EML 4552 Final Report

Team 9 – Phase Change Material Transient Heatsink for Power Semiconductor

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Unison Industries

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1.0 Project Overview

1.1 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 needed a highly-reliable, low-weight heat dissipation solution for power semiconductors in jet engine systems.

1.2 Scope

To stay within the temporal and monetary constraints of our project, we limited ourselves to the following objectives: determination of the design parameters that most strongly controlled our heatsink's performance, creation of a numerical model that would 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.

1.3 Goal

To meet our sponsor's need, this project aimed to create a heatsink containing a PCM that would serve as a thermal bridge between the power semiconductor and its housing. The PCM would have a melting temperature within the operating temperature range of the semiconductors, and would thus be able to absorb thermal energy as latent heat. In essence, the heatsink would act as a thermal capacitor: through melting of the PCM, it would temporarily store thermal energy from the semiconductor until this energy could be rejected through natural convection at the housing's surface. Specifically, we aimed to create a heatsink that could operate in an ambient temperature of 110°C and keep a semiconductor under 125°C during a duty cycle that would first entail five minutes of 1W dissipation, immediately followed by five minutes of 2W dissipation.

1.4 Objectives

The most important objectives for our team to achieve were 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

2.0 Background Research

Since our project was industry sponsored, it was necessary that we perform a search of patents to ensure that our design would not infringe on anyone else's intellectual property. Furthermore, to get a better grasp on possible simulation and testing methods, and to avoid pursuing design options already known not to work, we looked for technical articles that could inform our design process. From the patent search, it was determined that PCMs had already been patented as a possible heatsink component, but that the enclosure geometries were often very complex and application-specific. As such, the patents did not appreciably impact our design process. From the technical articles[1-4], we gained quantitative evidence that PCMs are a viable solution to electronics cooling.

3.0 Design Concept

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

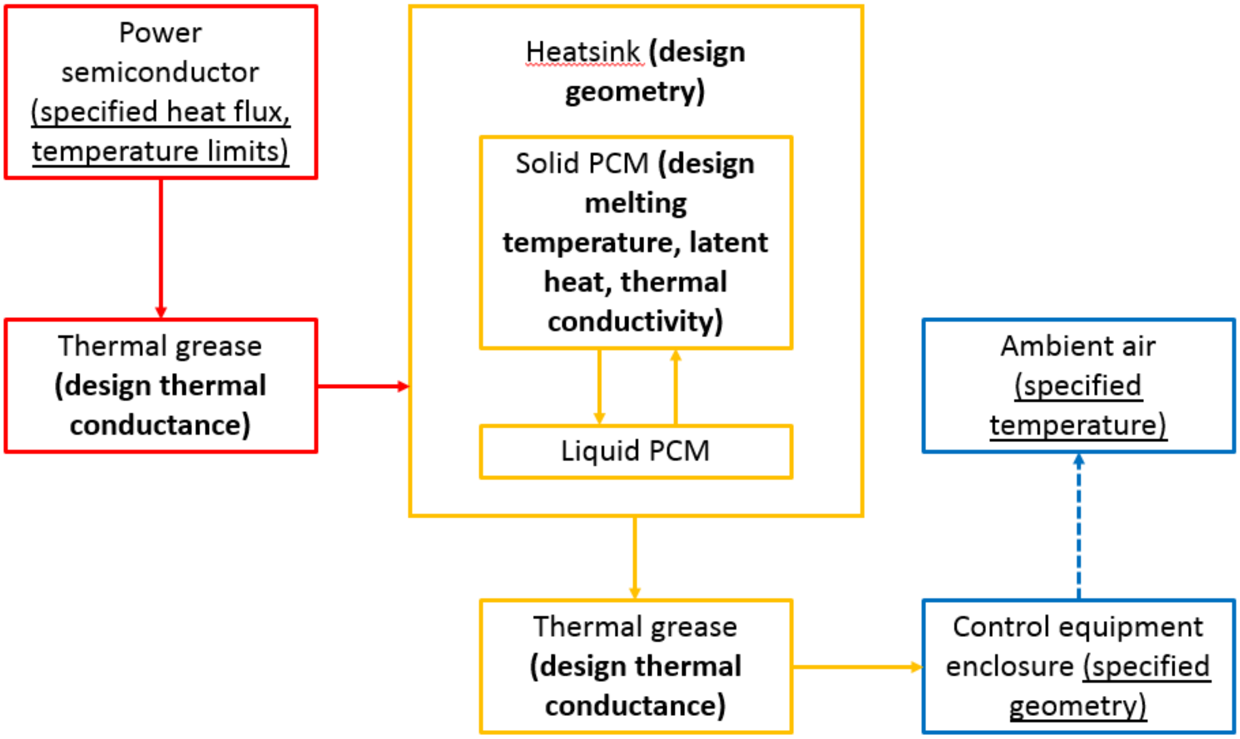

Figure 1. General schematic of heat transfer within control equipment assembly. Underlined words indicate sponsor-specified parameters, bold words indicate free design parameters. Arrows indicate desired direction of heat transfer. Solid arrows indicate conduction, dashed arrows indicate natural convection.

As can be seen from Fig. 1, it was necessary that our design operate within several sponsor specifications. Namely, the heatsink needed to 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 to 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.

