SENIOR PROJECT REPORT

MMTEG Heatsink Design

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Statement of Disclaimer

Abstract

In this document, Cal Poly Senior Design Team F16 presents a summary of its work developing a suitable heatsink for Gas Technology Institute's *Methane Mitigation Thermoelectric Generator*. After several months of iterating between experimental testing and simulated heat transfer, a suitable prototype was selected for use in further refining simulation parameters. This was called the *structural* prototype and it allowed Team F16 to confirm several remaining unknowns relating to component thermal conductivity. All documentation of this process can be found in Preliminary, Critical, and Interim Design Review documents (PDR, CDR, IDR), included in this report. Having a realistic model of the system enabled further rounds of simulation to select a heat fin array. This array was then added to the already existing structural prototype along with testing hardware to produce a final *verification* prototype. It performed satisfactorily during the team's experimental testing, per GTI's identified criteria and benchmarks. Team F16 also received sponsor confirmation that these results meet all project requirements. A final design and key recommendations for moving forward into high volume manufacturing are compiled along with this report.

1. Introduction

Cal Poly Senior Design Team F16 has been working with Gas Technology Institute on their *Methane Mitigation Thermoelectric Generator* (MMTEG) Project since the Fall of 2021. Further details on the context of the project are included in the PDR, CDR, and IDR sections of this document. A summary of Team F16's most recent manufacturing and testing efforts are included later in the FDR section. The layout of this document is briefly summarized below:

1) Scope of Work (SOW): Initial alignment with sponsor objective and a summary of the ideation phase. "First pass" models based on patent and market research, applied with engineering intuition. Selection of initial design direction.

2) Preliminary Design Review (PDR): First simulation results using initial design direction. Insights and learnings from this work along with rough manufacturing and testing plans. Initial prototype planning and budgeting.

3) Critical Design Review (CDR): Results from iterative simulation and experimental testing process, used to choose path forward for final prototype. Manufacturing process selection and sponsor alignment on performance criteria.

4) Final Design Review (FDR): Summary of manufacturing including learnings, successes, and failures. Experimental testing results, compared to sponsor-identified criteria. Further recommendations for hand-off and transition to high-volume manufacturing.

PART I - SCOPE OF WORK

MMTEG Heat Sink Design

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1. Executive Summary

Gas Technology Institute is investigating methods of reducing natural gas emissions in transfer stations, pipelines, and other remote infrastructure. Natural gas emissions are significantly more harmful to the environment if the natural gas is not burned before being released into the atmosphere. Existing drainage valve systems and associated actuators are currently powered by pressurized natural gas from the pipeline. After actuating a valve, the natural gas is at low pressure and is not worth adding back to the pressurize pipeline. The low-pressure natural gas is then vented into the atmosphere without combustion. The total impact of the combined venting of all natural gas vent valves in the United States is equivalent to between 3 and 5 million additional cars on the road every year. To combat this issue GTI is replacing natural gas with compressed air as the working fluid in these valves. Thermoelectric generators are heated by burning a smaller portion of natural gas to power air compressors to create a self-sufficient system for remote operations.

2. Introduction

The problem was introduced by Abdelallah Ahmed of the Gas Technology Institute in late 2021 as part of an effort to prepare a new emissions mitigation system for existing gas infrastructure. A group of dedicated Mechanical Engineering students at Cal Poly San Luis Obispo, Team F16, have taken on this challenge to further GTI's initiative. This represents a great example of how the energy sector has slowly been pivoting over the past ten years towards sustainability. Team F16 is excited to join this race for a cleaner future while furthering their knowledge in heat transfer analysis. Within this document we will outline the background research we have done thus far, problem statement, sponsor needs and wants, engineering specifications, project management, and the future deliverables.

3. Background

What is a Heat Sink?

Since the advent of the microprocessor, the need to dissipate excess heat due to inefficiencies in electronic hardware components has been the focus of much heat transfer research. Solutions range from portable units the size of a playing card, to massive units that dwarf their processor as seen in Figures 1 and 2.

Figure 1. A Common Laptop Heatsink Solution. [1]

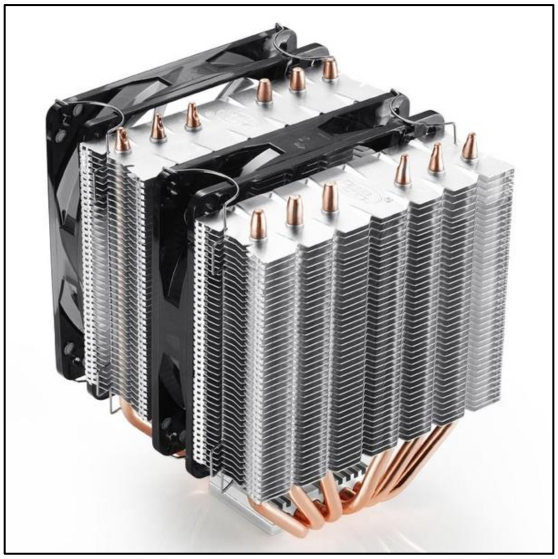


Figure 2. Industrial-Standard Commercial Heatsink. [2]

As water-cooling reaches new levels of popularity in small-scale performance computing applications, top tier air-cooling solutions have mostly become reserved for commercial use [3]. However, in recent years, their versatile size, widespread availability, and high thermal capacity has made air-cooled systems popular for use with thermoelectric generators (TEGs).

The TEG: a Generator the Size of a Computer Mouse

As seen in Figure 3, a TEG is similar in operation to a thermocouple, exploiting the variation in electrical properties of different metals to generate a voltage potential proportionate to an applied temperature gradient. In essence, two nodes will react differently to the same temperature difference (and heat transfer), resulting in a net flow of current [4].

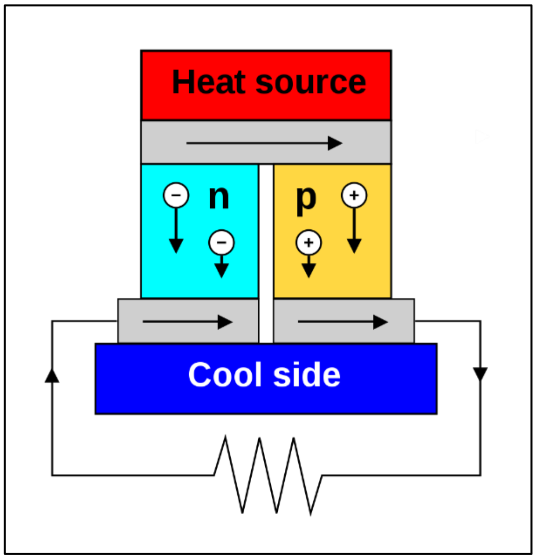


Figure 3. Basic Diagram of TEG Operation. [5]

The benefit of this method of generation is simplicity. Compared to a traditional combustion engine connected to an electrical generator, having no moving parts exponentially reduces opportunities for mechanical failure. The drawback is that a TEG is limited in performance by how large of a temperature gradient may be generated across its two contact surfaces [6].

The high temperature side is more easily regulated, fed by controlled combustion, solar radiation, or other forms of heat generation. Maintaining the cold side temperature, however, is more challenging. Efficiencies of most available TEGs are still well below 10%, meaning that most heat input is passed through the unit and must be dissipated from the cold side [3]. Further complicating matters, most TEG applications are remote and low maintenance, meaning that forced convection or water cooling is not an option [7]. Using a form of thermoelectric cooling would defeat the purpose of the thermoelectric generation. As a result, most TEGs are paired to a high-capacity passive heatsink, like that discussed in the previous section.

Gas Technology Institute: the MMTEG

For over 40 years, major natural gas (methane) infrastructure has built entirely self-sustained extraction sites. Simply put, these “wells” exploit pre-existing pressurized methane in the ground to operate their control system. This control system is used to drain water out of the system that is naturally brought up with the gas. That water gas mixture is naturally at high pressure which can be used to activate valves. However, once the useful pressure has been extracted from the gas, it must be expunged into the atmosphere and replaced with more drawn from the earth. This system is inherently flawed in that it will inevitably waste the methane that is vented into the atmosphere – posing economic and environmental concerns.

Gas Technology Institute, a sustainability nonprofit focused on driving a cleaner energy future, has designed a replacement for this dated control system. Its premise is simple: stop using natural gas as the working fluid of the system as seen in Figure 4. Instead, they propose to bleed a small portion of methane from the extraction, burn it, and use the resulting heat to power TEGs [8]. These TEGs maintain the charge on deep-cycle batteries, which in turn power an air compressor. The system can then use the pressurized air, as it had before with pressurized methane, to activate the drain valves. Called the *MMTEG* (Methane Mitigation Thermoelectric Generator), initial studies indicate that this method will reduce methane emissions by over 99%, with minimal overhead for retrofit compared to other alternatives [3].

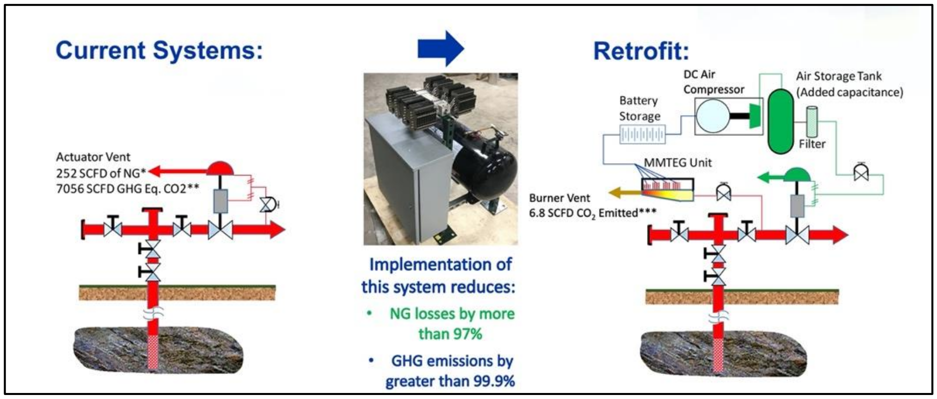


Figure 4. Provisioned Changes to Well Controls & TEG Configuration. [9]

Originally, the heatsinks used for the cold sides of the TEGs were a commercially available, passive unit. Now those have been discontinued. In response, GTI has tasked Team F16 with one goal: work with the Institute's team of engineers to design an in-house replacement that can be produced for their compressed air system.

The original heatsink is shown in Figure 5, below.

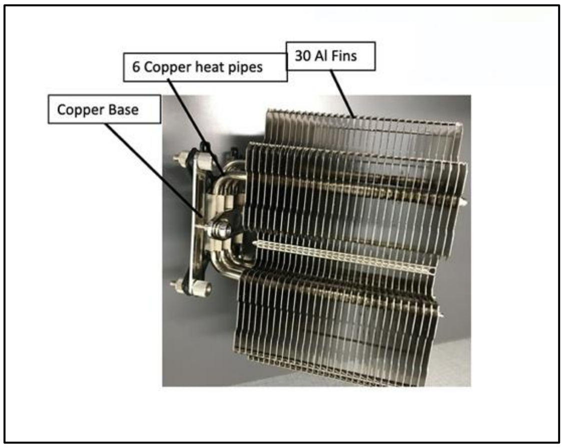


Figure 5. Previously Used Heatsink. [9]

Some simple analysis has been conducted on its performance, which will be used to create targets for Team F16's in-house replacement. See Appendix C for details.

Feedback from our sponsor influenced the scope of the project and solidified several design constraints that set the direction for future efforts. It became evident that the final product must be designed with large scale manufacturing in mind as 40,000 units will be manufactured every year if the design is successful. A set of manufacturing and work instructions will be presented with the final CAD design and associated drawings. This will enable a smooth transition between design by Team F16 and production through a vendor.

3.1 Summary Research Table

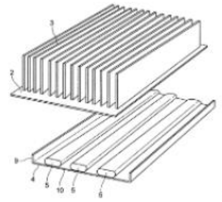
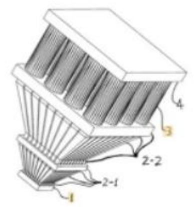
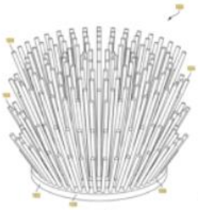
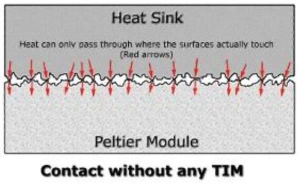
Heat Sink Type	*Examples*	*Comments*
Passive	 [10]  [11]  [12]  [13]  [14]	Heat pipes (shown in the top left image) greatly improve uniform heat distribution through the base of heat sinks. Heat sinks vary in complexity. Added performance must be balanced with additional production costs. Simple flat finned heat sinks can prove cost effective and efficient. Passive heat sinks are simple, durable and require little to no maintenance with no moving parts.
Forced Convection	 [15]  [16]	Forced convection can provide orders of magnitude more heat transfer for a given heat sink. However, the added complexity of moving parts could prove challenging in harsh environments where heat sinks are exposed to the elements.
Miscellaneous	 [17]	This image from Custom Thermoelectric highlights the importance of thermal interface material (TIM). Effective conduction is critical to performance. Machined heat sinks generally are more efficient than composite/assembled alternatives.

Figure 6. Background Product Research.

Other existing products are seen in Figure 6. These vary in size and application, but all fulfill the task of increasing the rate of heat transfer and decreasing the temperature of the electronics.

4. Objectives

4.1 Problem Statement and Boundary Diagram

Gas Technology Institute is looking to mitigate its carbon emissions by replacing methane-driven control valves with a compressed air alternative. However, the thermoelectric generators that will power the system require a better-suited heat dissipation device, since the current option is both being discontinued and is not specifically designed for the application.

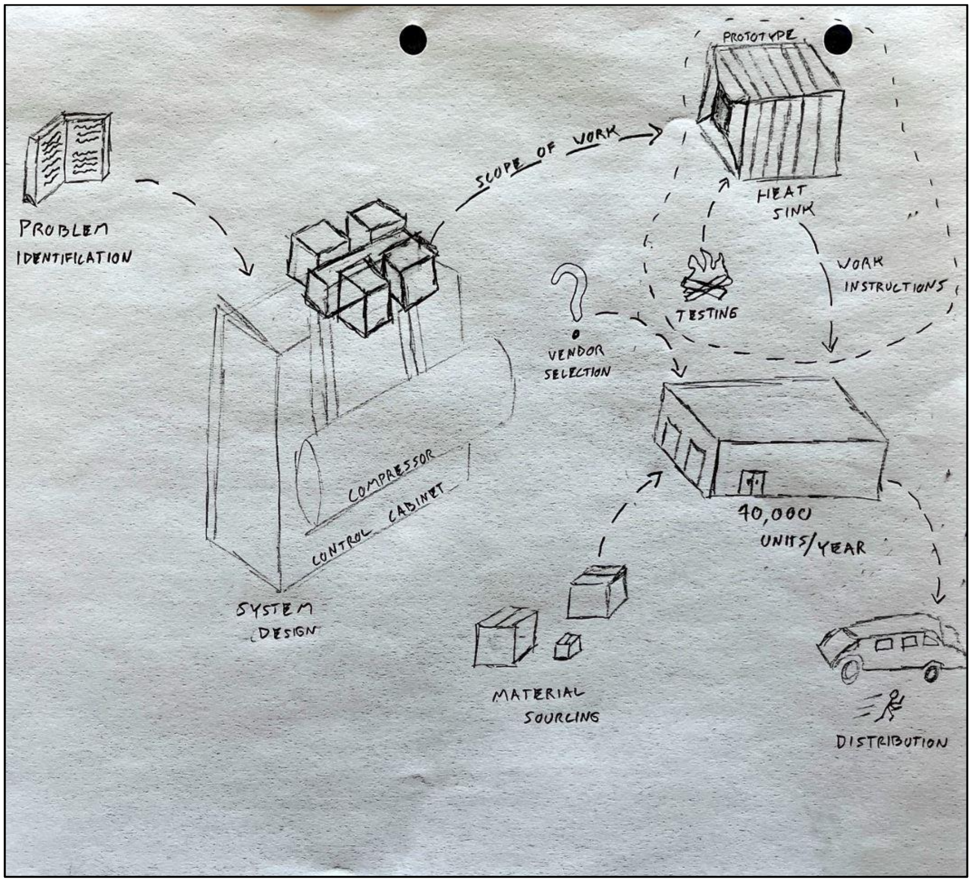


Figure 7. Boundary Diagram. [18]

To further understand the scope of the project, a Boundary diagram was created as seen in Figure 7. A boundary diagram explains the full scale of solving a problem, while specifying the scope to be accomplished. It also can serve to identify stakeholders. We oversee the design and physical prototype of the heat sink as well as a plan for manufacturing.

Continued on next page.

4.2 Needs and Wants Table

Table 1. Needs and Wants of the Customer.

Needs	Wants
Fabrication methods able to handle 40,000 heat sinks a year	Cost to be less than 60-75 dollars
Prototype costs below $2500	New bracket light enough to reduce stresses on existing support
Geometric Limitations (may vary)	Better heat transfer effectiveness
Heat transfer effectiveness equal to Table 2	Tamper-proof
Durable to remain operational in remote outdoor environment (how long and what temp)	
Fit in the geometric space given by GTI	

Table 2. Current Solution Heat Transfer Effectiveness.

Heat Transfer Effectiveness
95 W, 100°C
64W, 64°C
60W, 59°C

4.3 QFD House of Quality

In Appendix A, we attached our Quality Function Deployment which allows us to see what design parameters we need to meet as well to ensure we meet or exceed them. We were able to ensure that the tasks are worthwhile to the consumers and easily testable by using the House of Quality. Within the House of Quality, we identified the customers which included the Gas Technology Institute as well as those manufacturing our product and those onsite using the heat sink. After determining the customers, we created a list of their wants and needs, as seen in Table 1 and referring to Table 2. Using what we learned from our meeting sponsor, we assigned relative weights to the wants and needs which further proved relative importance. Using our background research on other commercially available products, we rated each product on its performance against our customers' wants and needs. Next, we created a list of specifications that correlated with the wants and needs of our customers and looked at the relationship between the specifications and the wants and needs. Lastly, after looking at the strongest relationships between the specifications and wants and needs, we determined engineering targets that we intend to reach in our final product.

The QFD House of Quality ensured that we were designing with the customer in mind and that their needs and wants were at the forefront of the project.

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Below are descriptions of the engineering specifications we determined after communicating with our sponsor and determining what the scope was:

Weight

This product must be shipped from production facilities to remote locations for installation. The heat sinks also must mount to the existing combustion chamber without breaking the assembly, because of this the soft weight limit being set initially by our group is 5lbs.

HT Thermocouple Test

To verify the temperature differential across our prototype a series of thermocouples and an electric heat source will be used to measure the performance of the design. This will help qualify the design as it moves into production.

Measure Dims

Measuring final dimensions in CAD and in the real world from our verification prototype will verify that the product will fit into the existing system.

Duty Cycle Test w/ System

As a means to evaluate performance and lifetime of the proposed solution a verification prototype will be integrated with the final system. Temperatures and power consumption will be measured throughout the test. That data in combination with a post-test evaluation of the system will provide valuable feedback about multi-cycle performance.

Drop Test

In order to ensure that the product will survive the transition between the end of the assembly line and installation in a remote location a series of drop tests should be conducted with the product fully packaged for shipping. This will likely influence packaging solutions more than the final design.

Thermal Simulation

Thermal models of heat sink design iterations will be created and run in Ansys to provide a higher fidelity delta temp estimation than is possible by hand. Books such as the Cal Poly standard heat transfer text [19] contain correlations for multi-fin heat sinks.

Consult with Venders

As the design moves into the late-stage consultation with vendors will ensure that selected design parameters and manufacturing techniques are feasible in for the targeted production volume from available vendors. Resources such as The Machinery's Handbook will also be consulted for manufacturing technique availability [20].

BOM Cost Analysis

Final assemblies and assembly drawings will be used to estimate total costs by adding all components on the BOM. Cost estimation will include raw material, COTS parts, manufacturing cost, and assembly cost.

Compare to Existing Solutions

Background research has already provided insight into existing solutions that will guide ideation and design efforts moving forward.

Consult with Professors

As the team encounters design issues consultation with professors will help overcome roadblocks and tackle unseen design issues before they arise.

Patent/Product Research

Has already been completed by the team. This research serves to provide a foundation of application specific knowledge that will be used to guide future design efforts.

Raw Material Availability

Standard vendors with publicly available online inventory systems (such as McMaster-Carr & Grainger) will be checked to ensure that no items selected for the final design are restrictively difficult to acquire in sufficient volume to satisfy volume requirements.

Work Instructions App. Test

To ensure that work instructions provided with the final product are clear and accurate an application test will be performed. During this test, a technician with relevant skills will be asked to follow the instructions without support from the engineers. Issues and errors made during manufacturing and assembly will be used to adapt and improve the work instructions.

Post Process Test & Sim Data

To get the most out of all the simulations and tests to be performed during this project all associated data must be collected and compiled for comparison and analysis. This process will start at the time of the first test or simulation and will continue through the end of the project.

Repair Procedure Test

After a functional prototype that is representative of the final product has been created a repair procedure for replacement or refurbishment of the product will be created. In order to ensure adequate instructions are provided to the sponsor, a test will be performed during which a simulated repair technician will try to follow the instructions without live support.

Installation Test

A representative functional prototype will be tested with the existing system to ensure seamless integration and adequate performance.

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4.4 Specifications Table

Table 3. Demonstrates the engineering specifications, risks, and methods for compliance pertaining to the scope of the mechanical engineering team.

Spec. #	**Parameter Description**	**Requirement/ Target**	**Tolerance**	**Risk***	**Compliance****
1	Light weight	5 lb	Max	M	I, A
2	Prototype cost	$2500	Max	H	A
3	Heat transfer effectiveness	Seen in Table 2	Min	M	T, A
4	Height	10in	Max	L	I
5	Length	10in	Max	L	I
6	Width	10in	Max	L	I
7	Final product cost	$60-$100	Max	H	A
8	Durable	4 ft drop while in packaging	Max	M	T, A
9	Required maintenance/ How often to replace	1 time/ year	Min	M	I, S

* Risk of meeting specification: (H) High, (M) Medium, (L) Low

**Compliance Methods: (A) Analysis, (I) Inspection, (S) Similarity to existing products, (T) Testing

Within Table 3, we specified which of the parameters are most imperative to complete and how challenging it will be to reach them. High risk specifications for our project include the weight and final cost. Given that the heat sink is made completely out of metal, we need to be weary that as the size of our design increases, the cost also will increase. But given that there is a negative correlation between the heat transfer effectiveness coefficient and both the cost and weight of the heat sink, we need to weigh the benefits and drawbacks of our final design.

The weight is important to the Gas Technology Institute since the heat sink will be attached to a bracket and mounted. Therefore, if the heat sink weighs too much, it will lead to failure in the bracket and it needs to be replaced more often; thus, more site visitations. The cost is also of utmost importance since the Gas Technology Institute wants to manufacture and use 40,000 units a year.

5. Project Management

Our design process will be divided into three distinct phases**: 1) brainstorming / concept ideation, 2) revision and theoretical analysis, and 3) prototyping and testing**.

Below are the three phases, in detail:

1) Brainstorming & Concept Ideation

We will interface with the sponsor to determine existing solutions that have contributed to early project learnings. Then, we will apply our own product and patent research to produce various concepts / ideas on how to improve the existing design. Then, we will interface with sponsor and peers to get additional feedback. After settling on one general idea space, in terms of what the approach to the heatsink is, we can move forward. Because we are relatively constrained on this solution in terms of geometry, material, performance, and cost of manufacturing, we will try to focus a maximum of three design "ideas" to take going forward. Sticky board posters and "brain dump" brainstorming techniques will be used in this early design phase.

- *Key takeaways: we will ideate and find a variety of different approaches to increasing the performance and applicability of existing solution to the problem*

2) Revision and Theoretical Analysis:

Next, finite element analysis and other theoretical methods will be used to build upon the ideas from stage (1). A weighted decision matrix will be pulled in to help evaluate the critical criteria for our designs before we choose one to move forward. The objective here will be to see which approach will be theoretically the most fit to take on to physical manufacturing and testing. Because of the prohibitive cost of tooling for such a complicated workpiece as a heatsink, we will try to focus on one solution before moving forward from this phase. Any issues that come up will be analyzed using Root Cause Analysis techniques, including but not limited to fishbone diagrams and "5-Whys".

- *Key takeaways: narrow down the key designs to one that will be taken forward to prototyping, with ranked alternatives.*

3) Prototyping and Testing:

Taking the design that we narrowed our choices down from in section (2), we will use actual manufacturing techniques to put together a real version of our selected model. Then, we will test it on an actual Thermo-Electric Generator with the help of GTI in their Agoura Hills location. The results of this will be used to evaluate our theoretical analyses used previously. That way, we can move back to our plan B options narrowed in (2), and then do some more "real life" testing on those after using our revised simulation processes.

- *Key takeaways: One final design will be chosen from prototyping and real-application testing. Because the sponsor is looking for a final product that has a manufacturing solution already figured out, we will be looking into vendors and suppliers at this stage as well.*

This process will be managed on a period agreed upon by the group and put into writing via the team Gantt Chart, which is included in Appendix [B].

The following dates for major deliverables, summarized below, will be sourced from the chart. Note that sub deliverables will be included in italics. Other items may be added to this list as the project develops.

Table 4. Future Deliverables and Corresponding Dates.

Targeted Completion	**Deliverable**	**Phase**
10/05/21	Finding 20 Products & Patents (*Initial Research Complete*)	Brainstorming & Concept Ideation
10/15/21	Scope of Work Draft Completion	
10/22/21	Scope of Work Final Draft	
11/1/21	First Concept Sketches of Possible Solutions	Revision & Theo. Analysis
11/7/21	CAD Analysis / Simulations	
11/16/21	Preliminary Design Review / Presentation	
1/15/22	Interim Design Review / Presentation	Prototyping & Testing
2/10/22	Critical Design Review / Presentation	
3/16/22	Verification Prototype Sign-Off	
4/11/22	Test Results of Prototype Delivered	
5/28/22	FDR Report Prepared for Presentation Day (*submitted to sponsor)*	

Further revisions will be made to Table 4, Future Deliverables and Corresponding Dates. This plan will incur revisions after more is known about the product and project layout has been aligned with the sponsor.

6. Conclusion

As an effort to decrease environmental impact from existing natural gas infrastructure, the Gas Technology Institute wanted to design a new heat sink to bolster the operation of a thermo-electric generator well control system. The goal is to design a heat sink that works with the given setup but better suits the needs of the Gas Technology Institute. Cal Poly Senior Project Team F16 has gladly taken on this challenge. To better understand the scope of this project and what we are expected to accomplish upon completion, we have created this document. Our key takeaways from our background research, sponsor meetings, and Quality Function Deployment are as follows. The scope of our project is to back calculate the needed heat transfer to allow for the thermo-electric generators to function, a functional prototype, and a manufacturing plan that will allow for 40,000 heat sinks to be made at a relatively low cost point. We need the sponsor's approval on the scope and upon agreement, we will move forward with ideation, preliminary design, and the conceptual prototype. To accomplish the end goals detailed in the Scope of Work in a timely manner, we are slated to complete the next major deliverables, the Preliminary Design Review (PDR), on November 18th, 2021. In the PDR we will document the selected design direction, explain the most current design, and support it with appropriate engineering evidence. However, as stated above we are first in need of our sponsor's approval or the scope and then the design process can resume.

7. References

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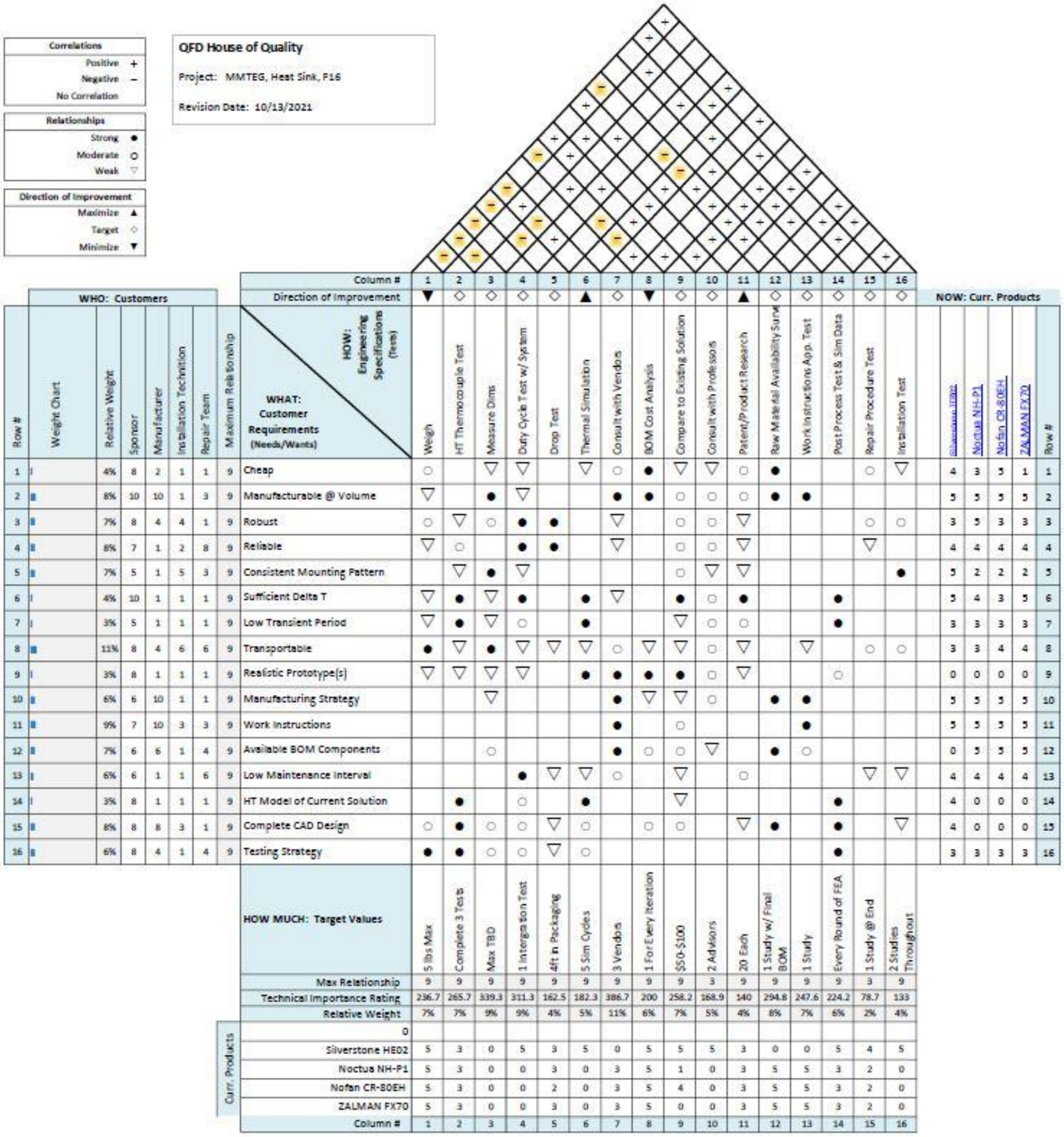
8. Appendices

[A] – Quality Function Deployment (House of Quality)
[B] – (1) Gantt Chart, (2) Gantt Chat, Full Project
[C] – Preliminary Analyses & Benchmarking Results

Appendix A – Quality Function Deployment



Correlations
Positive +
Negative −
No Correlation

Relationships
Strong ●
Moderate ○
Weak ▽

Direction of Improvement
Maximize ▲
Target ◇
Minimize ▼

QFD House of Quality

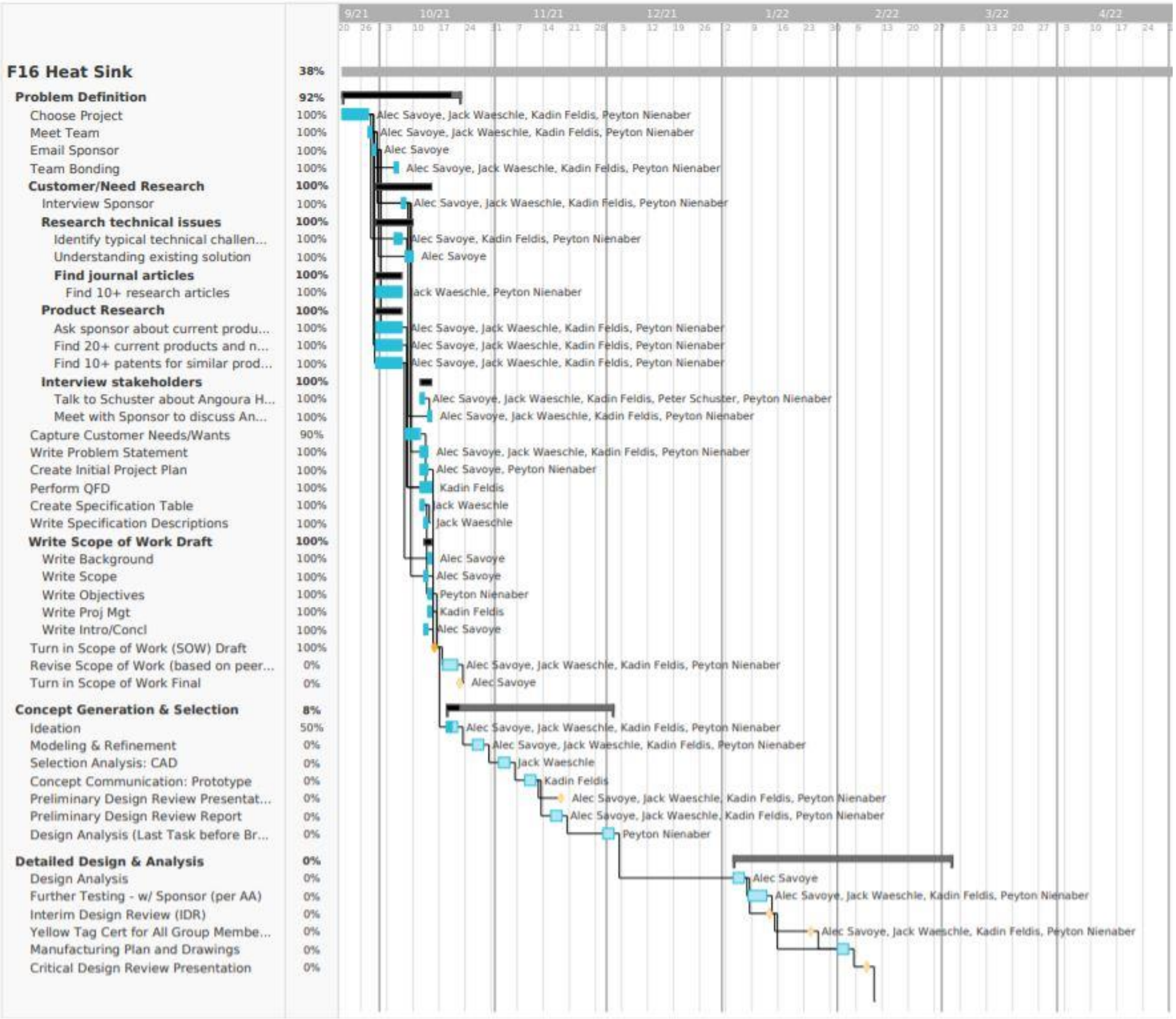
Project: MMTEG, Heat Sink, F16

Revision Date: 10/13/2021

			WHO: Customers																							NOW: Curr. Products				
								Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16						
								Direction of Improvement	▼	◇	◇	◇	◇	▲	◇	▼	◇	◇	▲	◇	◇	◇	◇	◇						
Row #	Weight Chart	Relative Weight	Sponsor	Manufacturer	Installation Technition	Repair Team	Maximum Relationship	HOW: Engineering Specifications (Tests) WHAT: Customer Requirements (Needs/Wants)	Weigh	HT Thermocouple Test	Measure Dims	Duty Cycle Test w/ System	Drop Test	Thermal Simulation	Consult with Vendors	BOM Cost Analysis	Compare to Existing Solution	Consult with Professors	Patent/Product Research	Raw Material Availability Surv	Work Instructions App. Test	Post Process Test & Sim Data	Repair Procedure Test	Installation Test		Silverstone HE02	Noctua NH-P1	Nofan CR-80EH	ZALMAN FX70	Row #
1		4%	8	2	1	1	9	Cheap	○		▽	▽		▽	○	●	▽	▽	○	●			○	▽		4	3	5	1	1
2		8%	10	10	1	3	9	Manufacturable @ Volume	▽		●	▽			●	●	○	○	○	●	●					5	5	5	5	2
3		7%	8	4	4	1	9	Robust	○	▽	○	●	●		▽		○	○	▽				○	○		3	5	3	3	3
4		8%	7	1	2	8	9	Reliable	▽	○		●	●		▽		○	○	▽				▽			4	4	4	4	4
5		7%	5	1	5	3	9	Consistent Mounting Pattern		▽	●	▽					○	▽	▽					●		5	2	2	2	5
6		4%	10	1	1	1	9	Sufficient Delta T	▽	●	▽	●		●	▽		●	○	●			●				5	4	3	5	6
7		3%	5	1	1	1	9	Low Transient Period	▽	●	▽	○		●			▽	○	○			●				3	3	3	3	7
8		11%	8	4	6	6	9	Transportable	●	▽	●	▽	▽	▽	○	▽	▽	○	▽		▽		○	○		3	3	4	4	8
9		3%	8	1	1	1	9	Realistic Prototype(s)	▽	▽	▽	▽		●	●	●	●	○	▽			○				0	0	0	0	9
10		6%	6	10	1	1	9	Manufacturing Strategy			▽				●	▽	▽	○		●	●					5	5	5	5	10
11		9%	7	10	3	3	9	Work Instructions							●		○				●					5	5	5	5	11
12		7%	6	6	1	4	9	Available BOM Components			○				●	○	○	▽		●	○					0	5	5	5	12
13		6%	6	1	1	6	9	Low Maintenance Interval				●	▽	▽	○		▽		○				▽	▽		4	4	4	4	13
14		3%	8	1	1	1	9	HT Model of Current Solution		●		○		●			▽					●				4	0	0	0	14
15		8%	8	8	3	1	9	Complete CAD Design	○	●	○	○	▽	○		○	○		▽	●		●		▽		4	0	0	0	15
16		6%	8	4	1	4	9	Testing Strategy	●	●	○	○	▽	○								●				3	3	3	3	16

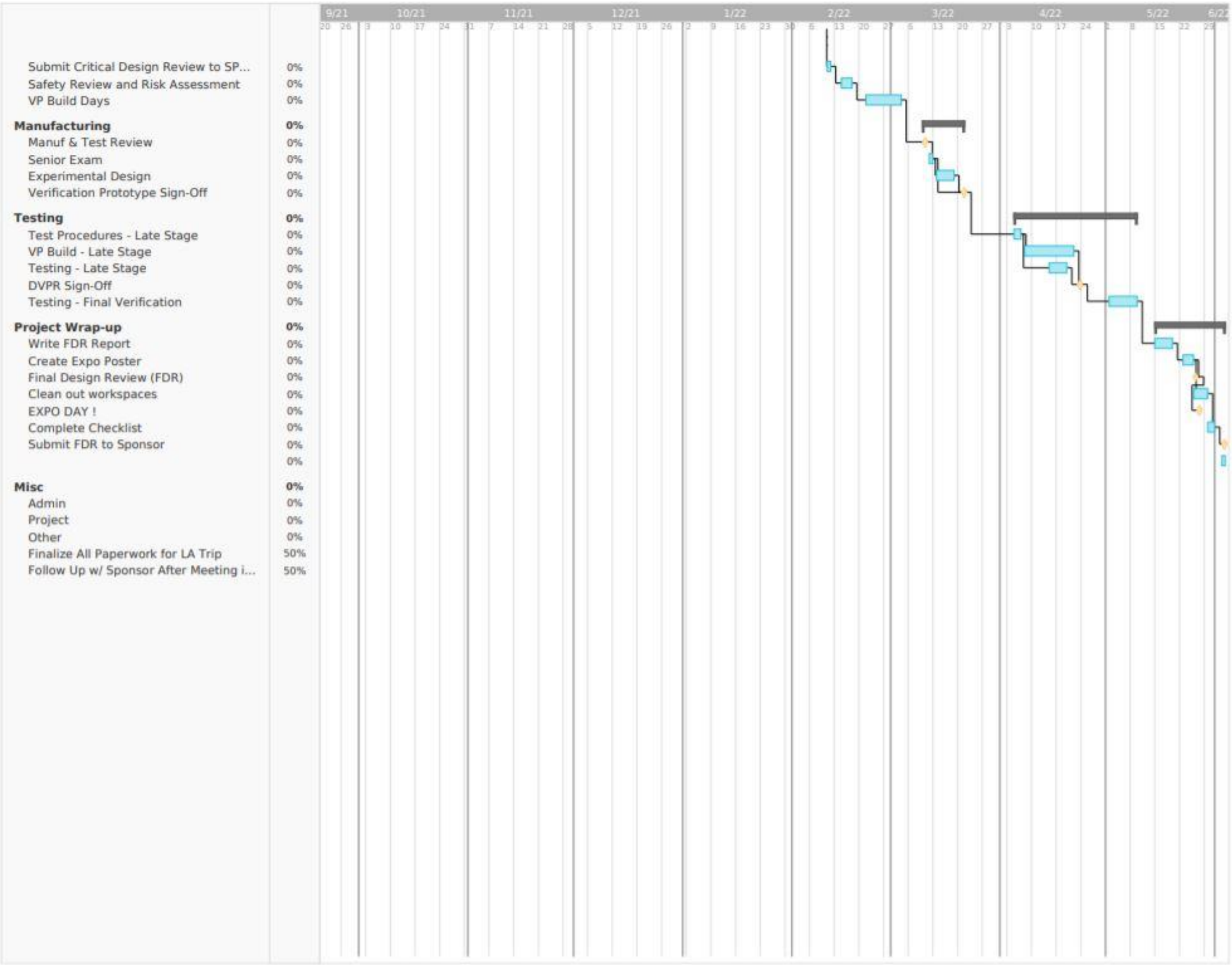
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	HOW MUCH: Target Values	5 lbs Max	Complete 3 Tests	Max TBD	1 Intergration Test	4ft in Packaging	5 Sim Cycles	3 Vendors	1 For Every Iteration	$50-$100	2 Advisors	20 Each	1 Study w/ Final BOM	1 Study	Every Round of FEA	1 Study @ End	2 Studies Throughout
	Max Relationship	9	9	9	9	9	9	9	9	9	3	9	9	9	9	3	9
	Technical Importance Rating	236.7	265.7	339.3	311.3	162.5	182.3	386.7	200	258.2	168.9	140	294.8	247.6	224.2	78.7	133
	Relative Weight	7%	7%	9%	9%	4%	5%	11%	6%	7%	5%	4%	8%	7%	6%	2%	4%
Curr. Products	0																
	Silverstone HE02	5	3	0	5	3	5	0	5	5	5	3	0	0	5	4	5
	Noctua NH-P1	5	3	0	0	3	0	3	5	1	0	3	5	5	3	2	0
	Nofan CR-80EH	5	3	0	0	2	0	3	5	4	0	3	5	5	3	2	0
	ZALMAN FX70	5	3	0	0	3	0	3	5	0	0	3	5	5	3	2	0
	Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

