Deliverable #3: Midterm Report I

Team 9 – Phase Change Material Transient Heatsink for Power Semiconductor

Sponsor:
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 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 begun to generate a numerical model in COMSOL to test their characteristics under transient thermal loads. We have not yet selected a final geometry for our design, as such a selection will have to await the completion of our numerical model. However, from the analytical model, we have identified the important design parameters for our heatsink; this accomplishment will allow us to design parametrically (and hence iterate more quickly) once our numerical model is developed. Finally, we have selected a PCM based on commercially available materials (details of this decision can be found in Section 3).

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.

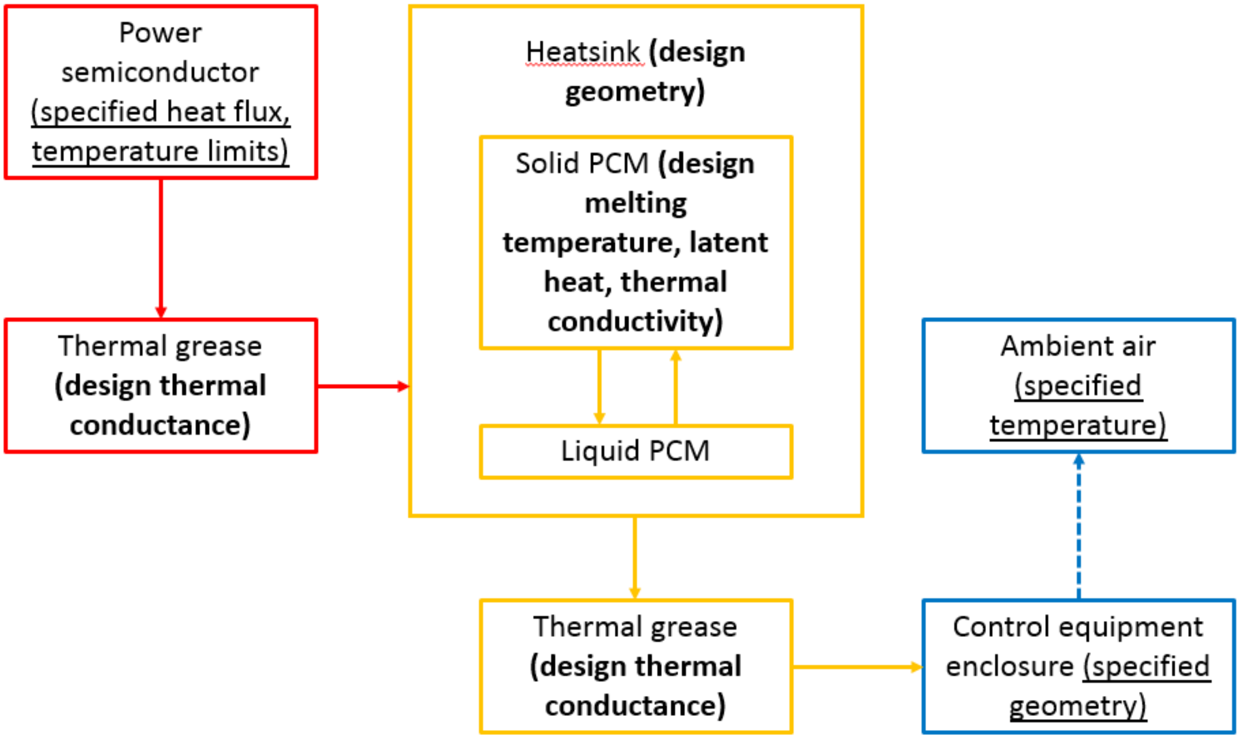


Figure . General schematic of heat transfer within control equipment assembly. Underlined words indicate sponsor-specified parameters, bold words indicate free design parameters. Arrows indicate desired direction of heat transfer. Solid arrows indicate conduction, dashed arrows indicate natural convection.

