on surface of Bead after Three Seconds

APPENDIX J – ARDUINO CODE

LINK HERE to the .ino File for the Arduino

```
//include wire library for I2C
#include <Wire.h>
//Indlude the NewLiquidCrystal Library for I2C
#include <LiquidCrystal_I2C.h>
//initializes the lcd address, which is 0x27
const int i2c_addr = 0x27;
int POT = A0; //Declaring the POT as Arduino Input A0
int WheatStone = 3; //Resistor as arduino output Pin 3
int analogreadvalue; //Use this variable to look at the 0-5V Potentiometer Voltageat PIN A0
int analogwritevalue; //Use this variable to write 0-5V through PWM to the Resistor

int ThermistorPin = A1;

int PotPin = A2;
int Vo ;
float R1 = 10000; //Known Resistor in Bridge
float Rp = 3022; //Known Resitor in Bridge, Calibrated Potentiometer Value
float R3 = 10000; //Known Resistor in Bridge
float logRt, Rt, T, C; //Resistance of the Thermistor in the Bridge
float c1 = 1.4052e-03, c2 = 2.3692e-04, c3 = 1.0125e-07; //Constants provided by Omega



LiquidCrystal_I2C lcd(0x27, 2, 1, 0, 4, 5, 6, 7, 3, POSITIVE);
//0x27 is the address for the lcd, use this for all new code outputting data to the lcd

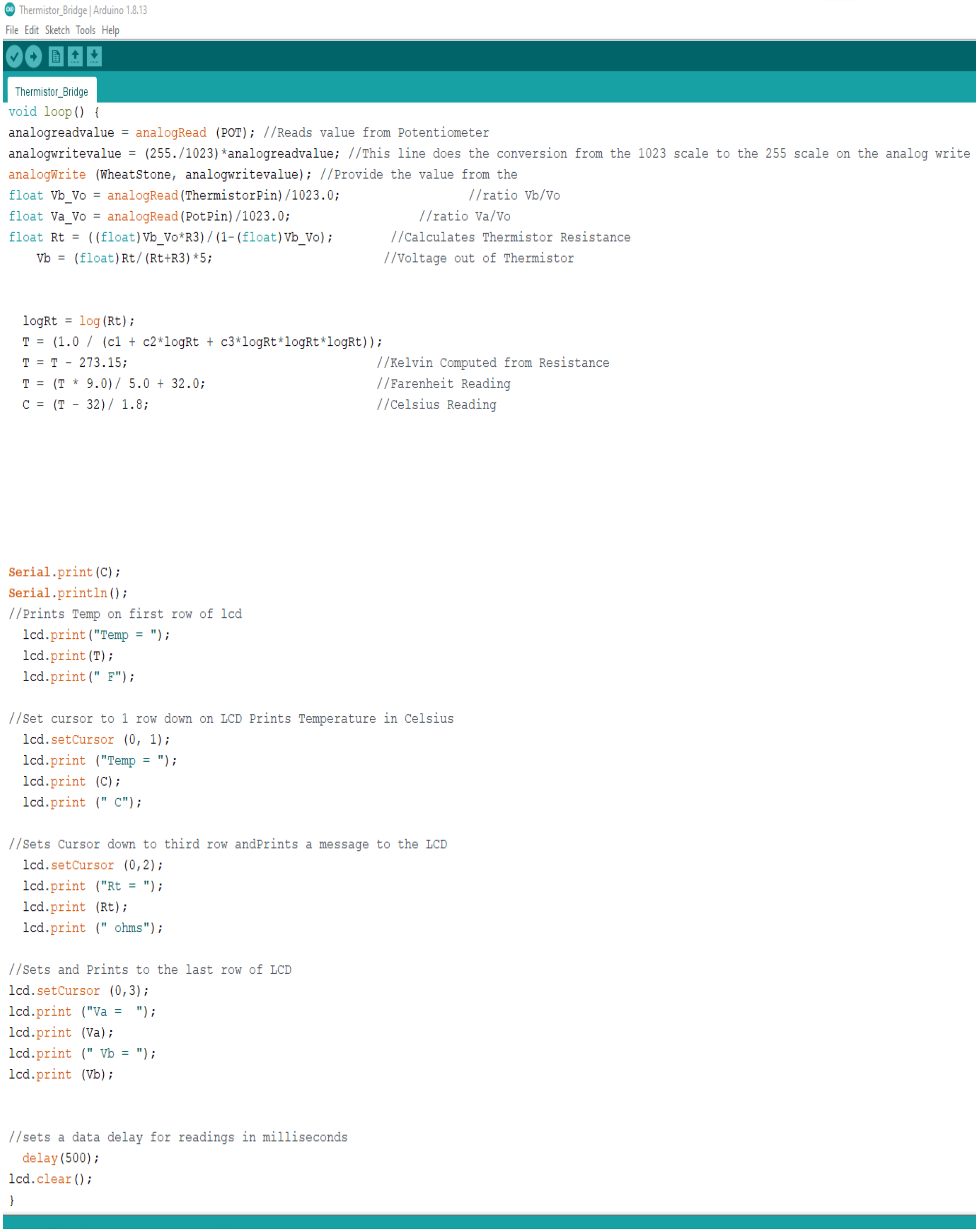
void setup() {
Serial.begin(9600);
//lcd begin sets the lcd to a 20x4 screen
  lcd.begin (20,4);


}

float Va = Rp/(R1+Rp)*5;
float Vb;

void loop() {
analogreadvalue = analogRead (POT); //Reads value from Potentiometer
analogwritevalue = (255./1023)*analogreadvalue; //This line does the conversion from the 1023 scale to the 255 scale on the analog write
analogWrite (WheatStone, analogwritevalue); //Provide the value from the
float Vb_Vo = analogRead(ThermistorPin)/1023.0;                  //ratio Vb/Vo
float Va_Vo = analogRead(PotPin)/1023.0;                  //ratio Va/Vo
float Rt = ((float)Vb_Vo*R3)/(1-(float)Vb_Vo);        //Calculates Thermistor Resistance
    Vb = (float)Rt/(Rt+R3)*5;                        //Voltage out of Thermistor