4.0 Numerical Simulation and Design Selection

4.1 PCM Selection

To eliminate the need to construct multiple physical prototypes, to allow for design optimization (for manufacturing, performance, etc.), and to create a design tool that could be suited to future applications, we constructed a three-dimensional heat transfer model using the COMSOL multiphysics solver (see Appendix A for details of the setup). To use this solver, it was necessary that we create a material that could emulate the energy absorption that occurs during a melting process, as COMSOL's heat transfer module assumes that all materials remain in a single phase. To create such a custom material, it was in turn necessary that we assume a PCM beforehand in order to calculate the amount of energy our custom material would absorb based on the actual material's properties. The PCM selected for this purpose was a 52In-48Sn solder. 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 into consideration. Since the operating temperatures were 115-125°C, the phase change material needed to have a melting point within that range. The latent heat of fusion was also key for this project. A higher latent heat of fusion would allow the heatsink to absorb more heat with less material. Furthermore, for the heatsink to be effective during steady operation, the thermal conductivity needed to be as large as possible. Therefore, only materials with high thermal conductivity were considered. Additionally, when the PCM reaches its melting point and changes phase, it will expand, thus causing a pressure rise inside the heatsink. If this pressure were to get too large it could compromise the entire structure. Therefore, it was important for the PCM to have the lowest possible coefficient of thermal expansion. Density was also considered since the heatsink has an application in aviation.

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 Table 1.

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	-	-	-	-	-	-

4.2 COMSOL Results

From the model, we found that the optimal cross-sectional geometry did not have any supporting internal members. This geometry is reproduced in Fig. 2. 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. 3, 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). Despite our numerical model's indication that the heatsink design selected for prototyping would be unable to handle the specified thermal load, we 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 was assumed that steady heat generation at a rate of 1W occurred for 30 minutes prior to the overdrive stage, and that the overdrive stage at 2W occurred for five minutes. The time spent in both of these stages was 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. 3, 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.

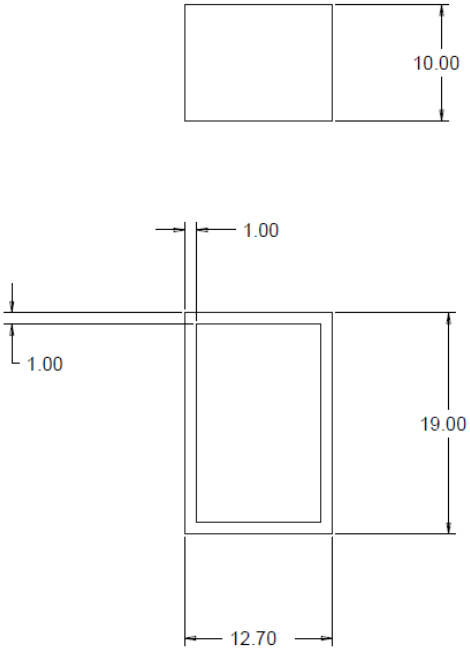

Figure 2. Heatsink geometry. All dimensions in mm.

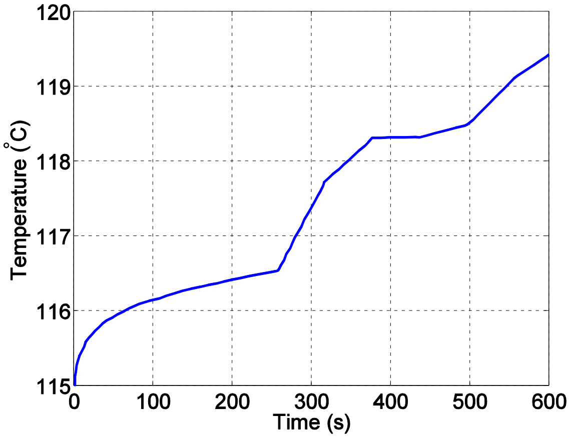

Figure 3. Temperature (volumetric average) of PCM during duty cycle.

5.0 Prototype Fabrication and Test Setup

5.1 Prototype Fabrication

The need statement called for a heatsink to absorb the additional heat that is generated during the overdrive condition. Our sponsor specified that the amount of additional thermal energy would be 1W for five minutes, or 300J in total. The volume of the PCM was calculated to absorb this energy through latent heat. The solder chosen as the PCM had a latent heat of fusion of $28.5\frac{kJ}{kg}$. With these parameters, the volume required was found to be 1445mm^3. It was determined that the geometry of the heatsink should match that of the semiconductor's base (12.7mm x 19mm) to minimize the thermal resistance contributed by the heatsink. The wall of the aluminum vessel was designed to be 1mm thick to ensure that pressure buildup from thermal expansion of the PCM would not result in rupture. This wall thickness resulted in the cross-sectional area of the PCM being 10.7mm x 17mm, or 182mm^2, with a consequent depth of 8 mm. Therefore the overall dimensions of the heatsink were 12.7mm x 19mm x 10mm (Fig. 2).

The heatsink body was created by water-jet. Aluminum tape was then used to cap off the bottom side. The aluminum tape was used because its thickness was close to 1 mm and because it was easy to form to the desired size. The PCM (originally received in ribbon form) was then melted into the vessel with assistance of a heat gun (Fig. 4). With the PCM in the enclosure, the interior was sealed by using another piece of aluminum tape. Finally, the entire prototype was placed into a lab oven at 140^{o}C to allow the PCM to settle.

Figure 4. Manual melting of solder (PCM) ribbon into heatsink using a heat gun.

5.2 Test Bed Fabrication

In order to ensure that the prototype would be able to meet the sponsor's requirements, and to validate the COMSOL model, an experimental test platform was designed. Most of the equipment utilized was provided by either the team's industry contact or by the National High Magnetic Field Laboratory (NHMFL). NHMFL is also where our tests were conducted.

