EML 4551 Final Report

Team 9 – Phase Change Material Transient Heatsink for Power Semiconductor

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Unison Industries

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Contents

1.0 Executive Summary

The objective of this senior design project is to create a heatsink for power semiconductors in aerospace applications. In order to accommodate transient thermal loading conditions encountered in such applications, the heatsink will incorporate a phase change material (PCM) in order to store thermal energy from the power semiconductors during those periods of the duty cycle in which convective heat transfer rates are low.

Thus far, our team has made several important strides towards the completion of our project. For one, since our project's sponsor is industrial, we have conducted a patent search to ensure that our design does not result in legal issues. With regard to the technical aspect of our project, we have generated an analytical model in MathCAD to test the steady-state operation of our design concepts, and have also generated a numerical model in COMSOL to test their characteristics under transient thermal loads. While the COMSOL model still has some issues in terms of its ability to model the absorption of thermal energy by the PCM, the two models have still allowed us to identify the important design parameters for our heatsink. This accomplishment, in turn, has allowed us to iterate quickly through different design concepts and select a heatsink geometry. Furthermore, we have selected both a PCM and a thermal contact interface material based on commercially available materials (details of these decisions can be found in Section 3). Finally, by leveraging our industry contact's experience in experimental design, we have developed a plan for prototype testing, complete with a list of specific materials and equipment that need to be procured. With this plan, our team is positioned to begin prototyping and testing at the outset of the spring semester.

2.0 Project Overview

2.1 Customer Requirements

From Unison's project description:

"Among the electrical products Unison designs and produces for the jet engine industry are ignition units and power regulators which contain power semiconductors. Thermal management of these is a critical part of the design process, maintaining the devices within their reliable operating limits under varying power dissipation levels and ambient conditions. Operating overloads and thermal transients in the ambient environment can be particularly challenging, often adding size and weight to the system."

From the project description, it can be seen that Unison has a need for a highly-reliable, low-weight heat dissipation solution for power semiconductors in jet engine systems.

2.2 Scope

To stay within the temporal and monetary constraints of our project, we have limited ourselves to the following objectives: determination of the design parameters that will most strongly control our heatsink's performance, creation of a numerical model that will allow us to simulate our design concepts’ performance under transient thermal loading conditions, and fabrication of both a prototype heatsink and an experimental rig to test its performance.

2.3 Goal

To meet our sponsor’s need, this project aims to create a heatsink containing a PCM that will serve as a thermal bridge between the power semiconductor and its housing. The PCM will have a melting temperature within the operating temperature range of the semiconductors, and will thus be able to absorb thermal energy as latent heat. In essence, the heatsink will act as a thermal capacitor: through melting of the PCM, it will temporarily store thermal energy from the semiconductor until this energy can be rejected through natural convection at the housing’s surface.

2.4 Objectives

The most important objectives for our team to achieve are as follows:

1. Identify preferred phase change material(s) for the heatsink, given that the operating temperature range will be 115 – 125°C.
2. Creation of a numerical model that will simulate the heatsink’s performance under various thermal loadings
3. An experimental rig for validation of the numerical model

2.5 Constraints

Time: Our entire team is composed of full-time students who also hold part-time positions. As such, it will be difficult not only to put a sufficient amount of work into our design, but also to coordinate our schedules for tasks that will require the entire team. To assist in alleviating the scheduling issue, we have created a Google Calendar that lists all of our individual obligations, in order that we can anticipate them and schedule tasks around them. Furthermore, we are using a project planning software known as OmniPlan to create Gantt charts that track our project progression and task responsibilities.

Budget: Our project has been allocated $2,000 by Unison, and our design/testing must stay within this limit. As such, we will have to ensure that any purchases we make are necessary to the completion or improvement of our project objectives, and that we make cost-conscious decisions when choosing between design or component alternatives.

3.0 Design and Analysis

3.1 Heat Transfer Schematic

The schematic shown in Fig. 1 shows the heat transfer mechanisms that will occur in the assembly containing our design.