Appendix B1 – Gantt Chart (Q1, Sep 21 – Dec 21)



F16 Heat Sink	**38%**	
Problem Definition	**92%**	
Choose Project	100%	Alec Savoye, Jack Waeschle, Kadin Feldis, Peyton Nienaber
Meet Team	100%	Alec Savoye, Jack Waeschle, Kadin Feldis, Peyton Nienaber
Email Sponsor	100%	Alec Savoye
Team Bonding	100%	Alec Savoye, Jack Waeschle, Kadin Feldis, Peyton Nienaber
Customer/Need Research	**100%**	
Interview Sponsor	100%	Alec Savoye, Jack Waeschle, Kadin Feldis, Peyton Nienaber
Research technical issues	**100%**	
Identify typical technical challen...	100%	Alec Savoye, Kadin Feldis, Peyton Nienaber
Understanding existing solution	100%	Alec Savoye
Find journal articles	**100%**	
Find 10+ research articles	100%	ack Waeschle, Peyton Nienaber
Product Research	**100%**	
Ask sponsor about current produ...	100%	Alec Savoye, Jack Waeschle, Kadin Feldis, Peyton Nienaber
Find 20+ current products and n...	100%	Alec Savoye, Jack Waeschle, Kadin Feldis, Peyton Nienaber
Find 10+ patents for similar prod...	100%	Alec Savoye, Jack Waeschle, Kadin Feldis, Peyton Nienaber
Interview stakeholders	**100%**	
Talk to Schuster about Angoura H...	100%	Alec Savoye, Jack Waeschle, Kadin Feldis, Peter Schuster, Peyton Nienaber
Meet with Sponsor to discuss An...	100%	Alec Savoye, Jack Waeschle, Kadin Feldis, Peyton Nienaber
Capture Customer Needs/Wants	90%	
Write Problem Statement	100%	Alec Savoye, Jack Waeschle, Kadin Feldis, Peyton Nienaber
Create Initial Project Plan	100%	Alec Savoye, Peyton Nienaber
Perform QFD	100%	Kadin Feldis
Create Specification Table	100%	ack Waeschle
Write Specification Descriptions	100%	Jack Waeschle
Write Scope of Work Draft	**100%**	
Write Background	100%	Alec Savoye
Write Scope	100%	Alec Savoye
Write Objectives	100%	Peyton Nienaber
Write Proj Mgt	100%	Kadin Feldis
Write Intro/Concl	100%	Alec Savoye
Turn in Scope of Work (SOW) Draft	100%	
Revise Scope of Work (based on peer...	0%	Alec Savoye, Jack Waeschle, Kadin Feldis, Peyton Nienaber
Turn in Scope of Work Final	0%	Alec Savoye
Concept Generation & Selection	**8%**	
Ideation	50%	Alec Savoye, Jack Waeschle, Kadin Feldis, Peyton Nienaber
Modeling & Refinement	0%	Alec Savoye, Jack Waeschle, Kadin Feldis, Peyton Nienaber
Selection Analysis: CAD	0%	Jack Waeschle
Concept Communication: Prototype	0%	Kadin Feldis
Preliminary Design Review Presentat...	0%	Alec Savoye, Jack Waeschle, Kadin Feldis, Peyton Nienaber
Preliminary Design Review Report	0%	Alec Savoye, Jack Waeschle, Kadin Feldis, Peyton Nienaber
Design Analysis (Last Task before Br...	0%	Peyton Nienaber
Detailed Design & Analysis	**0%**	
Design Analysis	0%	Alec Savoye
Further Testing - w/ Sponsor (per AA)	0%	Alec Savoye, Jack Waeschle, Kadin Feldis, Peyton Nienaber
Interim Design Review (IDR)	0%	
Yellow Tag Cert for All Group Membe...	0%	Alec Savoye, Jack Waeschle, Kadin Feldis, Peyton Nienaber
Manufacturing Plan and Drawings	0%	
Critical Design Review Presentation	0%	

Appendix B2 – Gantt Chart (Q1, Sep 21 – June 22)/



Submit Critical Design Review to SP...	0%
Safety Review and Risk Assessment	0%
VP Build Days	0%
Manufacturing	**0%**
Manuf & Test Review	0%
Senior Exam	0%
Experimental Design	0%
Verification Prototype Sign-Off	0%
Testing	**0%**
Test Procedures - Late Stage	0%
VP Build - Late Stage	0%
Testing - Late Stage	0%
DVPR Sign-Off	0%
Testing - Final Verification	0%
Project Wrap-up	**0%**
Write FDR Report	0%
Create Expo Poster	0%
Final Design Review (FDR)	0%
Clean out workspaces	0%
EXPO DAY !	0%
Complete Checklist	0%
Submit FDR to Sponsor	0%
	0%
Misc	**0%**
Admin	0%
Project	0%
Other	0%
Finalize All Paperwork for LA Trip	50%
Follow Up w/ Sponsor After Meeting i...	50%

Appendix C – Rough Heat Transfer Analysis on Existing Heatsink

Abdelallah Ahmed of Gas Technology Institute has performed some simple 1-dimensional numerical analysis on a rough performance model of the existing heatsink depicted in Figure 5 (see report body). The results have yielded performance metrics that will be used as objectives for future designs. Included below, in Figures C-1 and C-2, is a clipping that was provided to Team F16, for the reader's reference:

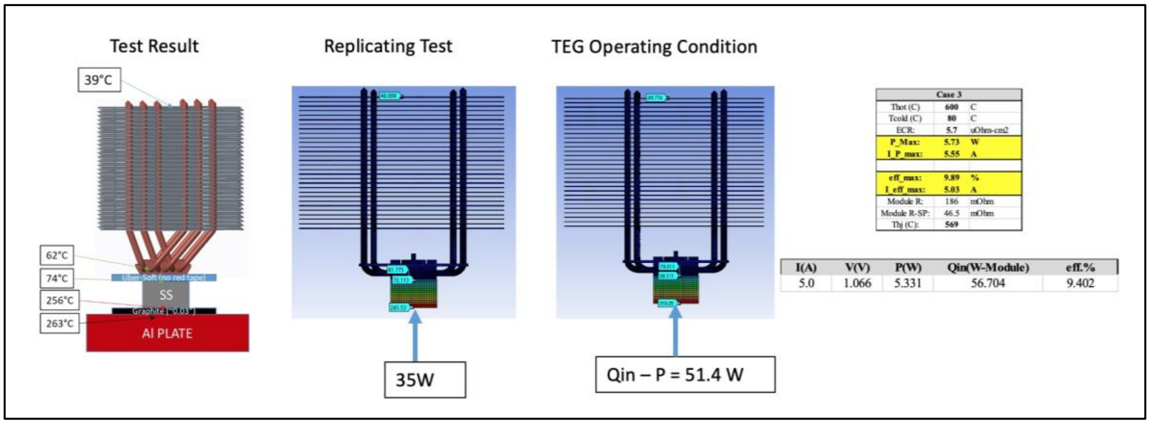
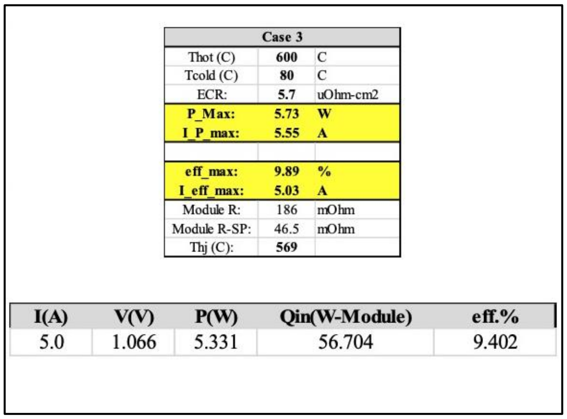


Figure C-1. Analysis of Discontinued Heatsink (Model) [6].

Inspection of Figure 5 reveals some insight into manufacturing heatsinks for low-cost applications. Note the use of closed-system condensation/evaporation heat pipes and relatively cheap assembly. Spacing of fins is also simply achieved via metal strips that can hold punched-out metal plates in place. This will serve as a basis for cheap manufacturing techniques moving forward.



Case 3		
Thot (C)	600	C
Tcold (C)	80	C
ECR:	5.7	uOhm-cm2
P_Max:	5.73	W
I_P_max:	5.55	A
eff_max:	9.89	%
I_eff_max:	5.03	A
Module R:	186	mOhm
Module R-SP:	46.5	mOhm
Thj (C):	569	

I(A)	V(V)	P(W)	Qin(W-Module)	eff.%
5.0	1.066	5.331	56.704	9.402

Figure C-2. Analysis of Discontinued Heatsink (Results) [6].

It should be noted that this analysis also encompasses the thermoelectric generator (TEG) efficiency. This data is slightly out of date, however, as it was based on technology available from a joint project with the aerospace private sector. The TEG that will be implemented into the MMTEG product is slightly less efficient, with the range of operation efficiencies spanning from 3 to 5%.

More detailed analysis will be conducted further into the project. The intention of this appendix is only to give context to this later work.

PART II - PRELIMINARY DESIGN REVIEW

MMTEG Heat Sink Design

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Nov. 12, 2021

Abstract

Since October of 2021, Team F16 has been working with Gas Technology Institute (GTI) to design a heatsink that can replace an existing commercial unit currently that is being phased out. At the time of this document's release, research and ideation has been performed, as well as qualitative testing to narrow the breadth of designs being considered. Several important conclusions have been gathered that will help lay the foundation for quantitative testing. First, it appears that the existing design paradigm of dissipating fins and heat pipes (i.e. "passive" cooler) in a rectangular prism shape will be the best suited for a balance of all design priorities. Considering overall project time frame through its various phases, the main objective will be to design, test, and coordinate with manufacturing on a first "iteration" of a potential replacement heatsink. This linear approach will allow GTI to complete development of related components – combustion chamber, control system, and structure – in parallel. On a technical level, geometric and performance constraints will be prioritized along with per-unit cost to generate the best possible solution. That solution has been identified and plans to move forward have been laid out. These ideas are divided into concrete steps and deliverables throughout this document.

Table of Contents

1. Introduction

Gas Technology Institute (GTI) presented the problem of developing a heatsink for their innovative *Methane Mitigation Thermoelectric Generator* (MMTEG) to Team F16 in late October of 2021. The project, aimed to prevent excess emissions of harmful greenhouse gases from methane well control systems, is in a key phase of its development. The system functions by bleeding a small amount of the methane being drawn from the ground and burning it in a small combustion chamber. Several thermoelectric generators (TEGs) then extract the thermal energy from this process and produce electricity, which in turn powers the control system. A TEG's operation is similar to that of a thermocouple, generating an electrical potential proportional to a temperature differential across its surfaces. Though the details of that phenomena are beyond the scope of this document, they can be found in Reference [1]. See Figure 1 below for a simple schematic of an example TEG / heatsink configuration:

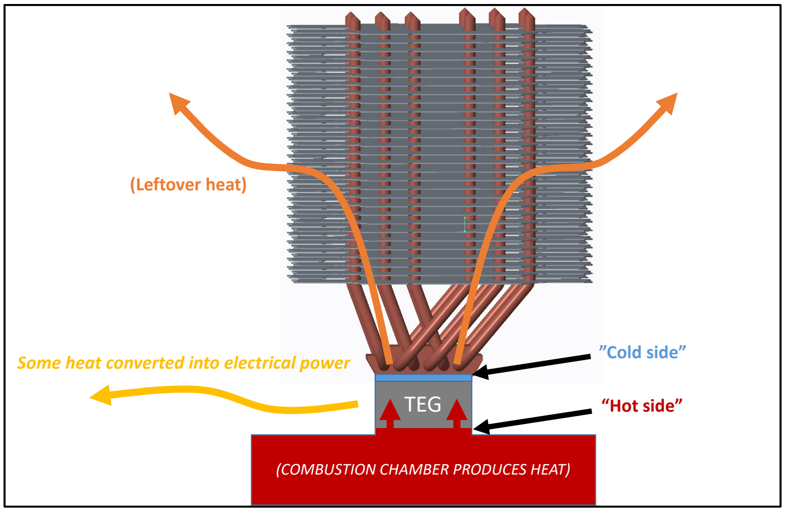


Figure 1. Distribution of Heat through TEG Unit & Role of Heatsink [2].

Inspection of Figure 1 above shows that a thermoelectric generator only converts some of the total thermal energy input from the combustion chamber into usable electrical energy. In fact, this efficiency can be quite low – on the order of 4 to 5% of the total heat input [3]. The result is that the remaining unused or "leftover" heat must be dissipated in order to maintain a temperature differential (and thus heat flow through the TEG!) The unit above is enlarged for clarity; in reality, a typical TEG is very thin (on the order of 0.25"). The result of this is that excess energy can only be removed via conduction through the "cold side". A heatsink is the natural solution to this problem, and the more effective it is as dissipating leftover heat, the more power can be drawn through and from its thermoelectric generator. Specifications for temperature differentials at various rates of heat input were provided by the sponsor early in the design process. These were used along with geometric constraints to determine the best direction for a possible heatsink solution.

Since the release of its original Scope of Work document, Team F16 has since identified several possible designs that fit the criteria and constraints defined in preliminary analysis. Conversations with GTI stakeholders along with controlled convergence ideation methods produced a "best" viable concept that will drive further prototyping and testing. The details of this concept, as well as the process described above, are provided in the following sections:

1) Concept Development: A summary of Team F16's "top" initial designs, as well as how they were generated, ranked, and compared against each other based on criteria derived from project objectives.

2) Concept Design: A description of the chosen "best" design, with key details such as geometric parameters, performance goals and CAD / detail views

3) Concept Justification: An engineering perspective on the "best" design, built on the team's learnings so far. This includes research into related technology and existing solutions, preliminary analyses, as well as other work that led to the selection of this design. Future considerations, like potential risks associated with the design and its testing, are also highlighted.

4) Project Management: A clear path for the project going forward from where it stands at the time of this document's release, to the Critical Design Review phase. This includes a detailed breakdown of the associated tasks, responsibilities and materials needed for analysis, testing, and evaluation of the chosen "best" concept.

5) Conclusion: An overview of implications of what has been discussed in sections (1) through (4) and the next steps in this design process.

2. Concept Development

Team F16's first steps after project assignment were to get a better understanding of sponsor objectives for the project and how those related to possible future heatsink designs. This was done as described in previous team documentation. Existing technologies and stakeholder concerns were then consolidated into a "House of Quality", a common Quality Function Deployment (QFD) strategy. See Appendix A for the details of this work.

The results, in turn, framed a "Functional Decomposition" of key design considerations, from which hundreds of simple ideas were generated. These can be found in Appendix B. Combinations of these simple ideas were used to create physical concept models that were compared to the geometry of GTI's existing combustion chamber. In order to come up the simple ideation models mentioned above, we engaged in ideation activities such as brain-walking, brainstorming, and brain writing. Using household items such as hot glue, foam board, and cardboard, we were able to come up with over 20 ideation models which led to new ideas about how to get configure the heat sinks in the most cost efficient and best performance manner. See Appendix C for views of the simple models with some details and commentary.

These new geometric learnings were brought in parallel with performance, cost, and system-level criteria introduced by the sponsor to generate a series of "top" ideas, the 5 most-suitable of which are detailed in subsequent sections.

2.1 Top 5 Heatsink Designs

Not ordered to show any preference. See sketches / pictorials of each top concept in Figures 2 through 6, below. Appendix C shows physical ideation models that inspired those sketched in this section.

A. <u>Lower-Cost Derivative of Existing</u>

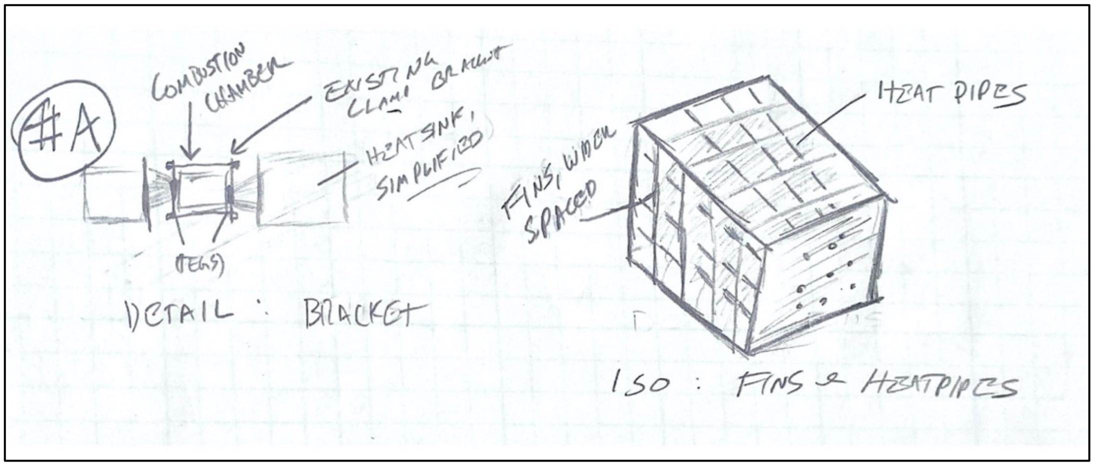


Figure 2. “Top” Concept #A

While considering possible heatsink concepts, it was important for Team F16 to acknowledge that the existing solution in use by GTI is already very effective. The main driver for its replacement, in fact, is not its performance. The main issues are its accessibility and cost. Since creating an in-house solution would already greatly improve on the prior solution, the focus of this concept was to optimize for the latter. Based on industry research, it was not unreasonable to expect a unit of similar geometry and material composition to match the performance of the existing heatsink. Concept #A focuses on doing so, while reducing unnecessary costs. This would include reducing the number of heat-dissipating plates, sourcing cheaper heat pipes, and making a simpler mounting bracket that would require less hardware. The reduction in the total number of plates would be achieved by replacing the closest plate to the combustion chamber with a thicker – slightly insulated – piece, preventing stray heat transfer to the heatsink.

A.5. Horizontally Extended Derivative of Existing

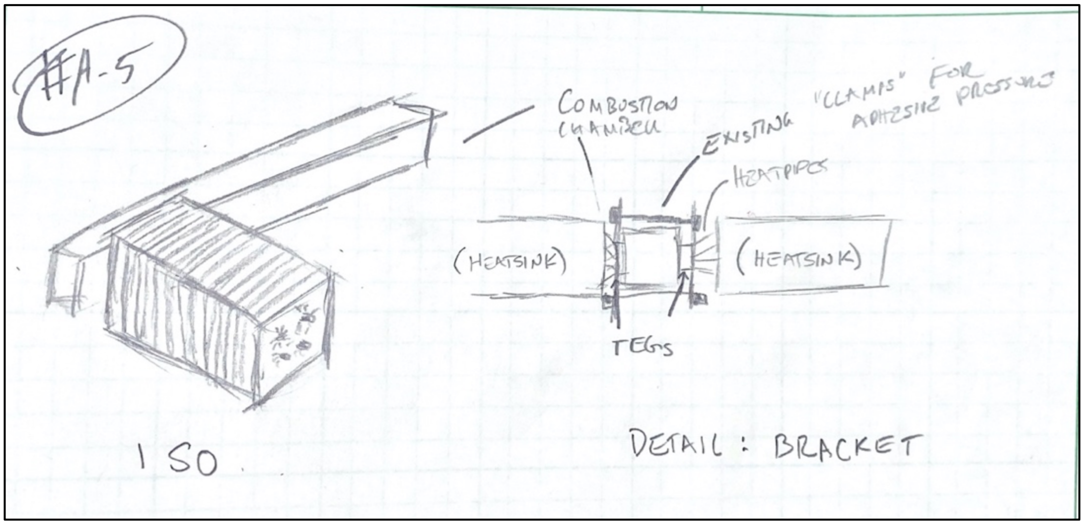


Figure 3. "Top" Concept #A.5

One guideline from the sponsor was clear: while the bottom line is to match the specifications of the existing configuration, modifications that could help increase performance aren't off the table. The only reason that GTI's current heatsink isn't larger is the fact that it was a commercially available unit, limited in size to fit inside a standard commercial computer casing. This fact inspired one potential concept for the new design – a unit with identical geometry to the existing in two directions, while being longitudinally extended away from the combustion chamber body. This would minimize impacts on the system-level design by maximizing geometric compatibility (mounts, etc.), while still yielding a potential increase in heat transfer capacity. A higher heat transfer capacity means a lower cold side temperature on the TEG for a given heat input, creating a higher temperature differential and greater electrical power output per generator. See the introduction for more details on these behaviors of a thermoelectric generator.

B. Multi-TEG "Centralized" Heatsink

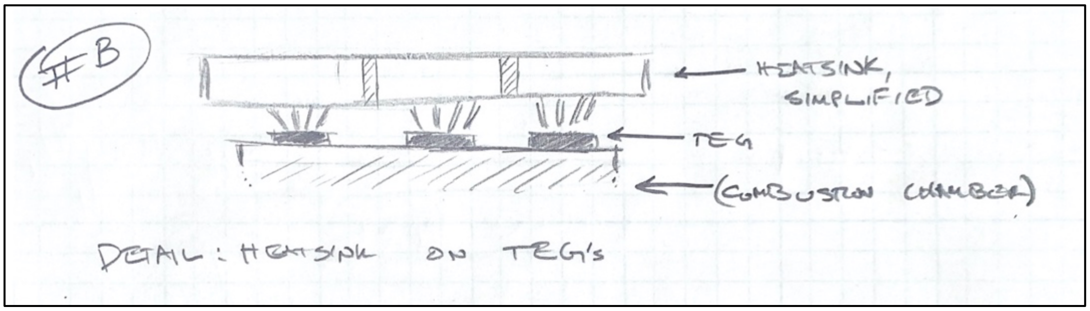


Figure 4. "Top" Concept #B

GTI currently employs one heatsink for every TEG, resulting in 4-6 heatsinks per full MMTEG apparatus, depending on its configuration. This configuration has two major implications. The first relates to scalability; with an objective of 10,000 MMTEGs shipping, that makes for 40,000 to 60,000 units being produced. All of these require their own discrete hardware and installation, increasing cost and time required for a given unit. The second is a performance concern – some heat dissipating surface area is inherently lost between each individual heatsink. Connecting one side of the combustion chamber to one "centralized" unit addresses these concerns. In addition to simplifying assembly and manufacturing, it would allow for some gains in terms of overall heatsink volume for a given number of TEGs (see cross-hatched area in figure above.) One design consideration that makes this unfavorable is that the modularity of single heat sink allows for the combustion chamber to be modified without a whole new heat sink design.

C. Vertically Extended Derivative of Existing

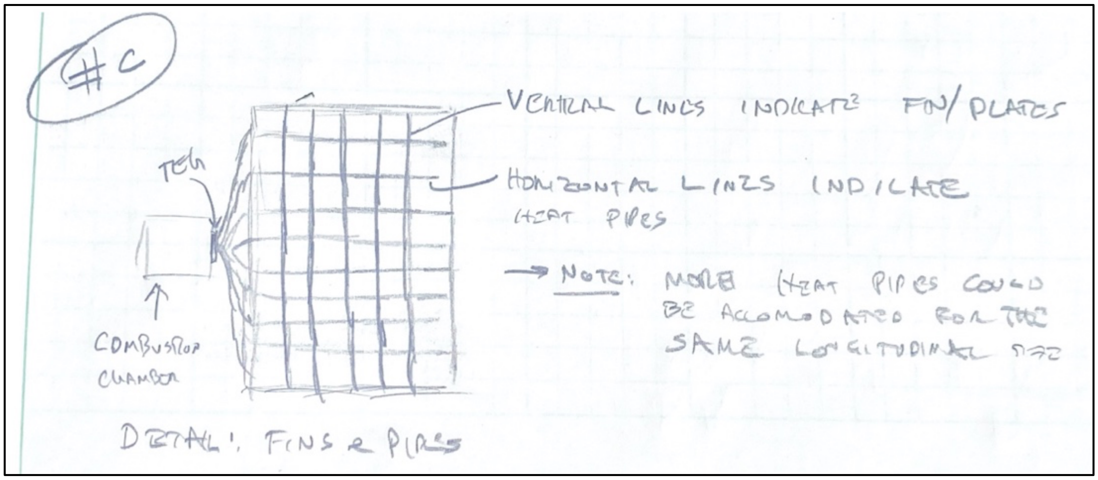
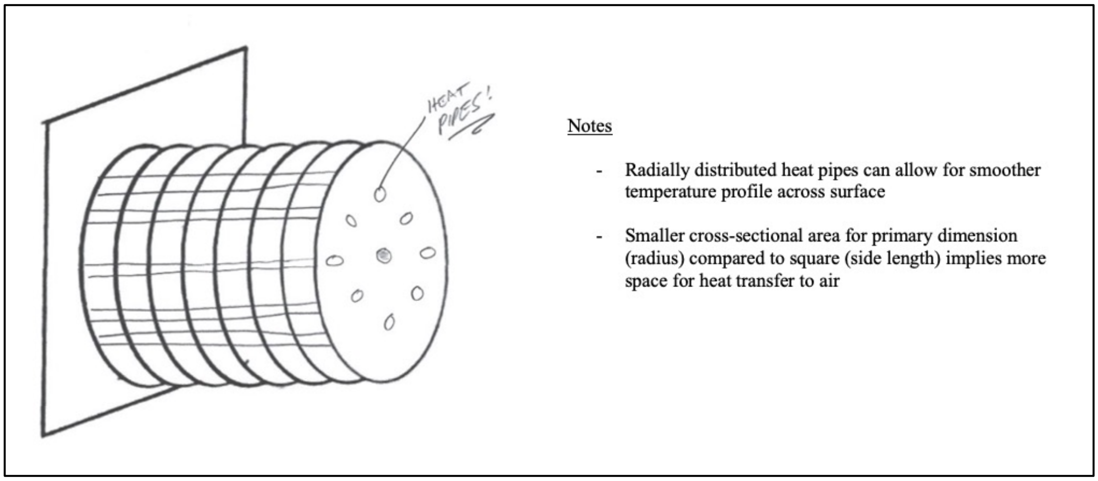


Figure 5. "Top" Concept #C

This concept is comparable to #A.5, pictured in Figure 5 that it intends to maintain a similar mounting scheme to the existing heatsink being used by GTI. The premise is that, rather than leveraging more total plates, this will try to fit more heat pipes vertically. In other words, two dimensions are still constrained to that of the original heatsink, but now the height is being modified instead of the longitudinal size away from the combustion chamber. Since the heat pipes are the primary vessels through which heat is transferred, the idea here is to maximize how many could be used for the same number of plates. A larger plate, with its larger surface area, should be able to accommodate this increased number of pipes. Although this design is relatively unproven compared to others, research into different heatsink designs suggests there is potential for a performance gain here.

D. Cylindrical Body



Notes

- Radially distributed heat pipes can allow for smoother temperature profile across surface
- Smaller cross-sectional area for primary dimension (radius) compared to square (side length) implies more space for heat transfer to air

Figure 6. "Top" Concept #D

Later in the ideation process, it was clear that there was a certain bias towards rectilinear geometry. This was attributed to the prevalent design language in most existing heatsinks being either rectangular or square in nature. Concept #D, pictured above, intends to explore alternatives, such as a cylindrical prism. One unexpected discovery was that this may enable a more even distribution of heat pipes through the cross-section of a given plate, resulting in a better heat flow distribution through the plate. "Hot spots", according to preliminary research, can form in certain right-angle geometries and greatly reduce the heat transfer efficiency of a given material, despite high thermal conductivity [4].

2.2 Choosing a Design Direction

Having identified these five "top" concepts, several methods were used to further refine design options. The full Pairwise Comparison (PC) and Weighted Decision Matrix (WDM) are included in Appendix D, and their role in the design process is summarized below.

Customer constraints and criteria were pulled from the QFD House of Quality created previously (see Appendix A). Each concept was then compared to all others to determine relative weights for each criterion. These results were inputted into a the WDM, where each design's score was calculated. The final outcomes of this process are included in Appendix D and intermediary Pugh Matrices utilized to select top ideas for WDM can be found in Appendix E.

Although appropriate measures were taken to avoid biases against one idea or another, the outcomes of this analysis weren't very surprising. The Cylindrical Body (D) had interesting potential for improved performance but suffered in more practical fields like development costs and hardware incompatibilities. Likewise, the Multi-TEG system (B) presented opportunities to optimize the existing system but was not selected because of potential mounting incompatibilities. The Heat Shielded / Lower-Cost concept closely matched its Vertically Extended (C) and Longitudinally Extended (A.5) counterparts but lost in performance to both. Between the top two, Vertically and Longitudinally Extended, the latter edged out in terms of performance.

In short, the design chosen moving forward is a Concept A.5, a longitudinally extended derivative of the existing heatsink being used by GTI. It ultimately won out as compatibility, cost, and simplicity of development became much more important considerations than originally anticipated before performing a pairwise comparison analysis. A.5 appears to balance these criteria with a slight "bonus" increase in performance, as well.

Further revisions will focus on optimizing (performance vs cost, etc.) upon all of these parameters, while coordinating with the sponsor on overall design objectives as necessary. It is possible that certain design elements from other concepts are combined with the core layout of A.5 if doing so helps enable better performance.

3. Concept Design

Our chosen concept design features heat tubes and plates, similar to the existing model, but extended further away from the combustion chamber with added vertical height. These modifications are intended to increase surface area and improve the temperature differential across the thermoelectric generator, increasing the power output. These modifications will have to be optimized with computer simulations (ANSYS) or other testing metrics, as the additional size and material adds cost to the heat sink. Parameters to optimize for heat dissipation include fin shape, spacing between fins, and number of fins, all while maintaining reasonable manufacturability, cost and performance.

Figure 7 and Figure 8 below show our initial CAD model, featuring additional fins, height and length. This design also only utilizes three heat pipes. ANSYS simulations will aid in determining if this number of heat pipes is adequate to insure appropriate heat distribution throughout the fins.

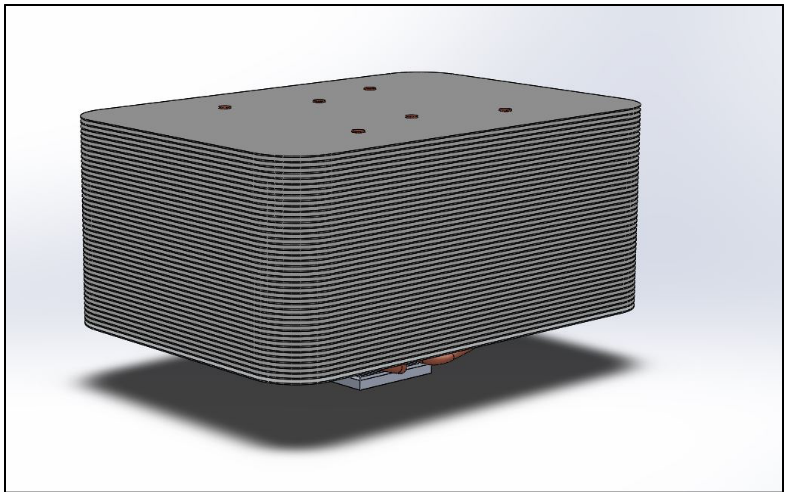


Figure 7. Heat sink concept isometric. Fin volume of 10x7x5in.

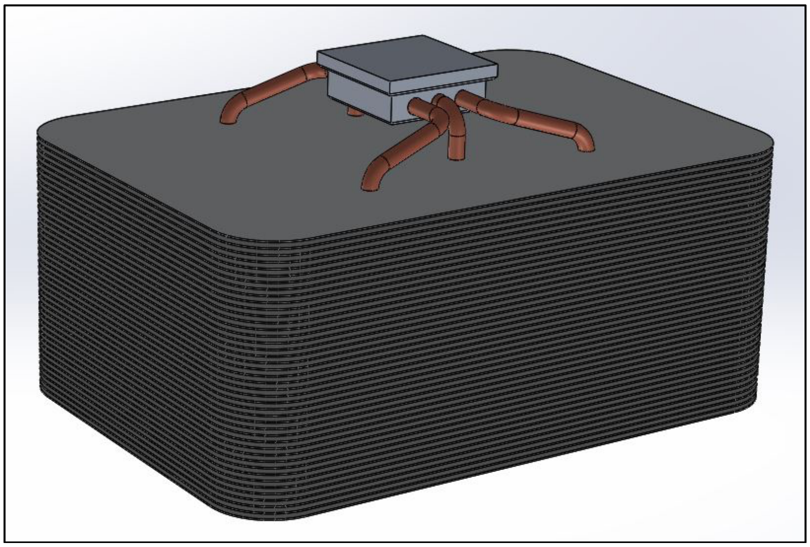


Figure 8. Heat sink concept isometric. Three discrete heat pipes. 2x2in contact patch. Mating system and geometry TBD.

Our concept prototype is focused on developing a reliable testing procedure and apparatus. It consists of a hot plate, a piece of metal to stand in for our heat sink, and thermocouples to measure both the temperature of the hot plate and temperature(s) of/throughout our heat sink model. This apparatus can be used to test our future heat sink prototype in a variety of ambient conditions, such as direct sunlight, shade, wind, and multiple air temperatures. These data will give us a more complete understanding of our prototypes, strengths and shortcomings and provide opportunities for further improvement.

We plan to use copper heat pipes, as these are widely available and effective for distributing heat through our heat sink. As with the existing design, these heat pipes provide structural support for the fins. During manufacturing, fins will be cut or punched out from sheet metal (likely steel) and brazed onto the heat pipes. To provide additional structural integrity, we intend to replicate the spacing tabs featured on the existing design, consisting of a strip of material with regular bent in tongs that are brazed to the edge of the fins. See Figure 9 below.

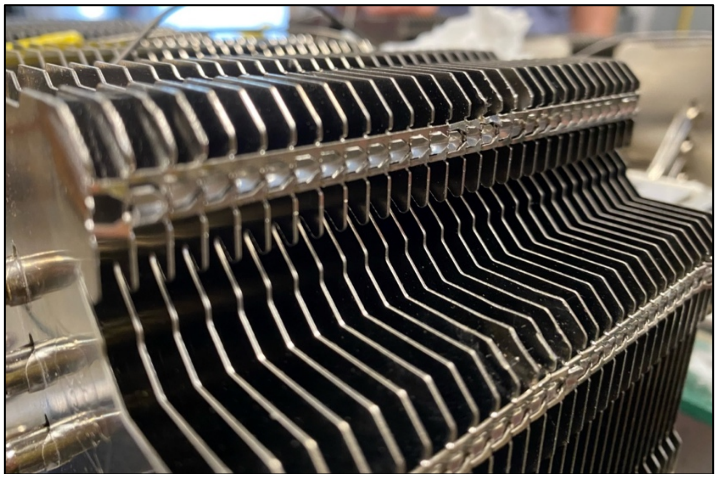


Figure 9: Close up view of existing heat sink structural design, featuring tong like strips of aluminum adhered to outer edge of fins, providing additional structure, and maintaining regular spacing between fins.

As discussed above, our heat sink geometry is subject to change, as we intend to iterate multiple times to optimize fin shape, spacing, number of heat pipes, their location, length, and size while maintaining a competitive price point. Our width is generally limited to seven inches, as this is the minimum spacing between TEGs for the combustion chamber to provide adequate heat, but the height and length away from the combustion chamber is still in flux. We believe a rectangular fin shape will best utilize the available space and maximize fin surface area.

One idea for optimizing the solution and using the energy in the system to further the heat transfer is to use the excess compressed air from valve motion and push it over the heat sinks to capitalize on the added heat transfer that comes from forced convection or free convection [5]. This is something we want to look at more and potentially propose to GTI since it would be a design change implemented on the system rather than just the heat sinks.

4. Concept Justification

This section intends to provide the engineering judgment that led to selection of the "best" design as described in the previous section. For convenience, this has been broken down into sub-topics that aim to address several aspects of the issue.

4.1 Engineering Judgement with Sponsor Input

GTI's previous design of their combustion chamber used commercially available heat sinks as shown in Figure 10.

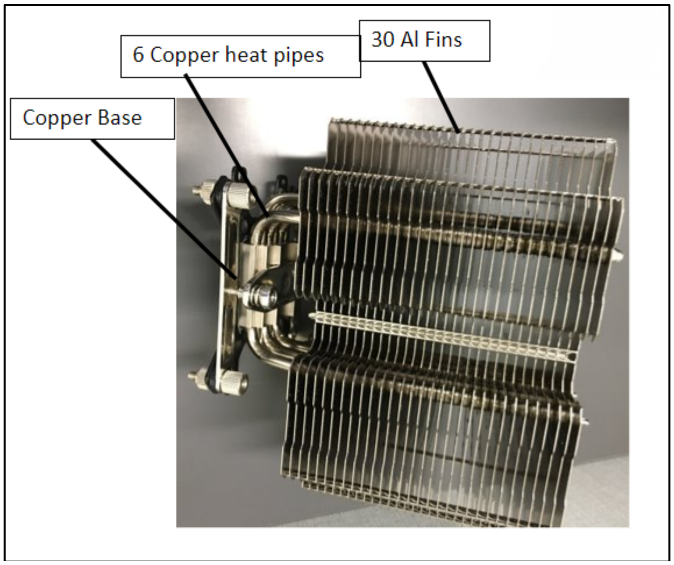


Figure 10. Commercially available heat sink previously used in the MMTEG configuration by GTI.

The design shown in Figure 10 was tested by GTI and resulted in the data seen in Table 1.

Table 1. Heat sink performance for the model used previously by GTI. [2]

Cold Side Temperature, [°C]	Power Dissipated [W]
100	95
64	64
59	60

These preliminary numbers were also confirmed with manufacturers of the existing heatsink and compared against other sources, provided during the interview captured in Reference [5]. These will be the performance specifications targeted by new designs, and in preliminary research this was kept in mind while trying to frame ideation. Several patents of similar material composition and geometry to the current solution (see figure above) were analyzed. Due to their similar performance, they were chosen going forward to inspire ideation. See Figures 11 and 12 below.

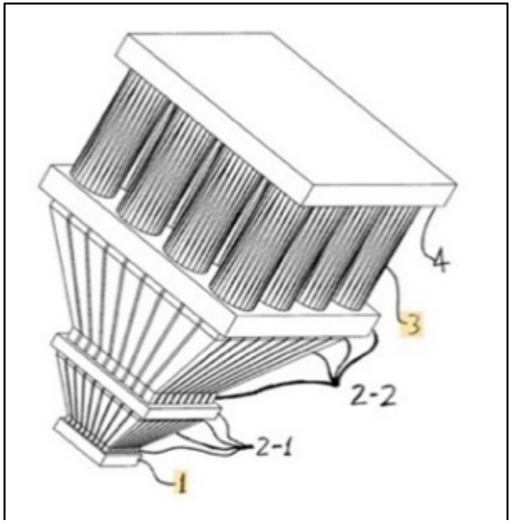


Figure 11. Similar Heatsink Patent #1. [6].

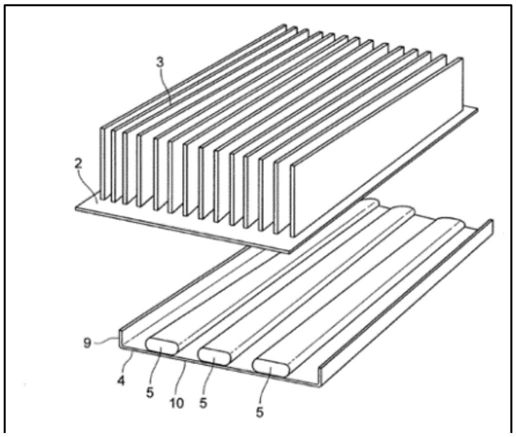


Figure 12. Similar Heatsink Patent #2. [7].