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:

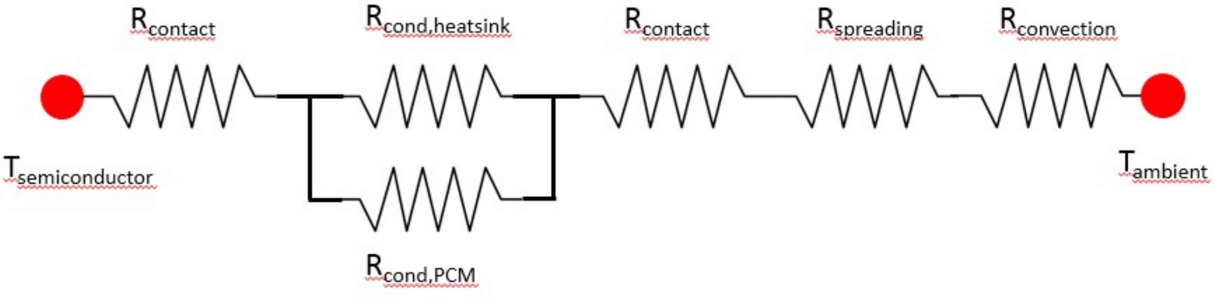


Figure . Schematic of thermal resistance network for steady-state analysis.

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:

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

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

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

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

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

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

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

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. Some representative geometries that will go under consideration once our numerical model is developed can be found in Appendix A. 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.

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.

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 improved simulation and 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	-	-	-	-	-	-

4.0 Conclusion

To this point, our team has successfully modeled the steady-state characteristics of our heatsink. From this first approximation, 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, we have developed several possible cross-sectional geometries for the heatsink that should support the stresses induced by the liquefaction of the phase-change material during transient operation. Pending the completion of our improved numerical model, these achievements have positioned us to rapidly perform design iteration and optimization.

5.0 Future Plans

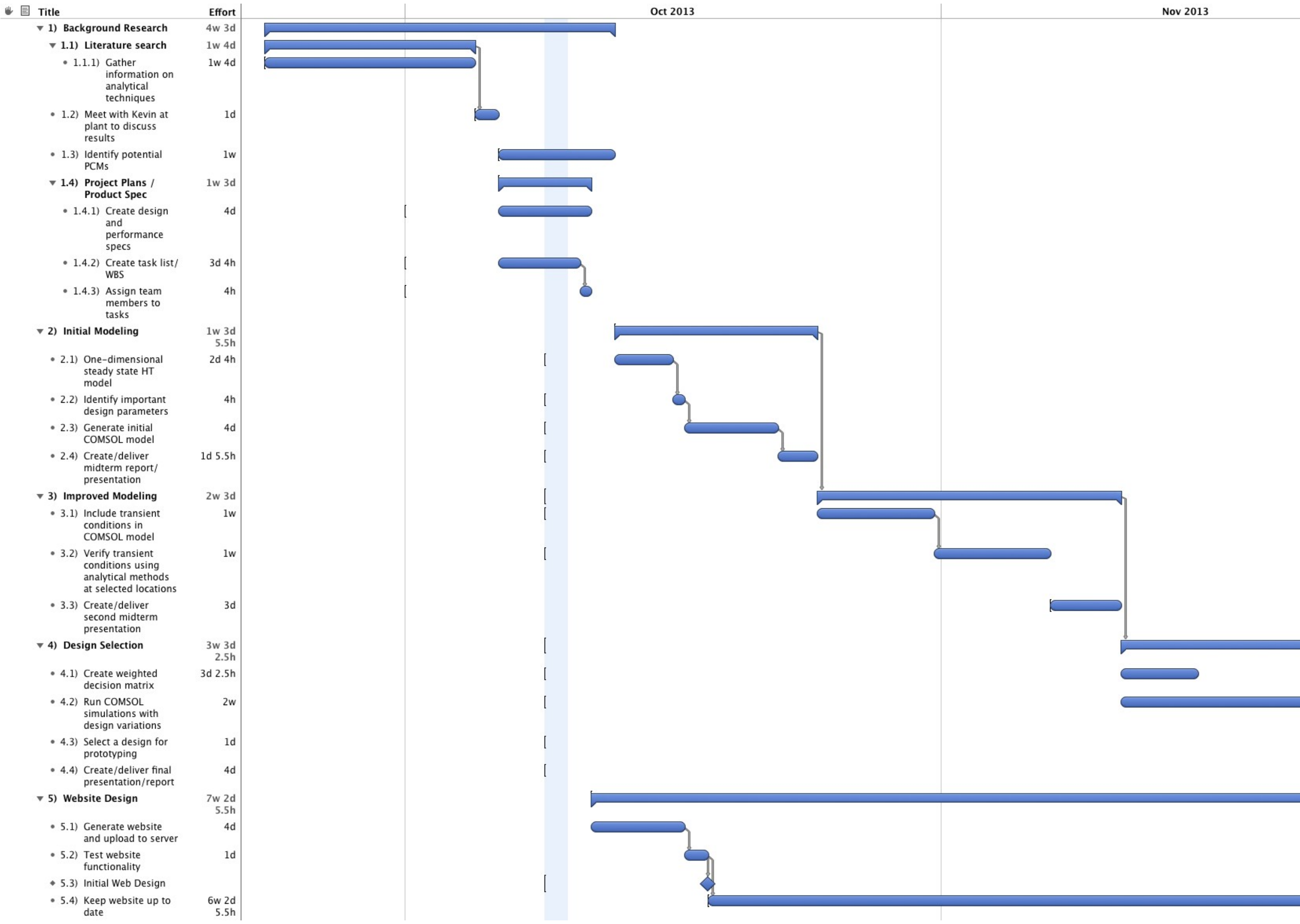
COMSOL will be used to simulate the four different heatsink design proposals and their respective dynamics in the transient case. There will be two key points to each model: heat transfer and the mechanics of the structure.