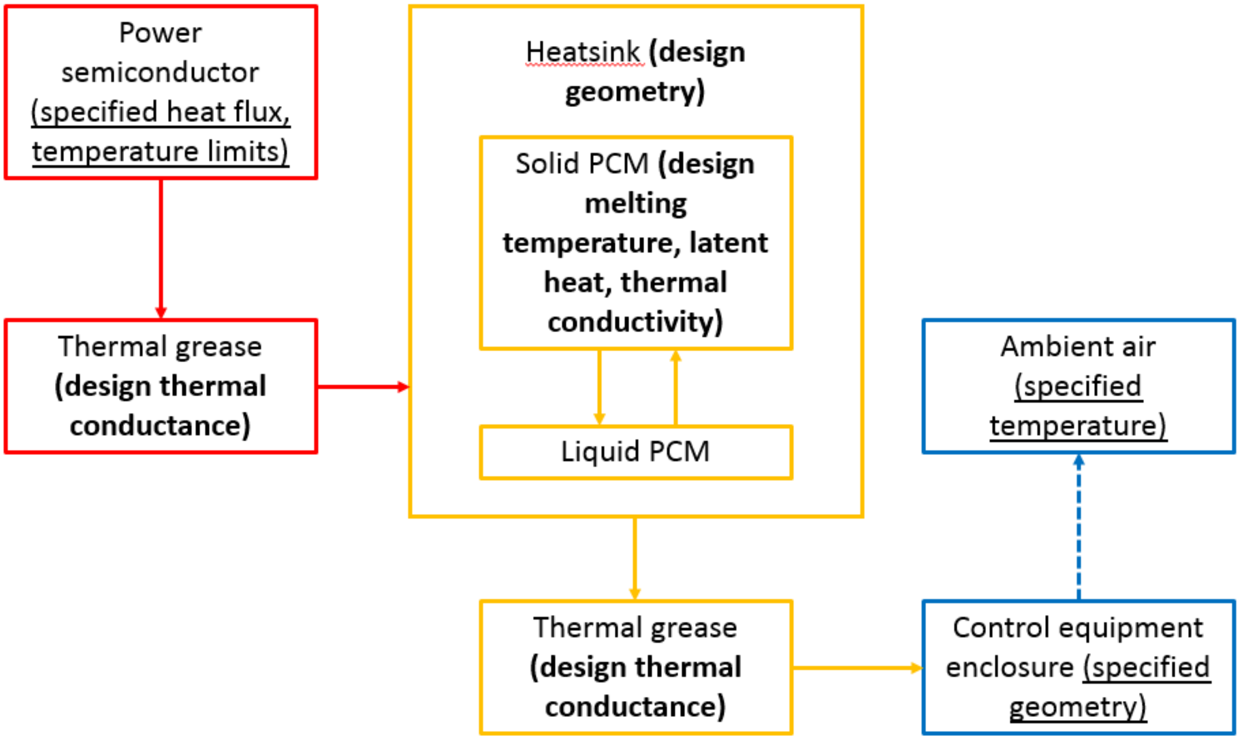


Figure 1. General schematic of heat transfer within control equipment assembly. Underlined words indicate sponsor-specified parameters, bold words indicate free design parameters. Arrows indicate desired direction of heat transfer. Solid arrows indicate conduction, dashed arrows indicate natural convection.

As can be seen from Fig. 1, our design must operate within several sponsor specifications. Namely, the heatsink must be able to not only handle a specified heat flux from the power semiconductor in order to keep it within safe temperature limits, but also must accomplish this objective while both fitting within the control equipment enclosure and dealing with the limitations that natural convection imposes on the system's heat rejection side.

3.1 Design for Steady-State

While the primary motivation for this design is to handle transient overload conditions produced by the power semiconductor, the duration of these conditions is supposed to be on the order of one to five minutes. Compared to the typical flight time of an aircraft, this time is very small. Therefore, it is also important to ensure that our design is able to dissipate heat during the steady conditions that will comprise most of its duty cycle. Furthermore, steady analyses are less computationally intensive than transient ones, while still allowing for determination of the general performance characteristics and governing parameters of a thermal system. Thus, we have developed a steady-state model of our system based on the principles of a thermal resistance network[4]. Such a network defines steady heat transfer using the following analogy to Ohm's law:

$$\dot{Q} = \frac{\Delta T}{R_T} \qquad (1)$$

In Eq. 1, $\dot{Q}$ represents the rate of heat transfer, ΔT is the temperature difference between the outermost parts of the network, and R_T is the network's total thermal resistance. The schematic of our network is presented in Fig. 2 below:

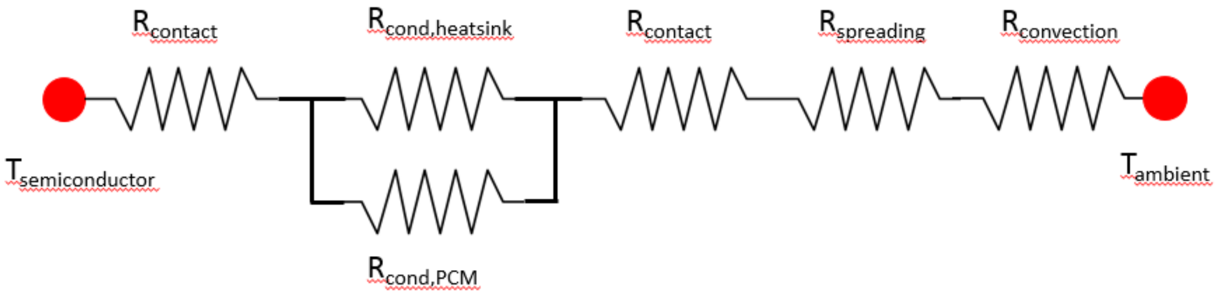


Figure 2. Schematic of thermal resistance network for steady-state analysis.

In Fig. 2, the semiconductor and ambient temperatures have been specified by Unison to be 120°C and 110°C, respectively. As such, the total temperature difference in Eq. 1 is fixed at 10°C. Unison has also specified the rate at which its semiconductors will generate heat in steady conditions to be 1W, meaning that $\dot{Q}$ is also fixed. From Eq. 1, we can then deduce that the maximum allowable thermal resistance of our system is:

$$R_{T,max} = \frac{10℃}{1W} = 10\,\frac{℃}{W} \qquad (1.1)$$

From Fig. 2, and using the principles of series and parallel resistors, the total thermal resistance of our system is computed as shown below:

$$R_T = 2R_{contact} + \frac{R_{cond,heatsink}R_{cond,PCM}}{R_{cond,heatsink}+R_{cond,PCM}} + R_{spreading} + R_{convection} \qquad (2)$$

In Fig. 2, the resistances (with the exception of spreading resistance) are defined as follows:

$$R_{contact} = \frac{1}{h_c A_c} \qquad (3)$$

$$R_{cond} = \frac{L}{kA_s} \qquad (4)$$

$$R_{convection} = \frac{1}{hwl} \qquad (5)$$

In Eq. 3, h_c represents the thermal conductance of the thermal grease we choose and A_c is the contact area. Thus, to minimize contact resistance, we need to maximize both the thermal conductance of the thermal grease and the contact area of the heatsink.

In Eq. 4, L represents the length of the component (either the PCM or the heatsink enclosure) in the direction of heat transfer, k represents thermal conductivity, and A_s represents the cross-sectional area normal to the direction of heat transfer. Thus, to minimize a given conductive resistance, it is necessary that we maximize thermal conductivity. However, defining relationships between cross-sectional area, length, and system performance is not as simple.

Since the PCM is contained within the heatsink, increasing the cross-sectional area of either the heatsink enclosure or the PCM will decrease the cross-sectional area available to the other. Moreover, it will be necessary to design a cross-sectional area for the heatsink that will allow it to support mechanical stresses induced by the thermal expansion of both itself and the PCM as it liquefies. Furthermore, while increasing the length of the heatsink will increase its conductive resistance during steady-state, it may also improve transient performance, as this will allow for more PCM inside the heatsink, thus improving its capacity to store thermal energy. Thus, to determine how the interplay of these design parameters would impact overall system performance, it was necessary to utilize our numerical model; the details of this analysis can be found in Section 3.3.