One notable feature exhibited in both of these designs was their heavy reliance on fins. Passive coolers of comparable size and configuration to that requested by GTI stakeholders, that also match performance requirements, appear to exhibit such trends. Taking this into consideration, along with sponsor's existing design and input on its replacement, the current “top” design described in the previous section was selected using best engineering judgement.

As see in the data within Table 1, plotted in Figure 13, the goal is to have our heat sink performance fall below the current trendline. Being below the trendline indicates a cooler cold side temperature of the thermoelectric generator for the same given heat input from the combustion chamber. A lower cold side temperature for the same heat input (and thus hot side temperature) on a TEG means a greater temperature differential, and thus higher power output for the same system configuration. This is desirable and thus this design parameter will drive further testing, either simulated or of physical prototypes.

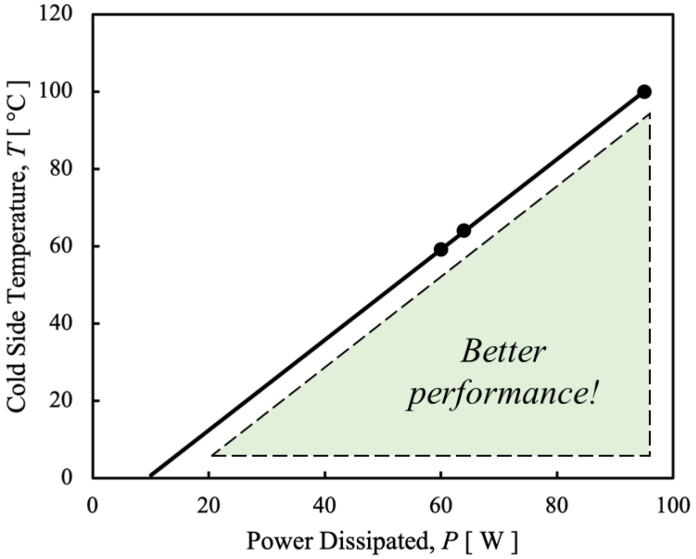


Figure 13. Cold side temperature vs power dissipated for the previously used heat sink in plot form.

Since our current design direction is to extend the heat sink longitudinally, we expect that we can meet or possibly exceed the current performance. One design specification that we need to take into consideration is that the heat sink previously used by GTI cost around 70 dollars per unit and the added length will add to the manufacturing and raw material cost. Design for manufacturing will play a very important role in our design efforts moving forward.

4.2 Preliminary Qualifications

Some initial 1-dimensional analysis of the existing heatsink was provided by the sponsor (see Appendix F). Although this drove some of the initial ideation, more physical testing and simulation is required to make balanced design choices. Using our initial CAD model, we intend to run an ANSYS simulations with quiescent ambient air at 60 degrees Fahrenheit, and uniform heat input on the TEG side of the heat sink for a range of values from 20 to 95 W. We will run the same simulations on the original heat sink, to get a datum for performance.

To supplement and provide an avenue for physical testing, we have developed a test setup prototype to gather data on how a variety of ambient conditions effect performance. The testing apparatus, detailed in Figure 14, consists of a hot plate to provide heat input, a strip of metal to stand in for the heat sink, and thermocouples to measure the temperature distribution throughout the metal strip and at the surface of the hot plate.

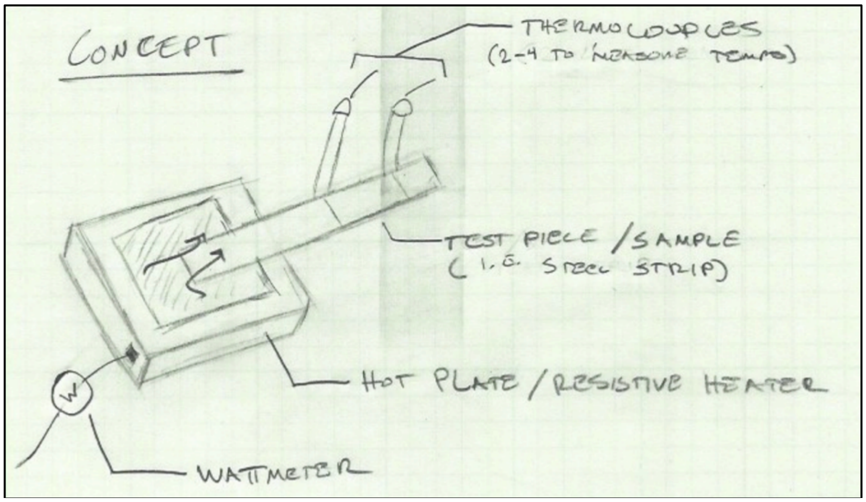


Figure 14a. Conceptual sketch of testing setup and apparatus.

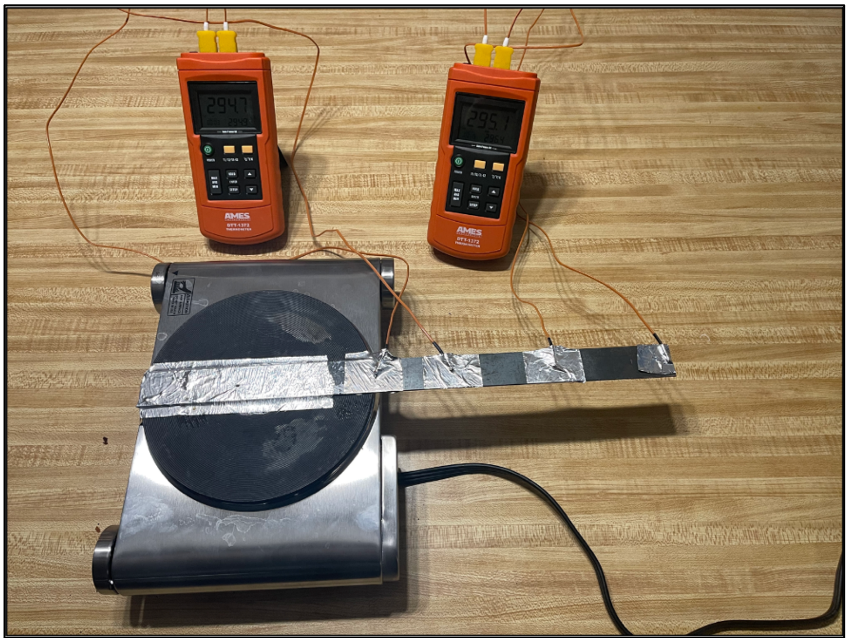


Figure 14b. Photo of testing setup and apparatus.

Ambient conditions of interest include direct sunlight, accumulations of dust and debris on the heat sink, wind, and colder conditions like those found at night. Appropriate time should be allowed for steady state conditions to develop.

On November 18, 2021, at 1pm we ran an experiment using our concept prototype to determine the convection heat transfer coefficients for a flat plate subjected to a hot plate. The ambient temperature was approximately 64 °F, the pressure was 1 atm, and an average wind speed of 4 mph. We used a 16 in long aluminum plank which we obtained from a machine shop on campus, hot plate bought from the Miner's ACE Hardware, and thermocouples were bought at Harbor Freight. We placed the plank on the hot plate and set it to the middle setting which corresponds to approximately a temperature of 300 °F and placed the thermocouples along the plank at locations of 0, 2.5, 6, and 10 inches. We then measured the surface temperature, and the resulting data can be found in Table 2.

Table 2. Raw data from an experimental test done on Nov 18th, 2021.

Thermocouple Location	Thermocouple Location	Surface Temperature
[in]	[m]	[K]
0	0	350.7
2.5	0.0635	312.3
6	0.1524	294.2
10	0.254	290.9

In order to solve for the theoretical convection heat transfer coefficient, we used the Natural Convection correlation equations in tandem with the Prandtl, Rayleigh, Nusselt numbers, and horizontal plate with a heated. The correlation that matched best with the Prandtl number, Rayleigh number, and the orientation can be seen in Equation 1.

$$\overline{Nu_L} = 0.52 {Ra_L}^{1/5} \tag{1}$$

The correlation in Equation 1 can only be used for an averaged film temperature, a Rayleigh number on the order of 10^4 to 10^9, and Prandtl number above 0.7, and a constant surface temperature. A discussion of how these boundaries contributed to our values can be seen below Table 3.

The Excel document is Appendix G and hand calculations can be seen in Appendix H.

Table 3. Theoretical and experimental convection heat transfer coefficients with corresponding percent differences.

	$h_{theoretical}$	$h_{experimental}$	Percent Difference
	[W/m^{2}K]	[W/m^{2}K]	[-]
Thermocouples 1-2	7.13	11.50	-46.94
Thermocouples 2-3	5.43	26.47	-131.90
Thermocouples 3-4	3.58	-125.30	-211.76

The discrepancies in the convection heat transfer coefficients are due to the correlations we used, the fact that we did not take into consideration the heat the left each section in the form of conduction and was gained the following section, and the constant surface temperature assumption. The correlation we used is only considered valid for Rayleigh numbers between 10^4 and 10^9. Our largest Rayleigh number corresponded to the section between thermocouples on and two and was approximately one third of the lowest bound for the chosen correlation. That means that the correlation is being extrapolated and the researchers did not consider heat transfer in that range. As we considered the thermocouples further down the plank, the Rayleigh number decreased even further which only compounded the problem. Secondly, we did not look at the small amount of conduction that occurs along the plank. That added energy in and out compounds as we move along the plank which meant that our data only diverged more. Lastly, our thermocouples had a constant temperature given that they looked at a single point but in the general the plank was not a constant temperature since we did not run the experiment completely to steady state.

4.3 Hazard Investigation

As in any design, we must account for all possible safety hazards both in manufacturing and testing. Given that our heat sink is a static system we do no need to account for any projectile motion, large forces, or accelerations but instead we need to consider the dangers that come with high temperatures, the use of electrical measuring devices, and a sharp metal beam partially off the edge of a surface. Please see Appendix I for our full Design Hazard Checklist. To create an adequate hot side temperature, we will be heating our hot plate to approximately 400 Kelvin. Long exposed contact to a surface at this temperature can cause burns and damage that could be long lasting. To avoid such injuries, we will ensure that all team members are always at least six inches from the workpiece and there is adequate warning before the hot plate is turned on. In addition, using an electronic temperature measuring device such a thermocouple and thermocouple reader comes with the risk of electric shocks and fire if there is contact with water. Mitigating these injuries can be done by not allowing water bottles within five feet of the workspace and giving adequate warning before each test is started. Lastly, we need to take into consideration the fact that we are working with a foot long piece of steel that will most likely be sharp. We sourced the steel workpiece from a machine shop on campus which does not ensure the best or smoothest surface finish. That means that there is a strong likelihood that there will be burrs and sharp edges. By handling the workpiece with care and sanding it before the experiments are done, we will reduce the likelihood of these injuries. In addition, the workpiece may extend partway off the table which allows for a potential that the workpiece will fall under gravity or pitch and slide off the table. To avoid injuries regarding the gravitational force on the workpiece and the workpiece pitching, we will keep everyone at least two feet from the overhanging piece and use clamps.

4.4 Current Challenges & Concerns Going Forward

We have concerns about modeling heat pipes in ANSYS, as this level of computer modeling is beyond the scope of any of our experiences. In our CAD model currently, our heat pipes are modeled as solid copper rods, which would transfer heats differently than a true heat pipe. An additional concern we have is the difficulty of manufacturing a heat sink prototype for physical testing. Since our budget is relatively constrained, and it is challenging to recreate manufacturing processes that would be used at scale when hand fabricating a single prototype, most of our analysis and testing will have to be done on ANSYS or equivalent computer programs.

5. Project Management

In Table 4, there is an overview of the deliverables for the rest of the year and the date we plan to complete each one. The Gantt chart containing all deliverables can be found in Appendix J.

Table 4. Large deliverables until completion of the project.

Targeted Completion	Deliverable	Phase
11/16/21	Preliminary Design Review / Presentation	Theoretical Analysis
1/15/22	Interim Design Review / Presentation	Prototyping & Testing
2/10/22	Critical Design Review / Presentation	
3/16/22	Verification Prototype Sign-Off	
4/11/22	Test Results of Prototype Delivered	
5/28/22	FDR Report, Verification Prototype, Project Expo Poster (*submitted to sponsor)*	

After the completion of the Preliminary Design Review, our next steps are to begin the prototyping and testing phase. In this phase we will be considering potential failures in our design, geometry, materials, manufacturing plan, and corresponding budget. See Table 5, below, for a summary of relevant deliverables:

Table 5. Deliverables before the Critical Design Review.

Target Completion	Deliverable
11/30/21	Failure Modes and Effects Analysis
1/13/22	Interim Design Review
1/25/22	Structural Prototype
1/27/22	Indented Bill of Materials
1/27/22	Drawing & Specifications Package
1/27/22	Design Verification Plan/ Report
1/27/22	Manufacturing Plan
2/3/22	Project Budget
2/11/22	Critical Design Review

Our first step in performing analysis is to determine the heat transfer of a steel plate using an experimental setup made of a hot plate and thermocouples. In addition, we plan to use the current CAD file in tandem with Ansys simulation to determine the theoretical heat transfer in the system and how changes such as more fins or more spacing will affect the heat dissipated. These tests will help us to iterate on our design and determine the most efficient design from both a heat transfer and economic standpoint.

We plan to use copper heat pipes to both provide structural support and simultaneously move the heat from the source to the heat sink fins. These pipes will be purchased from an outside manufacturer such as Advanced Thermal Solutions or McMaster Carr. The fins themselves can be manufactured in house using a CAD file and a laser cutter, water jet, or stamp.

Manufacturing of our structural prototype will be done via brazing and tube bending which can be completed on the Cal Poly campus in the Materials Joining lab. To test our final design, we plan to use the same experimental setup from our preliminary tests, using a heater and a variety of environmental conditions, but specific the voltage and heat from the source will be more comparable to the actual output from the thermo-electric generators and combustion chamber that will be used in the final design.

6. Conclusion

In an effort to decrease environmental impact from existing natural gas infrastructure, the Gas Technology Institute wants to design a new heat sink to bolster the operation of a thermo-electric generator valve control system. The goal is to design a heat sink that works with the given setup but better suits the needs of the Gas Technology Institute. Cal Poly Senior Project Team F16 gladly took on that challenge and so far, has completed the scope of work as well as ideation. The key takeaway from our idea generation, ideation models, and preliminary designs, is that a heat sink using steel or aluminum plates and copper heat pipes that extend outward from the TEGs is the most efficient design from both a heat transfer and economic standpoint. We need our sponsor's approval on our preliminary design and upon agreement, we will move forward into the Failure Modes, Effects Analysis, Structural Prototype, and Manufacturing Planning. To accomplish the end goals detailed in the Preliminary Design Review, we plan to complete our next major deliverable, the Critical Design Review (CDR), on February 10th, 2022. In the CDR we will provide complete details on the design, analysis proving that specifications were met, and a basic manufacturing plan.

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[2] A. Ahmed, "First Sponsor Meeting," 05-Oct-2021. See Team F16 shared drive.

[3] A. Ahmed, "info from sponsor." Gas Technology Institute, 2021.

[4] A. K. Mohiuddin, M. Y. Ameer, A. Rahman, and A. A. Khan, "Investigation of aluminum heat sink design with thermoelectric generator," *IOP Conference Series: Materials Science and Engineering*, vol. 184, p. 012062, 2017.

[5] G. Thorncroft, R. Emberly, "Experimental setup interview," 12-Nov-2021.

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[7] 賢也 川畑, 勝 大海, and 良次 大野, "Heat sink with heat pipe and method of manufacturing the same," 24-Dec-2009. [11] G. Cherian, "Sprdr- heat spreader- tailorable, flexible, passive," 04-Oct-2016.

Appendices

[A] Quality Function Deployment (QFD) “House of Quality”

[B] Ideation List for Concept Functions

[C] Ideation Models Photos & Descriptions

[D] Pairwise Comparison & Weighted Decision Matrix

[E] Pugh Matrix Analyses & Select Top Idea Descriptions

[F] Preliminary Thermal Analysis (Sponsor Efforts)

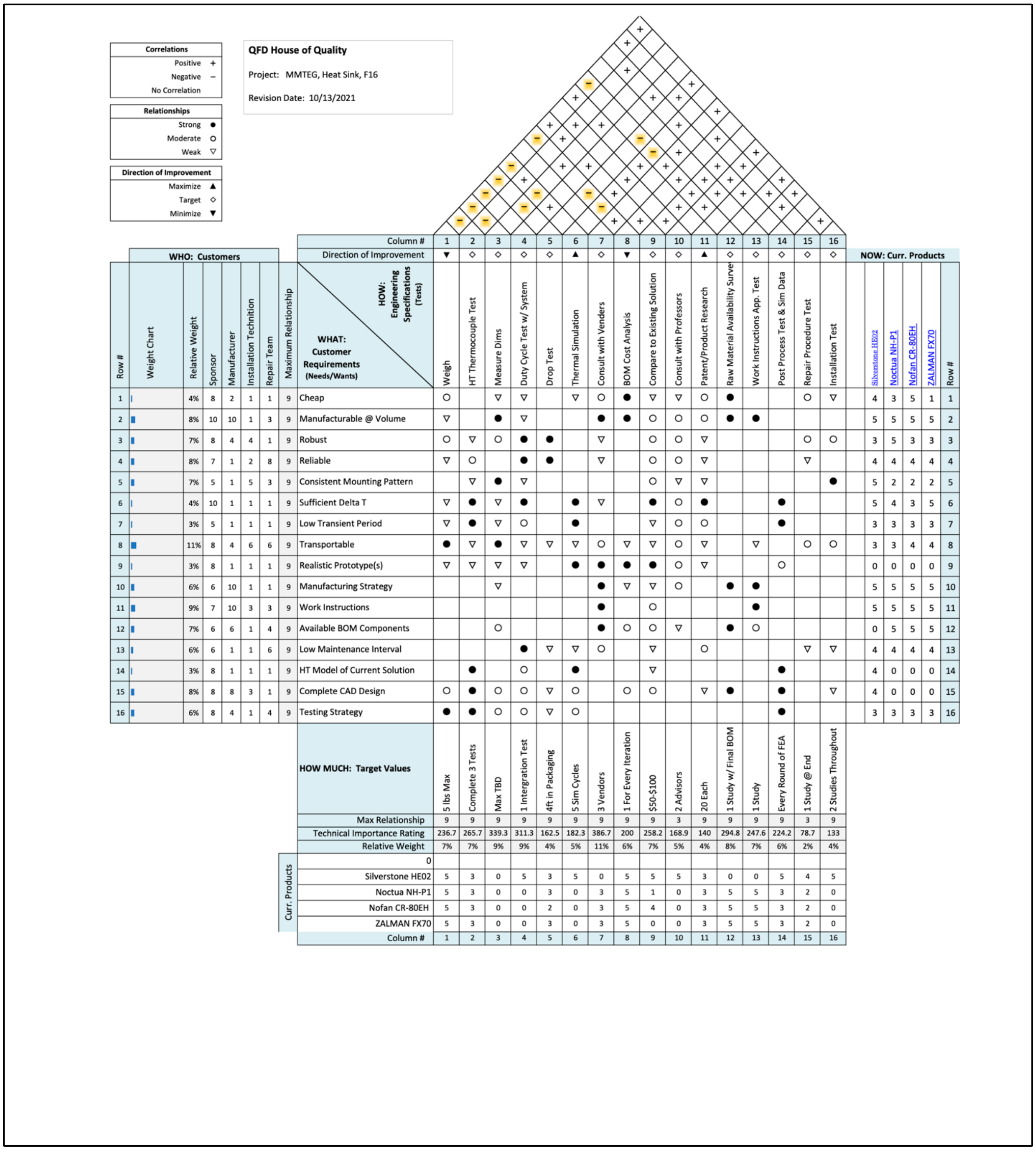
[G] Excel Post Processing of Concept Prototype Data

[H] Concept Prototype Post Processing Hand Calcs

[I] Design Hazard Checklist & Appropriate Measures

[J] Project Gantt Chart

Appendix A – Quality Function Deployment (QFD) “House of Quality”



Correlations	
Positive	+
Negative	–
No Correlation	

Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼

QFD House of Quality

Project: MMTEG, Heat Sink, F16

Revision Date: 10/13/2021

								Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16					
	WHO: Customers							Direction of Improvement	▼	◇	◇	◇	◇	▲	◇	▼	◇	◇	▲	◇	◇	◇	◇	◇	NOW: Curr. Products				
Row #	Weight Chart	Relative Weight	Sponsor	Manufacturer	Installation Technition	Repair Team	Maximum Relationship	HOW: Engineering Specifications (Tests) / WHAT: Customer Requirements (Needs/Wants)	Weigh	HT Thermocouple Test	Measure Dims	Duty Cycle Test w/ System	Drop Test	Thermal Simulation	Consult with Venders	BOM Cost Analysis	Compare to Existing Solution	Consult with Professors	Patent/Product Research	Raw Material Availability Surve	Work Instructions App. Test	Post Process Test & Sim Data	Repair Procedure Test	Installation Test	Silverstone HE02	Noctua NH-P1	Nofan CR-80EH	ZALMAN FX70	Row #
1		4%	8	2	1	1	9	Cheap	○		▽	▽		▽	○	●	▽	▽	○	●			○	▽	4	3	5	1	1
2		8%	10	10	1	3	9	Manufacturable @ Volume	▽		●	▽			●	●	○	○	○	●	●				5	5	5	5	2
3		7%	8	4	4	1	9	Robust	○	▽	○	●	●		▽		○	○	▽				○	○	3	5	3	3	3
4		8%	7	1	2	8	9	Reliable	▽	○		●	●		▽		○	○	▽				▽		4	4	4	4	4
5		7%	5	1	5	3	9	Consistent Mounting Pattern		▽	●	▽					○	▽	▽					●	5	2	2	2	5
6		4%	10	1	1	1	9	Sufficient Delta T	▽	●	▽	●		●	▽		●	○	●			●			5	4	3	5	6
7		3%	5	1	1	1	9	Low Transient Period	▽	●	▽	○		●			▽	○	○			●			3	3	3	3	7
8		11%	8	4	6	6	9	Transportable	●	▽	●	▽	▽	▽	○	▽	▽	○	▽		▽		○	○	3	3	4	4	8
9		3%	8	1	1	1	9	Realistic Prototype(s)	▽	▽	▽	▽		●	●	●	●	○	▽			○			0	0	0	0	9
10		6%	6	10	1	1	9	Manufacturing Strategy			▽				●	▽	▽	○		●	●				5	5	5	5	10
11		9%	7	10	3	3	9	Work Instructions							●		○				●				5	5	5	5	11
12		7%	6	6	1	4	9	Available BOM Components			○				●	○	○	▽		●	○				0	5	5	5	12
13		6%	6	1	1	6	9	Low Maintenance Interval				●	▽	▽	○		▽		○				▽	▽	4	4	4	4	13
14		3%	8	1	1	1	9	HT Model of Current Solution		●		○		●			▽					●			4	0	0	0	14
15		8%	8	8	3	1	9	Complete CAD Design	○	●	○	○	▽	○		○	○		▽	●		●		▽	4	0	0	0	15
16		6%	8	4	1	4	9	Testing Strategy	●	●	○	○	▽	○								●			3	3	3	3	16

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	HOW MUCH: Target Values	5 lbs Max	Complete 3 Tests	Max TBD	1 Intergration Test	4ft in Packaging	5 Sim Cycles	3 Vendors	1 For Every Iteration	$50-$100	2 Advisors	20 Each	1 Study w/ Final BOM	1 Study	Every Round of FEA	1 Study @ End	2 Studies Throughout
	Max Relationship	9	9	9	9	9	9	9	9	9	3	9	9	9	9	3	9
	Technical Importance Rating	236.7	265.7	339.3	311.3	162.5	182.3	386.7	200	258.2	168.9	140	294.8	247.6	224.2	78.7	133
	Relative Weight	7%	7%	9%	9%	4%	5%	11%	6%	7%	5%	4%	8%	7%	6%	2%	4%
Curr. Products	0																
	Silverstone HE02	5	3	0	5	3	5	0	5	5	5	3	0	0	5	4	5
	Noctua NH-P1	5	3	0	0	3	0	3	5	1	0	3	5	5	3	2	0
	Nofan CR-80EH	5	3	0	0	2	0	3	5	4	0	3	5	5	3	2	0
	ZALMAN FX70	5	3	0	0	3	0	3	5	0	0	3	5	5	3	2	0
	Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

Appendix B – Ideation list for Concept Functions

Based on preliminary research and discussions with sponsor, five primary "functions" of the heatsink design were identified to help frame ideation and concept development. They are listed below for convenience, along with their related ideas that were generated. Note that, as part of the ideation process, some ideas were intentionally unrealistic or "impossible" to help clearly define the bookends for possible solutions.

See below:

Create a temperature differential

1. Ice cubes
2. Compressed air cans
3. Industrial fans
4. Turbojet
5. Refrigerator
6. Blow torch
7. Camp fire
8. Gas fire
9. Wood fire stove
10. Natural Gas stove
11. Blow torch
12. Thermoelectric heater
13. Resistance heater
14. Welding process
15. Oxy-fuel torch
16. High wind
17. Hot springs near a cold river
18. Thermocline
19. Disposable lighter
20. Passive heat sink
21. Forced convection heat sink
22. Water cooled heat sink
23. High altitude cooling tower
24. Cooling tower
25. Cross flow heat exchanger
26. Parallel flow heat exchanger
27. Shell and tube heat exchanger
28. Liquid oxygen poured on anything
29. Evaporating liquid nitrogen
30. Hypergolic substances exposed to air in proximity to anything
31. Converging-diverging nozzles
32. Solar absorption heat exchanger
33. Coal fire
34. Massive electromagnetic insultation device
35. Fiberglass insulation between fire and ice

Appendix B – Ideation list for Concept Functions

Continued

Integrate with the current system:

1. Use the old bracket
2. Have old engineers approve the design
3. Put longer bolts that can hold heatsinks on while also helping structure
4. Develop CAD model and hold design competition at local ME events or clubs
5. 3D printed composite alternative
6. Build a bunch of prototypes and slap them onto the actual comb. Chamber in LA... which looks best?
7. Use strong people to hold the heatsinks on forever... feed them milk
8. Have a temporary frozen-on heatsink that melts off to expose fins... designed with material that only melts in extreme conditions
9. Use ropes
10. Torque-to-yield bolts
11. Regular wooden bolts (OAK)
12. Melt the devices together to ensure they don't come apart
13. Make an intermediary bracket for the old design and new design
14. Merge old heatsinks with new heatsinks by welding them together
15. PVC pipes that hold it all together
16. Have a removable bracket that can fit onto many different apparatuses
17. Epoxy to mount heat sink to combustion chamber
18. Tap new mounting holes for bolting that fit new heat sink design
19. Use large magnets to hold heat sinks on
20. Utilize a standard rail system
21. Velcro attachments for all components
22. Friction stir weld the final components together
23. Super glue
24. Put a box around the outside of entire system, creating a counter pressure on the outside of the heat sinks and pressing them into the combustion chamber
25. Make the heat sink integrated into the manufacturing of the combustion chamber
26. Threaded holes in combustion chamber for screws to secure heat sinks
27. Inflatable bladder that creates a structure to hold heat sinks
28. Interference fasteners (plugs / notches etc)
29. Cast parts for bracket – lowers cost and increases connection material
30. Plastic parts can be melted onto the metal

Operate in a remote system:

1. An umbrella to block the sun and rain
2. Plastic blockage for wind
3. Chimney above the heat sinks to direct the heat upwards. Heat avoids the rest of the product
4. Use code to monitor the system from far away
5. House the system so it is not exposed to the elements
6. Heat treat the system so it is stronger
7. Build it as part of the overall frame to make it stronger
8. Add supports that go into the ground to support
9. Strengthened screws

Appendix B – Ideation list for Concept Functions

Continued

10. Composite materials
11. Make them hot-swappable for easy replacement in remote location
12. Wind visor to protect against wind
13. Make unit run differently depending on ambient conditions
14. Ground well heat pump
15. Install rails that will move the old units out and new units in (hot swap)
16. Build massive wind funnels that will act as active cooling even though it's just passive cooling
17. Buy more materials than needed and then use that to reinforce the existing design
18. Sheet metal covers to protect
19. Aluminum metal covers to protect
20. Plastic covers to protect
21. Boost stability with concrete throughout the structure
22. Install duplicate system for redundancy
23. Periodically blast heat sinks with compressed air to clear out bug nests etc
24. Separate burner system that can briefly burn heat sinks to clean out insect nests
25. Bug spray coated device that will naturally repel insects...

Utilize only scalable manufacturing:

1. Casting with a permanent mold
2. Design for 3 axis cnc
3. Design for aluminum extrusion
4. Sand casting
5. Utilize only commercially available components
6. Use standard stock material sizes
7. Use standard metric or imperial bolts
8. Avoid class 1 and class 3 fasteners
9. Avoid liquid o-rings, gluing, welding, and all other cool or dry time methods
10. Design for robotic assembly
11. Reduce the number of operations per part
12. Design for preexisting assembly lines
13. Build in features for QC
14. Remove all unnecessary QC steps after assembly line ramp up
15. No custom parts
16. Use a composite of existing designs that have already been proven to be scalable
17. Test manufacturing processes as design goes on to make sure we don't run into any weird features
18. Develop new methods to scale manufacturing with methods you design your product around
19. Avoid 3d printing at all costs
20. Every machine in the line only performs one set of operations, eliminating setup time
21. Run at higher feeds and speeds and sacrifice surface finish on milled parts
22. Eliminate any steps completed by vendors
23. Only source readily available raw material
24. Buy all components of your supply chain
25. Additive MFG for lower cost
26. Develop systems that are very scalable

Appendix B – Ideation list for Concept Functions

Continued

27. Find large methods of manufacturing
28. Cheap stuff to make expensive stuff
29. Metal alloys with plastic in them
30. Develop a cheaper MFG process by outsourcing
31. Make the unit simple as possible
32. Minimize number of fins and maximize spacing
33. Factory is in-house
34. Use Industrial engineers to make our process more efficient
35. Biomaterials
36. Particle technologies
37. Simple fasteners that don't require specialized labor
38. Automated processes that put it together without labor at all
39. Staple style fin spacing that doesn't do much other than brazing
40. Reduce number of individual parts
41. Minimize overhangs or weird geometry features

Decrease cost:

1. Made of super cheap material that breaks easily but doesn't cost a lot
2. Made of expensive material that never needs to be replaced
3. Different attachments that allow for different uses with the same basic bracket
4. Recycled material
5. In-house manufacturing
6. Only use easily manufactured shaped, like blocks not any ellipses
7. Lost foam casting
8. Reduce number of technicians needed for assembly
9. Use lower grade fasteners
10. Target simple technology
11. Removable fins so they can be fixed on a single case basis
12. Keep a large inventory so heat sinks are not made on demand
13. Have a manager look over the process virtually instead of someone being on site
14. Scrap can be melted down into new fins
15. Composites so the material is strong and doesn't need to be replaces often

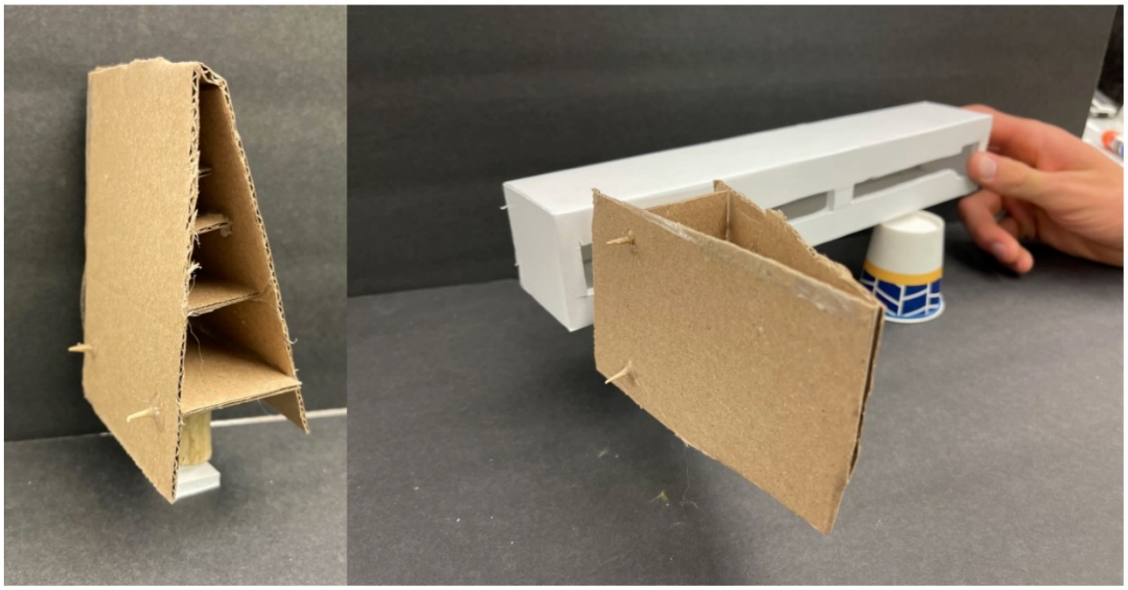
Appendix C - Ideation Model Photos & Descriptions

General Notes

1. All these designs will be shown first separately, and then mounted to our pseudo "heat exchanger", the rectangle made of white foam board.
2. My objective in this was to investigate the spatial/practical aspect of the heatsinks and how many / how large they would be compared to the heat exchanger layout. Little attention was put towards the actual heat dissipation performance. Pay more attention to the general form of each design and consider how the shape could be scaled / repeated across the exchanger.
3. Four models are included below. I drove the design and assembly of these, but we also pitched in to each other's ideas as we were assembling them. Some of my other teammates spent a significant amount of time making a high quality replica of the combustion chamber / heat exchanger, since this will likely be used again later in our design process.

Alec's Ideation Models

1. Wedge Shape

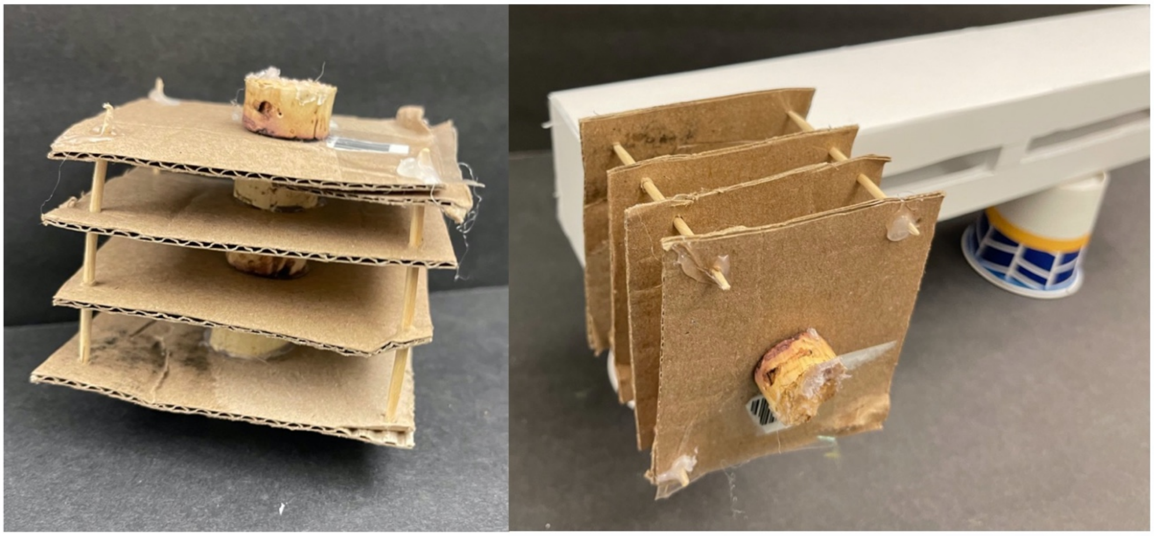


The approach here was to investigate non-rectilinear designs … what about spheres or wedges? We could try to optimize the number of TEGs were fitting together, while also allowing for air gap between their respective heatsinks. The thing that was constraining the output of the overall generator is the low number of TEGs, held back by heatsink interference. Could we fit more with this approach? Would be worth seeing if wedges could somehow make our use of space more efficient, depending on the clearance required between individual heatsinks.

Appendix C - Ideation Model Photos & Descriptions

Continued

2. “Standard” heatsink approach

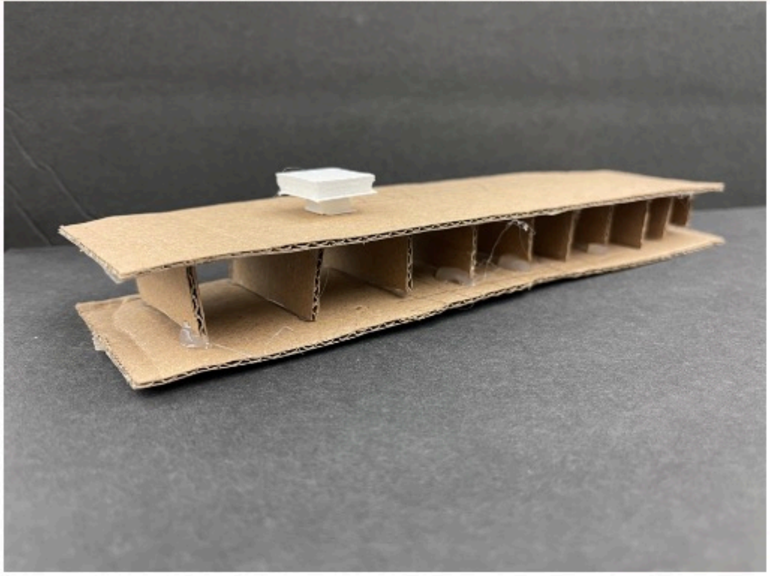


This is a rough concept of the heatsink designs that are currently in use on GTI’s MMTEG. Note that the general assembly consists of simple plates held together by “stringers” that run along the corners. In reality, these would be brazed on, but the concept here still holds. The cork in between I supposed to replicate the placement of a heat pipe that runs through these fins. It’s important to see how this geometrically fits onto the combustion chamber, and how many we might be able to fit, or how structurally sound a solution with heatsinks placed above / below etc. We’ll look into this when we’re moving forward. Creating this prototype indirectly inspired the next design.

Appendix C - Ideation Model Photos & Descriptions

Continued

3. "multi-TEG" solution

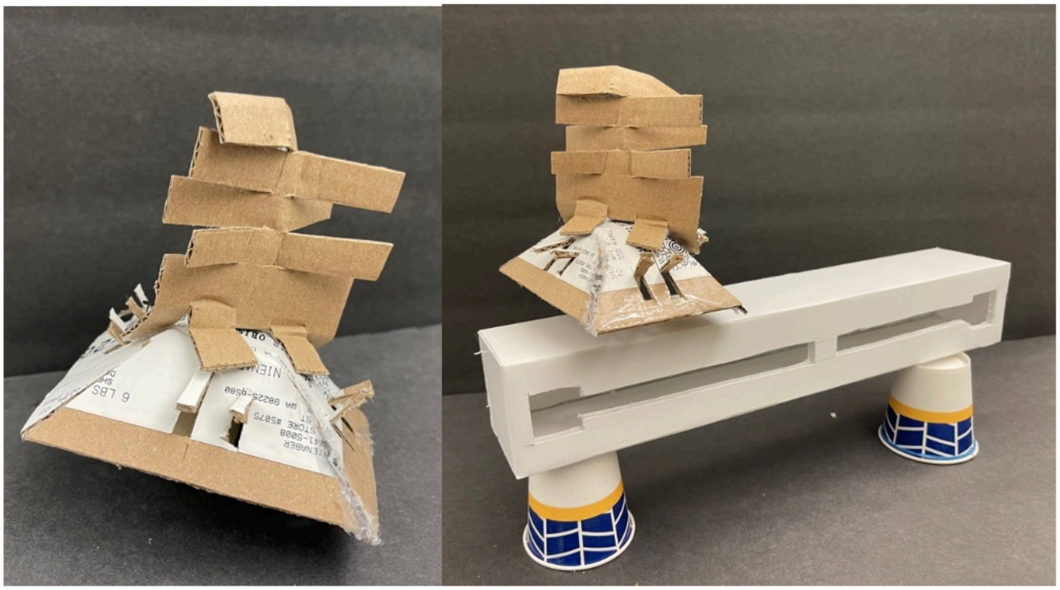


The idea behind this one was to see how we could fit a larger heatsink that connects to multiple TEGs… this solution would be more space-efficient, and via clever placement of heat pipes, we could connect many tegs to the same unit. This could greatly increase our power output for the same combustion of natural gas… After building this, we realized it could be quite a bit larger in the normal direction (away from heat exchanger) so that the heat transfer rate was sufficient for our purpose. Good takeaway!