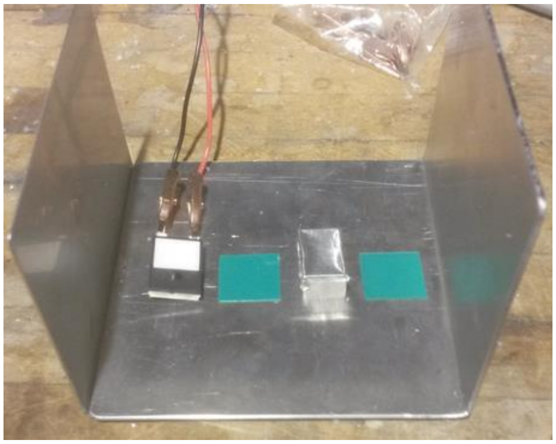

Figure 5. Test bed interior components before assembly. From left to right: 100Ω resistor with ceramic (white) heating surface, thermal interface material, heatsink prototype, and a final layer of thermal interface material.

Fig. 5 shows a disassembled view of the test platform's internal components. A 100Ω resistor (the black-and-white item with electrical leads attached) was purchased from Caddock in order to be able to simulate the semiconductor's Molybdenum base and act as the heat source. The team's sponsor provided an adhesive thermal interface material (the turquoise material) to reduce contact resistance between the surfaces and thus allow optimum conduction. A formed aluminum sheet was also supplied by the sponsor in order to properly simulate the housing where the semiconductor and heatsink would be encased.

Fig. 6 shows all of these components after assembly. Note that in the figure, all of the components have been bracketed together using bolts and a small piece of aluminum; this bracket was implemented after discovering that the thermal interface material was insufficiently adhesive to hold together the resistor, heatsink, and aluminum sheet.

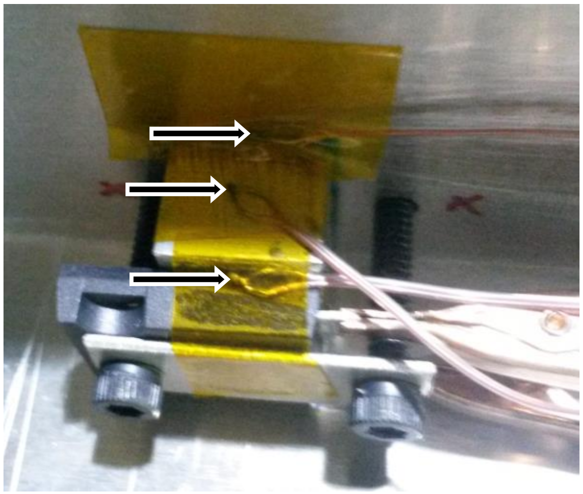
Figure 6. Interior components after assembly. Thermocouple mounting locations are highlighted by arrows.

Fig. 7 shows the overall test bed assembly. After the prototype was adhered to both the outer aluminum wall and resistor surfaces, a Styrofoam cover was cut (with the cutout for the interior components lined with Nomex for additional insulation) and placed over the internal assembly. This cover was made in order to simulate the thermal insulation that the heatsink would experience in its final configuration; in this configuration, both the semiconductor and heatsink would be sealed into a rubber overmold. Finally, the Styrofoam cover was joined to the aluminum sheet using aluminum tape. The tape was used for two reasons, the first of which was simply to prevent the Styrofoam's expansion at elevated temperatures. The latter reason was to provide a conductive path for the thermal energy from the semiconductor after it reached the outer wall, as such a path would be both realistic (the actual ignition unit assembly would have six walls) and was shown by our COMSOL model to improve the heatsink's performance.

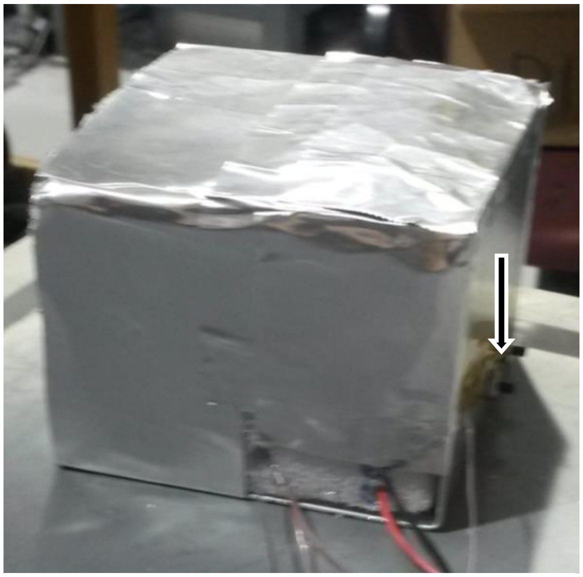
Figure 7. Overall test bed assembly. Thermocouple mounting location indicated by arrow. Note Styrofoam insulation (mostly covered by aluminum tape but visible in bottom-right corner).

5.3 Test Environment

A laboratory oven was supplied by NHMFL (Fig. 8) in order to properly simulate the ambient conditions specified by Unison. Since this design would be used inside jet engines' ignition units, the ambient temperature needed to be 110°C (230°F) to yield practical results.

5.4 Measurement Equipment

To quantitatively measure our heatsink's performance, we used Type E thermocouples (chosen for their small junction size). The thermocouples were mounted using thermal contact tape from TapeSouth, and their mounting locations can be seen in Figs. 6 and 7. To record the thermocouples' outputs, we used a 9211 thermocouple input module, cDAQ-9174 data acquisition system, and LabView, all from National Instruments.

6.0 Experimental Results

Note that for all of the tests discussed below, we attempted to hold the lab oven's temperature constant at 110°C. However, the lab oven's temperature PID controller exhibited large amounts of overshoot (±25°C) and settling time (over 20 minutes) for this nominal temperature.

Figure 8. Lab oven used for prototype testing.