In Eq. 5, h represents the convective heat transfer coefficient, while w and l represent the width and length of the heatsink normal to the direction of heat transfer. These parameters have all been specified by Unison, and as such, we do not have control over this component of our system's resistance.

The thermal resistance incurred by the fact that our heatsink is thermally coupled to a larger enclosure is known as spreading resistance. An exact analytical expression for this type of resistance has not been developed, but an approximate relationship for spreading resistance as a function of several similarity parameters has been developed by Lee et. al[5]. We made use of this relationship in our model, the entirety of which can be found in Appendix B.

Appendix B also shows the results of our calculations, assuming that all of the free parameters (i.e., those parameters not fixed by Unison) have been optimized for steady-state performance. From these calculations, it was found that the steady-state heat transfer rate was around 0.9 W. While this rate is lower than the rate specified by Unison (1 W), we decided (after reviewing the model with our sponsor) that the difference was not significant enough to merit further consideration prior to the prototyping stage. Furthermore, this model has verified the fact that aluminum 6061 is a suitable material for our heatsink's housing, as it does not contribute significantly to the overall thermal resistance of the system.

3.2 PCM Selection

The phase change material has been selected to be the solder 52In-48Sn. This selection is tentative, however, and may change upon experimentation. This material was chosen based on five main material characteristics: melting point, coefficient of thermal expansion, thermal conductivity, latent heat of fusion and density.

The melting point was the first criterion that was taken in consideration. Since the operating temperatures are 115-125°C, the phase change material must have a melting point within that range. The latent heat of fusion is also key for this project. The amount of energy that is required to change from a solid to liquid is called the latent heat of fusion. For this project, it is very desirable to have a large latent heat of fusion. This will allow the heatsink to absorb more heat with less material. For an effective heatsink, the thermal conductivity needs to be as large as possible. Therefore, only materials with high thermal conductivity were considered. When the PCM reaches its melting point and changes phase, the material will expand. This expansion will cause a pressure inside the heatsink. If this pressure gets too large it could compromise the entire structure. Therefore, it is important for the material to have the lowest possible thermal expansion. This characteristic will minimize the internal pressure rise. Density was also considered since the heatsink is being designed for aviation applications.

Other materials were not selected based on the lack of information available on them. In certain cases, some materials did not warrant further research based on the incompatibility of certain properties. For example, waxes did not have a melting point near the desired range. A summary of all the materials that were under consideration is presented in the following chart.

Table 1. Material property comparison of possible phase-change materials.

	Material						
	Solders					Other	
	52In-48Sn	Bi50-Pb28	In75-Cd25	Bi46.1-Pb34.2	Bi55.5-Pb44.5	Sulfur	Wax
Melting Point (°C)	118	109	120	123	124	115	~60
CTE (10^{-6}/K)	20	-	-	-	-	-	-
Density (kg/m^3)	7300	-	-	-	10440	-	-
Thermal Conductivity (W/m*K)	34	-	-	-	4	0.205	2
Latent Heat of Fusion (kJ/kg)	28.47	-	-	-	-	-	-

3.3 Design for Transient Loading

Since the primary objective of our project is a heatsink that can handle elevated transient thermal loads, it was obviously important that we create a model capable of simulating our design's performance under such loads. To that end, we have generated a three-dimensional numerical model using COMSOL's heat transfer module. The details of this model can be found in Appendix C.

From the model, we found that the optimal cross-sectional geometry of the three shown in Appendix A was the geometry without any supporting internal members. This geometry is reproduced in Fig. 3. It was found that the additional PCM allowed by the absence of these members significantly improved the heat absorption capacity of the heatsink. However, as shown in Fig. 4, the PCM was unable to absorb enough thermal energy to keep the PCM in its heat absorption stage for the specified overload time (five minutes).

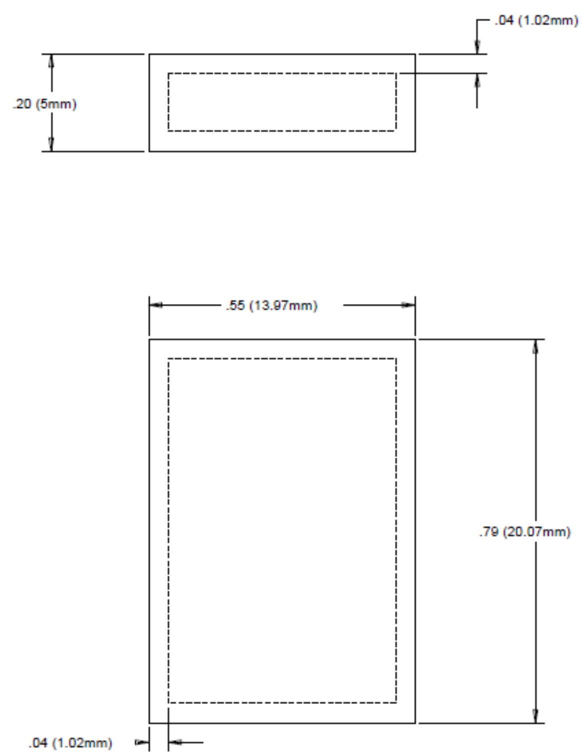


Figure 3. Heatsink geometry selected for prototyping.

Despite our numerical model's indication that the heatsink design currently selected for prototyping will be unable to handle the specified thermal load, we have decided after discussion with our faculty advisor and industry contact to move forward to the prototyping phase. This decision was made after consideration of the assumed thermal loading in the model. Specifically, it is assumed that steady heat generation at a rate of 1W occurs for 30 minutes prior to the overdrive stage, and that the overdrive stage at 2W occurs for five minutes. The time spent in both of these stages is much longer than the expected duty cycle; normal operation at 1W should be no longer than five minutes, and the overdrive period is expected to usually be one to two minutes in length. Thus, during actual operation, both the initial and final temperatures of the overdrive period should be lower. Moreover, as seen in Fig. 4, even with the worst-case scenario that was assumed, the temperature never rises to the maximum allowable semiconductor temperature (125°C). Therefore, even if the PCM fully liquefies, it should be able to keep the semiconductor functional.