Appendix C - Ideation Model Photos & Descriptions

Continued

4. Top-mounted heatsink



One of the challenges we're facing is that the exhaust gases from combustion have to go somewhere. In the case of the current combustion chamber, there are slots cut into the top of the heat exchanger to release these gases. That's a lot of heat transfer / power lost to the ambient that doesn't get used up by a TEG. If we could come up with a solution of heatsink that can deal with these hot exhaust gases without letting them affect the performance of the cold side for TEG, this could be a great addition! Those little slots are just a speculation as to how we could send out hot exhaust gases while also capturing a majority of the heat to be concentrated on the TEG. The fins on top are supposed to resemble the "actual heatsink" portion, which would scatter the heat appropriately. Some variation of that rectilinear funnel could probably push the exhaust gases away to satisfy this. Definitely worth investigating how we can make use of the upper section of the combustion chamber "real estate", though.

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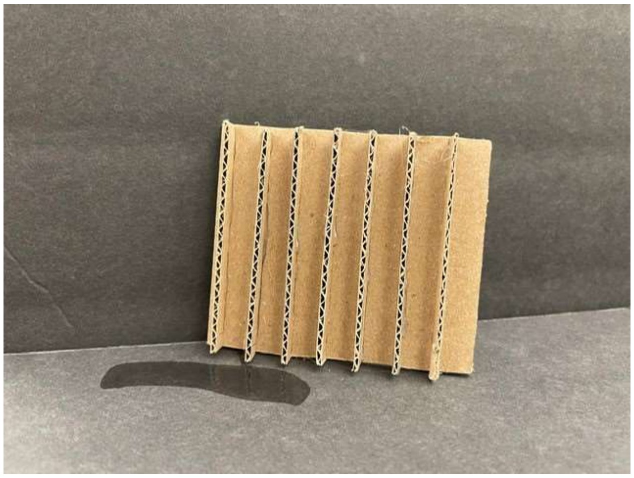
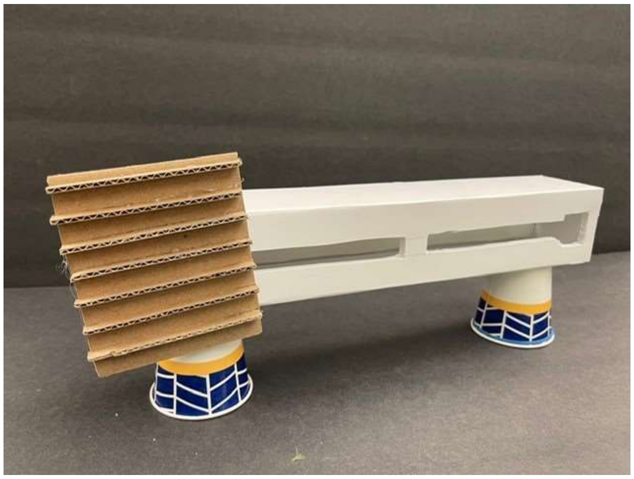
Appendix C - Ideation Model Photos & Descriptions

Continued

Ideation Model: 1



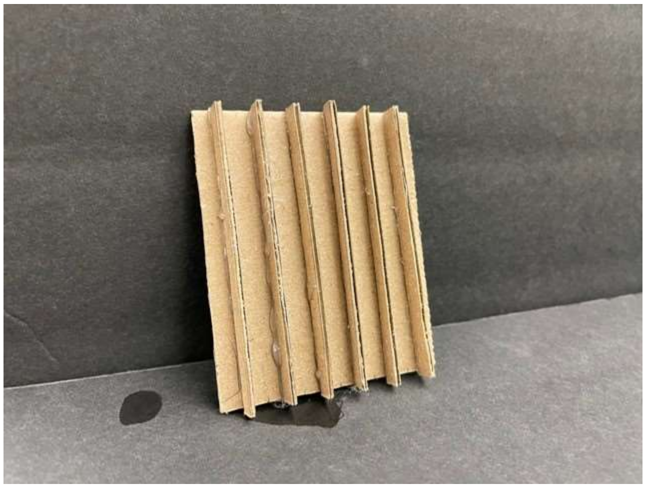


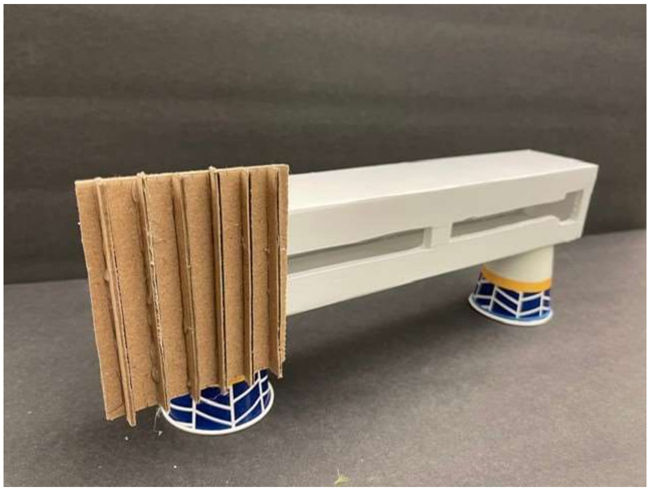
This model is a finned heat sink with shorter length fins but more of them. I learned that the vertical orientation allows for more heat sinks to be placed on the combustion chamber. This is a viable option for us since the vertical height is not a concern to our design. This idea led me to thinking that adjustable fins where more can be added as needed might be something to look into.

Appendix C - Ideation Model Photos & Descriptions

Continued

Ideation Model: 2



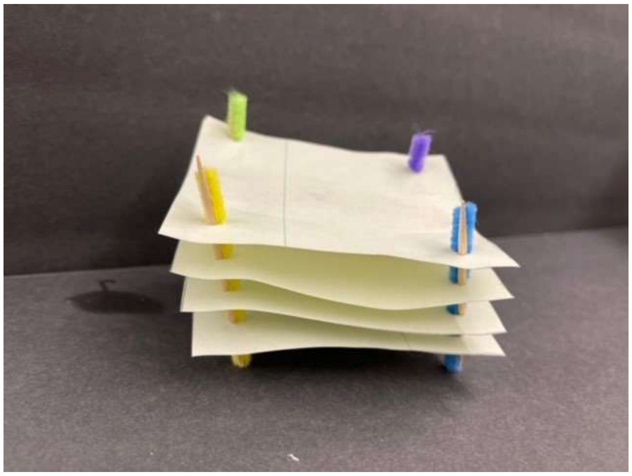


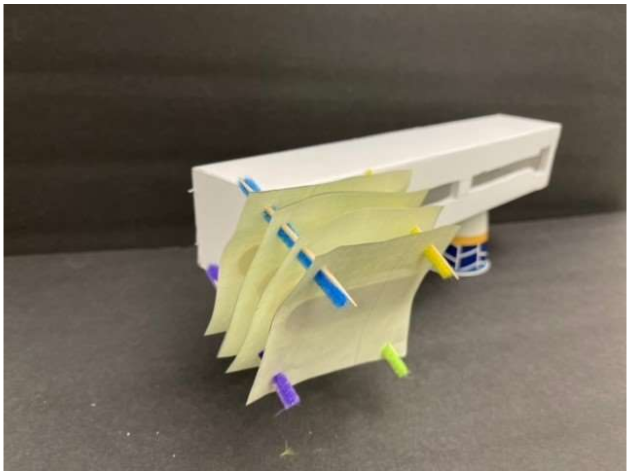
This model is a finned heat sink with longer length fins but less of them. I learned that the vertical orientation allows for more heat sinks to be placed on the combustion chamber. This is a viable option for us since the vertical height is not a concern to our design. This idea led me to thinking that adjustable fins where more can be added as needed might be something to look into. This idea is very similar to Ideation Model 1 but the finned area is different and I am excited to analyze which design performs better.

Appendix C - Ideation Model Photos & Descriptions

Continued

Ideation Model: 3



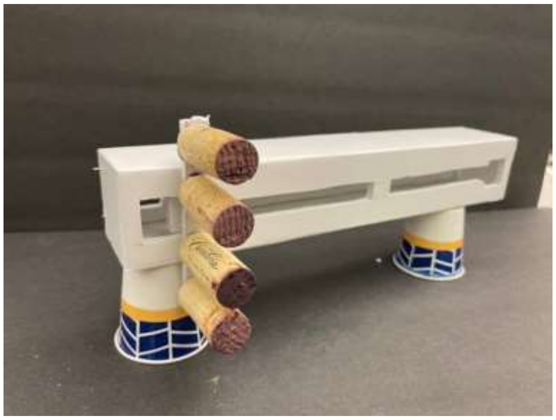


This model is a layered heat sink that sort of resembles the current model used by Gas Technology Institute except the heat pipes, denoted by pipe cleaners, are on the corners instead of closer to the middle. Due to the materials, it ended up being very flimsy and did not hold but I did like the fact that the layers could be removed and either repaired or replaced easily. One way to make this design better would be to have a heat pipe (or a pipe cleaner) go down the center too. That would lead to more stability and allow heat to flow down the center where most of the heat will be concentrated.

Appendix C - Ideation Model Photos & Descriptions

Continued

Ideation Model: 4

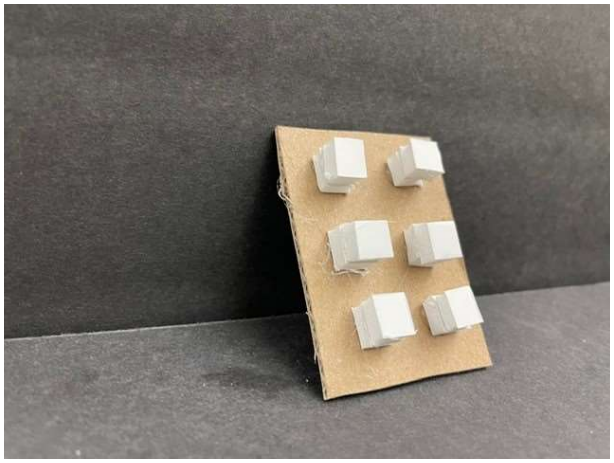


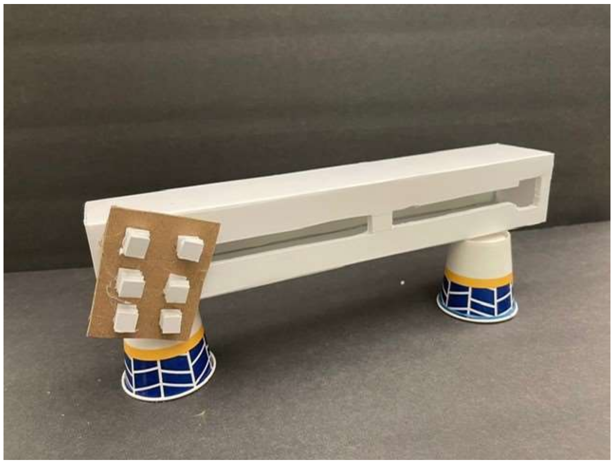
This model is a heat sink with cylindrical fins. I liked this design since cylinders might give rise to more heat transfer and take up less room. After building I still think this potential but worry that the amount of cylinders needed to accomplish the needed transfer will be excessive and lead to high manufacturing costs. I like the cylindrical shape since curved surfaces might lead to more heat transfer. This design made me think about the possibility of using a mix of rectangular and cylindrical shapes. It would be interesting to look at the difference in heat transfer for those two shapes.

Appendix C - Ideation Model Photos & Descriptions

Continued

Ideation Model: 5





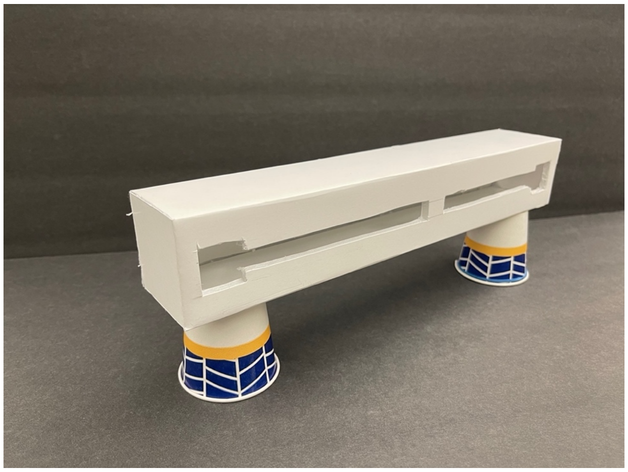
This model is a heat sink that uses cubes instead of long fins. I like that this design takes the standard heat sink configuration and then sort of implements the cylindrical pins idea. The upside of this design is that the pins can be removed and replaced as needed but I don't think it will have the needed heat transfer unless a lot of pins are used. The pins being rectangular makes it easier to decide where they will be positioned but could lead to some odd flow with the right angles.

Appendix C - Ideation Model Photos & Descriptions

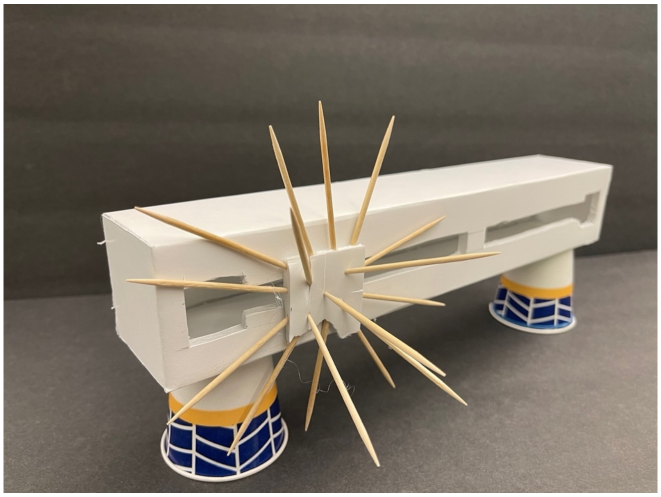
Continued

Jack Waeschle
10/27/2021
ME 428

Ideation Concept Models



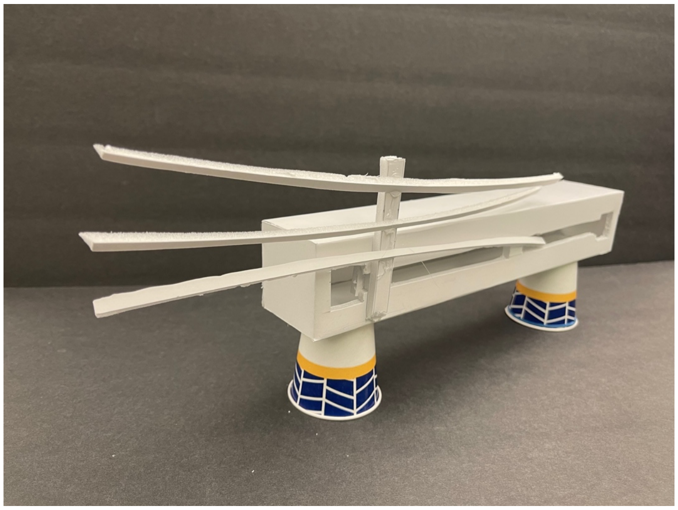
First, Kadin Feldis and I created a model of the combustion chamber used on our sponsors MMTEG. We created a track system to install models, and try out different configurations of heat sinks. This provided a tactile way to interact with out prototypes, and aided in visualization.



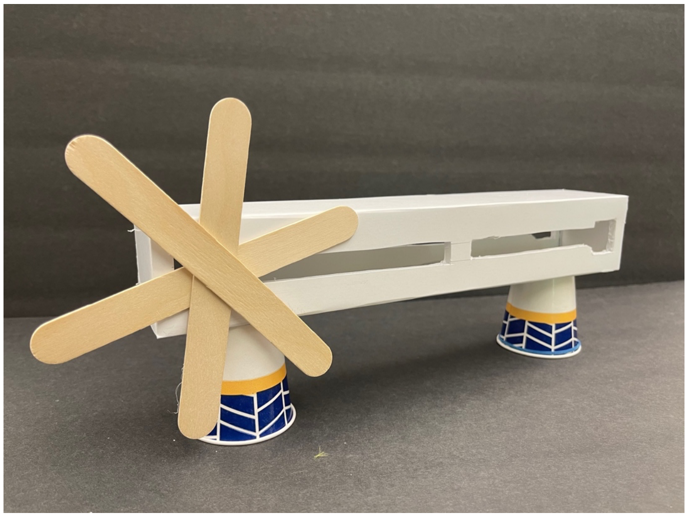
This model experimented with a radial rod styled heat sink. While interesting, it seems it would not optimize surface area in our application. This inspired further radial designs and experiments with rectangular alternatives, as seen below.

Appendix C - Ideation Model Photos & Descriptions

Continued



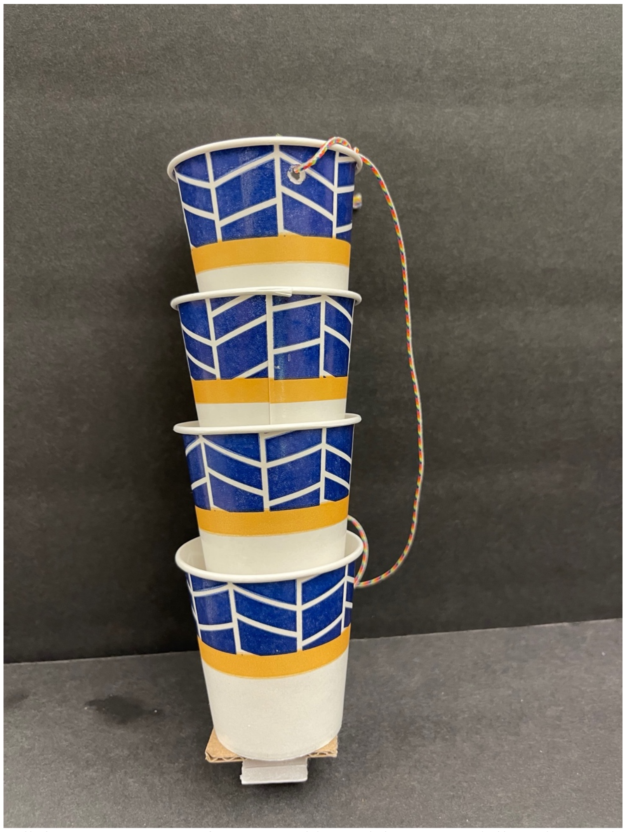
This model uses long fins. In this picture, the long fins are installed horizontally, however if installed vertically, it could prove far more space efficient. After visiting our sponsor in Agoura Hills and seeing the prototype in person, we noticed there was a lot of unused space below and above the existing heat sinks. We intend to investigate this idea further.



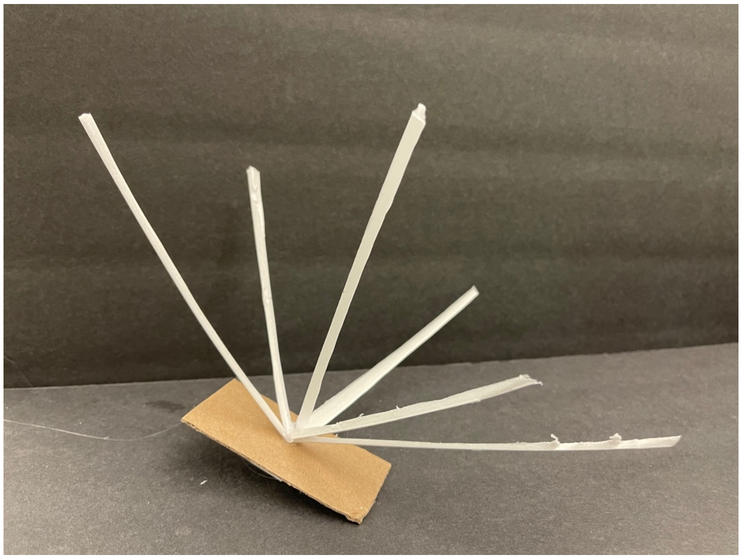
This model explores a flat radial design. While easy to manufacture, this specific design has limited surface area compared to others. A potential solution would be to add multiple plates of these radial designs to extend them away from the combustion chamber.

Appendix C - Ideation Model Photos & Descriptions

Continued



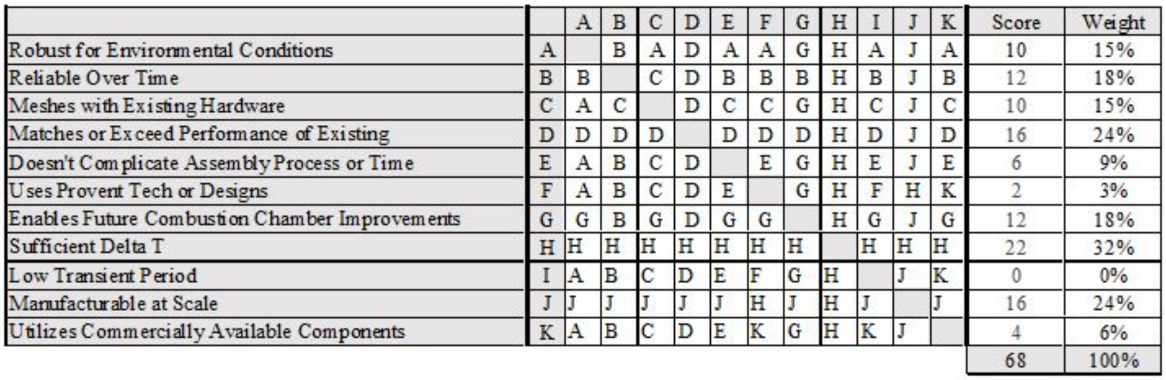
This model uses radial cups to create surface area. This model was especially unique as it extended quite far from the combustion chamber. One concern I have is limited air flow as each cup shelters the next. This could potentially be resolved with slits or vents cut into each cup. This analysis is entirely speculative, as no formal heat transfer analysis was performed.



This model uses radial fins to transfer heat away from the combustion chamber. One concern is the lack of conducting material on the base plate. A possible remedy would be to add multiple sets of radial fins overlapping on the base plate. Also of concern is the radial design. A rectangular prism will produce a much more space efficient heat sink creating more surface area for a given volume.

Appendix D – Pairwise Comparison & Weighted Decision Matrix

In order to determine which criterion are most important when selecting a final design direction, we utilized a pairwise comparison as seen in Figure D-1 below. This type of comparison pits every combination of two individual criteria against one another in order to get an unbiased weight for each category that is based on true relative importance not the feelings or general judgment of the ranking individual. The weights established here will be used in later in the Weighted Decision Matrix.



		A	B	C	D	E	F	G	H	I	J	K	Score	Weight
Robust for Environmental Conditions	A		B	A	D	A	A	G	H	A	J	A	10	15%
Reliable Over Time	B	B		C	D	B	B	B	H	B	J	B	12	18%
Meshes with Existing Hardware	C	A	C		D	C	C	G	H	C	J	C	10	15%
Matches or Exceed Performance of Existing	D	D	D	D		D	D	D	H	D	J	D	16	24%
Doesn't Complicate Assembly Process or Time	E	A	B	C	D		E	G	H	E	J	E	6	9%
Uses Provent Tech or Designs	F	A	B	C	D	E		G	H	F	H	K	2	3%
Enables Future Combustion Chamber Improvements	G	G	B	G	D	G	G		H	G	J	G	12	18%
Sufficient Delta T	H	H	H	H	H	H	H	H		H	H	H	22	32%
Low Transient Period	I	A	B	C	D	E	F	G	H		J	K	0	0%
Manufacturable at Scale	J	J	J	J	J	J	H	J	H	J		J	16	24%
Utilizes Commercially Available Components	K	A	B	C	D	E	K	G	H	K	J		4	6%
													68	100%

Figure D-1. Pairwise Comparison for final design direction selection criteria.

After weights were established with the Pairwise Comparison a Weighted Decision Matrix was developed as seen below in Figure D-2. This matrix starts by checking each proposed idea – as pulled from the Pugh Matrix analysis – against a set of constraints. Only ideas that satisfy all project constraints will be assigned a score. In this case all ideas satisfied all constraints. Next, each idea is scored in each category used in the Pairwise Comparison with a common rating scale. The scores are weighted using the aforementioned weights and then a final score is assigned for each idea. The idea with the highest score is the winner and therefore will represent the design direction for the project. In this case we will extend the heatsink longitudinally, but because each idea is not necessarily mutually exclusive we may also extend the heat sink vertically.

Appendix D – Pairwise Comparison & Weighted Decision Matrix

Continued

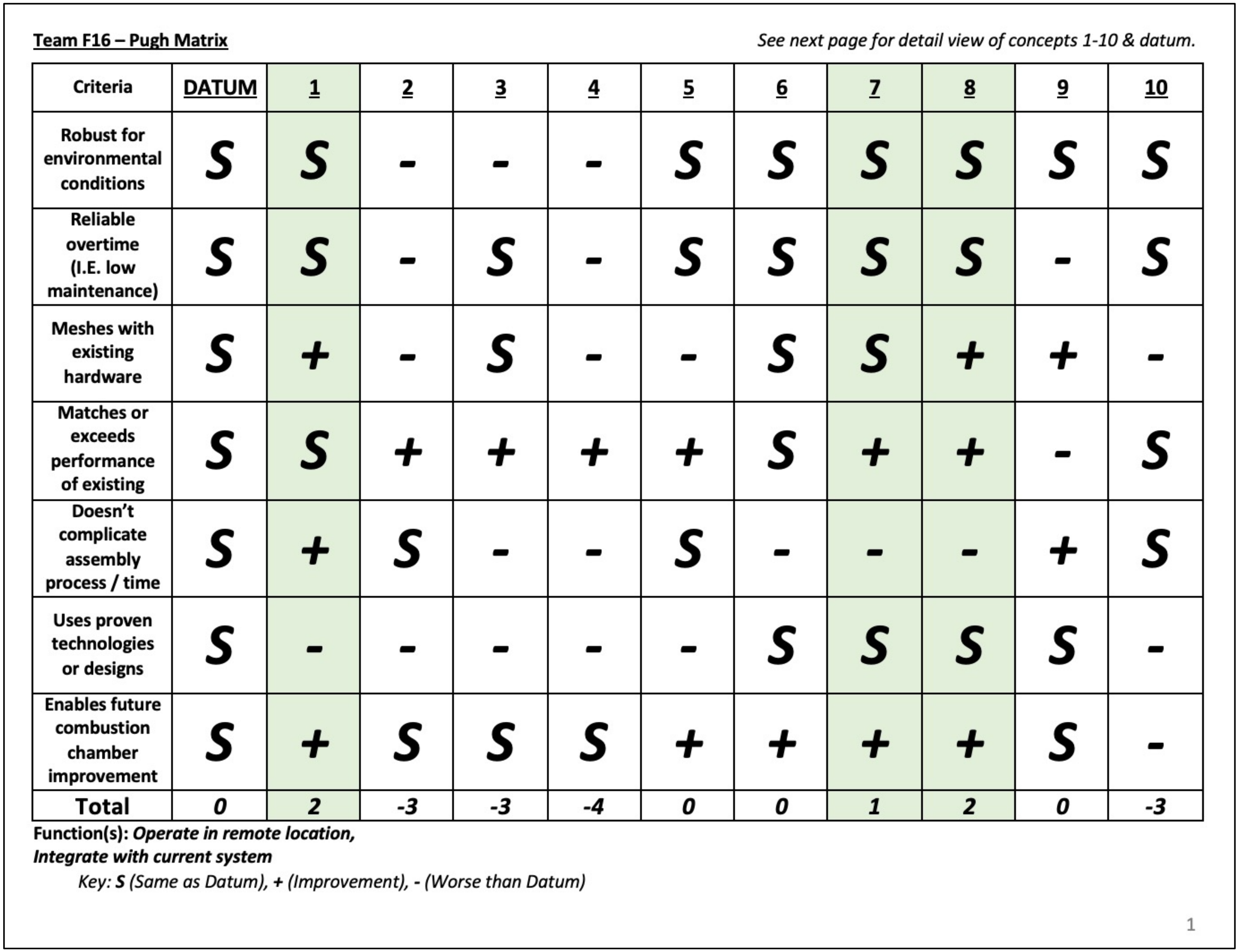
				Winner							
Constraints		Cylindrical Body		Longitudinally extended		Multi TEG system		Vertically extended		Replicated w/ Heat Shield	
Meets cost, 70 ish dollars		Y		Y		Y		Y		Y	
High volume manufacturing, 40,000 a year		Y		Y		Y		Y		Y	
Meets of exceeds performance		Y		Y		Y		Y		Y	
Criteria	Weight (%)	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Robust for Environmental Conditions	15%	5	73.5	4	58.8	5	73.5	4	58.8	3	44.1
Reliable Over Time	18%	4	70.6	4	70.6	5	88.2	4	70.6	4	70.6
Meshes with Existing Hardware	15%	5	73.5	5	73.5	4	58.8	5	73.5	5	73.5
Matches or Exceed Performance of Existing	24%	3	70.6	5	117.6	3	70.6	4	94.1	5	117.6
Doesn't Complicate Assembly Process or Time	9%	3	26.5	3	26.5	2	17.6	4	35.3	3	26.5
Uses Provent Tech or Designs	3%	2	5.9	3	8.8	3	8.8	3	8.8	4	11.8
Enables Future Combustion Chamber Improvements	18%	4	70.6	5	88.2	1	17.6	4	70.6	4	70.6
Sufficient Delta T	32%	3	97.1	5	161.8	5	161.8	5	161.8	5	161.8
Low Transient Period	0%	3	0.0	2	0.0	3	0.0	3	0.0	5	0.0
Manufacturable at Scale	24%	4	94.1	4	94.1	4	94.1	5	117.6	4	94.1
Utilizes Commercially Available Components	6%	4	23.5	3	17.6	3	17.6	3	17.6	3	17.6
Total	100%		**605.9**		**717.6**		**608.8**		**708.8**		**688.2**

Rating Scale

1 - Terrible
2 - Bad
3 - Neutral
4 - Good
5 - Excellent

Figure D-2. Weighted decision matrix for final design direction selection.

Appendix E – Pugh Matrix & “Top” Idea Selection



Team F16 – Pugh Matrix

See next page for detail view of concepts 1-10 & datum.

Criteria	DATUM	1	2	3	4	5	6	7	8	9	10
Robust for environmental conditions	S	S	-	-	-	S	S	S	S	S	S
Reliable overtime (I.E. low maintenance)	S	S	-	S	-	S	S	S	S	-	S
Meshes with existing hardware	S	+	-	S	-	-	S	S	+	+	-
Matches or exceeds performance of existing	S	S	+	+	+	+	S	+	+	-	S
Doesn’t complicate assembly process / time	S	+	S	-	-	S	-	-	-	+	S
Uses proven technologies or designs	S	-	-	-	-	-	S	S	S	S	-
Enables future combustion chamber improvement	S	+	S	S	S	+	+	+	+	S	-
Total	*0*	*2*	*-3*	*-3*	*-4*	*0*	*0*	*1*	*2*	*0*	*-3*

Function(s): *Operate in remote location, Integrate with current system*

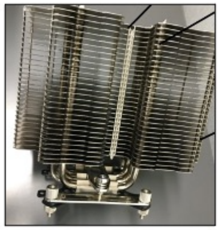
Key: ***S*** *(Same as Datum),* **+** *(Improvement),* **-** *(Worse than Datum)*

Appendix E – Pugh Matrix & “Top” Idea Selection

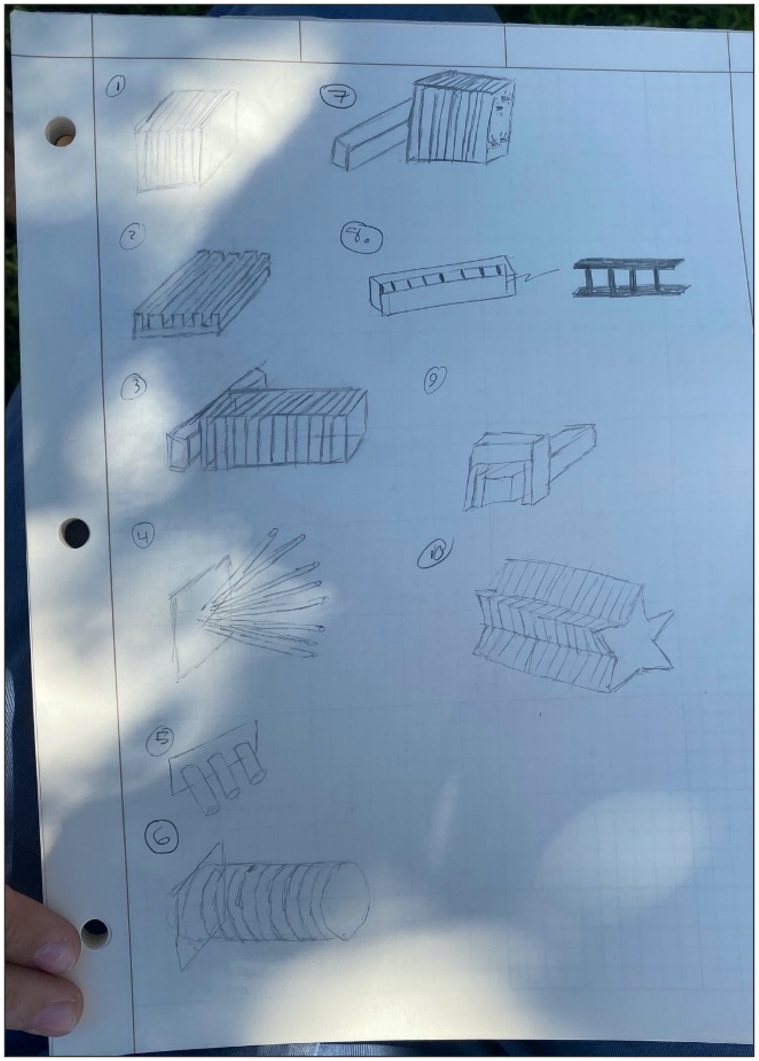
Continued

Key to Ideations Concepts from Pugh Matrix (as numbered in photo):

DATUM is the existing heatsink design (pictured below). Not numbered in the photo of designs to the right.

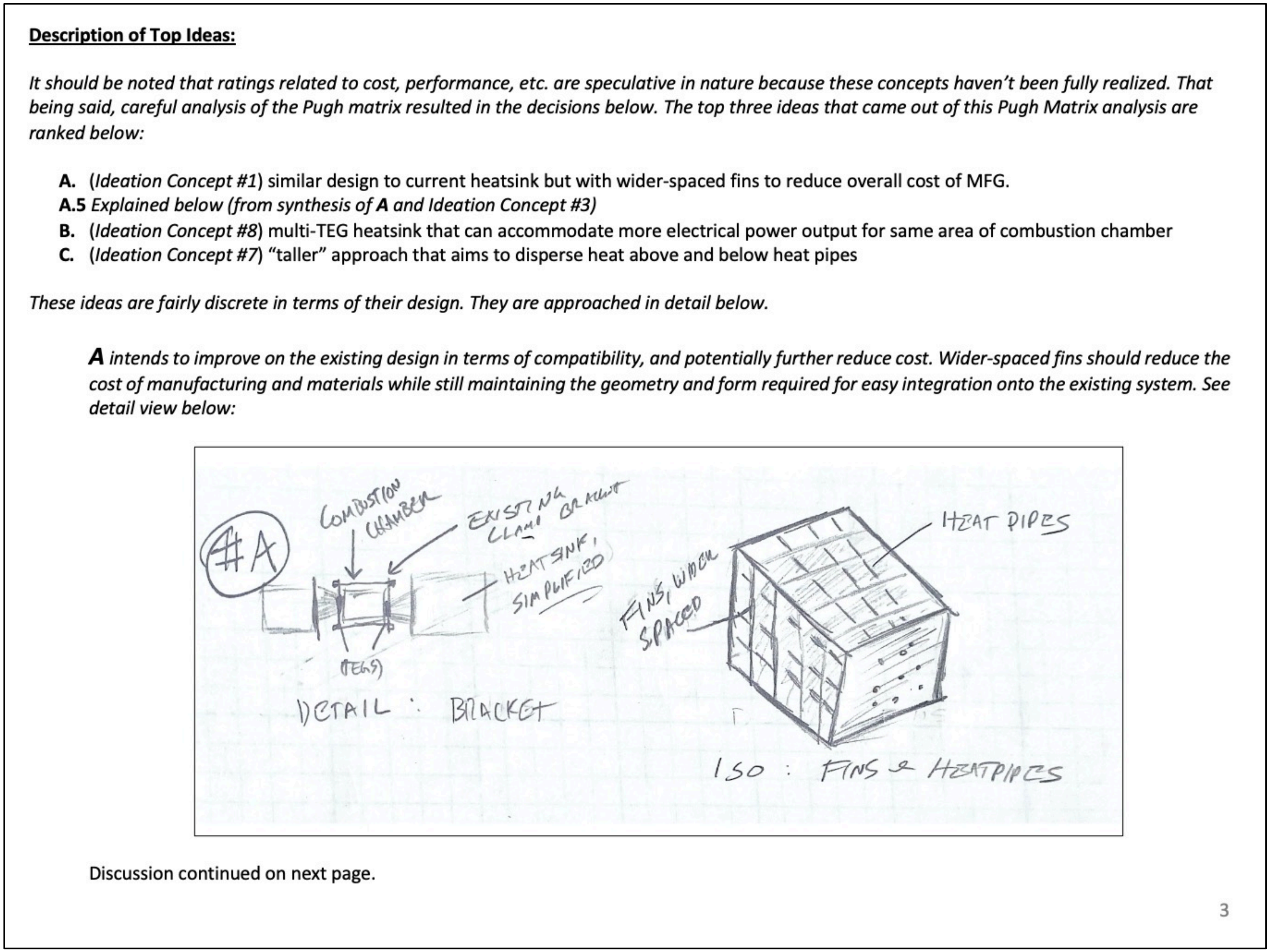


1. *similar design to current heatsink, but with wider-spaced fins to reduce overall cost of MFG. Potentially larger size?*
2. *open-sided heatsink that might radiate heat away more effectively, given that we have more longitudinal freedom than an industrial heatsink (like datum)*
3. *“wider” design that would expose a given heat pipe to more airflow than conventional design*
4. *“radial” design that pushes heat pipes away from center of heat. Might be cheapest to manufacture and not much less effective than the fins*
5. *dispersed “column” design that aims to have more mass of water in the heat pipes to increase capacity for heat transfer via phase change*
6. *cylindrical design – a cylinder might be cheaper and easier to manufacture*
7. *“taller” approach that aims to disperse heat above and below heat pipes*
8. *multi-TEG heatsink that can accommodate more power output on same area of combustion chamber*
9. *“arc to triomphe” design that connects two TEGs and might simplify delicate assembly process*
10. *star design could transfer heat through legs better than a square (surface area decreases but the air gap around it increases)*



Appendix E – Pugh Matrix & "Top" Idea Selection

Continued



Description of Top Ideas:

It should be noted that ratings related to cost, performance, etc. are speculative in nature because these concepts haven't been fully realized. That being said, careful analysis of the Pugh matrix resulted in the decisions below. The top three ideas that came out of this Pugh Matrix analysis are ranked below:

A. (*Ideation Concept #1*) similar design to current heatsink but with wider-spaced fins to reduce overall cost of MFG.
A.5 *Explained below (from synthesis of **A** and Ideation Concept #3)*
B. (*Ideation Concept #8*) multi-TEG heatsink that can accommodate more electrical power output for same area of combustion chamber
C. (*Ideation Concept #7*) "taller" approach that aims to disperse heat above and below heat pipes

These ideas are fairly discrete in terms of their design. They are approached in detail below.

***A** intends to improve on the existing design in terms of compatibility, and potentially further reduce cost. Wider-spaced fins should reduce the cost of manufacturing and materials while still maintaining the geometry and form required for easy integration onto the existing system. See detail view below:*

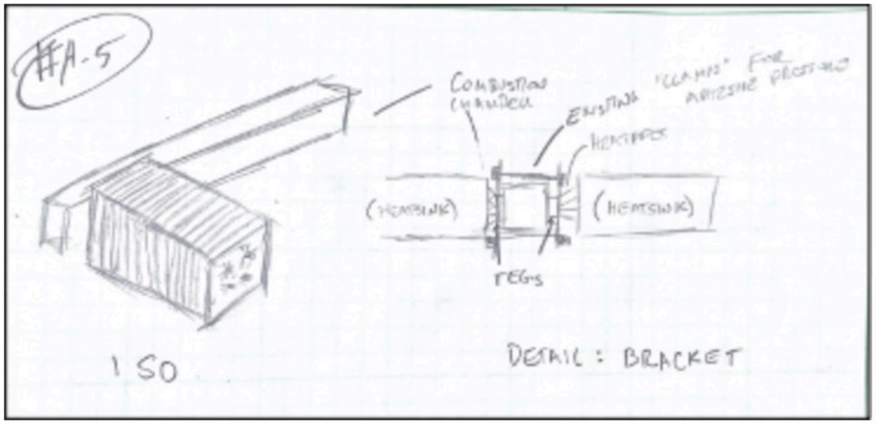
Discussion continued on next page.

Appendix E – Pugh Matrix & “Top” Idea Selection

Continued

That being said, given our recent conversation with the sponsor, it sounds like the highest priority here is to maximize the performance / power output of the system overall. Since then, we have also learned that it will be impossible to extract much more heat via the addition of more TEGs (the combustion chamber is the limit of its output capacity.) This means that it will be vital to not only recreate the existing heatsink’s performance, but hopefully to exceed it by adding more fins / heat-piping etc.