Heat transfer will be observed to ensure that the heatsink is effectively absorbing and dissipating heat from the semiconductor. To model the semiconductor, a time-dependent heat flux will be assigned as the hot-side boundary condition. On the cold side, a constant ambient temperature of to 110°C will be assigned as a boundary condition to represent natural convection. After these conditions have been entered, the heat transfer will be analyzed in terms of the heat flux on the outer surface of the control equipment assembly.

COMSOL will handle modeling of the PCM’s liquefaction and solidification. It will also model the pressure that will be caused by the phase change. From this pressure, the stress mechanics will be considered. This analysis is expected to reveal the areas of the structure that will be prone to failure due to stress concentration.

It is possible that certain dimensions will have to be altered and remodeled to satisfy the requirements of both heat transfer and structural mechanics. If it is discovered that a design is not suitable for both applications, then it will be discarded. Using the information from both the heat transfer and the structural mechanics results, the team will deliberate on which design proposal to pursue as a prototype.

6.0 Gantt Chart



Title	Effort
1) Background Research	4w 3d
1.1) Literature search	1w 4d
1.1.1) Gather information on analytical techniques	1w 4d
1.2) Meet with Kevin at plant to discuss results	1d
1.3) Identify potential PCMs	1w
1.4) Project Plans / Product Spec	1w 3d
1.4.1) Create design and performance specs	4d
1.4.2) Create task list/ WBS	3d 4h
1.4.3) Assign team members to tasks	4h
2) Initial Modeling	1w 3d 5.5h
2.1) One-dimensional steady state HT model	2d 4h
2.2) Identify important design parameters	4h
2.3) Generate initial COMSOL model	4d
2.4) Create/deliver midterm report/ presentation	1d 5.5h
3) Improved Modeling	2w 3d
3.1) Include transient conditions in COMSOL model	1w
3.2) Verify transient conditions using analytical methods at selected locations	1w
3.3) Create/deliver second midterm presentation	3d
4) Design Selection	3w 3d 2.5h
4.1) Create weighted decision matrix	3d 2.5h
4.2) Run COMSOL simulations with design variations	2w
4.3) Select a design for prototyping	1d
4.4) Create/deliver final presentation/report	4d
5) Website Design	7w 2d 5.5h
5.1) Generate website and upload to server	4d
5.2) Test website functionality	1d
5.3) Initial Web Design	
5.4) Keep website up to date	6w 2d 5.5h