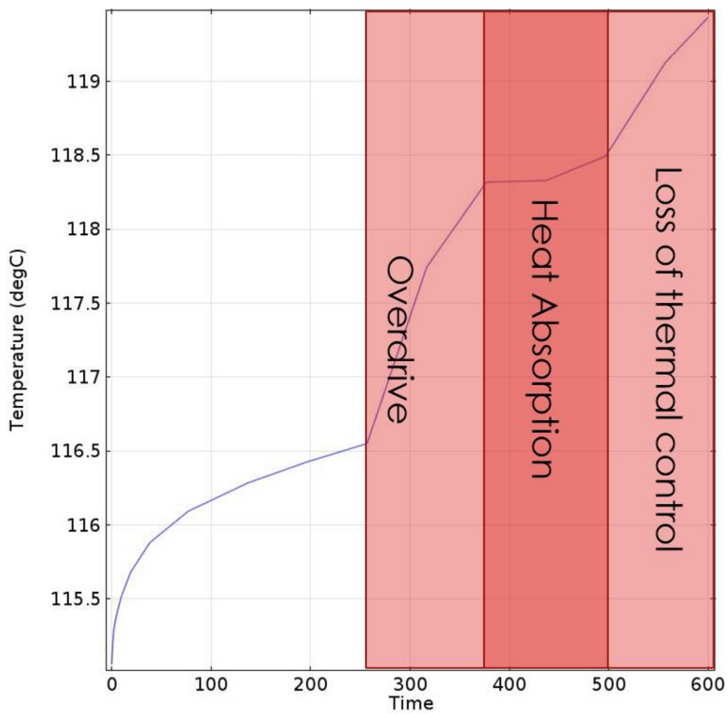


Figure 4. Temperature (in °C) as a function of time (in seconds) of the PCM as calculated by COMSOL.

4.0 Detailed Design (Design for Manufacturing/Prototyping)

4.1 Heatsink Fabrication

In the spring semester, we plan to fabricate a prototype of the design shown in Fig. 3 for validation. Our current prototyping plan is to have a hollow aluminum frame with the housing's outer dimensions machined in-house using the CNC, and to use aluminum tape to form the walls of the heatsink. Using this method to construct our prototype will allow for rapid fabrication at low cost, as the frame will only require a small amount of aluminum, and the tape will be easy to shape. Furthermore, the tape's adhesive backing will allow for easy sealing of the heatsink once the PCM is inserted (the process of which will likely take place by melting the PCM over a hot plate, then pouring it into the heatsink).

Despite the simplicity of our currently adopted fabrication process, forming the heatsink's walls out of aluminum tape is clearly not a feasible solution for manufacturing on the industrial scale. While we recognize this shortcoming and are currently working with our industry contact to develop a final manufacturing plan, this fabrication process has been approved by our sponsor as a sufficient method for the purpose of prototype testing.

4.2 Experimental Rig

To test the performance of our heatsink against our models' results, we have developed a list of equipment (manufacturers shown in bold) that we will need to purchase in order to create an experimental rig:

1. MP9100 resistor (**Caddock**): This resistor has a flat, rectangular, uninsulated ceramic surface of roughly the same area as the semiconductor whose thermal loads we aim to manage. Thus, by connecting this resistor to a DC power supply, we will be able to use Joule heating to generate a constant heat flux that will simulate the semiconductor's heat generation.
2. Thermal contact tape (**3M**): In order to monitor temperature during testing, we will need to mount thermocouples to different locations of our rig. To securely mount these thermocouples, we will use thermal contact tape; this tape has adhesive that performs at high temperatures, and also has a high thermal conductivity to avoid interfering with temperature measurements.
3. Aluminum tape (**3M**): This tape will be used to construct the walls of the heatsink.

In addition to equipment that we will need to purchase, we will also require the equipment listed below. This equipment, however, has been found at no cost from various sources:

1. Hi-Flow 300P (**Berquist**): We have selected this material as a thermal interface material for all contact surfaces (i.e., the contact areas between the heatsink and the semiconductor, and between the heatsink and the control equipment enclosure). It is a waxy material with a relatively high thermal conductivity, and will melt and flow into contact surface imperfections to reduce contact resistance.
2. NI 9211 (**National Instruments**): This 4-channel datalogger will be used to obtain the temperature readings from our thermocouples. It features an output to the cDAQ 9174 data acquisition system.
3. cDAQ 9174 (**National Instruments**): This data acquisition system interfaces with LabView to record thermocouple outputs.
4. LabView Full (**National Instruments**): This software will be used to save thermocouple readings to a digital file for later analysis.
5. DC power supply (**B&K Precision**): This power supply will be connected to the MP9100 resistor, and its voltage will be varied to provide specified heat fluxes through the resistor.
6. Lab oven (**Mellen**): Our entire test setup will be placed inside a laboratory-grade oven to imitate the high ambient temperatures (around 110°C) that our design will see when put into service.
7. Type K thermocouples (**Omega**): These standard thermocouples will be mounted to our test setup to monitor temperatures during thermal loading.
8. Aluminum plate: Plating of the same thickness as that used for the enclosure of Unison's control equipment will be needed to imitate natural convection at the enclosure surface.
9. Aluminum bar: Extruded Al 6061-T6 will be machined by the CNC mill in-house and used to form the frame of our heatsink housing.
10. 52In-48Sn solder (**IndiumCorp**): This solder will serve as our PCM.

4.3 Budget

As stated previously, Unison has allocated $2,000 towards this project. Our currently pending purchases and resulting remaining budget are tabulated in Table 2. Note that in Table 2, two budget estimates are displayed: one includes the cost of all items found at no cost, while the other excludes these items. Comparing the two figures, it can be seen that most of the cost of our project is incurred in the purchase of testing equipment (the lab oven or LabView license alone would put us well over our allotted budget). However, since this testing equipment is available to us, we are well under our budget (as shown by the second sum in Table 2), and anticipate to remain in this range for the remainder of our project. Furthermore, if this design were manufactured in an industrial setting, we believe that the one-time capital investment in testing equipment would be rapidly recaptured, given that the material cost of each heatsink is relatively low (each heatsink requires around 0.5 in^3 of solder and aluminum), and that the heatsinks would be made in much larger quantities.