6.1 Tests with Heatsink

The results of our first experiment, in which we attempted to emulate the semiconductor duty cycle specified by our sponsor (five minutes at 1W dissipation followed by five minutes at 2W), are compared to our computational results in Fig. 9. Note that the computational results displayed in Fig. 9 are not the same as those presented in Fig. 3 in Section 4.2. The results presented in this section were taken from a revised model that included the following changes: the initial condition was changed to 110°C from 115°C, and the melting rate of the PCM was altered such that it was able to dissipate 0.65W (up from 0.55W in the previous model) of thermal energy. These revisions were made after running our first set of experiments so that the model would better match reality. Furthermore, it should be recognized that from points B to C in Fig. 9, the resistor was accidentally set to 4W for a period of about 20 seconds. The reason that the mistaken voltage setting is displayed is to illustrate the high sensitivity of this design to power dissipation rates beyond its design point: though the heatsink performs well under 2W, its performance rapidly degrades afterwards. The data indicate that our heatsink outperformed its performance specifications, as even with an erroneous temporary voltage setting, the heatsink was able to keep the resistor under its failure condition (125°C) for over ten minutes. Additionally, the data show some qualitative agreement with our computational model, as both trends show a leveling off of the rate of change of temperature during the overdrive period (indicating a phase change). However, even with our revisions, the COMSOL model still underpredicted the heatsink's performance, as the rate of change of temperature begins to significantly increase again around 500 seconds (7 minutes), suggesting that the PCM should have completely melted by this point. This discrepancy was likely caused by our choice of boundary conditions within the model: we specified all of both the heatsink's and the resistor's walls to be adiabatic, while during the experiment they likely exhibited non-negligible amounts of both convective and radiative heat transfer.

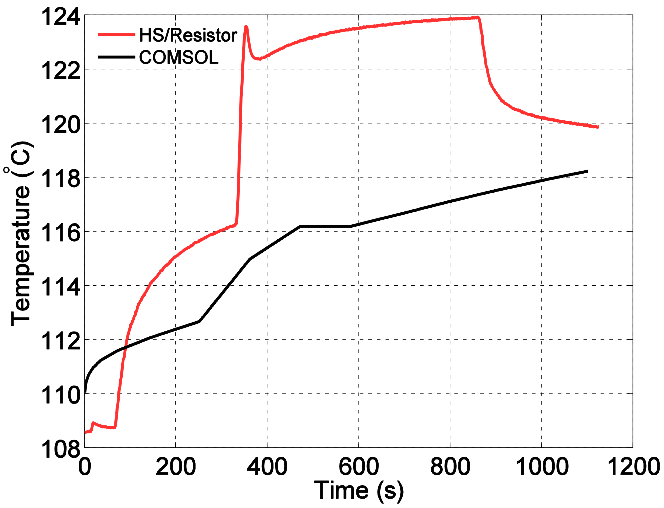

Figure 9. Comparison of temperatures at heatsink/resistor interface to revised COMSOL model.

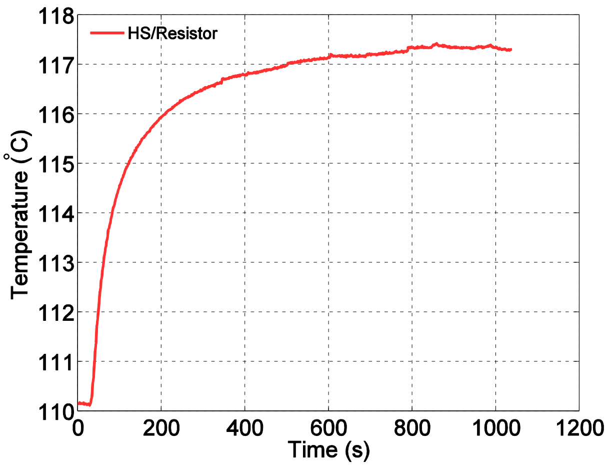

Figure 10. Temperature history with constant 1W resistive heat generation.

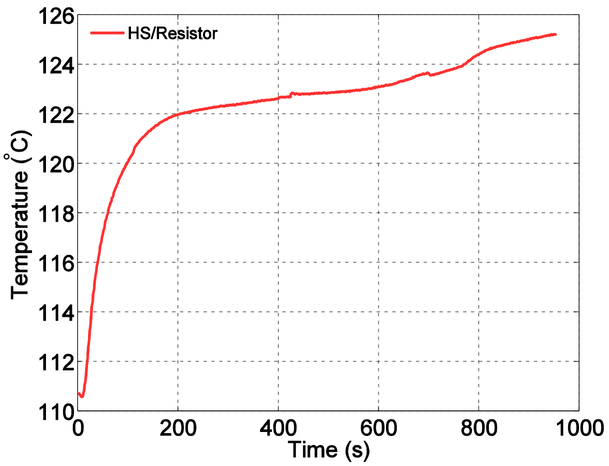

Figure 11. Temperature history with constant 2W resistive heat generation.

To determine the performance of our heatsink in the event of extended duty periods, tests were run at 1W and 2W until either the assembly reached a steady temperature, or the resistor's temperature exceeded 125°C. The results of these tests are shown in Figs. 10 and 11, respectively. The steady (1W) test showed that the heatsink could dissipate 1W for an indefinite period of time, as the resistor reached a steady temperature slightly above 117°C. This result is also encouraging because this steady-state temperature is below the melting temperature of the PCM (118°C), meaning that the heatsink would have its full heat capacity available in the event of an overdrive (2W) period. As shown in Fig. 11, if the heatsink began at an ambient temperature of 110°C, it could handle such an overdrive period for nearly 17 minutes (about three times its performance specification) before the semiconductor would exceed its failure temperature.