7.0 References

[1] Fossett, A. J. et. al., “Avionics Passive Cooling With Microencapsulated Phase Change Materials,” *Transactions of the American Society of Mechanical Engineers*, Vol. 120, 1998, pp. 238-242.

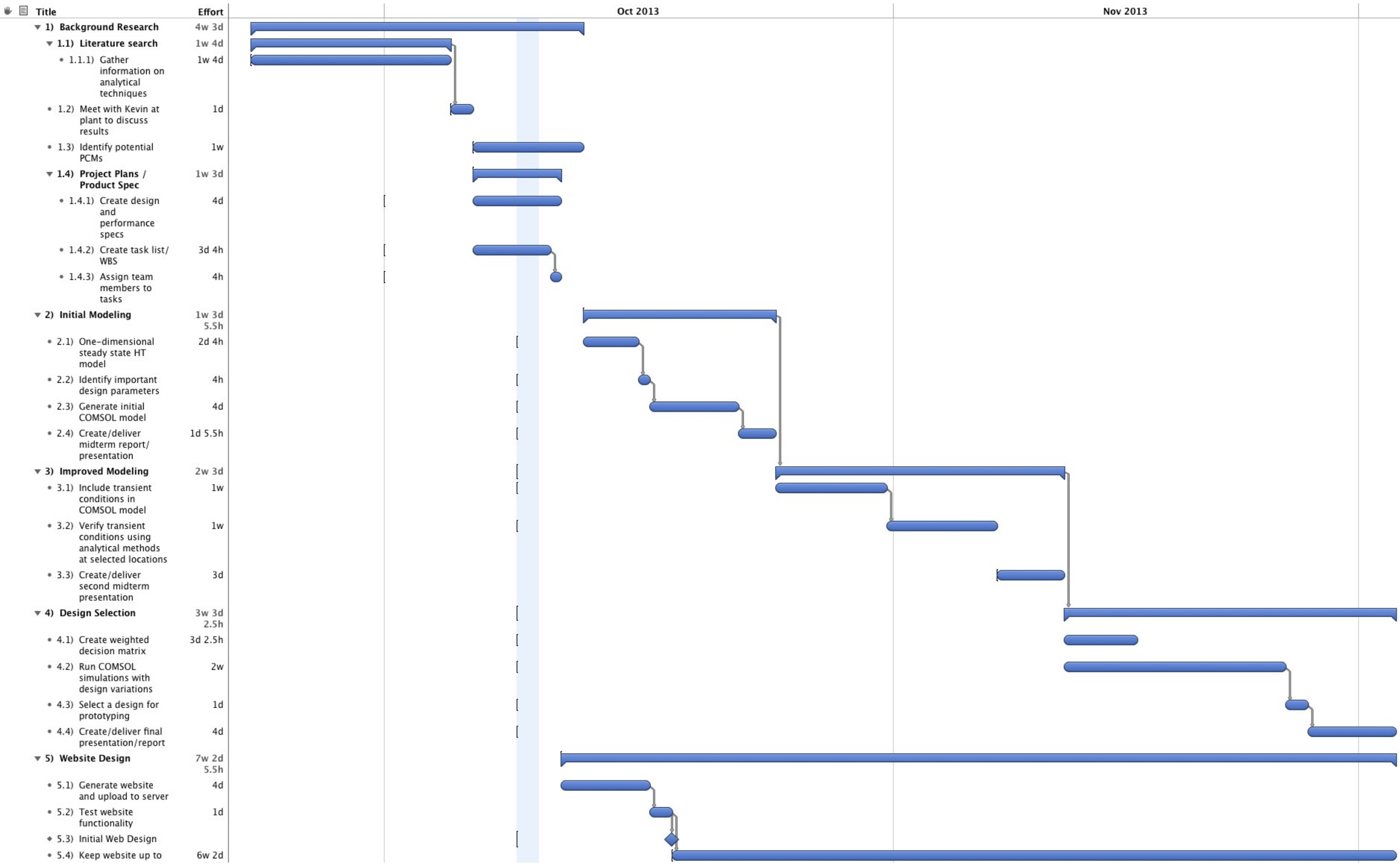
[2] Krishnan, S., Garimella, S. V., and Kang, S. S., “A Novel Hybrid Heat Sink using Phase Change Materials for Transient Thermal Management of Electronics,” *IEEE Transactions on Components and Packaging Technologies*, Vol. 28, 2005, pp. 281-289.