  logRt = log(Rt);
  T = (1.0 / (c1 + c2*logRt + c3*logRt*logRt*logRt));
  T = T - 273.15;                                   //Kelvin Computed from Resistance
  T = (T * 9.0)/ 5.0 + 32.0;                        //Farenheit Reading
  C = (T - 32)/ 1.8;                                //Celsius Reading
```



```
void loop() {
analogreadvalue = analogRead (POT); //Reads value from Potentiometer
analogwritevalue = (255./1023)*analogreadvalue; //This line does the conversion from the 1023 scale to the 255 scale on the analog write
analogWrite (WheatStone, analogwritevalue); //Provide the value from the
float Vb_Vo = analogRead(ThermistorPin)/1023.0;                  //ratio Vb/Vo
float Va_Vo = analogRead(PotPin)/1023.0;                  //ratio Va/Vo
float Rt = ((float)Vb_Vo*R3)/(1-(float)Vb_Vo);        //Calculates Thermistor Resistance
    Vb = (float)Rt/(Rt+R3)*5;                        //Voltage out of Thermistor


  logRt = log(Rt);
  T = (1.0 / (c1 + c2*logRt + c3*logRt*logRt*logRt));
  T = T - 273.15;                                   //Kelvin Computed from Resistance
  T = (T * 9.0)/ 5.0 + 32.0;                        //Farenheit Reading
  C = (T - 32)/ 1.8;                                //Celsius Reading







Serial.print(C);
Serial.println();
//Prints Temp on first row of lcd
  lcd.print("Temp = ");
  lcd.print(T);
  lcd.print(" F");

//Set cursor to 1 row down on LCD Prints Temperature in Celsius
  lcd.setCursor (0, 1);
  lcd.print ("Temp = ");
  lcd.print (C);
  lcd.print (" C");

//Sets Cursor down to third row andPrints a message to the LCD
  lcd.setCursor (0,2);
  lcd.print ("Rt = ");
  lcd.print (Rt);
  lcd.print (" ohms");

//Sets and Prints to the last row of LCD
lcd.setCursor (0,3);
lcd.print ("Va =  ");
lcd.print (Va);
lcd.print (" Vb = ");
lcd.print (Vb);


//sets a data delay for readings in milliseconds
  delay(500);
lcd.clear();
}
```