Table 2. List of pending purchases/acquisitions. Starred items (*) indicate they have been found at no cost.

Material/Equipment	Vendor	Amount	Unit Cost (USD)	Total Cost (USD)
MP9100 resistor	Digi-Key	1 pc.	10.90	10.90
Thermal contact tape	eBay	1 spool	4.50	4.50
Aluminum tape	eBay	1 spool	40.00	40.00
Hi-Flow 300P*	Orion	1 pc.	48.00	48.00
NI 9211*	National Instruments	1 pc.	351.00	351.00
cDAQ 9174*	National Instruments	1 pc.	762.00	762.00
LabView Full	National Instruments	1 license	2699.00	2699.00
DC power supply*	Digi-Key	1 pc.	489.00	489.00
Lab oven*	Mellen	1 pc.	2499.99	2499.99
Type K thermocouple*	Omega	4 pcs.	30.00	120.00
Aluminum bar*	Various	26 cu. in.	5.00	5.00
52In-48Sn solder*	IndiumCorp	1 spool	49.95	49.95
Machining*	N/A	2 hours	20.00	40.00
			Remaining Budget (including starred items):	**-5119.34**
			Remaining Budget (excluding starred items):	**1944.60**

5.0 Risk and Reliability Assessment

As outlined in Section 2.1, our sponsor needs a highly reliable thermal management solution for power electronics in their avionics equipment. This high reliability is critical because if these power electronics fail, the equipment that they govern may not perform as intended, possibly resulting in catastrophic failure of an aircraft's propulsion systems or control surfaces. As such, it is important for our team not only to design a heatsink that can perform up to its specifications during testing, but also to carefully consider all possible failure modes and causes. The possible failure modes and causes that we have considered thus far include:

1. Failure mode: Insufficient heat absorption during transient conditions
    a. Cause: Leakage of PCM due to housing rupture from mechanical stress
    b. Cause: Leakage of PCM due to insufficient housing sealing during fabrication
    c. Cause: Insufficient volume of PCM injected into housing during fabrication
    d. Cause: Insufficient break-in period of thermal interface material during fabrication
    e. Cause: Insufficient pressure placed on contact surfaces during fabrication
2. Failure mode: Insufficient heat absorption during normal operating conditions
    a. Cause: Insufficient volume of PCM injected into housing during fabrication left too much air within housing (air is a thermal insulator)
    b. Cause: Insufficient break-in period of thermal interface material during fabrication
    c. Cause: Insufficient pressure placed on contact surfaces during fabrication

As can be seen from the list above, both careful monitoring of the fabrication process, as well as the structural integrity and fatigue strength of the housing are critical to the reliability of our design. These factors become even more important in light of the fact that in this design's final packaging, potential failure causes will be virtually undetectable, as the entire heatsink will be enclosed into a rubberized overmold. As such, it will be both visually and mechanically inaccessible. Due to the inaccessibility of our design once it goes into service, a full FMEA has not been performed, as the RPN would be unacceptable for all failure modes due to the virtually non-existent probability of detection. However, we are cognizant of the fact that the severity of these failure modes could potentially be catastrophic, and will therefore recommend to our sponsor that rigorous processes be implemented for both testing and monitoring of the manufacturing process.

6.0 Environmental/Safety Issues

The potential environmental and safety issues that we have foreseen for this design include:

1. Solder toxicity: The solder we are using as a PCM is toxic when consumed by humans, and is also not bio-degradable. Therefore, we need to ensure that it is stored and disposed of properly.
2. Minor burn risk: We will be using a hot plate to melt the solder so that it can be poured into the heatsink housing, and will be placing our test setup into an oven at 110°C. As such, we will need to ensure that we use the proper PPE (likely insulated gloves) to avoid injury.
3. Minor shock risk: We will be using a DC power supply to generate Joule heating through a resistor to simulate the semiconductor's heat generation. While the power supply is on, improper handling could result in low-voltage shocks. Thus, we will need to take care not to short-circuit the power supply's terminals during testing.

7.0 Conclusion

To this point, our team has modeled the steady-state, normal operating, and transient characteristics of our heatsink. From these models, we have determined the properties of each component necessary to minimize thermal resistance and hence achieve optimal heat dissipation from the semiconductor. Using this analysis in concert with our research on commercially-available materials that will change phase within the operating temperature range of the semiconductor, we have tentatively selected a phase-change material for use within the heatsink. Furthermore, based on our knowledge of structural mechanics and the results of our numerical model, we have selected a cross-sectional geometry for the heatsink that should support the stresses induced by the liquefaction of the phase-change material during transient operation. Finally, we have worked with our sponsor to develop a plan to fabricate and test our selected design. These achievements have positioned us to begin prototyping and testing early in the spring semester.