A.5*, will be a combination of* ***A*** *and this new performance consideration. We will optimize for more heat flow by adding more fins / longitudinal size. (The only reason the old one wasn’t any longer is because it was manufactured for use in computer cases, where space is at a premium.) Here’s a quick sketch of what this new idea could be:*

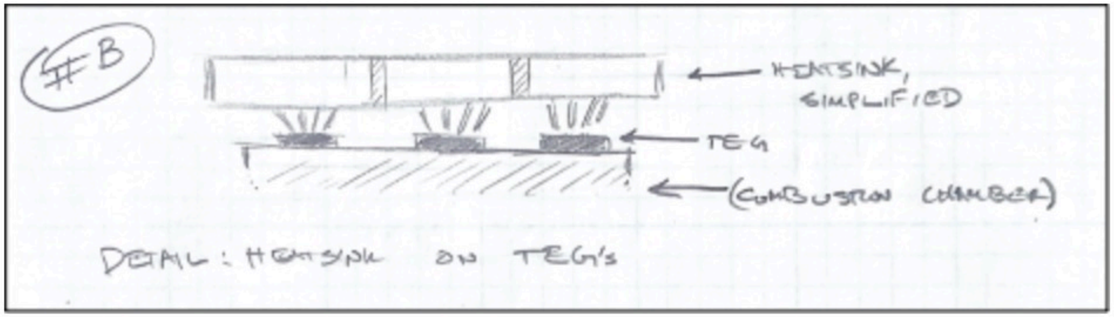


One could be forgiven for mistaking design ***A.5*** *for Ideation Concept #3). The key difference between these, and the reason why I.C. #3 didn’t make it to the final round, is that* ***A.5*** *is intended to better fit the existing hardware, and will be designed with this in mind. Given the information from the sponsor mentioned above, this seems like the natural direction to go. One specific detail of how this might be achieved is by accommodating for the existing mounting solution proposed by the sponsor. The heatsinks are very sensitive to normal surface pressure they experience during operation. By use of crush washers, the sponsor was able to use a “clamp” system to hold two heatsinks with threaded rod and specially chosen crush washers. We will try to accommodate for this in design* ***A.5****.*

B *will focus on trying to accommodate the most heat transfer area possible for the given number of TEGs. What’s interesting to note is that it was originally intended to enable the addition of further TEGs to the combustion chamber. Perhaps one could blame our thermodynamic naïveté, but our assumption was the combustion chamber had more to “give”. In reality, for the air inflow and exhaust outflow, the 4-6 # of TEGs is going to be optimal for the given geometry. It should also be noted that the sponsor is motivated to keep the existing combustion chamber given the timeline of the project on a larger scale. A slightly modified version of I.D. #8, with this in mind, is pictured on next page.*

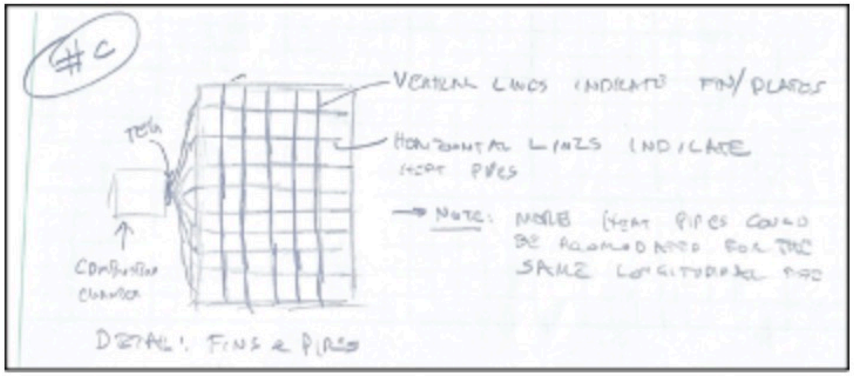
Appendix E – Pugh Matrix & "Top" Idea Selection

Continued



Note the cross-hatched sections in the sketch above. These indicate the potential cross-sectional area of heatsink that would be gained via this design. Obviously, with different approaches to the geometry, this "gained" area over individual units could be maximized. Another advantage here is that, with two identical "long" heatsinks, one on each side of the combustion chamber, mounting hardware could be minimized since it's only one body being held on with the TEGs for a given side. This could potentially simplify install, assembly, and BoM complexity, but it still remains to be seen if a consistent pressure can be obtained on the TEGs with this proposed design.

***C** is another take on how to improve the ability of the unit to dissipate heat for a given TEG. The idea is to allow for more heat transfer across a given fin/plate as its cross-sectional area is expanded up and down for the same number of heat pipe(s) passing through it – or potentially more! This definitely a viable concept and worth investigating. It also raises the interesting question of whether a wider or taller heatsink would be more efficiency compared to a common baseline. The decision between a design like **A.5** versus a design like **C** will likely be driven by system-level geometric constraints, depending on the outcomes of simulations and further testing. See detail view below:*



Appendix E – Pugh Matrix & "Top" Idea Selection

Continued

Peyton Nienaber (Team F16) – Pugh Matrix

Key: ***S*** *(Same as Datum),* **+** *(Better than Datum), - (Worse than Datum)*

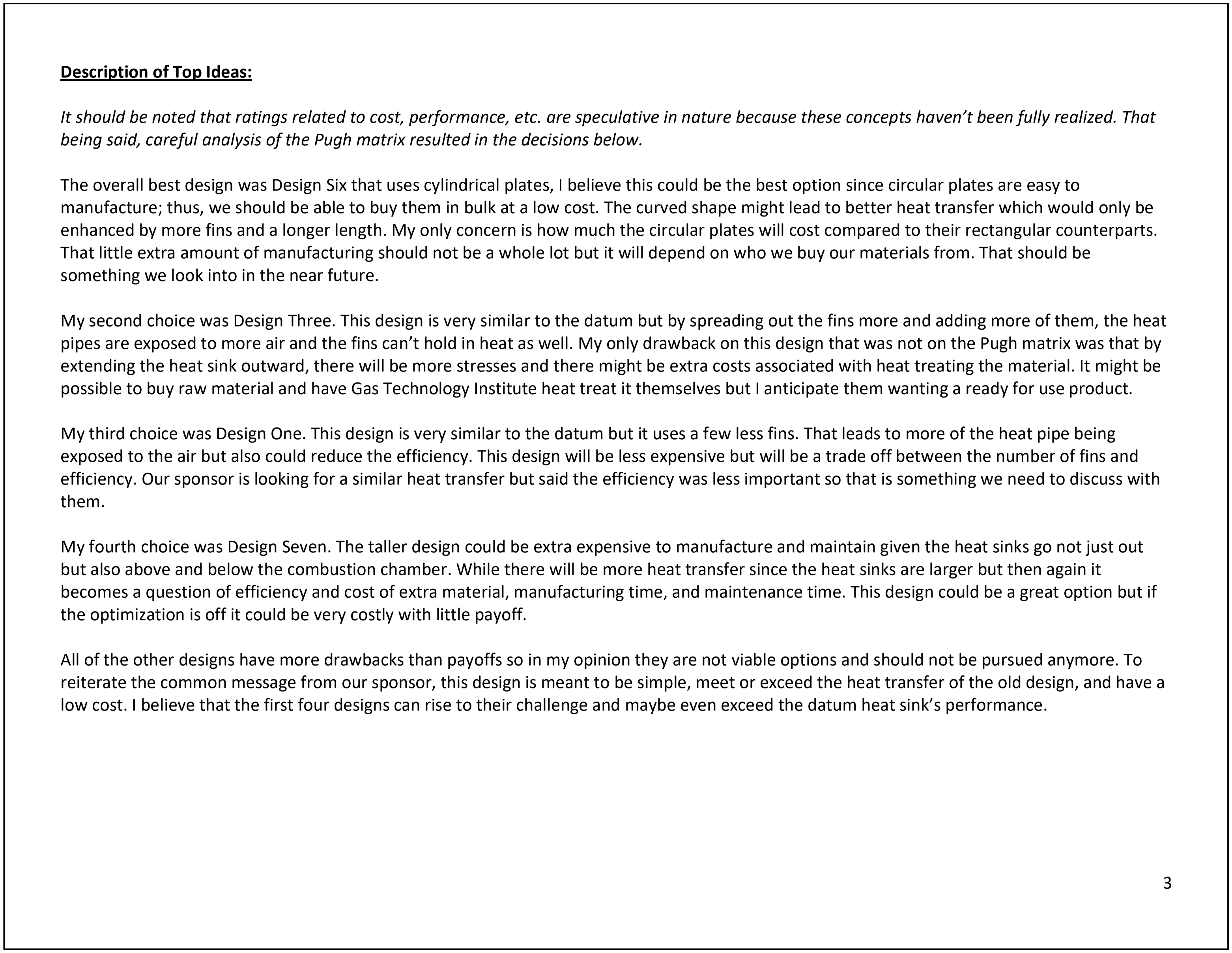
Criteria	**DATUM**	1	2	3	4	5	6	7	8	9	**10**
Sufficient ΔT	S	-	+	+	-	-	+	+	S	S	+
Low Transient Period	S	-	+	+	-	-	+	+	S	S	+
Inexpensive to manufacture	S	+	-	-	+	-	S	-	-	-	-
Low Maintenance Interval	S	S	+	S	-	+	S	-	+	+	-
Manufacturable at a large volume	S	+	-	S	+	+	S	S	-	-	-
Utilizes commercially available materials	S	S	-	S	-	-	S	S	-	-	-
Utilize inexpensive manufacturing techniques	S	S	-	S	+	-	S	S	-	-	-

Function(s): ***Create a temperature differential, Decrease cost, utilize only scalable manufacturing***

See next page for detail view of concepts 1-10 & datum.

Appendix E – Pugh Matrix & “Top” Idea Selection

Continued



Description of Top Ideas:

It should be noted that ratings related to cost, performance, etc. are speculative in nature because these concepts haven’t been fully realized. That being said, careful analysis of the Pugh matrix resulted in the decisions below.

The overall best design was Design Six that uses cylindrical plates, I believe this could be the best option since circular plates are easy to manufacture; thus, we should be able to buy them in bulk at a low cost. The curved shape might lead to better heat transfer which would only be enhanced by more fins and a longer length. My only concern is how much the circular plates will cost compared to their rectangular counterparts. That little extra amount of manufacturing should not be a whole lot but it will depend on who we buy our materials from. That should be something we look into in the near future.

My second choice was Design Three. This design is very similar to the datum but by spreading out the fins more and adding more of them, the heat pipes are exposed to more air and the fins can’t hold in heat as well. My only drawback on this design that was not on the Pugh matrix was that by extending the heat sink outward, there will be more stresses and there might be extra costs associated with heat treating the material. It might be possible to buy raw material and have Gas Technology Institute heat treat it themselves but I anticipate them wanting a ready for use product.

My third choice was Design One. This design is very similar to the datum but it uses a few less fins. That leads to more of the heat pipe being exposed to the air but also could reduce the efficiency. This design will be less expensive but will be a trade off between the number of fins and efficiency. Our sponsor is looking for a similar heat transfer but said the efficiency was less important so that is something we need to discuss with them.

My fourth choice was Design Seven. The taller design could be extra expensive to manufacture and maintain given the heat sinks go not just out but also above and below the combustion chamber. While there will be more heat transfer since the heat sinks are larger but then again it becomes a question of efficiency and cost of extra material, manufacturing time, and maintenance time. This design could be a great option but if the optimization is off it could be very costly with little payoff.

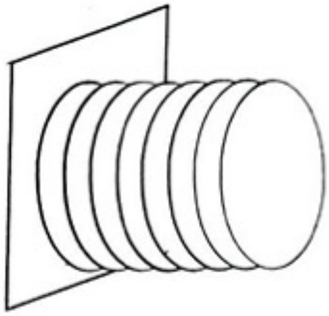
All of the other designs have more drawbacks than payoffs so in my opinion they are not viable options and should not be pursued anymore. To reiterate the common message from our sponsor, this design is meant to be simple, meet or exceed the heat transfer of the old design, and have a low cost. I believe that the first four designs can rise to their challenge and maybe even exceed the datum heat sink’s performance.

Appendix E – Pugh Matrix & “Top” Idea Selection

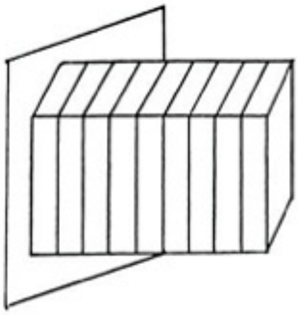
Continued

ME 428 PUGH MATRIX P. NIENABER

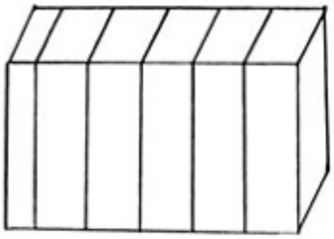
TOP DESIGN



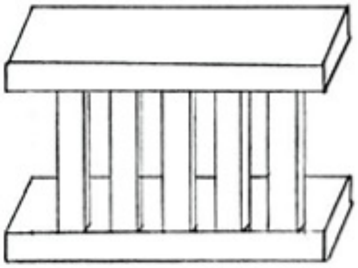
SECOND CHOICE



THIRD CHOICE



FOURTH CHOICE (TOP VIEW)



Appendix E – Pugh Matrix & “Top” Idea Selection

Continued

Jack Waeschle (Team F16) – Pugh Matrix

Criteria	DATUM	1	2	3	4	5	6	7	8	9	10
Maximize Temperature Differential	**S**	**-**	**+**	**+**	**-**	**-**	**-**	**+**	**S**	**-**	**S**
Comparable performance to existing design	**S**	**S**	**+**	**+**	**-**	**-**	**S**	**+**	**S**	**-**	**S**
Functions in variety of temperatures	**S**	**S**	**S**	**S**	**S**	**-**	**S**	**S**	**S**	**-**	**S**
Insulated from hot side combustion chamber	**S**	**S**	**+**	**+**	**+**	**S**	**-**	**S**	**S**	**-**	**+**
Space Efficient	**S**	**-**	**-**	**+**	**-**	**-**	**-**	**+**	**+**	**+**	**-**

Function(s): ***Create a Temperature Differential***

Key: ***S*** *(Same as Datum),* ***+*** *(Improvement), - (Worse than Datum)*

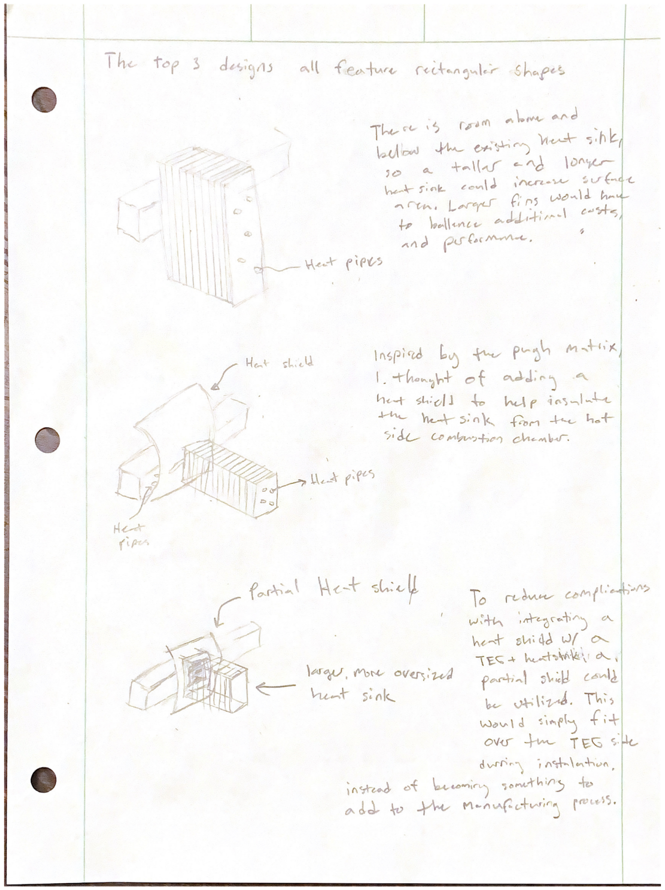
See next page for detail view of concepts 1-10 & datum.

Appendix E – Pugh Matrix & “Top” Idea Selection

Continued

Description of Top Ideas:

It should be noted that ratings related to cost, performance, etc. are speculative in nature because these concepts haven’t been fully realized. Careful analysis of the Pugh matrix resulted in the decisions below



The top 3 designs all feature rectangular shapes

There is room above and bellow the existing heat sink, so a taller and longer heat sink could increase surface area. Larger fins would have to ballence additional costs, and performance.

Inspired by the pugh matrix, I thought of adding a heat shield to help insulate the heat sink from the hot side combustion chamber.

To reduce complications with integrating a heat shield w/ a TEG + heatsink, a partial shield could be utilized. This would simply fit over the TEG side during instalation, instead of becoming something to add to the manufacturing process.

Appendix F – Preliminary Thermal Analysis (Sponsor Efforts)

Abdelallah Ahmed of Gas Technology Institute has performed some simple 1-dimensional numerical analysis on a rough performance model of the existing heatsink used by GTI. The results have yielded performance metrics that will be used as objectives for future designs. Included below, in Figures F-1 and F-2, is a clipping that was provided to Team F16 for reference:

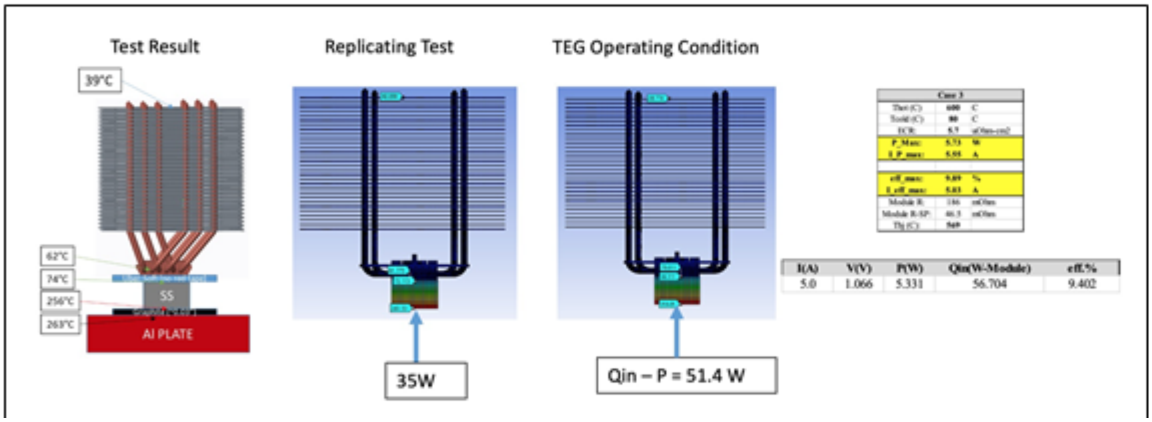
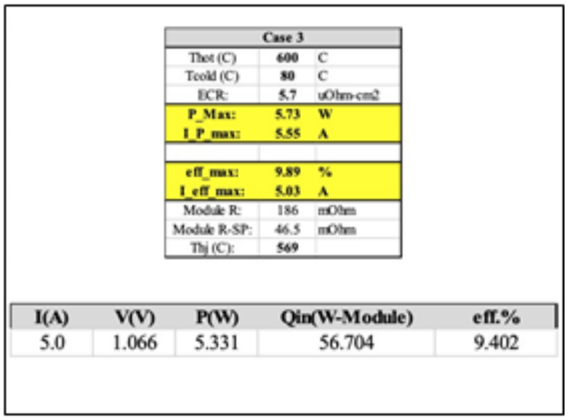


Figure F-1. Analysis of Discontinued Heatsink (Model) [2].

Inspection of Figure 9 (see report body) reveals some insight into manufacturing heatsinks for low-cost applications. Note the use of closed-system condensation/evaporation heat pipes and relatively cheap assembly. Spacing of fins is also simply achieved via metal strips that can hold punched-out metal plates in place. This will serve as a basis for cheap manufacturing techniques moving forward.



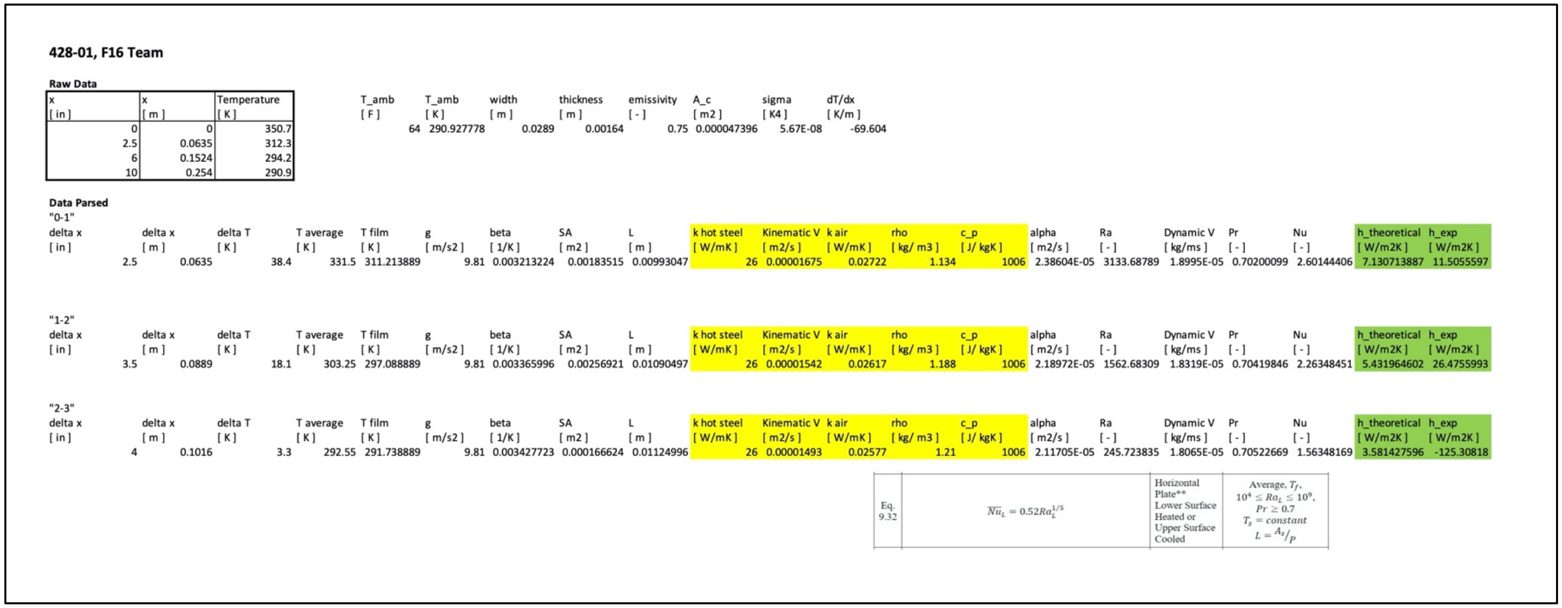
Case 3		
Thot (C)	600	C
Tcold (C)	80	C
ECR:	5.7	uOhm-cm2
P_Max:	5.73	W
I_P_max:	5.55	A
eff_max:	9.89	%
I_eff_max:	5.03	A
Module R:	186	mOhm
Module R-SP:	46.5	mOhm
Thj (C):	569	

I(A)	V(V)	P(W)	Qin(W-Module)	eff.%
5.0	1.066	5.331	56.704	9.402

Figure F-2. Analysis of Discontinued Heatsink (Results) [3].

It should be noted that this analysis also encompasses the thermoelectric generator (TEG) efficiency. This data is slightly out of date; however, as it was based on technology available from a joint project with the aerospace private sector. The TEG that will be implemented into the MMTEG product is slightly less efficient, with the range of operation efficiencies spanning from 3 to 5%. More detailed analysis will be conducted further into the project. The intention of this appendix is only to give context to this later work.

Appendix G – Excel Post-Processing of Concept Prototype Data



428-01, F16 Team

Raw Data

x [in]	x [m]	Temperature [K]
0	0	350.7
2.5	0.0635	312.3
6	0.1524	294.2
10	0.254	290.9

T_amb [F]	T_amb [K]	width [m]	thickness [m]	emissivity [-]	A_c [m2]	sigma [K4]	dT/dx [K/m]
64	290.927778	0.0289	0.00164	0.75	0.000047396	5.67E-08	-69.604

Data Parsed

"0-1"

delta x [in]	delta x [m]	delta T [K]	T average [K]	T film [K]	g [m/s2]	beta [1/K]	SA [m2]	L [m]	k hot steel [W/mK]	Kinematic V [m2/s]	k air [W/mK]	rho [kg/ m3]	c_p [J/ kgK]	alpha [m2/s]	Ra [-]	Dynamic V [kg/ms]	Pr [-]	Nu [-]	h_theoretical [W/m2K]	h_exp [W/m2K]
2.5	0.0635	38.4	331.5	311.213889	9.81	0.003213224	0.00183515	0.00993047	26	0.00001675	0.02722	1.134	1006	2.38604E-05	3133.68789	1.8995E-05	0.70200099	2.60144406	7.130713887	11.5055597

"1-2"

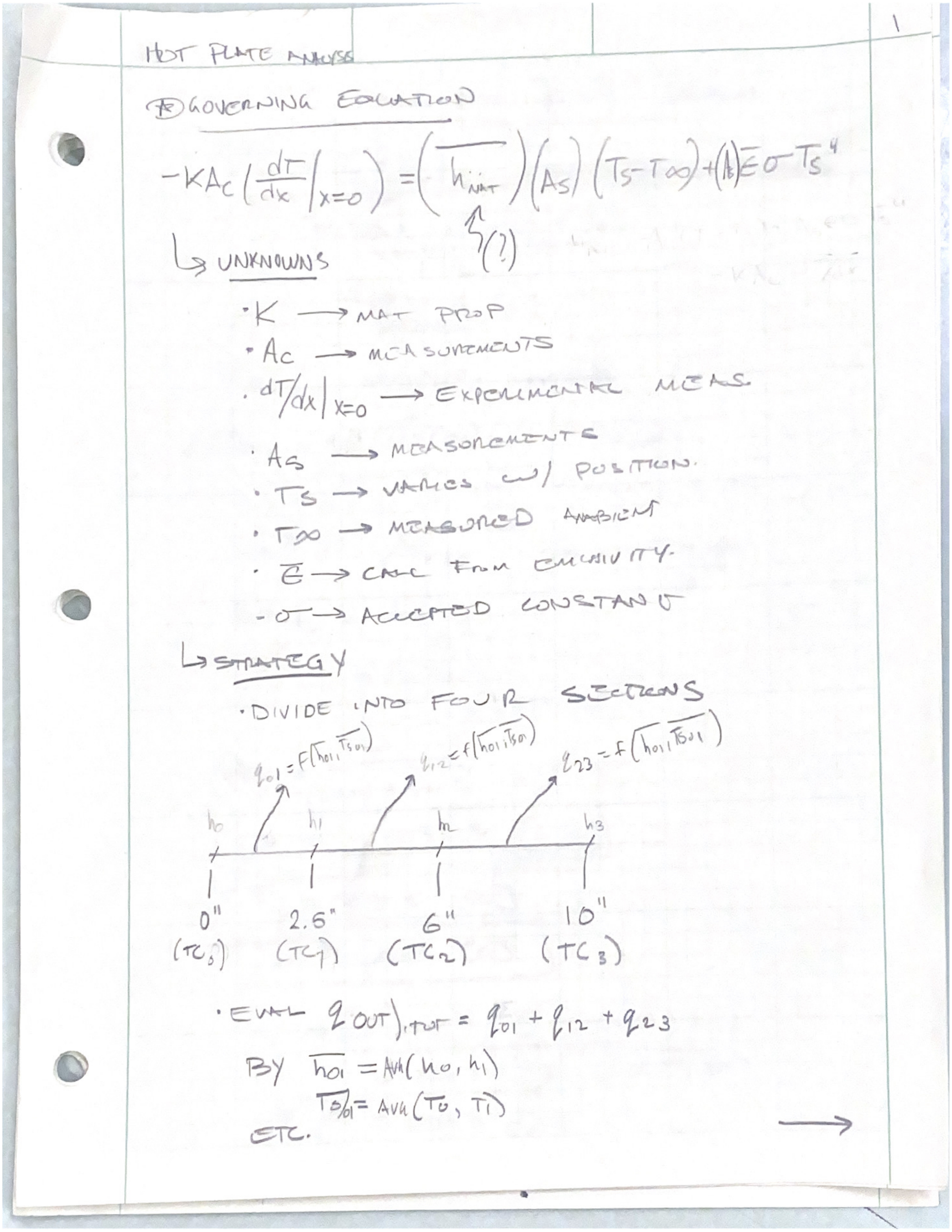
delta x [in]	delta x [m]	delta T [K]	T average [K]	T film [K]	g [m/s2]	beta [1/K]	SA [m2]	L [m]	k hot steel [W/mK]	Kinematic V [m2/s]	k air [W/mK]	rho [kg/ m3]	c_p [J/ kgK]	alpha [m2/s]	Ra [-]	Dynamic V [kg/ms]	Pr [-]	Nu [-]	h_theoretical [W/m2K]	h_exp [W/m2K]
3.5	0.0889	18.1	303.25	297.088889	9.81	0.003365996	0.00256921	0.01090497	26	0.00001542	0.02617	1.188	1006	2.18972E-05	1562.68309	1.8319E-05	0.70419846	2.26348451	5.431964602	26.4755993

"2-3"

delta x [in]	delta x [m]	delta T [K]	T average [K]	T film [K]	g [m/s2]	beta [1/K]	SA [m2]	L [m]	k hot steel [W/mK]	Kinematic V [m2/s]	k air [W/mK]	rho [kg/ m3]	c_p [J/ kgK]	alpha [m2/s]	Ra [-]	Dynamic V [kg/ms]	Pr [-]	Nu [-]	h_theoretical [W/m2K]	h_exp [W/m2K]
4	0.1016	3.3	292.55	291.738889	9.81	0.003427723	0.000166624	0.01124996	26	0.00001493	0.02577	1.21	1006	2.11705E-05	245.723835	1.8065E-05	0.70522669	1.56348169	3.581427596	-125.30818

Eq. 9.32	$\overline{Nu}_L = 0.52Ra_L^{1/5}$	Horizontal Plate** Lower Surface Heated or Upper Surface Cooled	Average, T_f, $10^4 \le Ra_L \le 10^9$, $Pr \ge 0.7$ $T_s = constant$ $L = {A_s}/{P}$

Appendix H – Concept Prototype Post-Processing Hand Calculations



HOT PLATE ANALYSIS

1

⊛ GOVERNING EQUATION

$$-KA_C\left(\frac{dT}{dx}\Big|_{x=0}\right)=\left(\overline{h_{NAT}}\right)(A_S)(T_S-T_\infty)+(A_S)\bar{\varepsilon}\sigma T_S^4$$

(?)

↳ UNKNOWNS

- K → MAT PROP
- A_C → MEASUREMENTS
- $dT/dx|_{x=0}$ → EXPERIMENTAL MEAS.
- A_S → MEASUREMENTS
- T_S → VARIES W/ POSITION.
- T_∞ → MEASURED AMBIENT
- $\bar{\varepsilon}$ → CALC FROM EMISSIVITY.
- σ → ACCEPTED CONSTANT

↳ STRATEGY

- DIVIDE INTO FOUR SECTIONS

$q_{01}=f(\overline{h_{01}},\overline{T_{s01}})$

$q_{12}=f(\overline{h_{01}},\overline{T_{s01}})$

$q_{23}=f(\overline{h_{01}},\overline{T_{s01}})$

- EVAL $q_{OUT})_{TOT}=q_{01}+q_{12}+q_{23}$

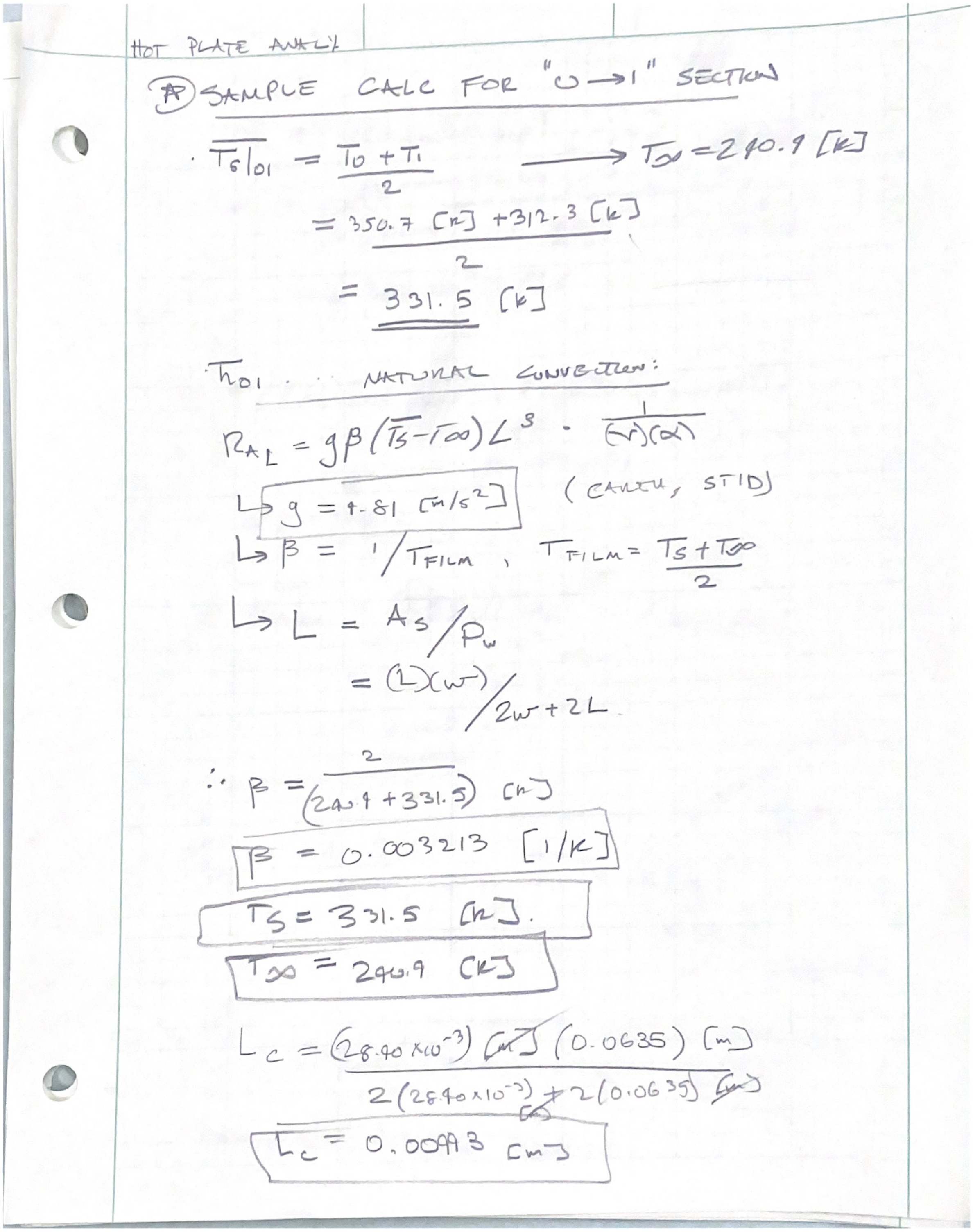
BY $\overline{h_{01}}=AVG(h_0,h_1)$

$\overline{T_{S01}}=AVG(T_0,T_1)$

ETC. →

Appendix H – Concept Prototype Post-Processing Hand Calculations

Continued



HOT PLATE ANALY

Ⓐ SAMPLE CALC FOR "0 → 1" SECTION

$$\overline{T_S}\big|_{01} = \frac{T_0 + T_1}{2} \longrightarrow T_\infty = 240.9\ [K]$$

$$= \frac{350.7\ [K] + 312.3\ [K]}{2}$$

$$= \underline{\underline{331.5}}\ [K]$$

h_{01} ... NATURAL CONVECTION:

$$Ra_L = g\beta(\overline{T_S} - T_\infty)L^3 \cdot \frac{1}{(\nu)(\alpha)}$$

$$\hookrightarrow \boxed{g = 9.81\ [m/s^2]}\ \text{(EARTH, STD)}$$

$$\hookrightarrow \beta = 1/T_{FILM}\ ,\quad T_{FILM} = \frac{T_S + T_\infty}{2}$$

$$\hookrightarrow L = A_S / P_w$$

$$= (L)(w) / 2w + 2L$$

$$\therefore \beta = \frac{2}{(240.9 + 331.5)}\ [K]$$

$$\boxed{\beta = 0.003213\ [1/K]}$$

$$\boxed{T_S = 331.5\ [K].}$$

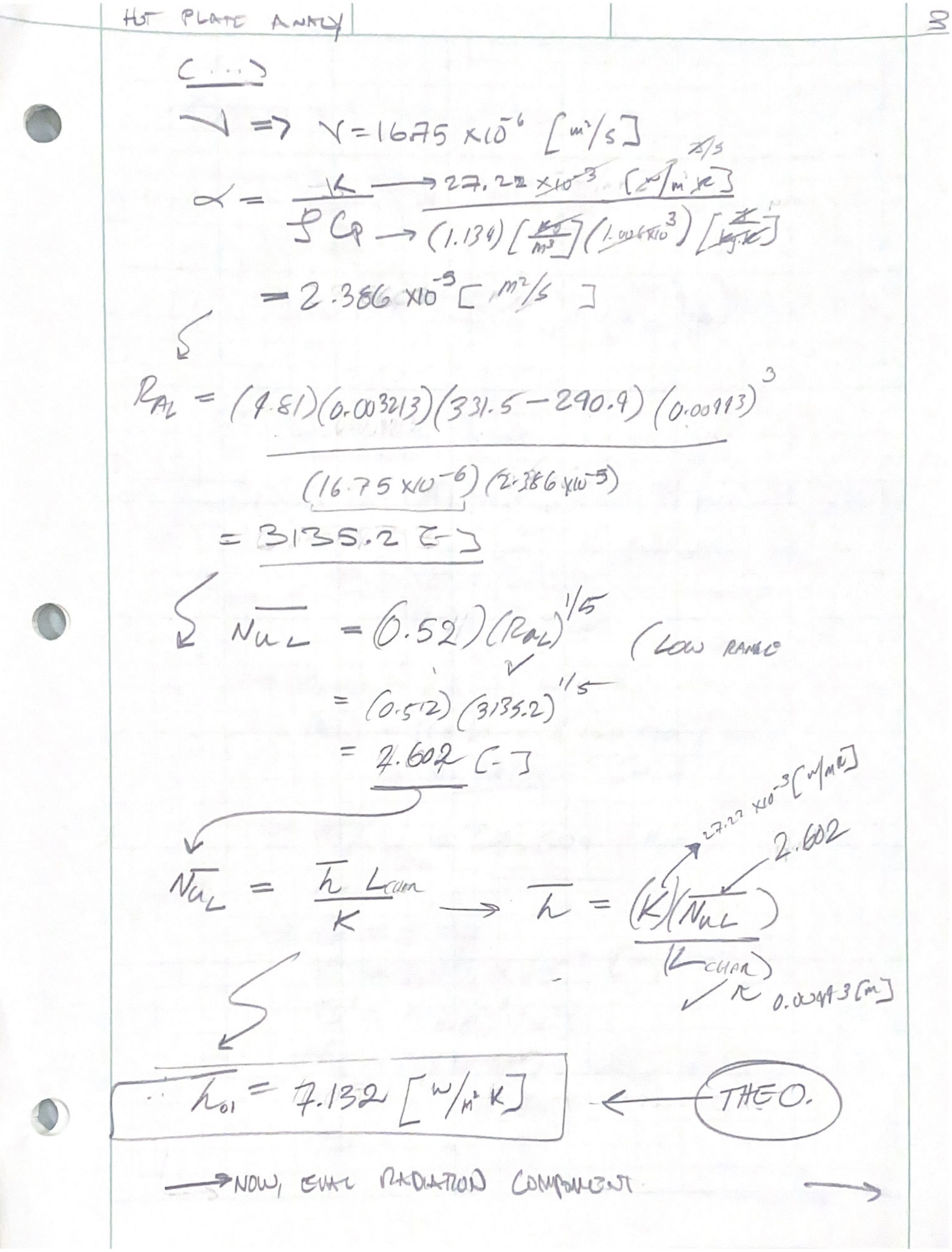
$$\boxed{T_\infty = 240.9\ [K]}$$

$$L_c = \frac{(28.40 \times 10^{-3})\ \cancel{[m]}\ (0.0635)\ [m]}{2(28.40 \times 10^{-3})\ \cancel{[m]} + 2(0.0635)\ \cancel{[m]}}$$

$$\boxed{L_c = 0.00993\ [m]}$$

Appendix H – Concept Prototype Post-Processing Hand Calculations

Continued



HOT PLATE ANALY

3

(...)