6.2 Tests without Heatsink

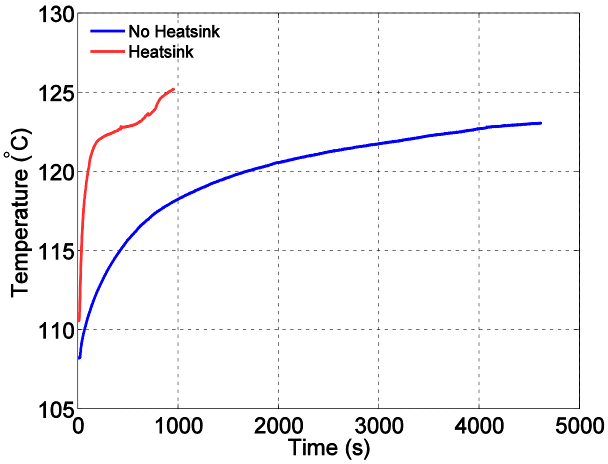

Figure 12. Comparison of constant 2W resistive heat generation with and without heatsink placed in test bed.

To isolate the effect of the heatsink, the heatsink was removed from the test bed (i.e., the resistor was put in direct contact with the enclosure wall) and was set to constant 2W resistive heat generation. The results of this experiment are displayed in comparison to those from Fig. 11 in Fig. 12. From the figure, it is clear that the addition of the heatsink imposed a significant thermal resistance penalty to the overall thermal network: without the heatsink, the resistor took over an hour longer to display the 15°C temperature change that would be necessary to cause failure in an ambient environment of 110°C. Consequently, we concluded that our heatsink may not be necessary for this application, as it appeared that natural convection could keep the resistor's temperature low enough for the duty cycle specified.

7.0 Manufacturing Plan

7.1 Design for Manufacturing

Shown in Fig. 1 is the basic geometry for our design's enclosure. In the prototyping phase, we constructed the heatsink from a combination of aluminum sheet and aluminum tape: we used a waterjet to create a box with two open faces, sealed one face with aluminum tape, melted the solder into the box, then sealed the remaining face with another piece of tape. In an industrial setting, this manufacturing plan would obviously be infeasible, as it is both unsuitable for batch processing and introduces too much human variability with the sizing of tape and the sealing pressure with which it is applied.

To manufacture our design on a large, repeatable scale, we have developed the following plan in conjunction with our sponsor at Unison:

1. Contract Hudson Technologies[5] to form the enclosure as an open box and a lid with a close fit (to be sealed with epoxy after the insertion of the solder). We have chosen Hudson for their capability to make enclosures through deep drawing, as this process allows for very thin walls (necessary for the 1 mm wall thickness we desire) with a tolerance of ±2% (±0.02 mm). Additionally, Hudson can deliver at high volume (up to 5,000,000 pieces), and would thus easily be able to fill Unison's demand (500 to 1,000 pieces per year). Finally, Hudson can form our enclosure out of materials other than aluminum; this capacity would allow for the heatsink to be made out of a more thermally conductive metal (such as copper) if future tests show that such a change in material would result in a significant change in performance.
2. Contract IndiumCorp[6] to deliver ingots of the 52In-48Sn solder that would serve as the heatsink's phase change material. We desire the solder in ingot form because during our prototyping phase, we discovered that the ribbon form we received was very difficult and time-consuming to completely melt into the small space of our enclosure. If the solder were instead sold in ingots of the volume and shape necessary to fit inside a single heatsink, it would speed up manufacturing time and reduce labor costs significantly.
3. Have enclosure and solder delivered to Unison's plant. Assemble a batch of heatsinks by inserting solder into the open enclosure, then sealing the lid with either an epoxy preform or the manual application of epoxy from a tube.
4. Place batch into oven. Take oven to 150ºC and hold for 40 minutes (see Appendix C for the oven temperature profile developed for a typical Unison oven) to ensure complete break-in (i.e., good solder-to-enclosure wetting) of solder and curing of epoxy. After cooling, heatsinks are fully assembled and ready for testing or insertion into the ignition unit.

7.2 Design for Reliability

As mentioned in our problem statement, high reliability is critical for our design, as its failure could result in a cascade of other component failures whose worst-case end effect would be a failure to ignite within the combustion chamber, and thus a loss of power out of the engine. With this realization in mind, we have developed the following considerations for our manufacturing plan:

- Enclosure/solder durability: Since our heatsink will be sealed with the semiconductor into a rubber overmold within the complete ignition unit or power regulator assembly, it will not be accessible for repair. As such, it will be expected to last for the entire useful life of the complete assembly. During this service period, the heatsink will be subjected to unsteady mechanical and thermal loading. It will therefore be necessary to perform fatigue tests on completed heatsinks to ensure that a sudden fatigue failure will not occur while the heatsink is in service.
- Enclosure variability: Part of our reason for selecting Hudson Technologies as our enclosure manufacturer is that they guarantee all dimensions to ± 0.05mm. Given that our smallest dimension is 1mm, this variance amounts to a maximum of only 2% of our smallest dimension.
- Solder variability: For ingots the size of our enclosure's interior, IndiumCorp guarantees dimensions accurate to ±0.127 mm for the length and width and ±5% for the thickness. This variance amounts to a minimum of 282J and a maximum of 324J in terms of the ingot's heat capacity. Given that the nominal heat capacity is 300J, and that the heatsink far outperformed its performance specifications (see Section 6.1 and Fig. 11), we do not expect this variance to result in the heatsink's failure under a typical duty cycle.
- Epoxy variability: If the epoxy were manufactured as preforms, the variability would simply be that of the fabrication process. While this variance is unknown, it would certainly be less than the variance that would be introduced if the epoxy were to be manually applied from a tube. Furthermore, the preform's variance would be quantifiable, whereas the variance introduced from manual application would change between technicians. As such, in terms of optimizing reliability, the preform would be a better option.
- Oven temperature variability: Unison's ovens have a temperature tolerance of ±10°F (5.56°C). Given that we specify the oven to be set at 150°C, that the epoxy Unison typically uses sets at 300 ± 10°F (149 ± 5.56°C), and that the solder melts at 118°C, we do not expect the oven's variance to affect the quality of the heat treatment.
- Assembly variability: Once a batch of heatsinks is fully assembled, processed, measured, and tested, it will be necessary to perform a statistical analysis to determine part-to-part variability in terms of size, performance, and fatigue life.