[3] Leland, J. and Recktenwald, G., “Optimization of a Phase Change Heat Sink for Extreme Environments,” PhD thesis, Portland State University, Mechanical Engineering Department.

[4] Cengel, Y., Cimbala, J., and Turner, R., “Steady Heat Conduction,” *Fundamentals of Thermal-Fluid Sciences*, 4th ed., McGraw-Hill, New York, 2012, pp. 663-680.

[5] Lee, S., Song, S., Au, V., and Moran, K.P., “Constriction/Spreading Resistance Model for Electronic Packaging,” Proceedings of ASME/JSME Engineering Conference, Vol. 4, 1995.

Appendix A: Representative Cross-Sectional Geometries



Title	Effort
1) Background Research	4w 3d
1.1) Literature search	1w 4d
1.1.1) Gather information on analytical techniques	1w 4d
1.2) Meet with Kevin at plant to discuss results	1d
1.3) Identify potential PCMs	1w
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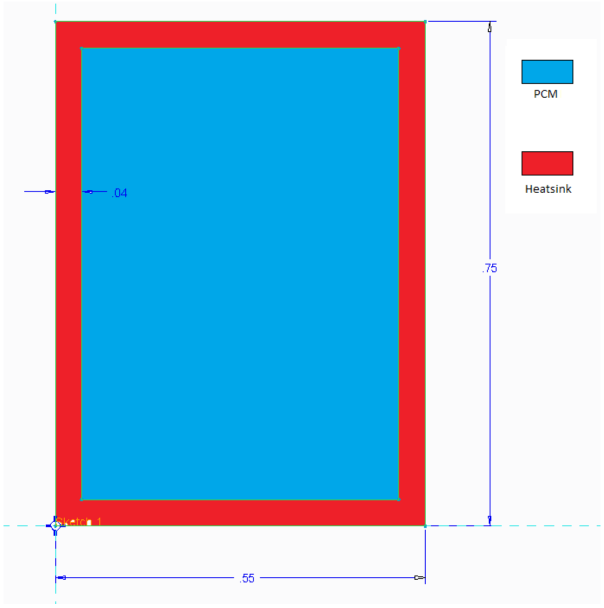
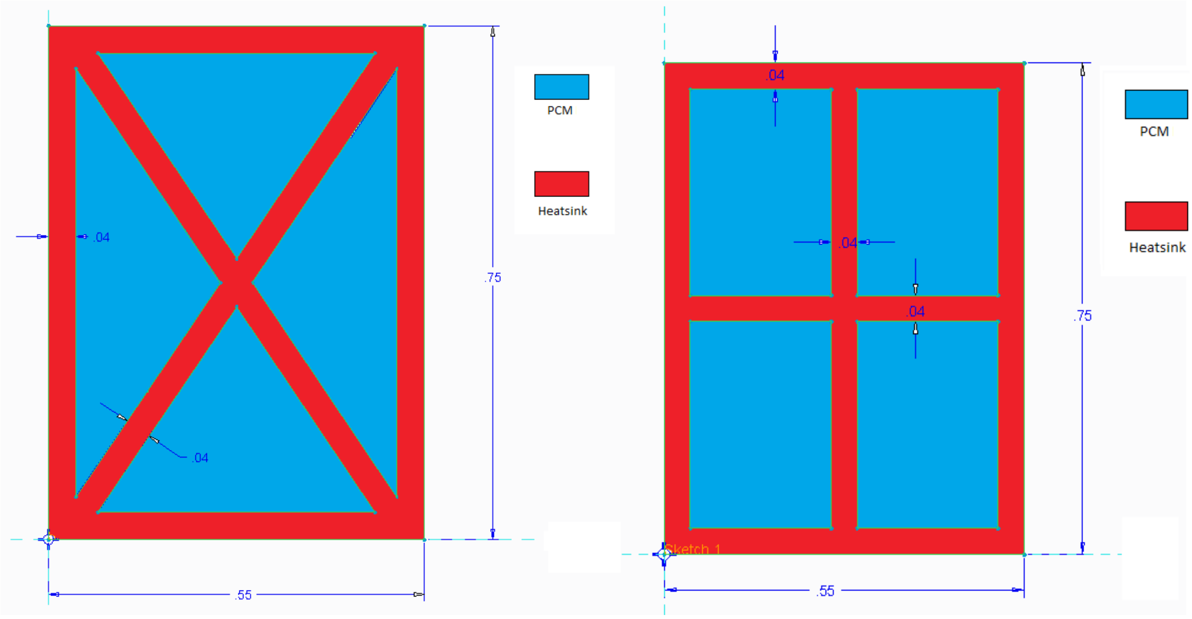
5.4) Keep website up to	6w 2d