$\nu \Rightarrow \nu = 1675 \times 10^{-6}\ [m^2/s]$

$$\alpha = \frac{k}{\rho C_p} \rightarrow \frac{27.22\ \cancel{\times 10^{-3}}\ [\cancel{W}/m \cdot \cancel{K}]}{(1.134)\,[\cancel{kg}/m^3]\,(1.006 \times 10^3)\,[\cancel{J}/\cancel{kg \cdot K}]}$$

J/s

$= 2.386 \times 10^{-5}\ [m^2/s]$

$$Ra_L = \frac{(9.81)(0.003213)(331.5 - 290.9)(0.00993)^3}{(16.75 \times 10^{-6})(2.386 \times 10^{-5})}$$

$= \underline{3135.2\ [-]}$

$\overline{Nu_L} = (0.52)(Ra_L)^{1/5}$ (LOW RANGE

$= (0.512)(3135.2)^{1/5}$

$= \underline{7.602}\ [-]$

$$\overline{Nu_L} = \frac{\overline{h}\, L_{char}}{k} \rightarrow \overline{h} = \frac{(k)(\overline{Nu_L})}{(L_{char})}$$

$27.22 \times 10^{-3}\ [W/mK]$

2.602

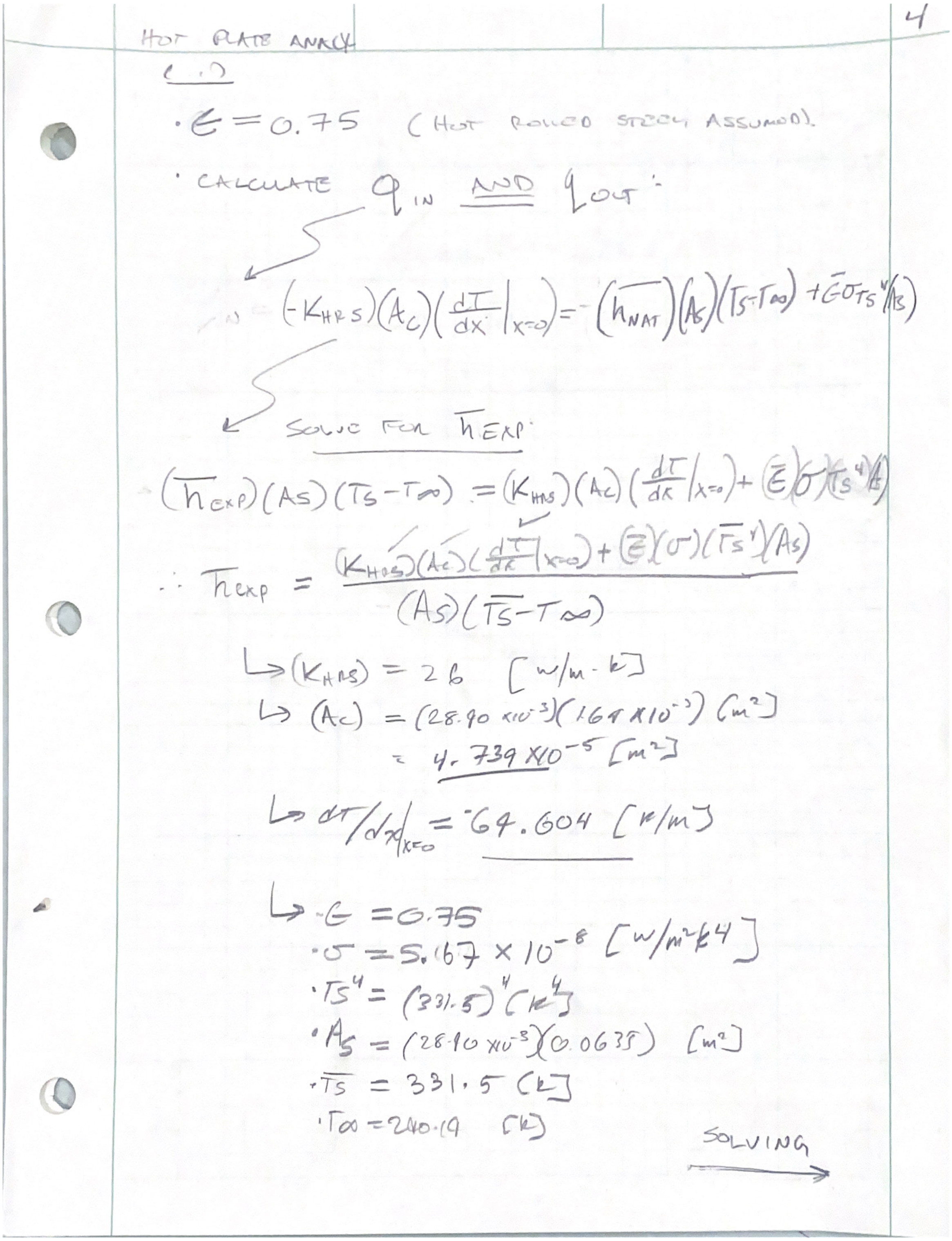
$0.00993\ [m]$

$$\boxed{\therefore\ \overline{h}_{o1} = 7.132\ [W/m^2 K]} \leftarrow \text{THEO.}$$

→ NOW, EVAL RADIATION COMPONENT →

Appendix H – Concept Prototype Post-Processing Hand Calculations

Continued



4

HOT PLATE ANALY

[illegible]

- $\epsilon = 0.75$ (HOT ROLLED STEEL ASSUMED).
- CALCULATE q_{IN} AND q_{OUT}:

$$q_{IN} = (-K_{HRS})(A_c)\left(\frac{dT}{dx}\Big|_{x=0}\right) = -(\bar{h}_{NAT})(A_s)(T_s - T_\infty) + \epsilon\sigma T_s^4 (A_s)$$

SOLVE FOR $\bar{h}_{EXP}$:

$$(\bar{h}_{EXP})(A_s)(T_s - T_\infty) = (K_{HRS})(A_c)\left(\frac{dT}{dx}\Big|_{x=0}\right) + (\bar{\epsilon})(\sigma)(T_s^4)(A_s)$$

$$\therefore \bar{h}_{exp} = \frac{(K_{HRS})(A_c)\left(\frac{dT}{dx}\Big|_{x=0}\right) + (\bar{\epsilon})(\sigma)(\bar{T}_s^4)(A_s)}{(A_s)(\bar{T}_s - T_\infty)}$$

$\hookrightarrow (K_{HRS}) = 26$ [w/m · k]

$\hookrightarrow (A_c) = (28.90 \times 10^{-3})(1.64 \times 10^{-3})$ [m²]

$= \underline{4.739 \times 10^{-5}}$ [m²]

$\hookrightarrow dT/dx|_{x=0} = \underline{-64.604}$ [K/m]

$\hookrightarrow$
- $\epsilon = 0.75$
- $\sigma = 5.67 \times 10^{-8}$ [w/m²k⁴]
- $T_s^4 = (331.5)^4$ [k⁴]
- $A_s = (28.90 \times 10^{-3})(0.0635)$ [m²]
- $\bar{T}_s = 331.5$ [k]
- $T_\infty = 240.19$ [k]

SOLVING $\longrightarrow$

Appendix H – Concept Prototype Post-Processing Hand Calculations

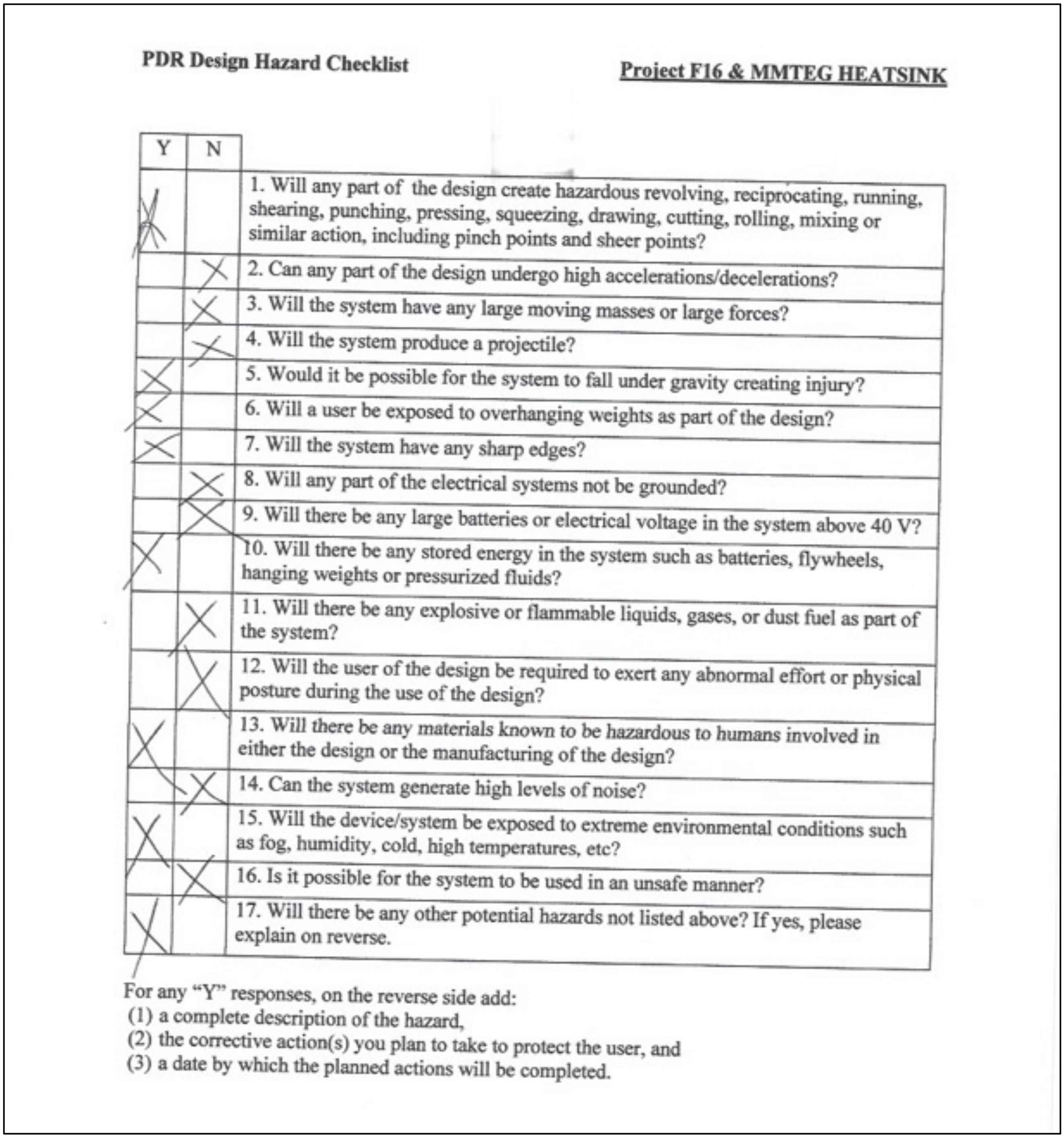
Continued

HOT PLATE ANALY.

$$\therefore \bar{h}_{exp})_{01} = \left\{ (26)(4.739 \times 10^{-5})(-69.604) + (0.75)(5.67 \times 10^{-8})(331.5)^4 (28.90 \times 10^{-3})(0.0635) \right\} \cdot \frac{1}{(1)(26.40 \times 10^{-3})(0.0625)(331.5 - 290.19)}$$

$$\boxed{\bar{h}_{exp})_{01} = 11.300 \; [W/m^2 K]}$$

Appendix I – Design Hazard Checklist & Appropriate Measures



PDR Design Hazard Checklist

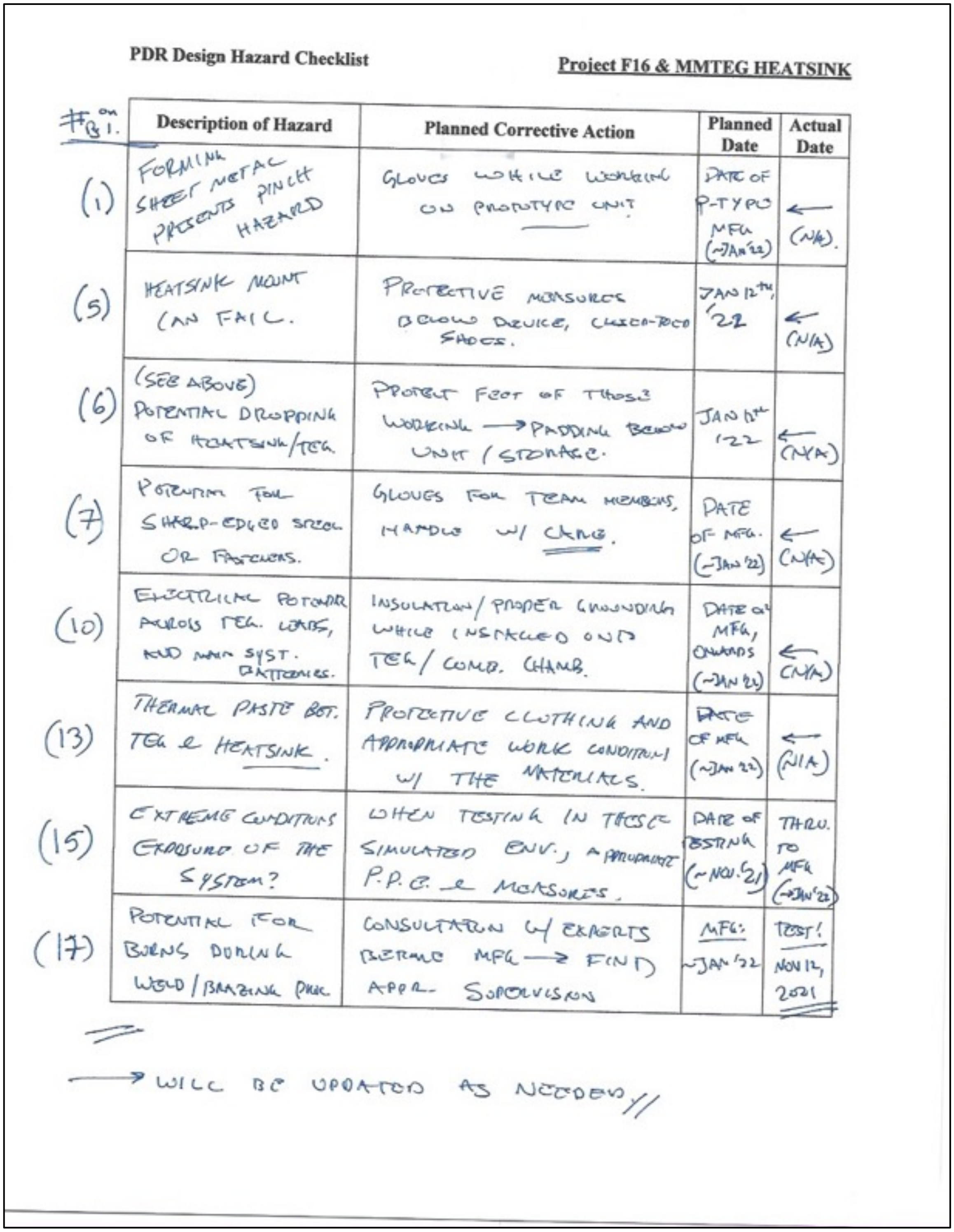
Project F16 & MMTEG HEATSINK

Y	N	
X		1. Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?
	X	2. Can any part of the design undergo high accelerations/decelerations?
	X	3. Will the system have any large moving masses or large forces?
	X	4. Will the system produce a projectile?
X		5. Would it be possible for the system to fall under gravity creating injury?
X		6. Will a user be exposed to overhanging weights as part of the design?
X		7. Will the system have any sharp edges?
	X	8. Will any part of the electrical systems not be grounded?
	X	9. Will there be any large batteries or electrical voltage in the system above 40 V?
X		10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
	X	11. Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?
	X	12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
X		13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
	X	14. Can the system generate high levels of noise?
X		15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc?
	X	16. Is it possible for the system to be used in an unsafe manner?
X		17. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

For any "Y" responses, on the reverse side add:
(1) a complete description of the hazard,
(2) the corrective action(s) you plan to take to protect the user, and
(3) a date by which the planned actions will be completed.

Appendix I – Design Hazard Checklist & Appropriate Measures

Continued



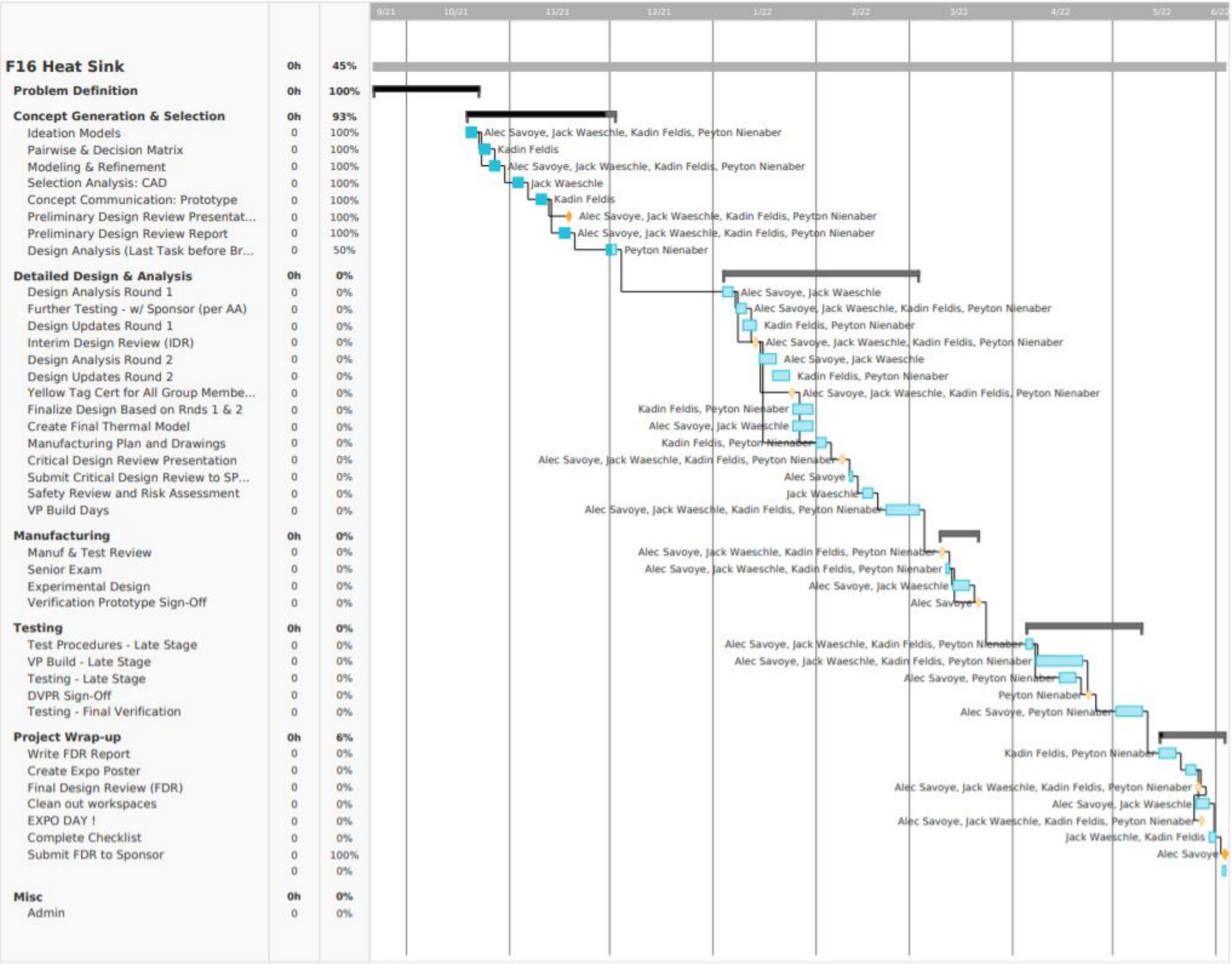
PDR Design Hazard Checklist

Project F16 & MMTEG HEATSINK

# on B.I.	Description of Hazard	Planned Corrective Action	Planned Date	Actual Date
(1)	FORMING SHEET METAL PRESENTS PINCH HAZARD	GLOVES WHILE WORKING ON PROTOTYPE UNIT	DATE OF P-TYPE MFG (~JAN '22)	← (N/A).
(5)	HEATSINK MOUNT CAN FAIL.	PROTECTIVE MEASURES BELOW DEVICE, CLOSED-TOED SHOES.	JAN 12th, '22	← (N/A)
(6)	(SEE ABOVE) POTENTIAL DROPPING OF HEATSINK/TEG	PROTECT FEET OF THOSE WORKING → PADDING BELOW UNIT / STORAGE.	JAN 12th '22	← (N/A)
(7)	POTENTIAL FOR SHARP-EDGED STEEL OR FASTENERS.	GLOVES FOR TEAM MEMBERS, HANDLE W/ CARE.	DATE OF MFG. (~JAN '22)	← (N/A)
(10)	ELECTRICAL POTENTIAL ACROSS TEG. LEADS, AND MAIN SYST. BATTERIES.	INSULATION/ PROPER GROUNDING WHILE INSTALLED ONTO TEG / COMB. CHAMB.	DATE OF MFG, ONWARDS (~JAN '22)	← (N/A)
(13)	THERMAL PASTE BET. TEG & HEATSINK.	PROTECTIVE CLOTHING AND APPROPRIATE WORK CONDITIONS W/ THE MATERIALS.	DATE OF MFG (~JAN '22)	← (N/A)
(15)	EXTREME CONDITIONS EXPOSURE OF THE SYSTEM?	WHEN TESTING IN THESE SIMULATED ENV., APPROPRIATE P.P.E. & MEASURES.	DATE OF TESTING (~NOV. '21)	THRU. TO MFG (~JAN '22)
(17)	POTENTIAL FOR BURNS DURING WELD / BRAZING PROC.	CONSULTATION W/ EXPERTS BEFORE MFG → FIND APPR. SUPERVISION	MFG: ~JAN '22	TEST! NOV 12, 2021

→ WILL BE UPDATED AS NEEDED //

Appendix J – Project Gantt Chart



F16 Heat Sink	**0h**	**45%**
Problem Definition	**0h**	**100%**
Concept Generation & Selection	**0h**	**93%**
Ideation Models	0	100%
Pairwise & Decision Matrix	0	100%
Modeling & Refinement	0	100%
Selection Analysis: CAD	0	100%
Concept Communication: Prototype	0	100%
Preliminary Design Review Presentat...	0	100%
Preliminary Design Review Report	0	100%
Design Analysis (Last Task before Br...	0	50%
Detailed Design & Analysis	**0h**	**0%**
Design Analysis Round 1	0	0%
Further Testing - w/ Sponsor (per AA)	0	0%
Design Updates Round 1	0	0%
Interim Design Review (IDR)	0	0%
Design Analysis Round 2	0	0%
Design Updates Round 2	0	0%
Yellow Tag Cert for All Group Membe...	0	0%
Finalize Design Based on Rnds 1 & 2	0	0%
Create Final Thermal Model	0	0%
Manufacturing Plan and Drawings	0	0%
Critical Design Review Presentation	0	0%
Submit Critical Design Review to SP...	0	0%
Safety Review and Risk Assessment	0	0%
VP Build Days	0	0%
Manufacturing	**0h**	**0%**
Manuf & Test Review	0	0%
Senior Exam	0	0%
Experimental Design	0	0%
Verification Prototype Sign-Off	0	0%
Testing	**0h**	**0%**
Test Procedures - Late Stage	0	0%
VP Build - Late Stage	0	0%
Testing - Late Stage	0	0%
DVPR Sign-Off	0	0%
Testing - Final Verification	0	0%
Project Wrap-up	**0h**	**6%**
Write FDR Report	0	0%
Create Expo Poster	0	0%
Final Design Review (FDR)	0	0%
Clean out workspaces	0	0%
EXPO DAY !	0	0%
Complete Checklist	0	0%
Submit FDR to Sponsor	0	100%
	0	0%
Misc	**0h**	**0%**
Admin	0	0%

PART III - CRITICAL DESIGN REVIEW

MMTEG Heatsink Design

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February 10th, 2022

Abstract

In this document, Cal Poly Senior Design Team F16 presents their most recent findings in the development of a heatsink for Gas Technology Institute's *Methane Mitigation Thermoelectric Generator*. Preliminary trade studies have been conducted with the help of ANSYS® heat transfer modeling software to determine manufacturable base geometry with satisfactory performance. With the outcomes of this work, a similar configuration to GTI's existing heatsink has been identified. It consists of six heat pipes and an array of 40 heat-dissipating fins. Team F16 is currently moving into the prototyping phase, with two models that will be built to further evaluate the results of initial computer simulations. The first is a *structural* prototype that will focus on the heatsink base with heat pipes. The second, to be built later, is a *verification* prototype that will include sufficient test equipment to evaluate design performance. Manufacturing plans for both prototypes have been developed, including an indented Bill of Materials. Moving forward, Team F16 intends to work with GTI to develop a fin array through a combination of further ANSYS®-based trade studies and physical testing on the verification prototype. The results of experimental trials will be leveraged to improve future computer simulation models. This iterative process will drive Team F16's final design proposal that will be submitted for high volume manufacturing.

Table of Contents

1. Introduction

Cal Poly Senior Design Team F16 has been working with Gas Technology Institute on their *Methane Mitigation Thermoelectric Generator* (MMTEG) Project since the Fall of 2021. GTI's system is powered by an array of thermoelectric generators (TEGs), which require heatsinks to maintain a temperature differential for their operation. Team F16's task is to develop a cost-effective replacement for the existing heatsinks in use by GTI as they are no longer available for purchase. After identifying initial performance constraints, brainstorming and design convergence methods were used to select a preliminary concept direction. The details of this are included in prior documentation, notably in the Preliminary Design Review Report (PDR, released Fall of 2021). Since, Team F16 has used the results of initial ANSYS® trade studies to plan two manufacturable prototypes for further experimental testing. Although the latest design resembles original concepts presented in PDR, with six high-conductivity heat pipes rising from a copper base into 40 aluminum heat-dissipating fins, various performance and DFMA-related changes have been implemented. The details of initial trade studies, prototype development, as well plans for future testing and analysis are included in the following sections, summarized below:

1) System Design: Details of the latest heatsink design concept, including 3D views of geometry, figures, and technical specifications. Functionality of different subsystems for both prototypes will be described as well as manufacturing and cost documentation (iBoM, Drawings, etc.)

2) Design Justification: All relevant analyses, simulations, trade studies and research conducted to date since PDR that drove Team F16's design direction. Results from these are analyzed and their implications for future heatsink design choices are explained. Looking forward, implementation considerations (compatibility with existing system, safety, maintenance) are addressed and potential solutions identified.

3) Manufacturing Plan: Specific details on how both prototypes will be manufactured. Material sourcing and cost, procurement / supply chain methods, assembly, and accountability-tracking methods including a Team Gantt chart.

4) Design Verification Plan: How the verification prototype will be used to evaluate design performance against GTI's identified constraints, including relevant results and details from initial testing.

2. System Design

The heatsink system assembly consists of two major subassemblies, the heatsink and the test jig. Together, these subassemblies will enable accurate performance testing using the exact same TEG that GTI plans to use in the final system. Figure 1 below highlights the system assembly. For this phase of the project, we are planning to build one test jig and two heatsinks at a total cost of about $570 as shown in Appendix A.

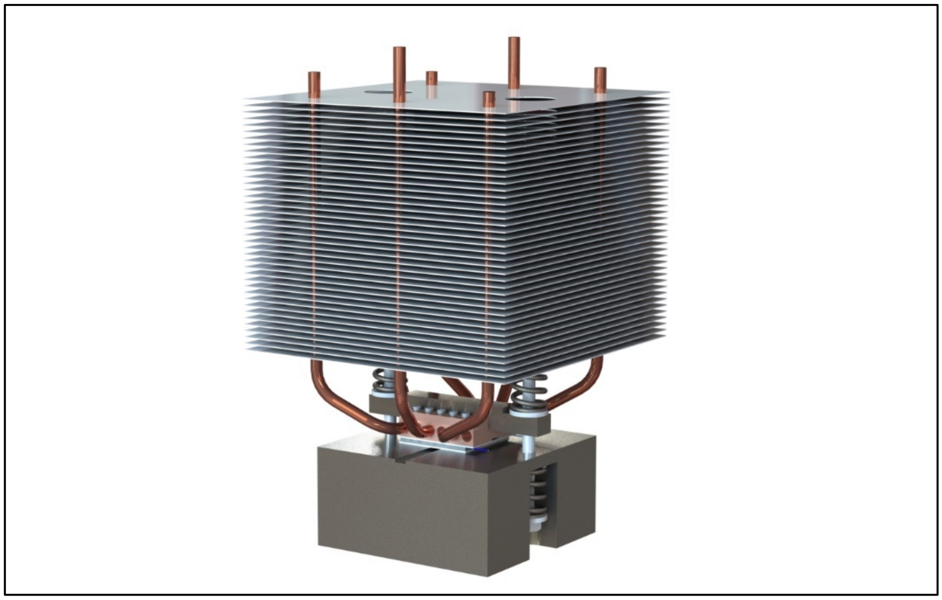


Figure 1. Heatsink system assembly.

The focus of the system assembly is the heatsink subassembly seen in Figure 2 below. The heatsink subassembly is responsible for creating and maintaining the cold-side temperature on the TEG which enables production of electricity. Six 6mm heat pipes pull heat from the base and up into the fin array where it can be dissipated via natural convection. The set screws visible on the top of the copper base are only for the prototype version, they will allow us to adjust the heat pipes as we assemble this subassembly. The final design will feature press fit heat pipes. This will be possible because of better tolerances in production and more accurate bends on custom, CNC bent, heat pipes. The heatsink subassembly will cost approximately $160.

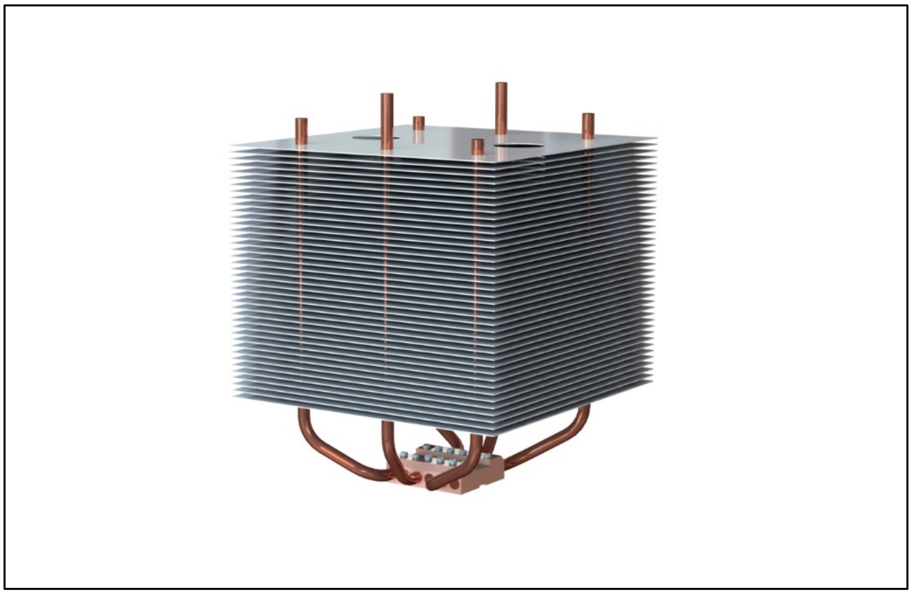


Figure 2. Heatsink subassembly side view.

The bottom of the heatsink subassembly base has a slot cut into it as seen in Figure 3 below. This slot is for a thermocouple to be placed in contract with the cold side of the TEG during testing. The final production model will not need thermocouple readings so the slot can be removed. The two large circular holes in the heat fins allow the installation of mounting screws during assembly with the larger GTI system. Based on our ANSYS® models, as discussed later in this document, the holes do not significantly impact thermal performance.

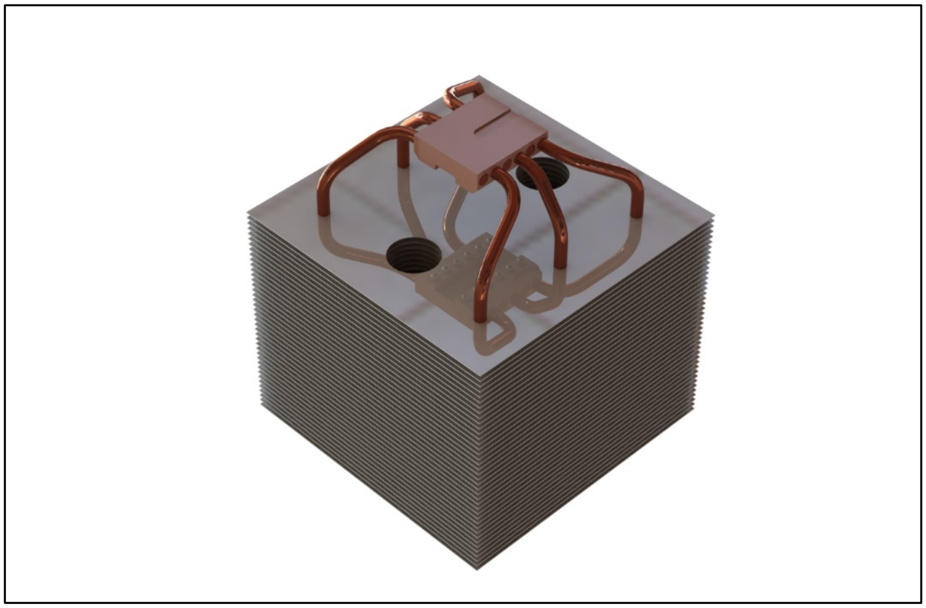


Figure 3. Heatsink subassembly bottom view.

Figure 4 below features the test jig subassembly. The large steel block on the bottom serves to create a constant temperature for the bottom of the TEG. The slot in the steel block is for a thermocouple to be placed in contact with the hot side of the TEG during prototype testing. The crossbar on top will run across the copper heatsink base, fixing it in place. Springs have been selected such that at full compression of all the springs there will be exactly 100psi of clamping pressure on the TEG as specified by the manufacturer. The test jig cost estimate is currently $260.

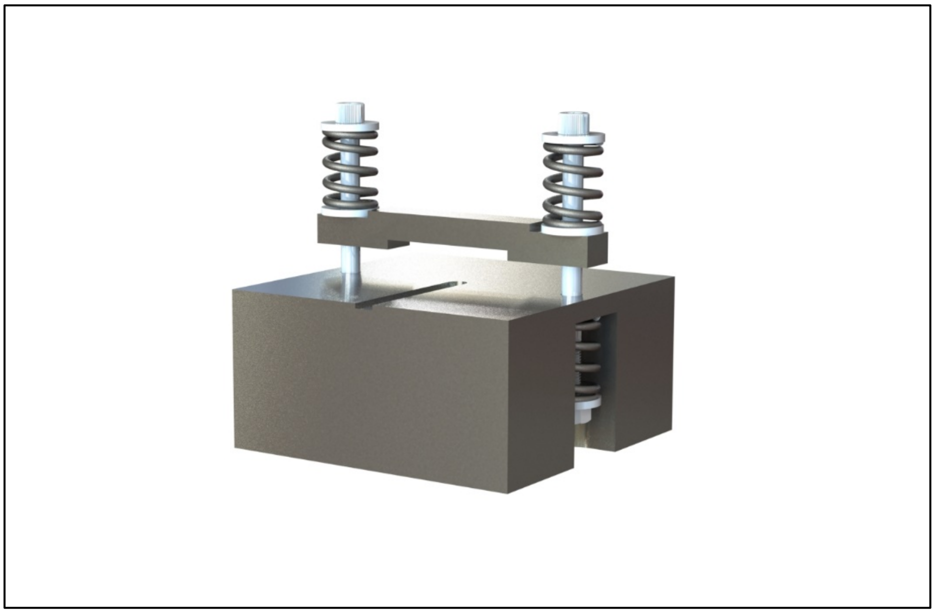


Figure 4. Test jig subassembly.

A final exploded view of the top-level assembly can be seen in Figure 5. The exploded view does not include the entire heat fin array for clarity. The final spacing, material thickness, dimensions, and count of heat fins will be determined after this report's conclusion as we gather more system test data. All heat fins will be brazed or bonded with thermal epoxy to the heat pipes. During testing of the prototype thermocouple slots and heat pipe holes in the heatsink base will all be filled with thermal paste to decrease unrepresentative thermal resistance as much as possible. A final parts list can be found in the iBOM (see Appendix A).

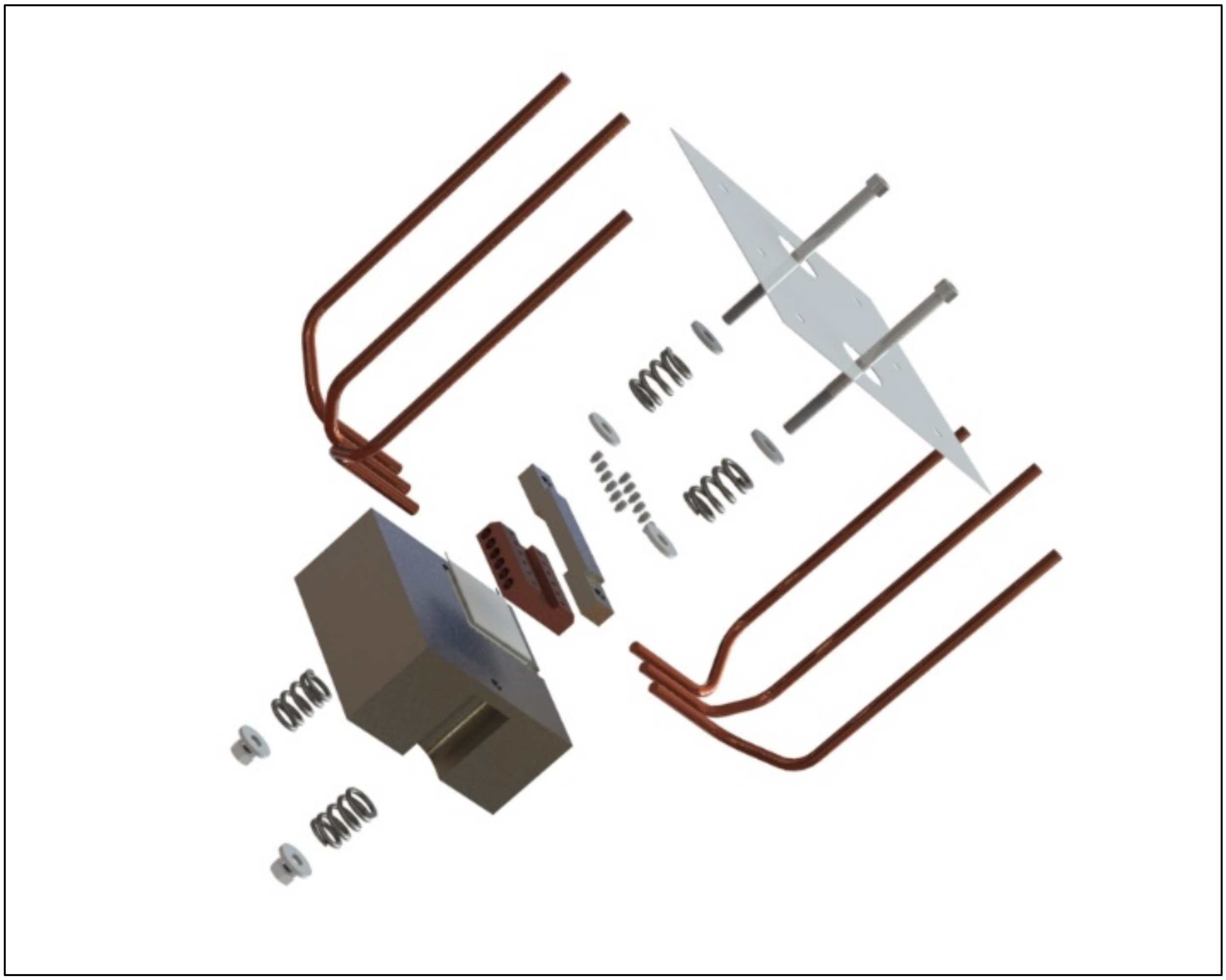


Figure 5. Full assembly exploded view. Full heatsink array omitted for clarity.

3. Design Justification

ANSYS® simulations were conducted on several different configurations of heat pipes with two different base geometries to determine the optimum design. The heat fin geometry has not been optimized or studied yet, and further trade studies are required to determine final geometries. As such, heat fins shown in models below are subject to change.

3.1. Base Geometry Study

The copper base is critically important as it is the site of the effective cold side temperature for the TEG. The first design integrated mounting "tabs" into the base to simplify attachment to the combustion chamber, as seen below in Figure 6.