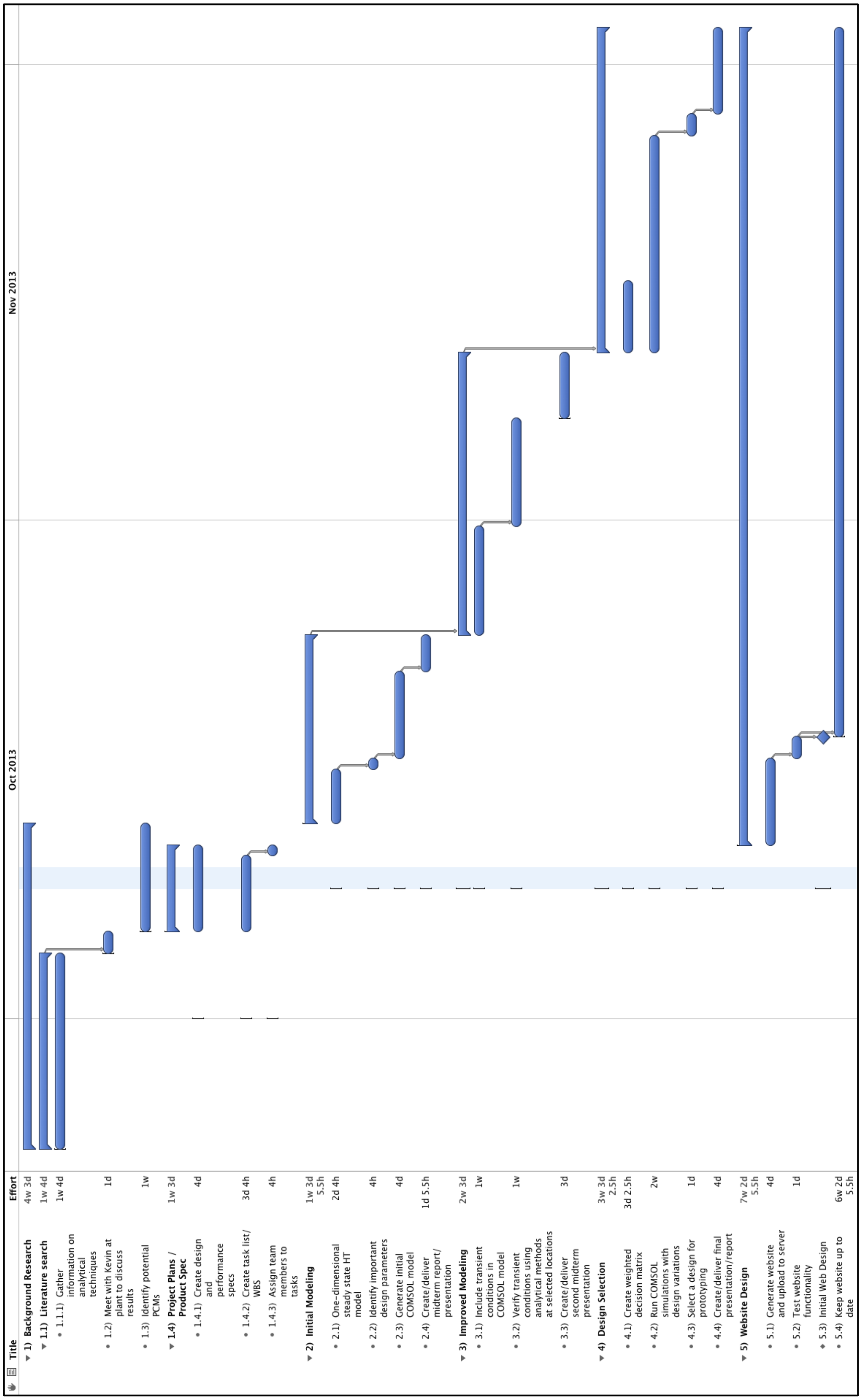
8.0 Future Plans

Immediately upon beginning the spring semester, we plan to fabricate our first prototype and build an experimental rig for testing. With this prototype and rig, we will test the performance of our design under both steady and transient thermal loading profiles. We will then compare the results of these tests to our computational models, and use our comparisons to refine the models and, if necessary, improve our prototype. Also, we will be working closely with our sponsor to develop a final manufacturing plan for our design, as the current fabrication process is only suitable for prototyping, and is insufficient for industrial-scale manufacturing.

9.0 Communications

In order to improve our models, our technical writing, and our skill in delivering oral presentations, we have been seeking feedback on at least a monthly basis from both our faculty advisor and our industry contact. From this feedback, we have recognized the importance in using visuals to present complex ideas, especially in the context of oral presentations. Moreover, we have realized that it is important to seek regular outside review of technical work, as new perspectives can often lead not only to novel solutions to roadblocks, but also to awareness of potential issues that would otherwise have gone without consideration.

10.0 Gantt Chart



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[3]Leland, J. and Recktenwald, G., “Optimization of a Phase Change Heat Sink for Extreme Environments,” PhD thesis, Portland State University, Mechanical Engineering Department.
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Appendix A: Representative Cross-Sectional Geometries