PCM
Heatsink
.04
.75
.55
Sketch 1


PCM
Heatsink
.04
.04
.75
.55
.04
.04
.04
PCM
Heatsink
.75
Sketch 1
.55

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

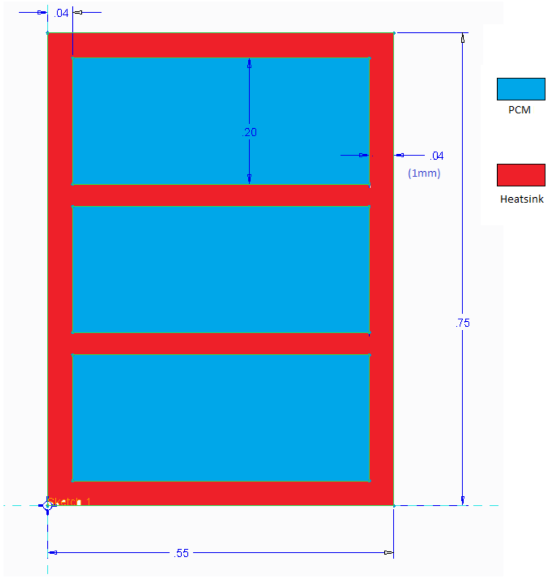


Figure – These are the four proposed designs for the heatsink. Analysis will be conducted on each design to determine which one will be most suitable for our arrangement. The dimensions shown in the diagrams are not final and are likely to change as the parameters demand.

Appendix B: Steady-State MathCAD worksheet

Heatsink/exciter housings: Aluminum (properties taken at 125 deg. C)
PCM: 52In-48Sn
$T_1 := 120\,°C$
Assumed materials: **Assumed values:** The ... semiconductor temperature 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/

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

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

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

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

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

$Biot := \frac{h_e \cdot r_2}{k_h} = 1.863 \times 10^{-3}$

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

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

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

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

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

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

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

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

$R_{conv} := \frac{1}{h_e \cdot w_e \cdot 2 \cdot l_e} = 10.417 \cdot \frac{K}{W}$ convective resistance of exciter housing

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