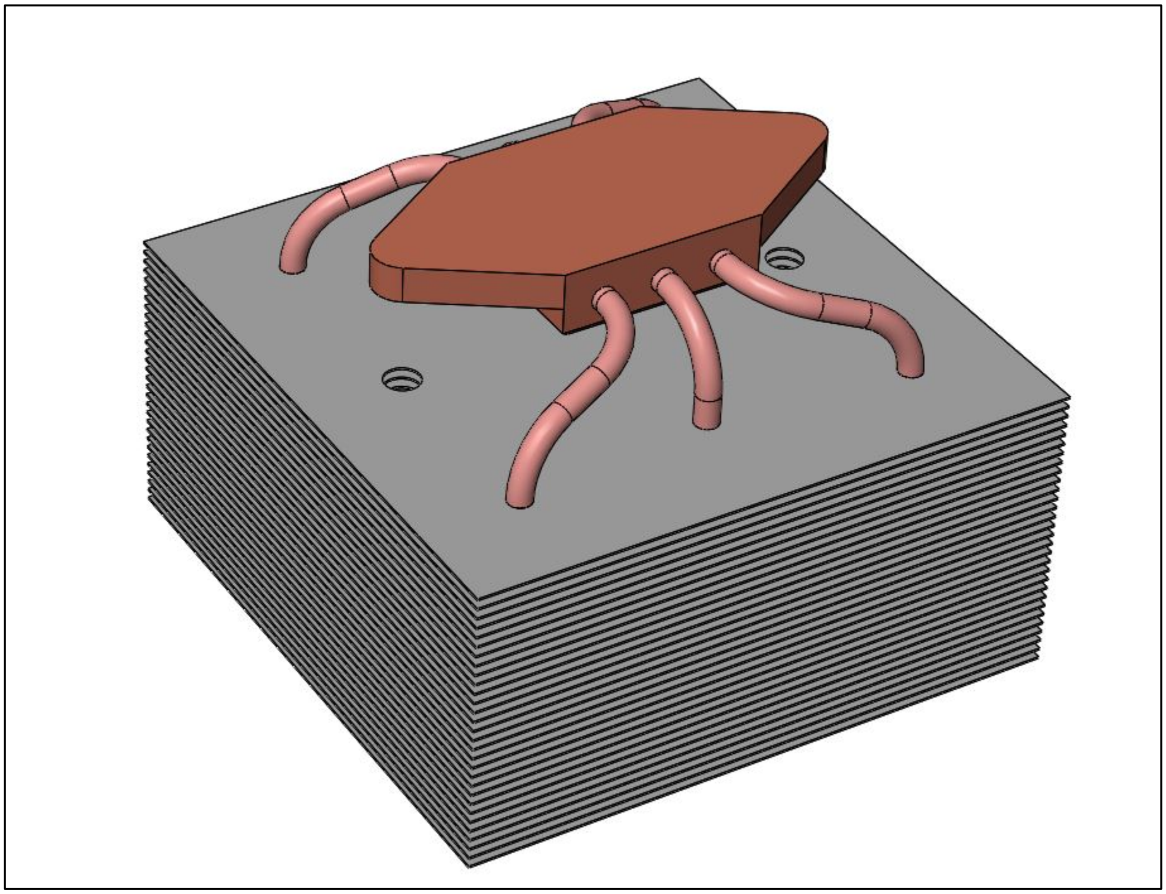


Figure 6. Tabbed base design featuring 6 mm heat pipes and insufficient fin spacing.

It is worth noting that the fin spacing shown on this design is too tight to adequately provide space for natural convection, and heat pipes were modeled with an overestimated conduction value of 100,000 W/mK. The following ANSYS® simulation operated on erroneous assumptions of heat transfer coefficient and conduction, and temperature magnitudes should be treated qualitatively. Regardless, the simulation provided valuable insight into the limitations of this design, as discussed below.

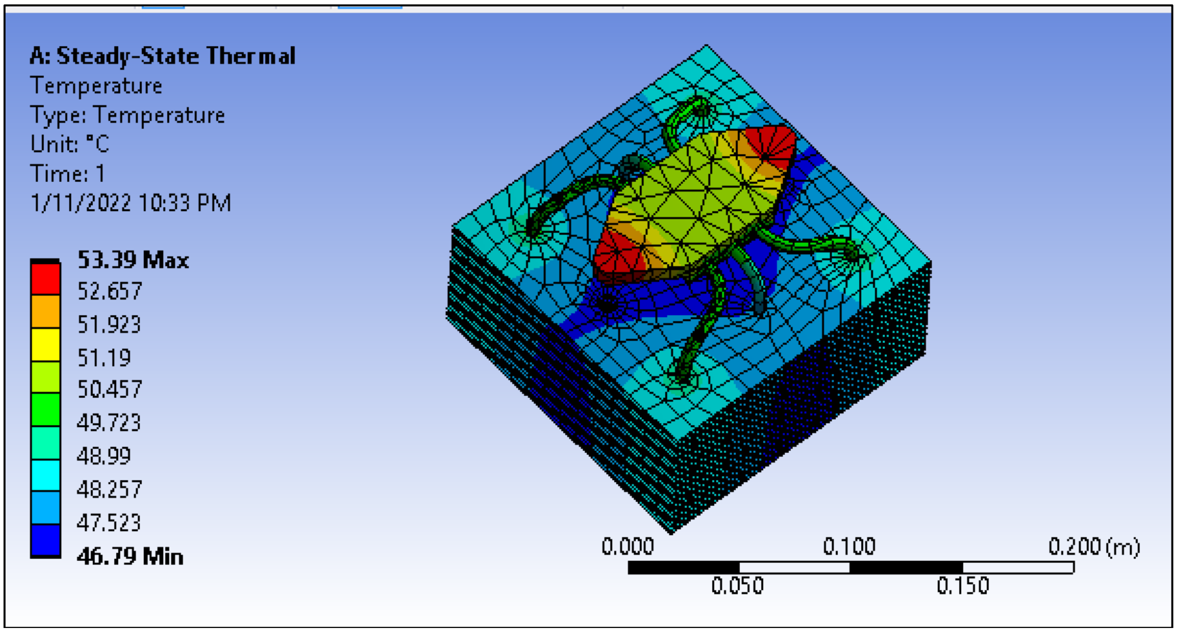


Figure 7. ANSYS® simulation of tabbed base design.

The tabs of this preliminary design became localized temperature maxima, as heat pipes that carried heat to the fin array were unable to effectively access these areas of the base. When installed on the combustion chamber, these tabs would absorb heat from the combustion chamber through radiation and convection that otherwise would not be transferred to the cold side of the TEG. To mitigate these inefficiencies, our subsequent base was a simple square with a recessed grove in the back to seat a separate mounting bracket. This design and subsequent analysis are discussed below.

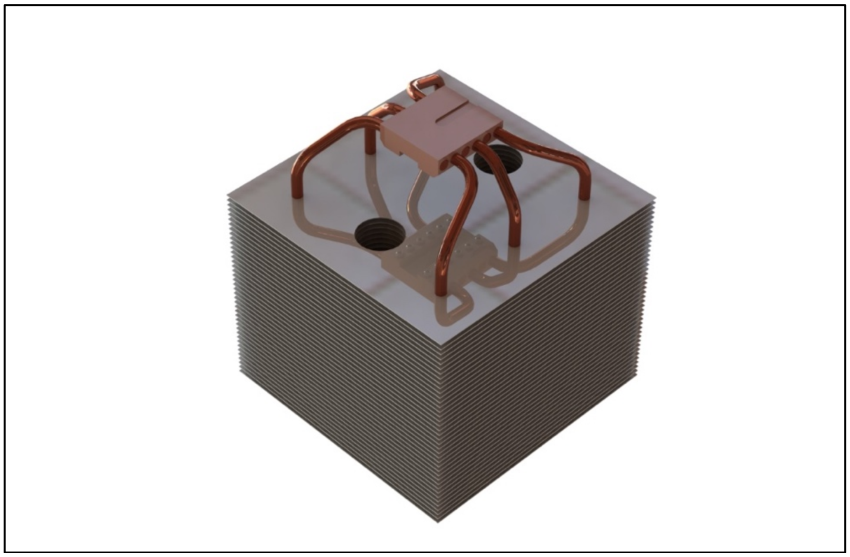
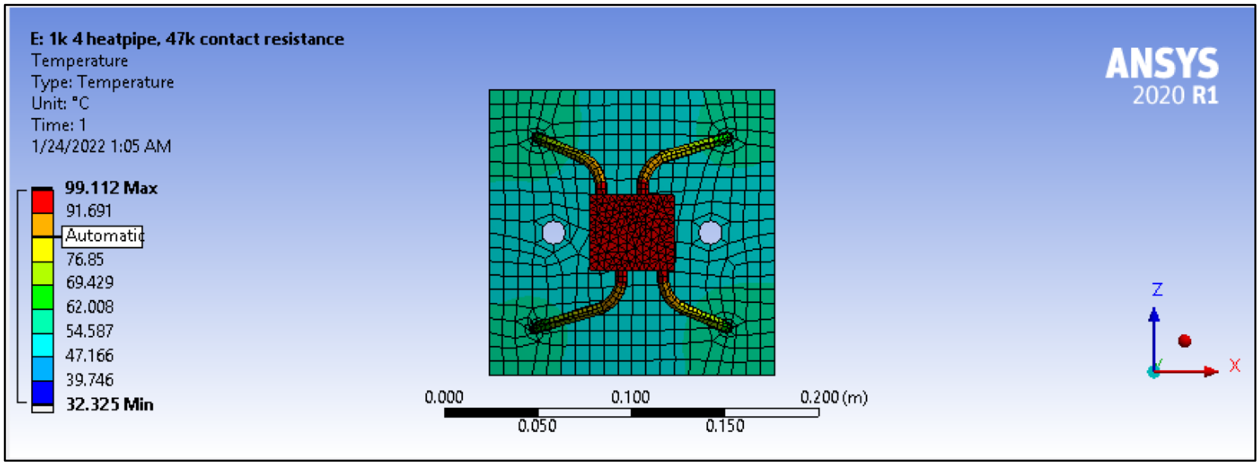


Figure 8. Square base design, featuring milled slot for thermocouple insertion during testing.

The square base eliminated the localized temperature maxima and reduced material use. The simpler geometry requires a smaller block of copper to mill and features minimal complex features that would require extensive material removal. As discussed in the previous section, the mounting crossbar and bolt assembly features springs that when fully compressed correspond to the required 100 psi pressure on the TEG, insuring proper installation.

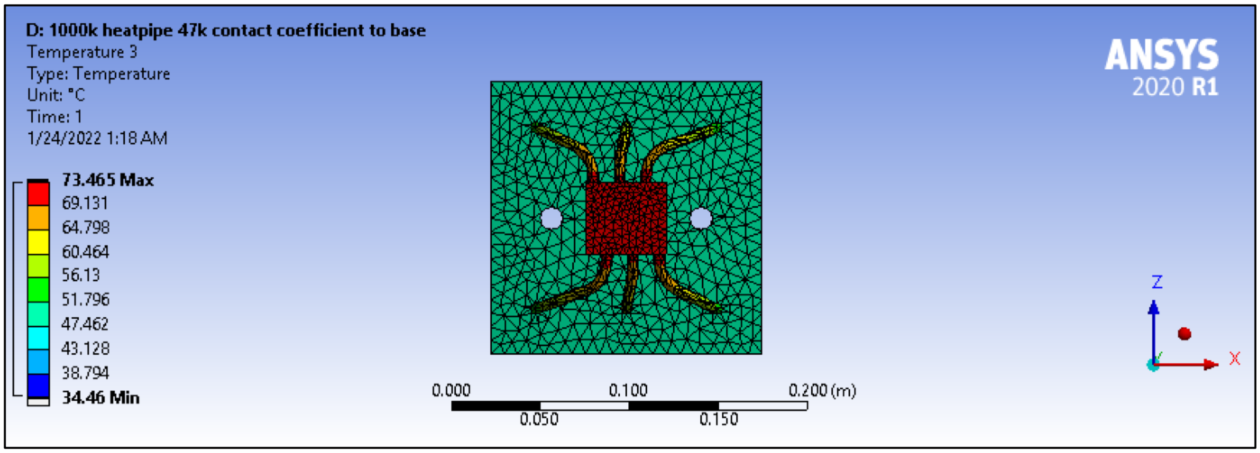
3.2. Heat Pipe Study

With the base geometry more constrained, two heat pipe configurations were considered. Since additional heat pipes increase the cost of fabrication, added performance needed to justify the additional expenses.



E: 1k 4 heatpipe, 47k contact resistance
Temperature
Type: Temperature
Unit: °C
Time: 1
1/24/2022 1:05 AM

Figure 9. Two heat pipe ANSYS® simulation, featuring a cold side temperature of 99 ˚C.



D: 1000k heatpipe 47k contact coefficient to base
Temperature 3
Type: Temperature
Unit: °C
Time: 1
1/24/2022 1:18 AM

Figure 10. Three heat pipe ANSYS® simulation, featuring a cold side temperature of 73.5 ˚C.

As Figures 9 and 10 above show, the 6-heat pipe configuration reduced the cold side temperature by over 25 ˚C and created a more homogenous heat distribution across each fin. This translates into higher power output from the TEG and a more efficient heat fin array, more than justifying the additional cost of the two extra heat pipes per unit in this configuration.

While this second round of ANSYS® more accurately modeled heat pipe conduction as 1000 W/mK and included a contact resistance between the heat pipes and the copper base, these results still need to be verified with experimental testing.

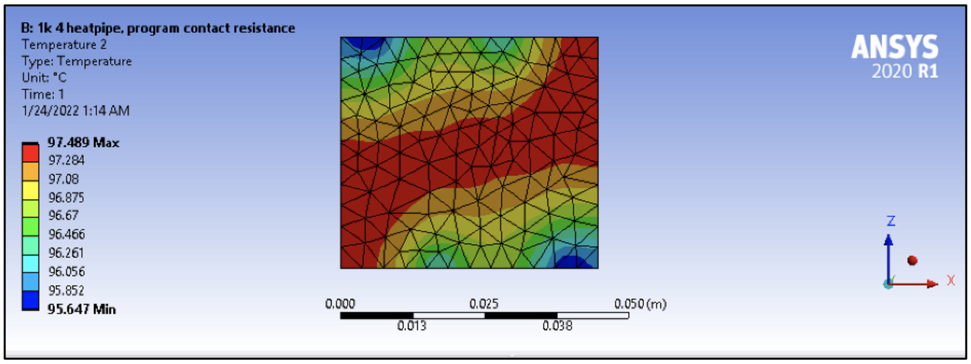


Figure 11. ANSYS® simulation of 4 heat pipe configuration base, featuring a 1.8 °C gradient and 96.5 °C.

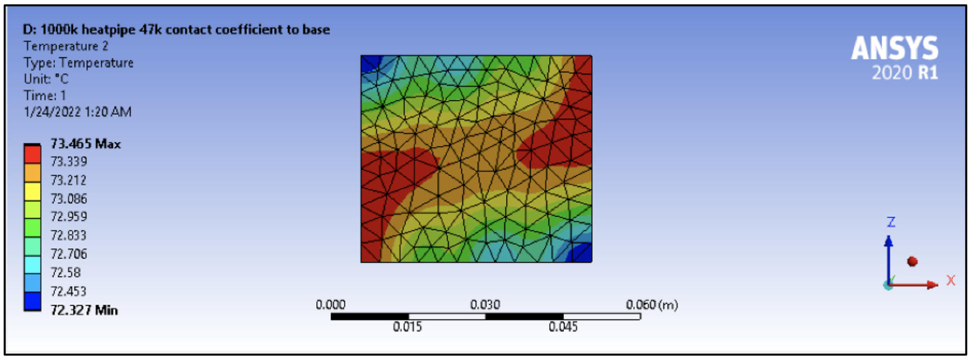


Figure 12. ANSYS® simulation of 6 heat pipe configuration base, featuring a 1.1 °C gradient and average temperature of 73.9 °C.

For further support of the 6-heat pipe configuration, Figures 11 and 12 show how the increased number of heat pipes create a more uniform temperature gradient across bottom of the copper base, once again providing more uniform loading of the TEG. Please note that the color gradients of the ANSYS® figures are unique to each figure and fail to effectively capture the 23 ˚C average temperature difference on the base between the two heat pipe configurations.

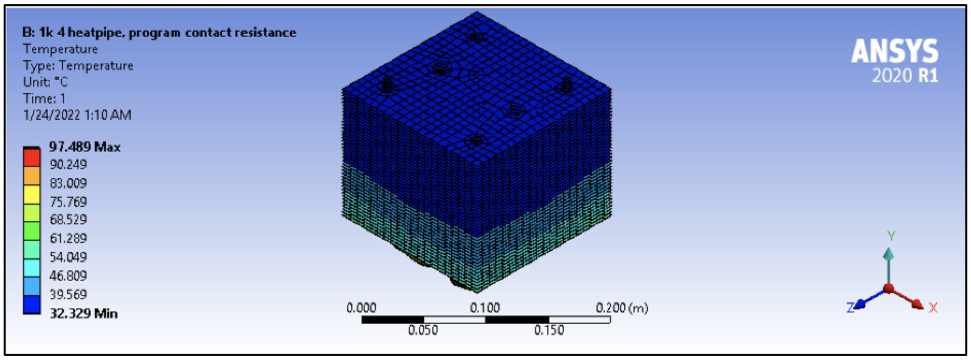


Figure 13. ANSYS® simulation of 4 heat pipe configuration with a 97 °C cold side temperature.

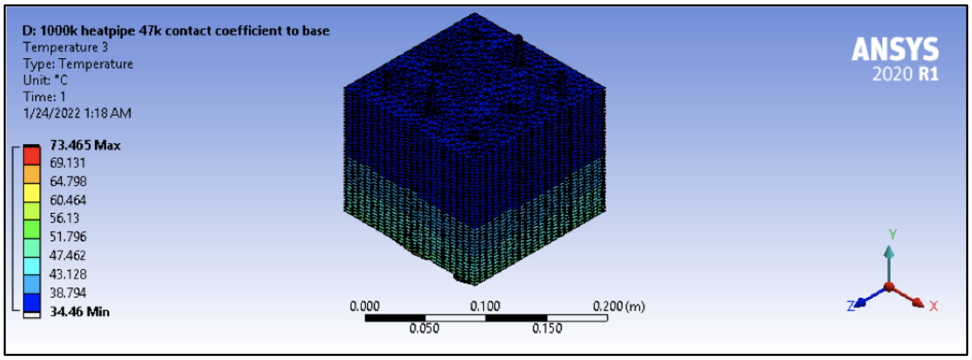


Figure 14. ANSYS® simulation of 6 heat pipe configuration with 73 °C cold side temperature.

As a final note from this second round of ANSYS®, Figures 13 and 14 above show how the 6-heat pipe configuration maintains a higher minimum temperature within the fin array, translating into a larger average magnitude of heat transfer for each fin, and a more optimized design overall.

It should be noted that the newest iteration of our fin design will include a larger “access hole” to assist in manufacturing. This DFMA consideration should significantly improve the usability of the prototype without significantly hindering performance. Further ANSYS® simulations have been run on this more recent design and are included in Appendix B as “Run V”.

3.3. Similarity to Existing Design

The chosen design fundamentally is quite similar to the existing heatsink, featuring all the same major components such as a solid copper base, copper heat pipes and aluminum heat fins. This provides rational for the performance of this design.

3.4. Stress Analysis and Failure Modes Discussion

The crossbar and bolt assembly are the only components that see significant loads. Appendix C provides hand calculations that found the factor of safety to be 4 from pure bending stresses. It was assumed that the bracket would deflect slightly, resolving the contract forces to just the edges of the copper base. This factor of safety is reassuring that this design is sufficiently strong and will not yield.

As seen in Appendix D, initial failure modes were addressed, including potential insufficient power generation. ANSYS® simulations used a convection heat transfer coefficient of 1.5 W/m^2K, which matches values the project sponsor found when conducting experimental testing of the existing heatsink under stagnant air conditions. This value is only valid with sufficient fin spacing. In the future fin trade study, particular care will be taken to ensure this requirement is met. Also, as seen in Appendix E (Design Hazard Checklist), appropriate safety measures will be taken when manufacturing prototypes including chamfering sharp edges and burn hazards will be considered when conducting testing.

The conditions in which this heatsink configuration operates will always be a cause for concern in terms of maintaining the best possible temperature gradient across the TEG, but sufficient testing should confirm this to be a non-issue.

4. Manufacturing Plan

Due to the two-part nature of the manufacturing portion of the scope of this project, the verification prototype will be manufactured differently compared to the 40,000 units per year target that GTI has in mind. The verification prototype will be manufactured via one off parts from McMaster-Carr and local hardware stores such as Ace Hardware or Harbor Freight. By contrast, the large-scale manufacturing plan will utilize mass metal suppliers and CNC made parts that have a higher upfront cost but a reduction in cost with increasing production numbers.

The planned verification prototype will be comprised of three different sections: the already manufactured structural prototype, test stand base, and the heat fins. The planned structural prototype will be comprised of the copper base, heat pipes, set screws, and the thermal compound.

The copper base and heat pipes will be procured through Cal Poly using the budget provided by Cal Poly and the Senior Project fund. The test stand base steel base, cross bar steel bar, thermal compound, set screws, bolts, nuts, washers, and springs will be purchased by the Gas Technology Institute. The aluminum sheet for the heat fins will be purchased by GTI after initial testing is completed. Additionally, the TEG will be provided by GTI from the current design. See Appendix A for the Team Budget and iBOM for more details about the cost, procurement, and the materials chosen.

All materials will be purchased through McMaster Carr due to ease of purchasing, fast delivery, and the reliability except for the TEG which was given from GTI.

The specific costs, quantity, and other details of all materials can be found in the Bill of Materials in Appendix A. In order to account for any failures in manufacturing, extra materials were ordered. Four extra heat pipes specifically were purchased since the heat pipe bending is difficult to do accurately without a CNC tube bender.

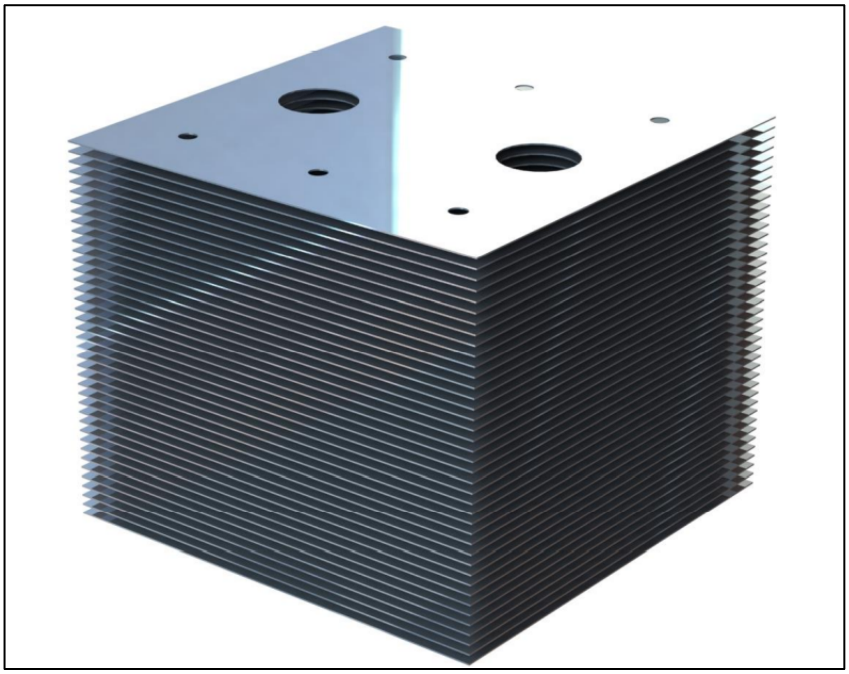


Figure 15. Heat fins included in the heat mitigation subsystem of the heatsink.

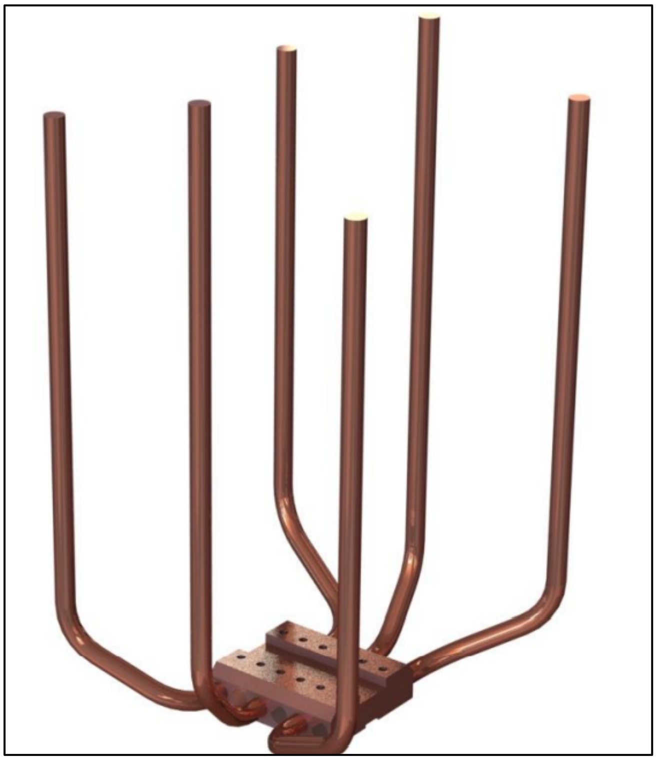


Figure 16. Copper base, heat pipes, and set screws as the rest of the heat mitigation subsystem of the heatsink.

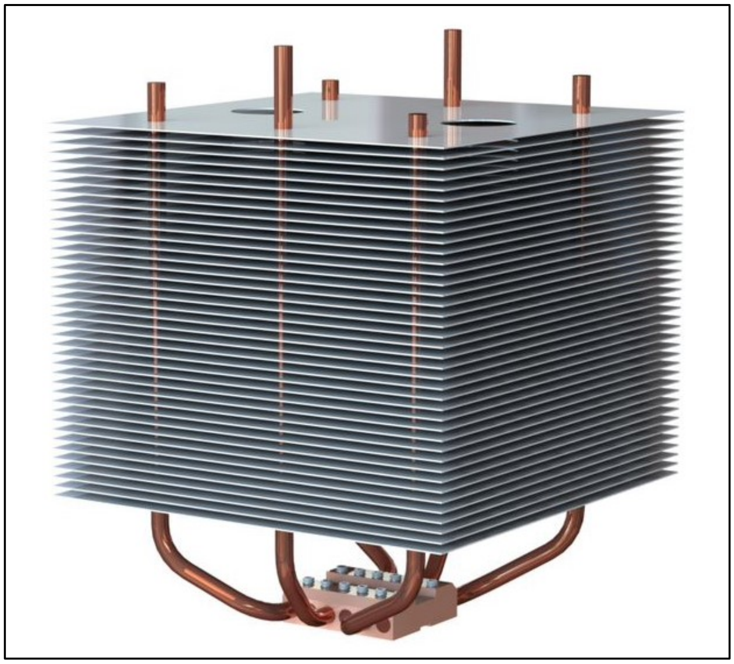


Figure 17. Copper base, heat pipes, copper base, and set screws that are a part of the heat mitigate subsystem of the heatsink.

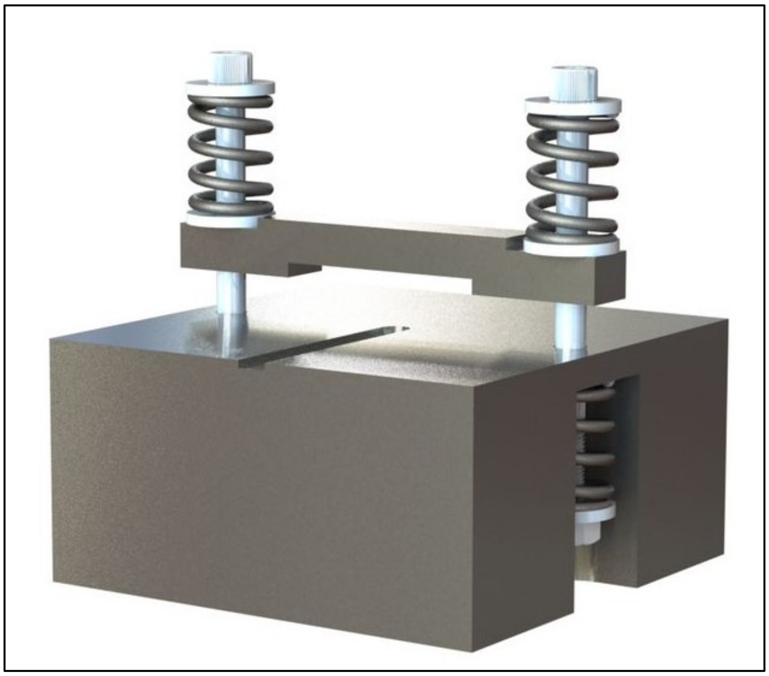


Figure 18. Test jig stand with the steel base block, crossbar, spring, nuts, washer, and bolts. The purpose of the jig is to provide the necessary 100 psi of pressure along with the adhere to the combustion chamber.

The Copper base was manufactured on the BridgePort Manual Mill and can be seen in Figure 19. The 12 set screw holes were successfully drilled; however, the final of the six through holes having a slight misalignment to the rest of the holes. While this is not a problem performance-wise, it is unsightly and will lead to more thermal paste being needed for the heat pipe to fit.

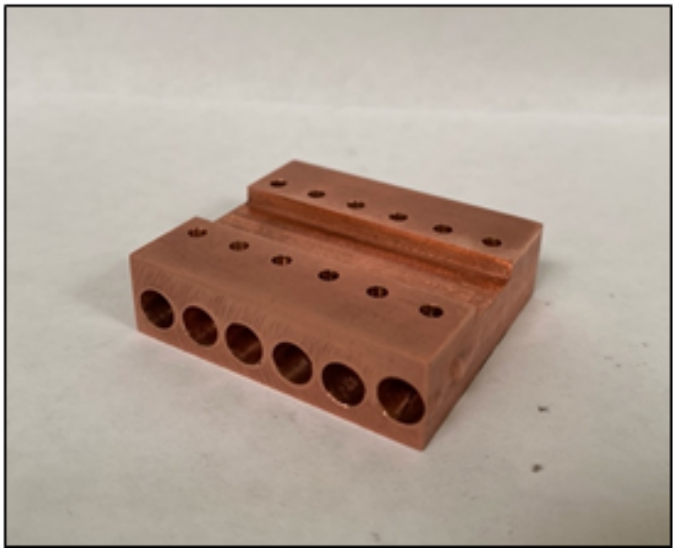


Figure 19. Copper base for structural prototype.

The Heat Pipes are going to be manufactured using the 6mm heat pipe bender available in the Mustang 60 machine shop. See the Manufacturing Plan in Appendix F. After an initial first attempt at bending the heat pipes, it was determined that the tube bender procured in the Cal Poly Mustang 60 machine shops was out of spec and the actual diameter was not at the noted 6 mm. This led to the heat pipes becoming crimped and the final products being bent to both different heights and angles. An example of the heat pipes in their current configuration is in Figure 20.

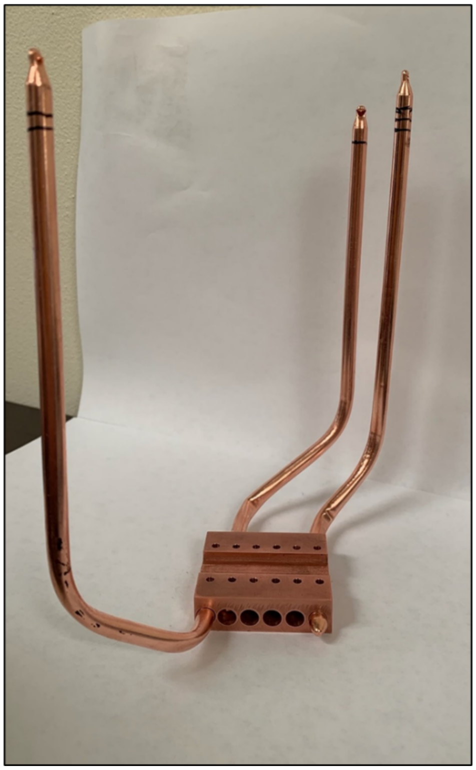


Figure 20. Current structural prototype with the copper base and the heat pipes.

The copper base will be manufactured in the Mustang 60 machine shop using the BridgePort Manual Mill. In order to operate the mill, all members who plan to manufacture this piece will need to obtain their yellow tag. The two most important manufacturing steps in the creation of the copper base is ensuring that the diameter of the 6 mm through holes create a transition fit with the 6 mm diameter heat pipes. Secondly, the surface finish on the bottom face of the copper base is crucial in the functionality of the TEG. For more details on how the copper base will be milled, see the Manufacturing Plan in Appendix F.

The cross bar will also be manufactured using the BridgePort. Again, see Appendix F for the full manufacturing details, Appendix G for the drawings, and Appendix C for calculations that prove that the load from the springs will lead to satisfactory factors of safety.

The heat fins will be manufactured using the Water Jet cutter in Mustang 60. The manufacturing of the fins will occur after the manufacturing of the structural prototype since the design of the fins depends on the accuracy of the thermal conductivities from testing. After the design is finalized, a .dxf file will be created and with the assistance of a shop technician, the fins will be cut to the final geometry. See Appendix F for the whole manufacturing plan and Appendix G for the current drawing of the heat fins, again with the condition that the heat fin design will not be completed until after the structural prototype and initial testing is completed.

The test stand base will also be milled using the BridgePort manual mill in the Mustang 60 Machine Shop. Much like the copper base's bottom surface, the upper face of the test stand base needs to have a better surface finish compared to the rest of the piece since the top face interfaces with the TEG. See Appendix F for the whole manufacturing plan and Appendix G for the drawings of the base.

In Appendices F and G, the Assembly Plans can be found. The general plan is to create the structural prototype with the copper base and heat pipes and then attach the test stand base, cross bar, and spring/bolt/washer structure. The heat fins will be attached afterwards at a fin-to-fin distance that will be determined after the structural prototype and initial testing are completed.

In general, the manufacturing of parts such as the copper base and the bending of the heat pipes are expected to take an increased amount of time due to the complex geometries and the availability of the BridgePort machines in the machine shop. These increases in time were considered and accounted for by ordering parts early and team members obtaining yellow tag certifications as soon as possible. In order to cut down on the amount of manufacturing that the is needed for the final verification prototype, the structural prototype will be integrated into the verification prototype. While this does increase the complexity of the structural prototype and forces the construction to be at the highest level, it will decrease the final workload when the heat fins are being constructed.

5. Design Verification Plan

At this stage in testing, most design choices have been made from engineering judgement and research into similar fields. Experimental testing of the selected design will begin with the Design Verification Prototype, described earlier in this report and in other team documentation. The plan is to first refine computer-assisted modeling of the system in heat transfer software, Phase 1, before attempting to experimentally evaluate any fin array, Phase 2. Phase 1 will be largely focused on determining an experimental value for heat transfer coefficient through the heat pipes and heatsink assembly. Phase 2 will be driven by the results of Phase 1 and ANSYS heat transfer simulations coupled with a cost trade studies to iterate towards a final fin design.

We hope to maximize efficiency of development going forward by iterating between this real-world experimentation and computer-assisted simulation. A summary of each phase is included below with key details. For more information, see the Design Verification Plan attached to this report as Appendix H.

5.1. Phase 1: CAD Model Refinement

The main objective of this phase is to determine a realistic value for the thermal conductivity of the heat pipes that will be used to run more trials in the ANSYS® thermal simulation environment. Original calculations were performed assuming a "back of the envelope" value of approximately 100,000 [W / m-K], but this proved to be a significant overestimation. Bringing values on the order of 1,000 [W / m-K] brought results that landed near sponsor expectations. Note that other factors play into the accuracy of a simulation, including choices for thermal contact resistance between the various bodies and convection coefficient.

The Structural Prototype will be assembled and subjected to a constant heat input of 500 [W] using a currently undetermined heat source. After reaching steady state, the heat pipes which will not yet have any heat fins installed, will be analyzed. In four discrete sections, four thermocouples will be placed in series to approximate a temperature gradient. Using a similar method to that described in the Preliminary Design Report (PDR) in previous team documentation, the heat rate can be experimentally determined. Based on the geometry and material of the heat pipes, a heat transfer conductivity coefficient will be derived. See Appendix C for details on these calculations from prior work.

Since the orientation of the heat pipes will affect their performance due to gravitational effects on the evaporating / condensing fluid, it will be important to perform these tests with them installed in the manner that they will actually be when in use. In order to decrease the effects of radiation or convection, the testing location will be specifically chosen with low solar radiation and mostly stagnant air. This will allow for the condition to be the most similar to what the actual heatsink will experience in the field.

Table 1. Facilities and equipment requirements, data to be measured.

#	Description	Source	Method to Obtain
1	Hot plate, DV Prototype, Thermocouples	Team equipment	Source from team
2	Testing area away from solar rad. / stray heat transfer	School campus	Confirm with Prof Schuster on location
3	Access to power	School campus	Based on location of testing

Table 2. Measured data for CAD model.

#	Description	Metric	Spec.	Qualitative Notes / Comments
1	Thermocouple Probe 1	Temp [°C]	n/a	For gradient measurements
2	Thermocouple Probe 2	Temp [°C]	n/a	For gradient measurements
3	Thermocouple Probe 3	Temp [°C]	n/a	For gradient measurements
4	Thermocouple Probe 4	Temp [°C]	n/a	For gradient measurements

Note this will be repeated for each of the four "sections" of heat pipe that is measured for a temperature gradient. Four k-type thermocouples and their corresponding readers, described in previous team documentation, will be used for collecting this data.

The resulting heat transfer coefficients that are obtained from each subsection will be averaged, and this value will be inputted into ANSYS® Mechanical for further testing into Phase 2.

Note that, headed into actual performance evaluation in Phase 2, heat transfer convection coefficients and solar radiation coefficients are not as great of a concern. This is due largely to the availability of tabulated data. Based on results from the main work in Phase 1, however, some experimentation might be performed as needed to obtain better values.

5.2. Phase 2: Heat Fin Experimental Design & Testing

After the competition of Phase 1, the final phase of our design verification can occur. This will serve to highlight the performance of the heat fins as well as the design as a whole. The 'cold' and 'hot' side temperatures, top and bottom of the copper base respectively, will be measured with thermocouples. The heat input will be tuned so that the hot side temperature is representative of the expected operating hot side temperature provided by the project sponsor. The difference between that hot side temperature and the cold side temperature indicates system performance. If the cold side temperature is low enough our design efforts will be completed, and we can focus on finalizing mass production aspects. If the heatsink does not meet the temperature drop requirements, we might be forced to redesign parts of the system and repeat the testing.

Table 3. Measured data for heat fin experimental design.

#	Description	Metric	Spec.	Qualitative Notes / Comments
1	TEG Hot Side Temperature	Temp [°C]	n/a	Measured for later calculations Simulated "combustion chamber" side
2	TEG Cold Side Temperature	Temp [°C]	< 100	Critical for TEG temp. differential Will be key performance metric
3	Time to steady state	Time [s]	n/a	Due to long run times of actual MMTEG, non-critical Mainly for evaluating simulation effectiveness

The same facilities and equipment will be required for Phase 2 as in Phase 1, along with additional equipment for subjecting the heatsink / heat fin apparatus to various simulated real-world testing conditions such as full fun, overcast conditions, and fouling using dust. These are described in line-item format along with their corresponding test in the full Design Verification Plan, provided in Appendix H.

As an example, here is a detailed breakdown of the "control" experimental run of the heatsink apparatus. See Design Verification Plan (Appendix H) for more details:

- Test will be conducted indoors, preferably away from any direct sources of solar or other radiation

- Attach test fixture ("design verification prototype") to 1000 [W] duty cycle-modulated hot plate via mounting defined in CAD geometry

- Turn on hot plate and allow steel block to reach steady state temperature (dependent on ambient conditions
  record initial temperatures on "hot" and "cold" side of TEG, as well as ambient

- Allow system to reach steady state... when measurements plateau (changes between 1s time increments drop below 5% of nominal
  plot response
  repeat this process twice and average results

- Will serve as nominal / "control" performance baseline against which other more dynamic condition tests can be evaluated

- Max allowable test time: 90 minutes

It should be noted that the results from Phases 1 and 2 will drive further design iteration. There will be other simulations conducted to evaluate other ideas for fin geometry without having to go through the lengthy (and costly) process of assembling and brazing an entire new assembly. Changes will be made to this testing plan as further discussions with sponsor and Professor Schuster help us define objectives and what is realistic with the resources available to us.

The goal is to complete the primary testing of the heat pipes by 2/18/2022 in order to stay on task with the ANSYS simulations of the heat fins. The secondary testing, thermal performance of the heatsink, will be completed by 4/19/2022 to ensure that the rest of the design process can move ahead as scheduled. See Appendix I for the Gantt chart which outlines the exact timing of the testing.

6. Conclusion

In an effort to decrease environmental impact from existing natural gas infrastructure, the Gas Technology Institute wants to design a new heatsink to bolster the operation of a thermo-electric generator valve control system. The goal is to design a heatsink that works with the given setup but better suits the needs of the Gas Technology Institute. Cal Poly Senior Project Team F16 gladly took on that challenge and so far, has completed the scope of work, ideation, interim design, and now the critical design review. The key takeaway from our idea generation, ideation models, preliminary designs, simulations, and structural prototype is that a heatsink utilizing three different sections, heat dissipation copper base, heat fins, and a test stand jig is the most efficient design from both a heat transfer and economic standpoint. We need our sponsor's approval on our design and upon agreement, we will move forward into continued structural prototype manufacturing, the manufacturing of the test stand base and the heat fins, as well as testing and the subsequent simulations. To accomplish the end goals detailed in the Critical Design Review, we plan to complete our next major deliverable, the Final Design Review (FDR), on June 3rd, 2022. In the FDR will provide complete details on the design, analysis proving that specifications were met, the large-scale manufacturing plan, and the finalized verification prototype. For more details on Team F16's next steps, see Appendix I for Gantt Chart for our plan going forward.

References

[1] “Tube Bender Brake Line Pipe Bender 6, 8, 10 mm,” aliexpress.com. [Online]. Available: https://www.aliexpress.com/item/32835777844.html. [Accessed: 25-Jan-2022].