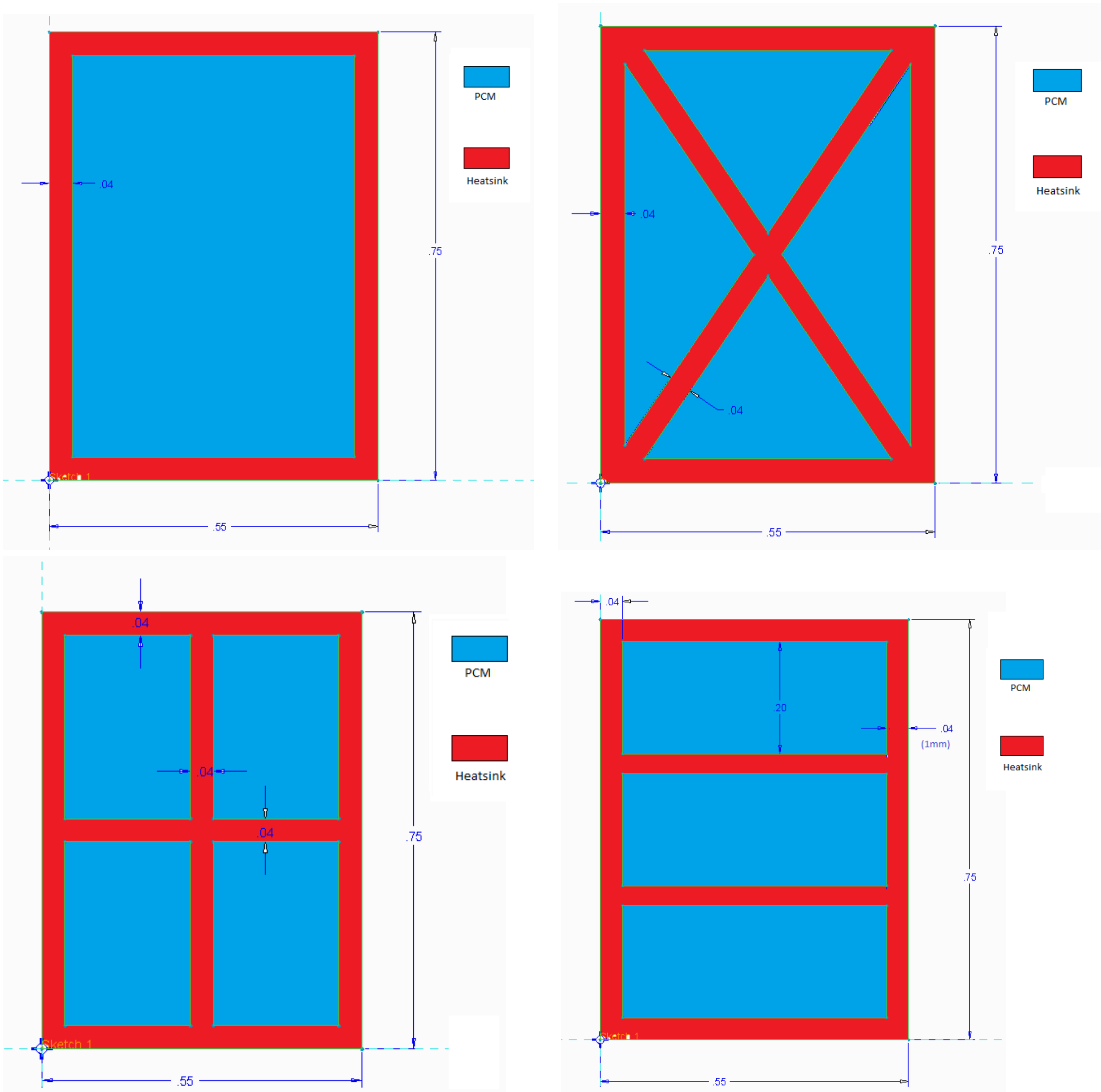

Figure 5. The four proposed designs for the heatsink housing. Analysis in COMSOL found that the design in the upper-left was optimal.

Appendix B: Steady-State MathCAD Analysis

This worksheet is for calculation of steady heat transfer using the model of a thermal resisance network. It assumes the following:

Heat transfer is steady and one-dimensional
Radiative heat transfer is neglected
The PCM has a uniform thermal conductivity
Since the PCM will melt, it should fill gaps in the housing; therefore, the contact resistance between the PCM and the housing is negligible
Spreading resistance at the exciter housing is calculated assuming that the heatsink's surface area is square
Convective resistance is calculated assuming a uniform effective heat transfer coefficient over a square portion of the exciter's surface
The required amount of heat transfer during steady operation is 1W
The heatsink's walls do not deflect (thus changing contact areas) due to the PCM's expansion/contraction

Assumed materials:

Heatsink/exciter housings: Aluminum (properties taken at 125 deg. C)
PCM: 52In-48Sn
Thermal grease: Glycerin

Assumed values:

$T_1 := 120°C$	semiconductor temperature
$T_2 := 110°C$	ambient temperature
$k_s := 34\dfrac{W}{m \cdot K}$	thermal conductivity of PCM
$h_c := 37.7\dfrac{kW}{m^2 \cdot K}$	thermal conductance of thermal grease
$h_e := 0.008\dfrac{W}{in^2 \cdot K}$	convective heat transfer coefficient of exciter housing (empirically specified by Unison)
$A_s := .55in \cdot .79in$	surface area of semiconductor/heatsink
$A_h := 0.5A_s$	cross-sectional area of housing
$k_h := 215\dfrac{W}{m \cdot K}$	thermal conductivity of heatsink housing
$w := 1mm$	heatsink wall thickness
$l_h := 5mm$	total length of heatsink
$t_e := 2mm$	exciter wall thickness
$l_e := 4in$	exciter wall length
$w_e := 3in$	exciter wall width

Calculations of PCM geometry:

$l_{PCM} := l_h - 2w = 3 \times 10^{-3}\,m$ — length of PCM contained in heatsink

$A_{PCM} := A_s - A_h = 1.402 \times 10^{-4}\,m^2$ — cross-sectional area of PCM

Spreading resistance calculations: Method taken from http://www.electronics-cooling.com/2004/05/simple-formulas-for-estimating-thermal-spreading-resistance/

$s_1 := \sqrt{A_s} = 0.017m$ equivalent side length of heatsink

$r_1 := \sqrt{\frac{{s_1}^2}{\pi}} = 9.446\times 10^{-3}m$ equivalent radius of heatsink

$r_2 := \sqrt{\frac{w_e \cdot l_e}{\pi}} = 0.05m$ equivalent radius of exciter wall

$$eps := \frac{r_1}{r_2} = 0.19$$

$$tau := \frac{t_e}{r_2} = 0.04$$

$$Biot := \frac{h_e \cdot r_2}{k_h} = 2.863\times 10^{-3}$$

$$\lambda := \pi + \frac{1}{eps \cdot \sqrt{\pi}} = 6.107$$

$$\phi := \frac{\tanh(\lambda \cdot tau) + \frac{\lambda}{Biot}}{1 + \frac{\lambda}{Biot} \cdot \tanh(\lambda \cdot tau)} = 4.139$$

$$\psi_{max} := \frac{eps \cdot tau}{\sqrt{\pi}} + \frac{1}{\sqrt{\pi}} \cdot (1 - eps) \cdot \phi = 1.895$$

$R_{spr} := \frac{\psi_{max}}{k_h \cdot r_1 \cdot \sqrt{\pi}} = 0.526\frac{K}{W}$ spreading resistance

Note: The aspect ratio of the exciter wall is between 2 and 3, so the error in the spreading resistance is likely between 5% and 10% according to the reference listed at the beginning of this section.