8.0 Conclusion and Future Work

Our team was tasked with the development of a heatsink for power semiconductors in elevated ambient temperatures. To achieve this goal, we identified a solder whose material properties would allow it to serve as a phase change material that would act as a thermal capacitor, absorbing excess thermal energy from the semiconductor as latent heat. To test the solder's performance and iterate through possible enclosure geometries, we created a model using COMSOL's heat transfer module; from these results, we selected a prototype geometry. To test this geometry and to validate our COMSOL model, we designed and built a test platform and placed it into a laboratory oven to simulate the elevated ambient temperatures that the heatsink would face. From our experimental results, we determined that as a result of the solder's melting, the heatsink would be able to keep the semiconductor under its specified failure temperature for the specified duty cycle. However, we also determined that the heatsink imposed a significant resistance penalty to the overall thermal network, and that it may not be necessary for the ambient environment and duty cycle particular to this application, as removal of the heatsink from the test platform did not result in a failure condition during the duty cycle specified.

Over the course of our project, we recognized several areas for improvement. These areas would serve as good objectives for future teams that undertake this project, and are listed below:

- Improve COMSOL model: Though it showed qualitative agreement with experiments, our model significantly underpredicted the heatsink's performance. To serve as a useful design tool, the model needs to be able to match experimental results reasonably well. To improve the model, radiative and convective effects at the heatsink and resistor walls should be included. Furthermore, the PCM model should likely be changed, as it is currently modeled as a material that removes energy from the system at a starting time and rate that have to be set by the user through trial and error; this model is thus both tedious to setup and not firmly rooted in the physics of the problem.
- Develop adjustable test platform: Due to the bracket that we had to create to hold the resistor, heatsink, and aluminum sheet together, the test platform can only accommodate heatsink geometries whose cross-sectional area is close to that of our current prototype. To allow for quick testing of multiple prototypes, it would thus be useful to have an adjustable bracketing system, perhaps by having slots for the bolts instead of simple holes.
- Source a better lab oven: As mentioned in Section 6, the overshoot and settling time of the lab oven's temperature controller made it difficult to obtain a precise ambient temperature of 110°C. More reliable data could therefore be obtained with the use of a better lab oven.
- Insert thermocouple into PCM: During our experiments, we measured the heatsink's temperature at its top surface. While this measurement serves as an acceptable estimate of the solder's temperature, a more direct measurement would be instructive, as it would likely show the phase change more clearly.
- Source/develop less costly PCM: Our team was allocated $2,000 for this project, and while we only spent half of this budget (see Appendix D for a detailed table of both incurred expenditures and those expected in an industrial setting), over 80% of our expenditures (around $800) was on the solder. As such, a cheaper PCM would vastly reduce the overall material cost of this design.
- Soakback (elevated ambient temperature) testing: After the shutdown of a jet engine, cooling air stops flowing and ambient temperatures within the engine rise as hot components dissipate energy to the air. As such, the ignition unit would be exposed to elevated ambient temperatures (nominally up to about 140°C). While not explicitly specified as one of the heatsink's necessary functions, it would nonetheless be useful to see if it could protect the semiconductor under these conditions.

9.0 References

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[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.

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Appendix A: COMSOL Model Details