Resistance network calculations:

$R_{c1} := \frac{1}{A_s \cdot h_c} = 0.095 \frac{K}{W}$ contact resistance of thermal grease

$R_{c2} := R_{c1} = 0.095 \frac{K}{W}$

$R_{housing} := \frac{l_h}{k_h \cdot A_h} = 0.166 \frac{K}{W}$ conductive resistance of housing

$R_{PCM} := \frac{l_{PCM}}{k_s \cdot A_{PCM}} = 0.63 \frac{K}{W}$ conductive resistance of PCM

$R_{conv} := \frac{1}{h_e \cdot w_e \cdot l_e} = 10.417 \frac{K}{W}$ convective resistance of exciter housing

$R_{total} := R_{c1} + \frac{R_{housing} \cdot R_{PCM}}{R_{housing} + R_{PCM}} + R_{c2} + R_{spr} + R_{conv} = 11.264 \frac{K}{W}$ total resistance of system

$Q_{dot} := \frac{T_1 - T_2}{R_{total}} = 0.888 W$ total heat transfer through system (needs to be greater than or equal to 1W)

Appendix C: Transient COMSOL Analysis

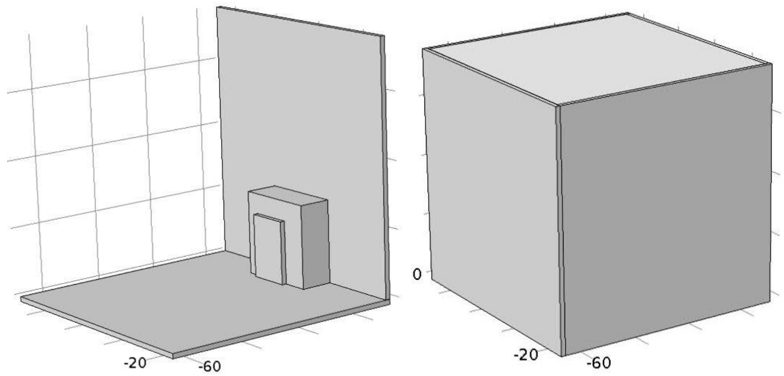

Figure 6 –The 3D model that was used in COMSOL. 6.1 shows an open view of 6.2 to help visualize the location of the heatsink.

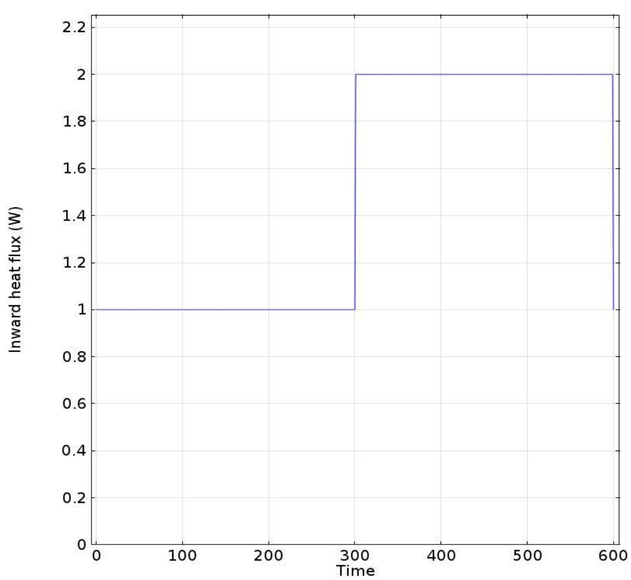

Figure 7 – The duty cycle that the COMSOL model experiences in the simulation. The normal operation parameter is 1W and the overdrive is 2W.

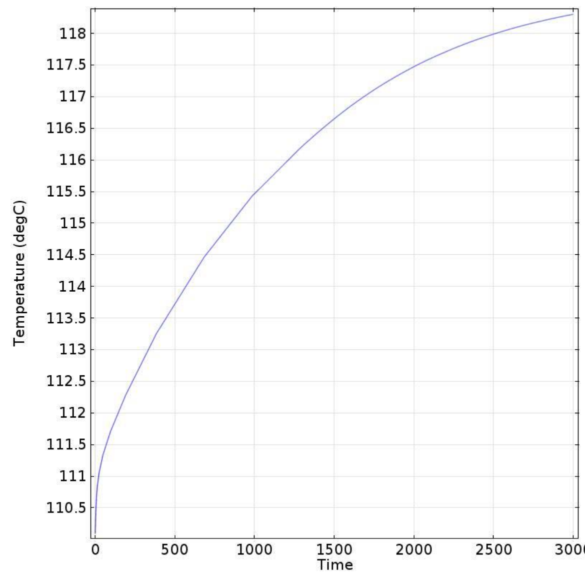

Figure 8 – A extended graph of the normal operating conditions. The system does not experience a duty cycle longer than 600 seconds. This simulation was done to determine the initial temperature during the transient case.

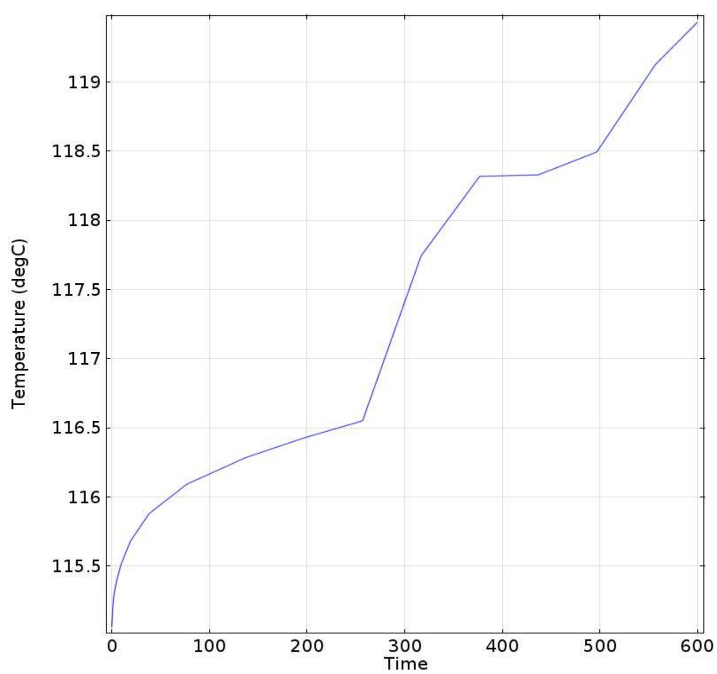

Figure 9 – The transient model. The first 300 seconds was 1W of heat generation and then from 300 – 600 seconds the overdrive occurred. The phase change can be seen to occur at 375 – 500 seconds.