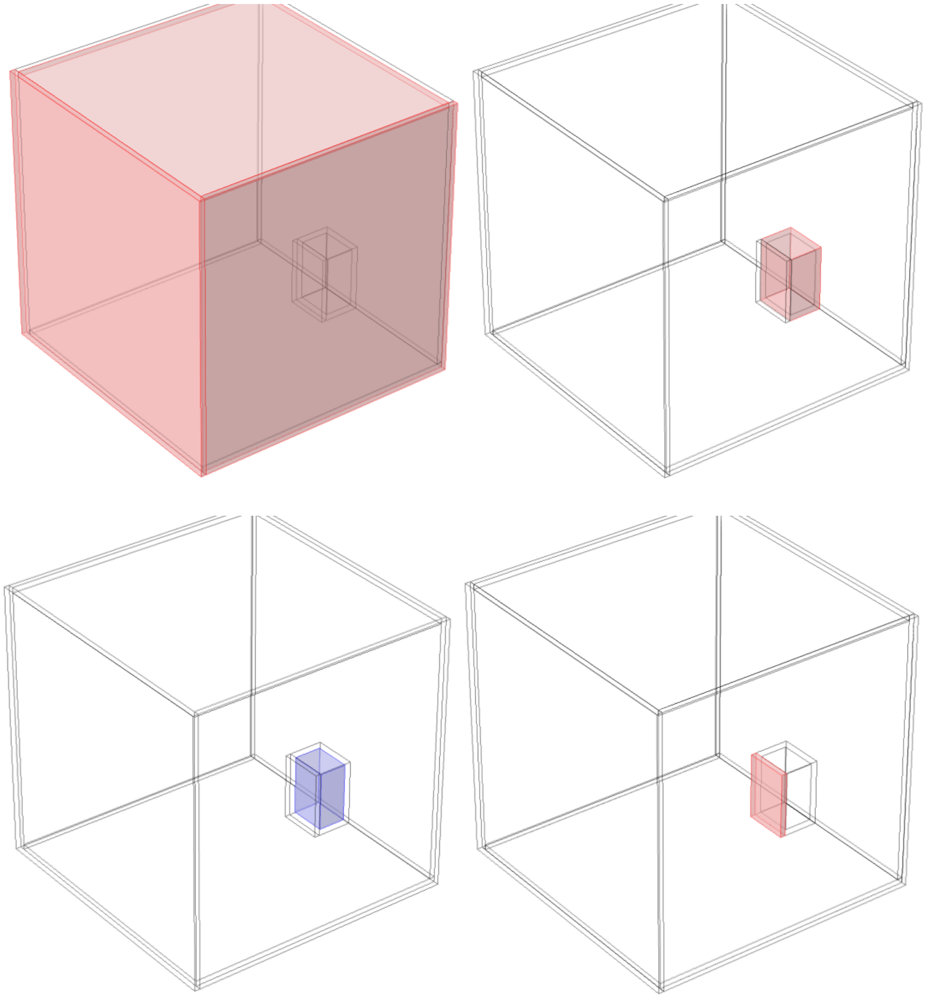

Figure A.1. Schematic of computational setup. Top left is ignition unit housing, assumed to have heat transfer through natural convection. Top right is the heatsink's aluminum enclosure, assumed to have adiabatic surfaces except where the heatsink contacts the semiconductor and housing wall interior. Bottom left is the phase change material, assumed to have the material properties of solid 52In-48Sn solder. Bottom right is the semiconductor base, assumed to have constant heat fluxes totaling either 1W or 2W depending on time within the duty cycle.

Appendix B: Additional Experimental Results

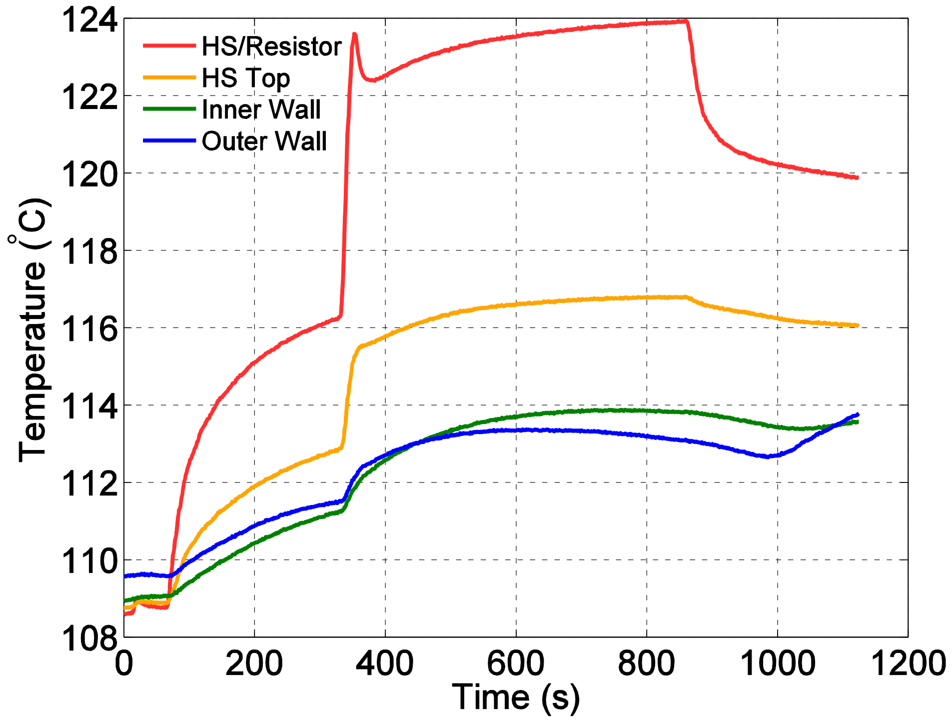

Figure B.1. Results from first test (5 minutes at 1W, ~30 seconds at 4W, ~ 8 minutes at 2W) for all thermocouples.

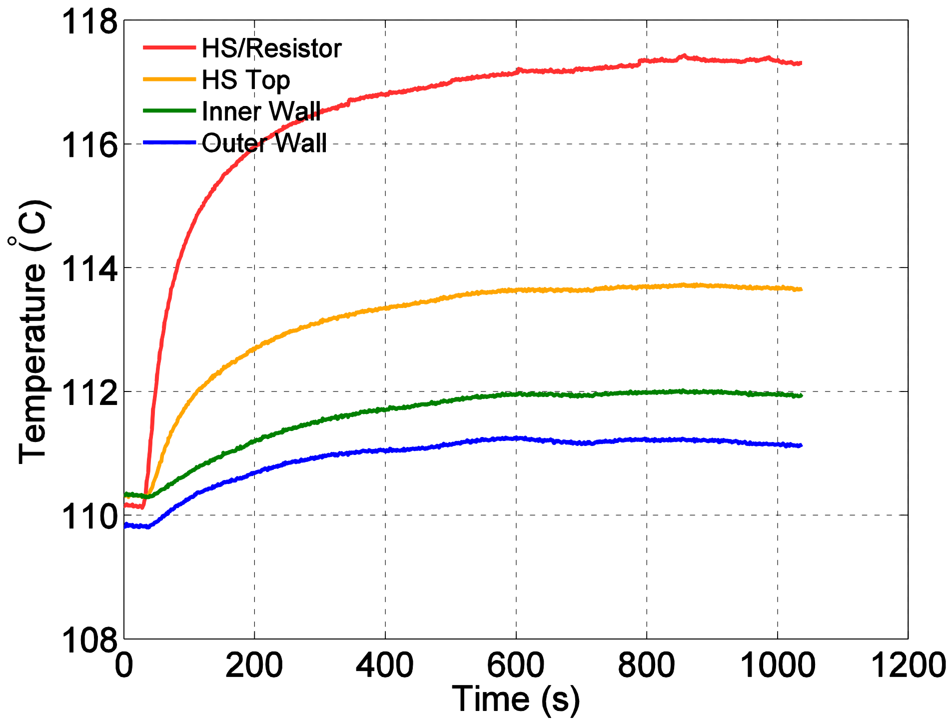

Figure B.2. Results from constant 1W dissipation for all thermocouples.

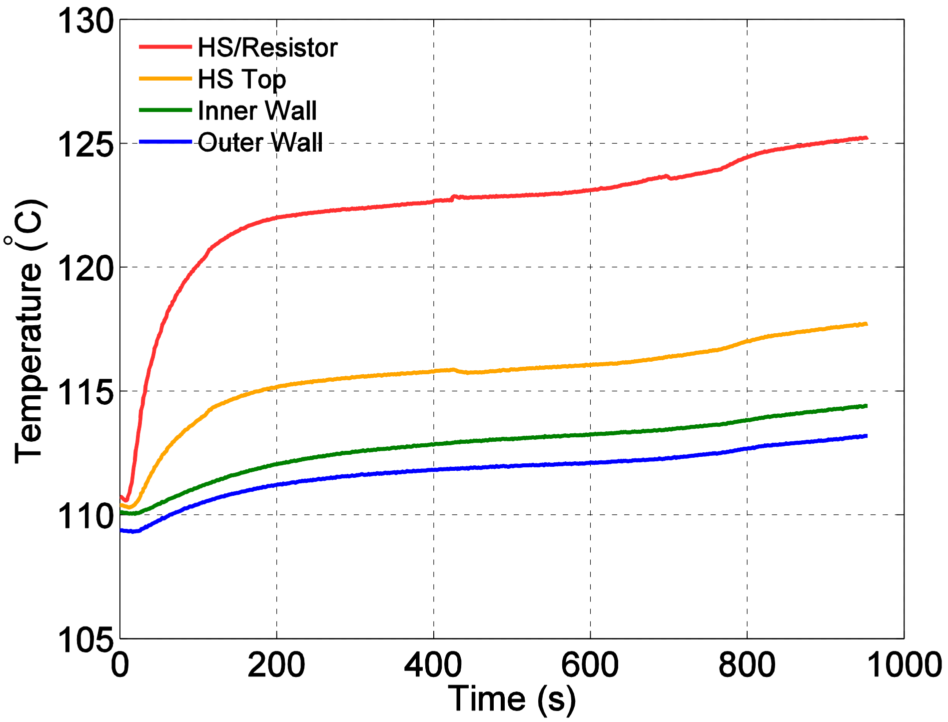

Figure B.3. Results from constant 2W dissipation for all thermocouples.

Appendix C: Proposed Heat Treatment Profile

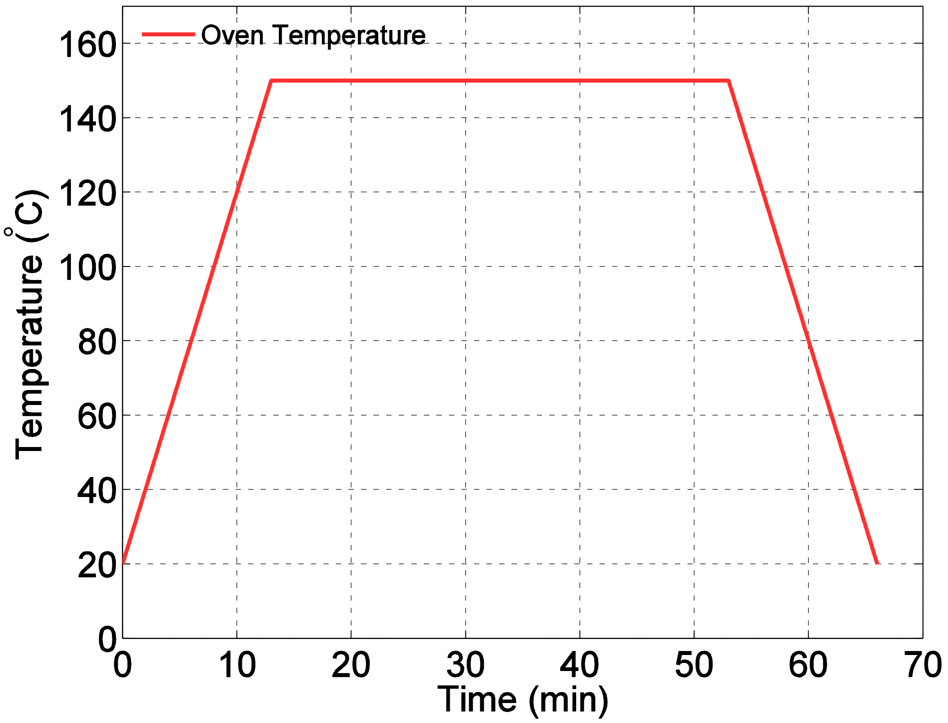

Figure C.1. Proposed oven temperature profile for heat treatment discussed in Section 7.1. This profile assumes an oven capable of a 15°C/min ramp rate.

Appendix D: Budget

Table D.1. Project budget. Note that starred items were obtained at no cost from either Unison or various labs affiliated with the College of Engineering.

Material/Equipment	Vendor	Amount	Unit Cost (USD)	Total Cost (USD)
MP9100 resistor	Digi-Key	1 pc.	10.90	10.90
52In-48Sn solder	IndiumCorp	3 ft	265.00	795.00
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
Thermal contact tape*	eBay	1 spool	4.50	4.50
Machining*	N/A	2 hours	20.00	40.00
Remaining Budget (including starred items):				**-5864.39**
Remaining Budget (excluding starred items):				**1154.10**