[2] “Copper,” McMaster-Carr. [Online]. Available: https://www.mcmaster.com/catalog/128/4182/. [Accessed: 25-Jan-2022].

[3] “Heat Sinks,” McMaster. [Online]. Available: https://www.mcmaster.com/catalog/128/610. [Accessed: 25-Jan-2022].

[4] “Set Screws,” McMaster. [Online]. Available: https://www.mcmaster.com/catalog/128/3376. [Accessed: 25-Jan-2022].

[5] “Alloy Steel,” McMaster. [Online]. Available: https://www.mcmaster.com/catalog/128/4117. [Accessed: 25-Jan-2022].

[6] “Stainless Steel,” McMaster. [Online]. Available: https://www.mcmaster.com/catalog/128/4142. [Accessed: 25-Jan-2022].

[7] “Flat Washers,” McMaster. [Online]. Available: https://www.mcmaster.com/catalog/128/3536. [Accessed: 25-Jan-2022].

[8] “Socket Head Screws,” McMaster. [Online]. Available: https://www.mcmaster.com/catalog/128/3422. [Accessed: 25-Jan-2022].

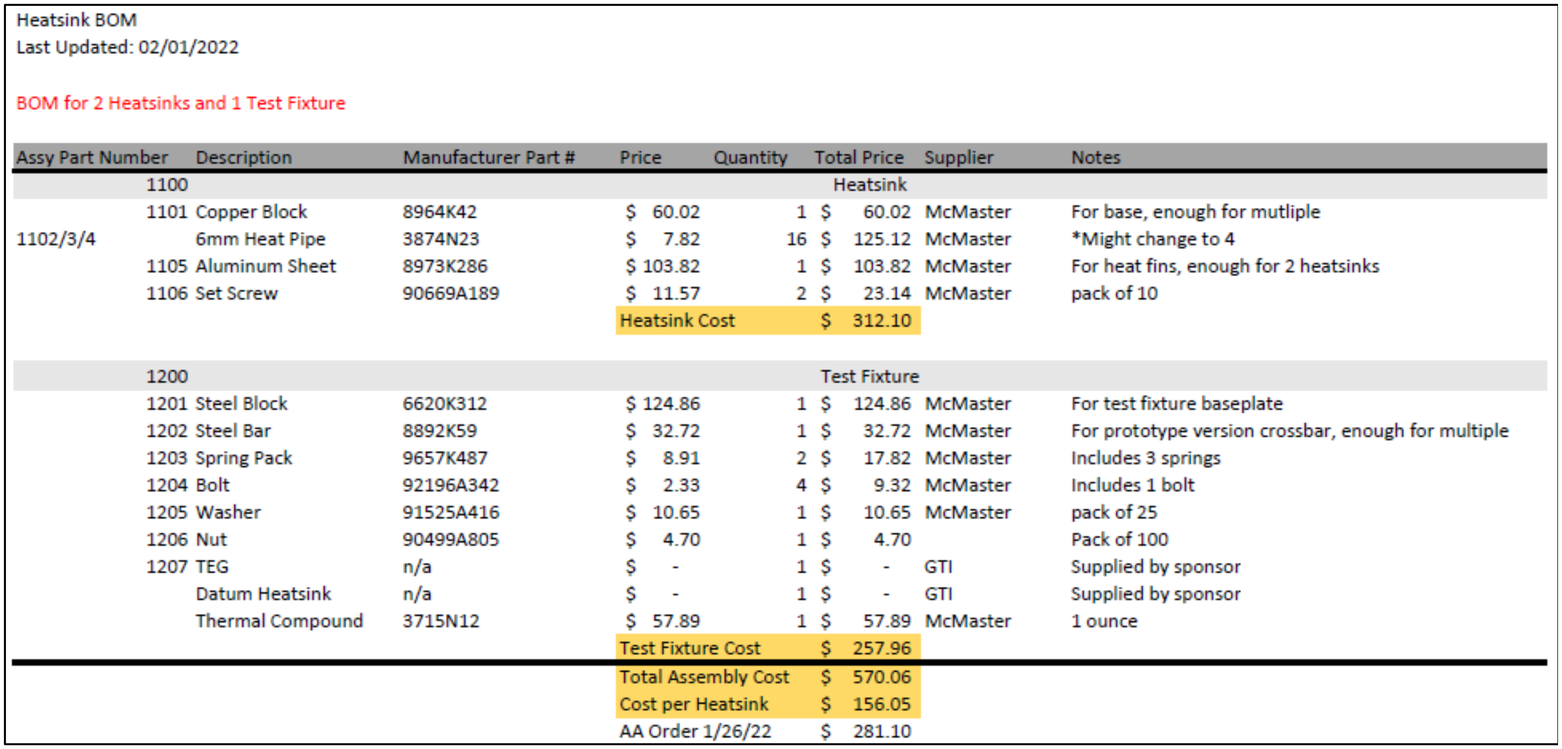
[9] “Compression Springs,” McMaster. [Online]. Available: https://www.mcmaster.com/catalog/128/1415. [Accessed: 25-Jan-2022].

[10] “Hex Nuts,” McMaster. [Online]. Available: https://www.mcmaster.com/catalog/128/3497. [Accessed: 25-Jan-2022].

Appendices

A. Indented Bill of Materials and Team Budget
B. Supplementary Simulation Results
C. Hand-Calculations for Normal and Shear Stress Loading on Crossbar
D. Failure Modes and Effects Analysis
E. Hazard Checklist (Updated)
F. Manufacturing Plan
G. Team F16 Relevant Manufacturing Drawings
H. Design Verification Plan
I. TeamGantt® Gantt Chart

Appendix A – Indented Bill of Materials & Team Budget



Heatsink BOM
Last Updated: 02/01/2022

BOM for 2 Heatsinks and 1 Test Fixture

Assy Part Number	Description	Manufacturer Part #	Price	Quantity	Total Price	Supplier	Notes
1100					Heatsink		
1101	Copper Block	8964K42	$ 60.02	1	$ 60.02	McMaster	For base, enough for mutliple
1102/3/4	6mm Heat Pipe	3874N23	$ 7.82	16	$ 125.12	McMaster	*Might change to 4
1105	Aluminum Sheet	8973K286	$ 103.82	1	$ 103.82	McMaster	For heat fins, enough for 2 heatsinks
1106	Set Screw	90669A189	$ 11.57	2	$ 23.14	McMaster	pack of 10
			Heatsink Cost		$ 312.10		
1200					Test Fixture		
1201	Steel Block	6620K312	$ 124.86	1	$ 124.86	McMaster	For test fixture baseplate
1202	Steel Bar	8892K59	$ 32.72	1	$ 32.72	McMaster	For prototype version crossbar, enough for multiple
1203	Spring Pack	9657K487	$ 8.91	2	$ 17.82	McMaster	Includes 3 springs
1204	Bolt	92196A342	$ 2.33	4	$ 9.32	McMaster	Includes 1 bolt
1205	Washer	91525A416	$ 10.65	1	$ 10.65	McMaster	pack of 25
1206	Nut	90499A805	$ 4.70	1	$ 4.70		Pack of 100
1207	TEG	n/a	$ -	1	$ -	GTI	Supplied by sponsor
	Datum Heatsink	n/a	$ -	1	$ -	GTI	Supplied by sponsor
	Thermal Compound	3715N12	$ 57.89	1	$ 57.89	McMaster	1 ounce
			Test Fixture Cost		$ 257.96		
			Total Assembly Cost		$ 570.06		
			Cost per Heatsink		$ 156.05		
			AA Order 1/26/22		$ 281.10		

Description of Item	Vendor	Vendor Part Number	Part Number	Material Price	Shipping/Handling/Tax	Procurement	Account Used	Date Material Purchased	Current Location
Rental Car to LA	Enterprise Car Rentals	N/A	N/A	$ 42.00	$ -	Team Reimbursement	Cal Poly	10/19/21	N/A
Rental Car Gas	Chevron Gas	N/A	N/A	$ 62.21	$ -	Team Reimbursement	Cal Poly	10/19/21	N/A
Dual Input Thermometer	Harbor Freight	N/A	N/A	$ 89.92	$ 7.87	Team Reimbursement	Cal Poly	12/9/21	Alec Savoye Residence
Kill-a-Watt Electric Monitor	Harbor Freight	N/A	N/A	$ 25.99	$ 2.27	Team Reimbursement	Cal Poly	12/9/21	Alec Savoye Residence
Single Electric Burner	Miner's Ace Hardware	N/A	N/A	$ 32.99	$ 2.89	Team Reimbursement	Cal Poly	12/9/21	Alec Savoye Residence
Multi Purpose Foil	Home Depot	1541239	N/A	$ 7.88	$ 0.69	Team Reimbursement	Cal Poly	12/9/21	Alec Savoye Residence
Copper Block	McMaster Carr	8964K42	1101	$ 60.02	$ 4.20	ME Pro-Card	Cal Poly	1/24/22	Locker in Mustang 60
16 6mm Heat Pipes	McMaster Carr	3874N23	1102/3/4	$ 7.82	$ 0.55	ME Pro-Card	Cal Poly	1/24/22	Locker in Mustang 60
Aluminum Sheet	McMaster Carr	8973K286	1105	$ 103.82	$ 7.27	Sponsor	GTI	1/27/22	Locker in Mustang 60
Set Screws	McMaster Carr	90669A189	1106	$ 11.57	$ 0.81	Sponsor	GTI	1/27/22	Locker in Mustang 60
Steel Block	McMaster Carr	6620K312	1201	$ 124.86	$ 8.74	Sponsor	GTI	1/27/22	Locker in Mustang 60
Steel Bar	McMaster Carr	8892K59	1202	$ 32.72	$ 2.29	Sponsor	GTI	1/27/22	Locker in Mustang 60
Spring Pack	McMaster Carr	9657K487	1203	$ 8.91	$ 0.62	Sponsor	GTI	1/27/22	Locker in Mustang 60
Bolts	McMaster Carr	92196A342	1204	$ 2.33	$ 0.16	Sponsor	GTI	1/27/22	Locker in Mustang 60
Washer	McMaster Carr	91525A416	1205	$ 10.65	$ 0.75	Sponsor	GTI	1/27/22	Locker in Mustang 60
Nut	McMaster Carr	90499A805	1206	$ 4.70	$ 0.33	Sponsor	GTI	1/27/22	Locker in Mustang 60
Thermal Compound	McMaster Carr	3715N12	N/A	$ 57.89	$ 4.05	Sponsor	GTI	1/27/22	Locker in Mustang 60

Appendix B – Supplementary Simulation Results

Note that these results are provided only as a supplement to discussion in the CDR and should be taken *only* as an all-else-equal comparison of different heat sink configurations. Each sub-section is prefaced by the specific simulation parameters used for that given run.

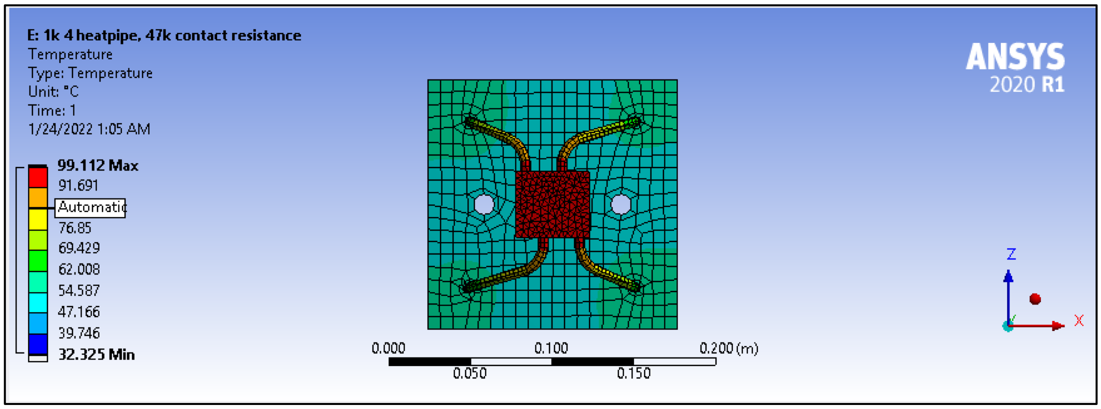
Note also that the thermal temperature gradients depicted use the same color range, but colors do not correspond to the same temperature. This may lead to misleading comparisons between runs unless care is taken to discern between maximum / minimum temperatures.

Run I.

4 Heatpipes

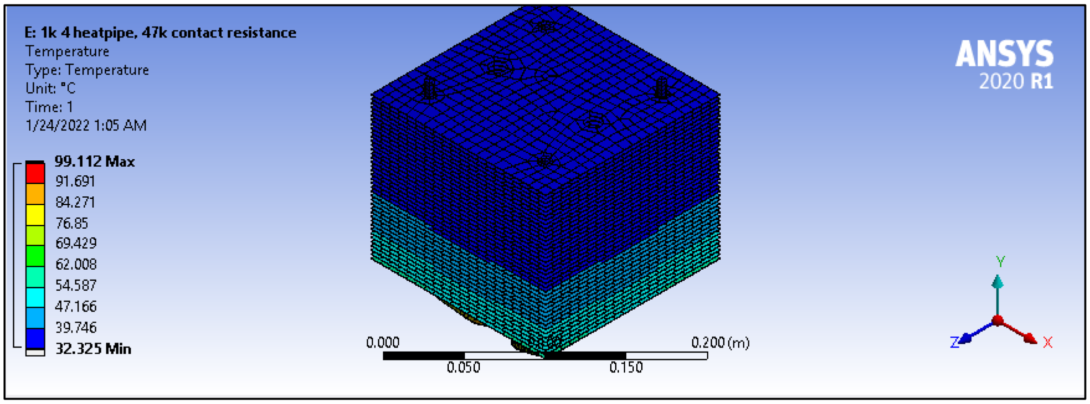
1,000 [W / m-K]

47k [°C / W] contact resistance between heatpipes and copper base



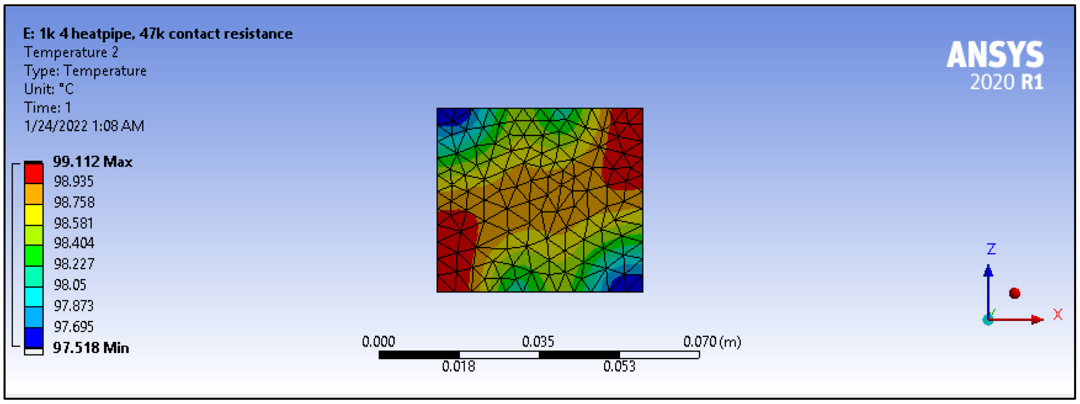
E: 1k 4 heatpipe, 47k contact resistance
Temperature
Type: Temperature
Unit: °C
Time: 1
1/24/2022 1:05 AM

Figure X.I.1



E: 1k 4 heatpipe, 47k contact resistance
Temperature
Type: Temperature
Unit: °C
Time: 1
1/24/2022 1:05 AM

Figure X.I.2



E: 1k 4 heatpipe, 47k contact resistance
Temperature 2
Type: Temperature
Unit: °C
Time: 1
1/24/2022 1:08 AM

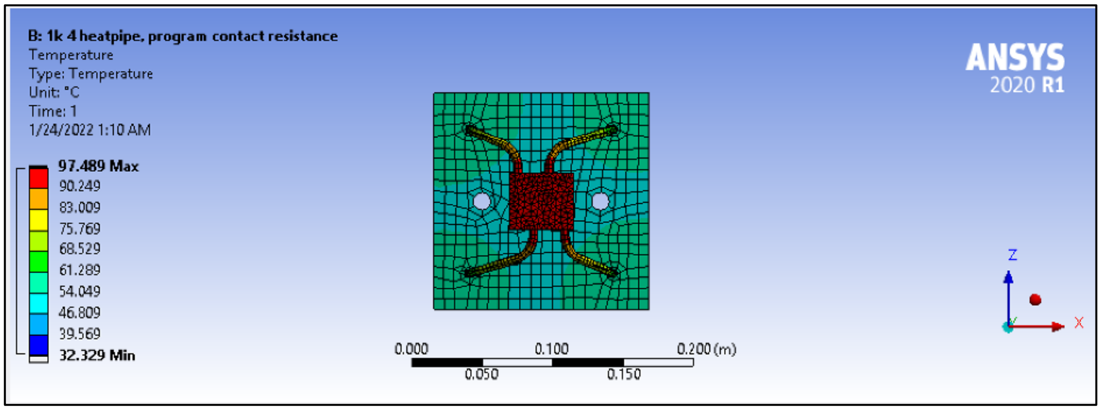
Figure X.I.3

Run II.

4 Heatpipes

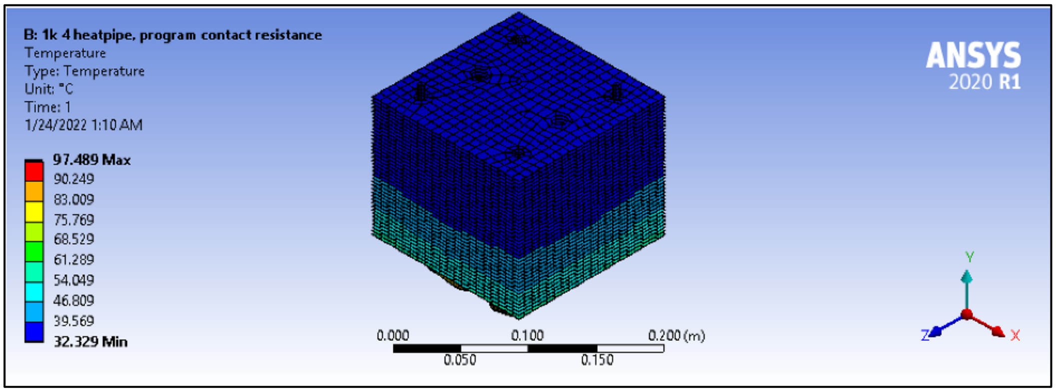
1,000 [W / m-K]

Automatic contact resistance between heatpipes and copper base



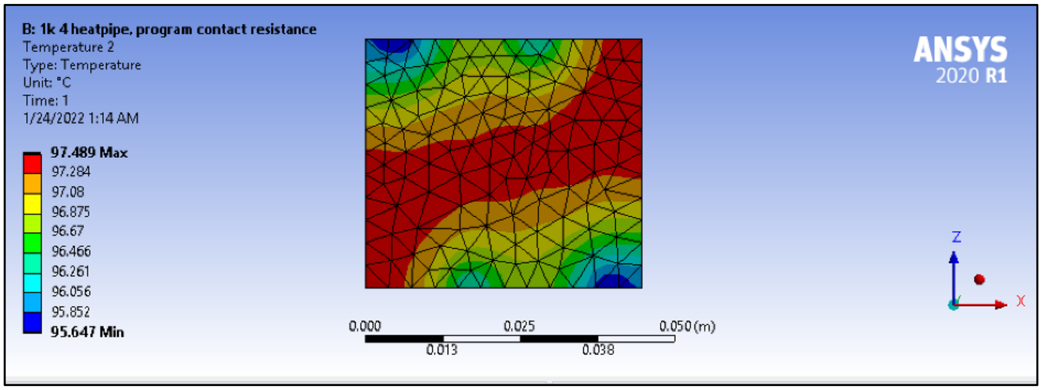
B: 1k 4 heatpipe, program contact resistance
Temperature
Type: Temperature
Unit: °C
Time: 1
1/24/2022 1:10 AM

Figure X.II.1



B: 1k 4 heatpipe, program contact resistance
Temperature
Type: Temperature
Unit: °C
Time: 1
1/24/2022 1:10 AM

Figure X.II.2



B: 1k 4 heatpipe, program contact resistance
Temperature 2
Type: Temperature
Unit: °C
Time: 1
1/24/2022 1:14 AM

Figure X.II.3

Run III.

6 Heatpipes

1,000 [W / m-K]

47,000 [°C / W] contact resistance between heatpipes and copper base

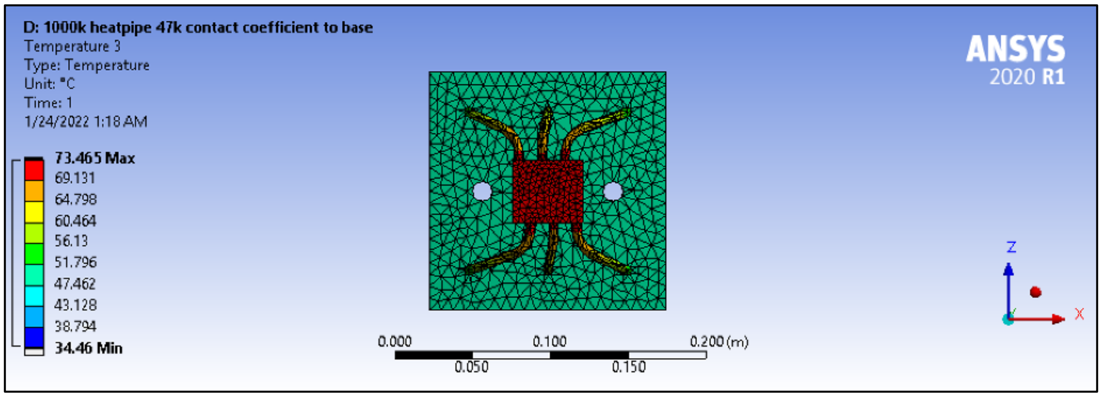


Figure X.III.1

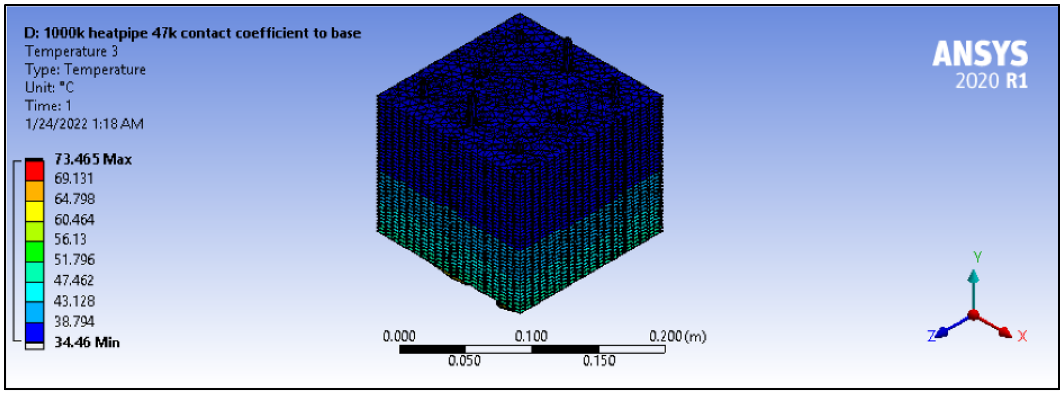


Figure X.III.2

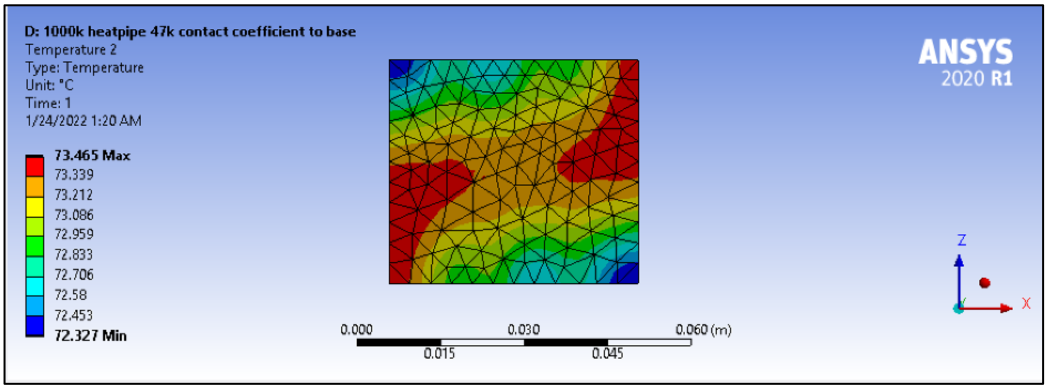


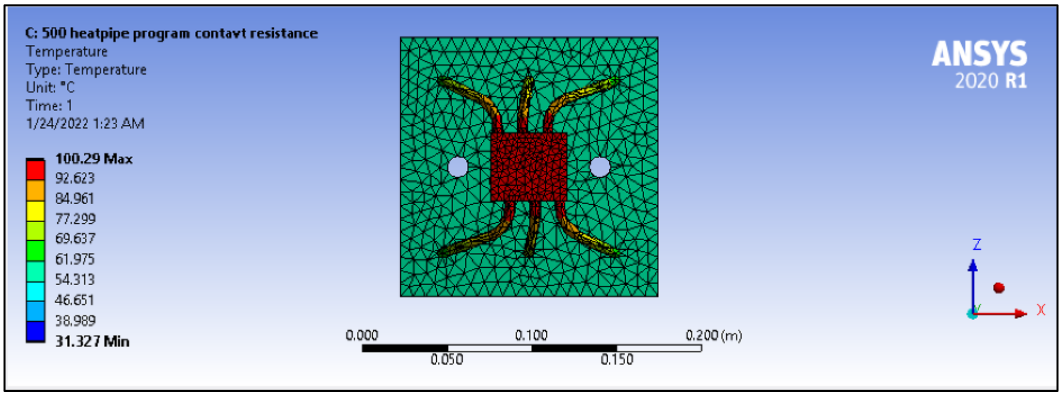
Figure X.III.3

Run IV.

6 Heatpipes

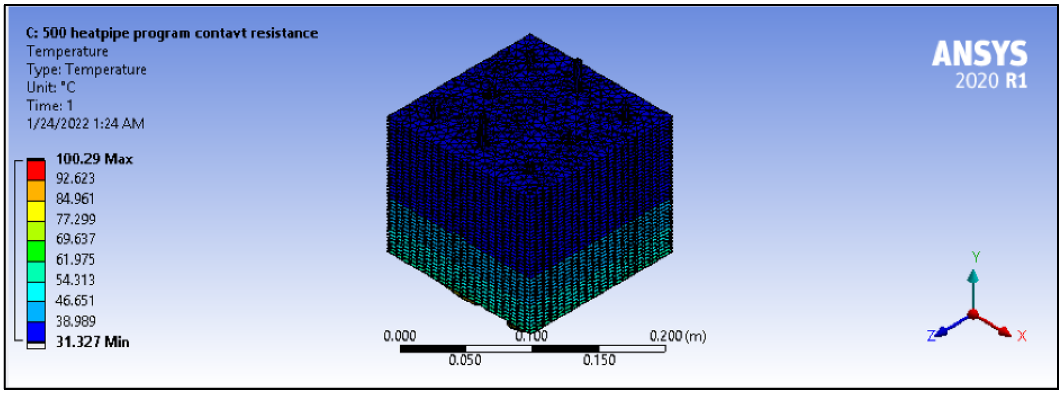
500 [W / m-K]

47,000 [°C / W] contact resistance between heatpipes and copper base



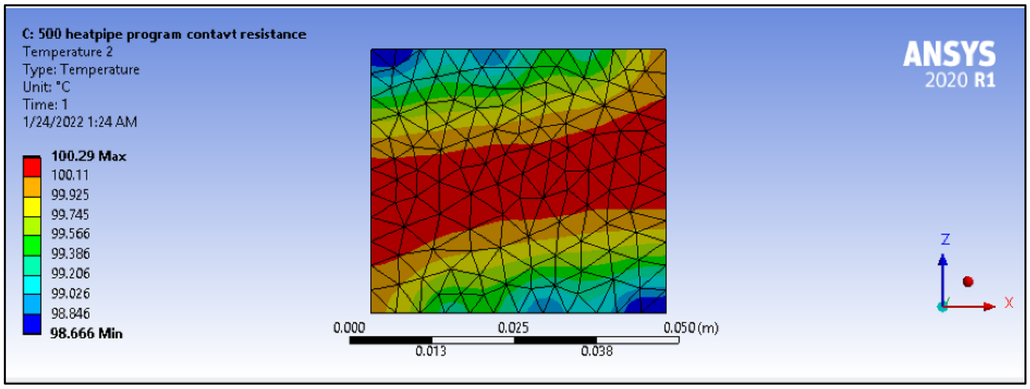
C: 500 heatpipe program contavt resistance
Temperature
Type: Temperature
Unit: °C
Time: 1
1/24/2022 1:23 AM

Figure X.IV.1



C: 500 heatpipe program contavt resistance
Temperature
Type: Temperature
Unit: °C
Time: 1
1/24/2022 1:24 AM

Figure X.IV.2



C: 500 heatpipe program contavt resistance
Temperature 2
Type: Temperature
Unit: °C
Time: 1
1/24/2022 1:24 AM

Figure X.IV.3

Run V.

6 Heatpipes with enlarged heat fin access holes (DFMA)

500 [W / m-K]

47,000 [°C / W] contact resistance between heatpipes and copper base

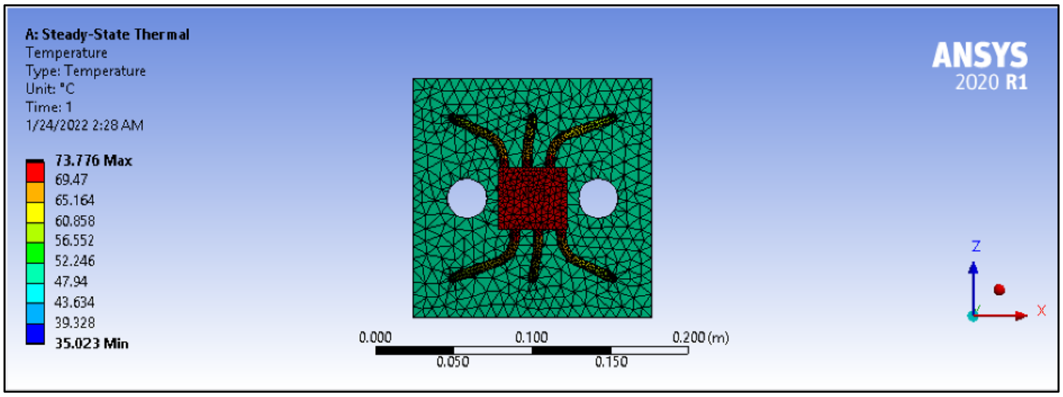


Figure X.V.1

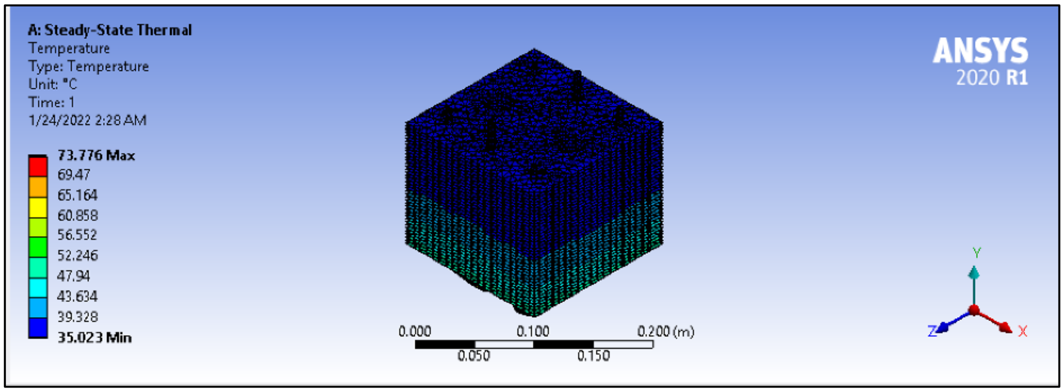


Figure X.V.2

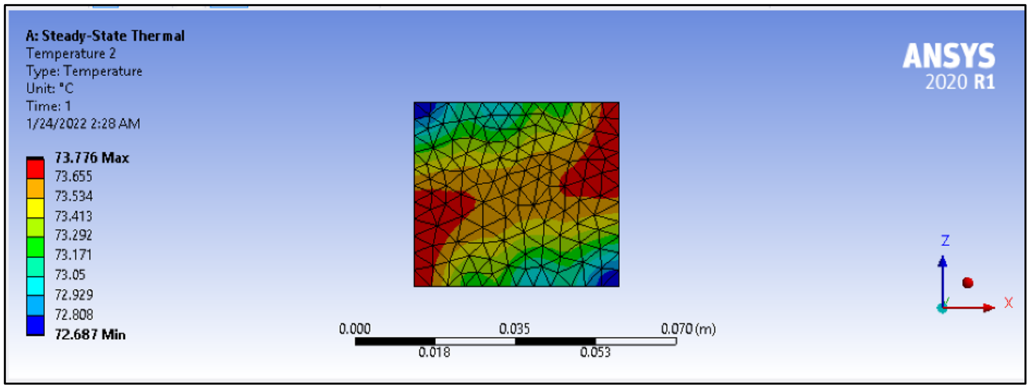
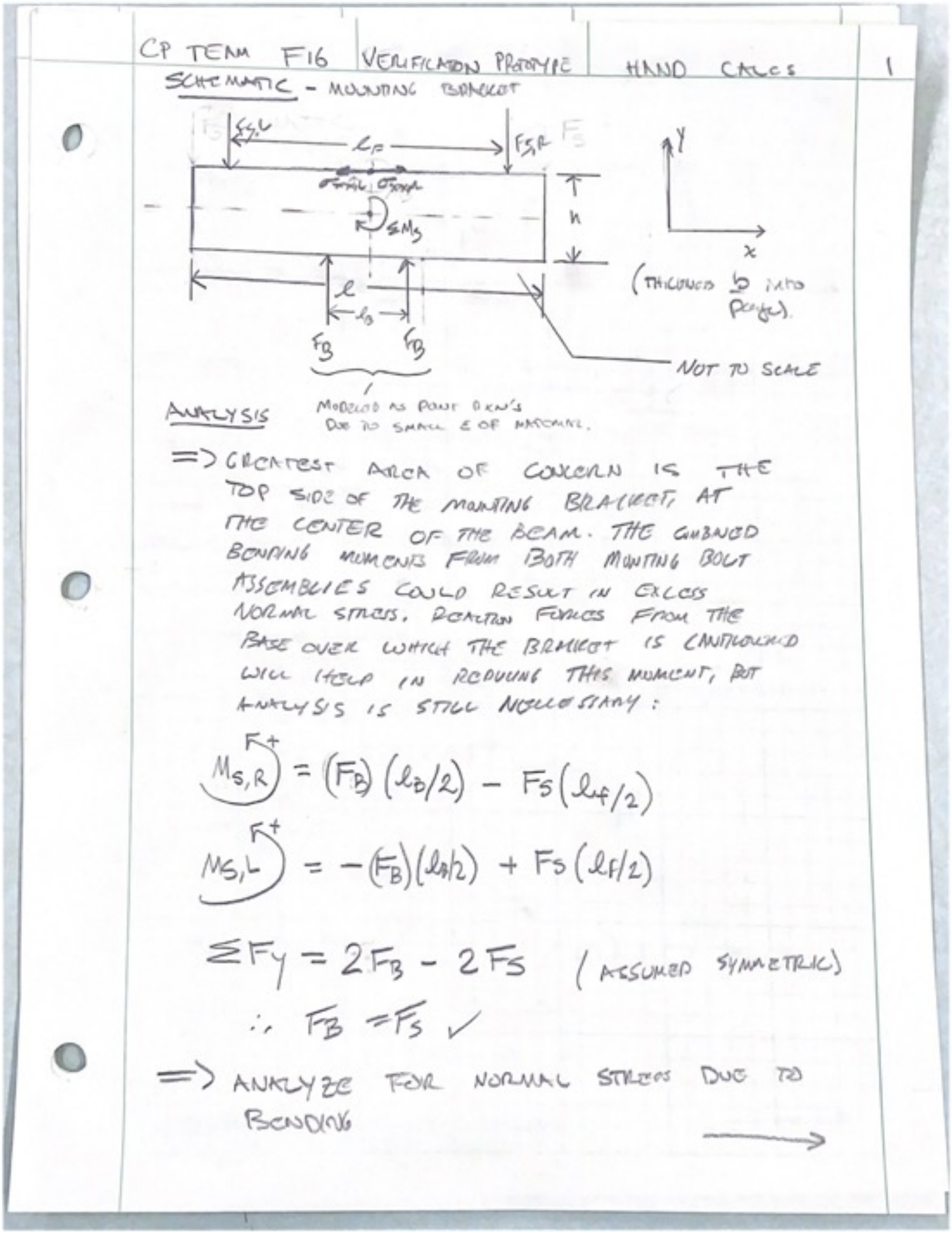


Figure X.V.3

Appendix C – Hand Calculations for Normal & Shear Stress Loading on Crossbar



CP TEAM F16 | VERIFICATION PROTOTYPE | HAND CALCS | 1

SCHEMATIC - MOUNTING BRACKET

ANALYSIS

⟹ GREATEST AREA OF CONCERN IS THE TOP SIDE OF THE MOUNTING BRACKET, AT THE CENTER OF THE BEAM. THE COMBINED BENDING MOMENTS FROM BOTH MOUNTING BOLT ASSEMBLIES COULD RESULT IN EXCESS NORMAL STRESS. REACTION FORCES FROM THE BASE OVER WHICH THE BRACKET IS CANTILEVERED WILL HELP IN REDUCING THIS MOMENT, BUT ANALYSIS IS STILL NECESSARY:

$$\overset{\curvearrowleft +}{M_{S,R}} = (F_B)(\ell_B/2) - F_S(\ell_f/2)$$

$$\overset{\curvearrowleft +}{M_{S,L}} = -(F_B)(\ell_B/2) + F_S(\ell_f/2)$$

$$\Sigma F_y = 2F_B - 2F_S \quad \text{(ASSUMED SYMMETRIC)}$$

$$\therefore F_B = F_S \checkmark$$

⟹ ANALYZE FOR NORMAL STRESS DUE TO BENDING

⟶

(...)

$$\sigma_{bend_y} = \pm \frac{M_z (h/2)}{I_{xx}}$$ → NEUTRAL AXIS AT CENTER OF BEAM

$$I_{xx} = \frac{(b)(h)^3}{12}$$

⇒ EVALUATE σ_{bend} FROM **BOTH** $F_{S,L}$ AND $F_{S,R}$.

- THEY WILL ACT OPPOSITE AT SAME POINT (AT TOP OF BEAM)

⇒ SAMPLE CALCULATION FOR:

- $l_F = 3.5$ [in]
- $F_{S,M} = 140$ [lbf]
- $b = 0.495$ [in]
- $h = 0.375$ [in]
- $\sigma_y = 65$ [Kpsi]
- $l_B = 1.76$ [in]

} - POTENTIAL BAR TO PURCHASE

→ $F_{BL} = F_S$
$= 140$ [lbf]

∴

$$M_{S,R} = (140)\left(\frac{1.76}{2}\right)^{[lbf \cdot in]} - (140)\left(\frac{3.5}{2}\right) \text{ [lbf·in]}$$

$= \underline{-121.8}$ [lbf-in]
$= {}^{-}M_{S,R}$ (SYMMETRY)

<u>EVALUATE NORMAL STRESS</u> ⟶

$$\sigma_{bending} = \frac{(-121.8)\ [lbf\text{-}in]\left(\frac{0.375}{2}\right)[in]}{\left(\frac{(0.495)(0.375)^3\ [in^4]}{12}\right)}$$

$$= 10{,}498.6\ [lbf/in^2]$$

$$\therefore \Sigma\sigma_{bend} = 2\left(\sigma_{bending}\right) \quad 10{,}498.6\ [lbf/in^2]$$

$$= 20997.17\ [psi]$$

$$\therefore \sigma_{bend} = 20.99\ [kpsi]$$

$$\therefore FS)_{bend} = \frac{85\ [kpsi]}{20.99\ [kpsi]}$$

$$\boxed{\therefore FS)_{BEND} = 4.05\ [-]}$$

→ SUFFICIENT CONSIDERING THERMAL LOADING, FATIGUE FROM CYCLES AND NOTCHES IN ENDS.

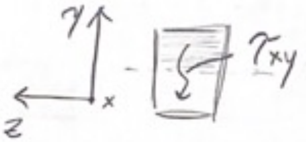
⇒ BY MOHR'S CIRCLE, ASSUMING ISOTROPIC / LINEAR BEHAVIOR OF MATERIAL, $\tau_y = \frac{\sigma_y}{2}$

$= 42.5$ [kpsi]

MAX SHEAR IS 140 [lbf] BETWEEN THE F_5 AND F_3...

↳ EVALUATE SHEAR STRESS →

$$\tau_{xy,max} = \frac{QV}{Ib} \rightarrow \frac{3V}{2A}$$



$$\tau_{xy,max} = \frac{(3)(140)\ [lbf]}{2\ (0.495)(0.375)\ [in^2]}$$

$$= 1131.3\ [lbf/in^2]$$

$$\therefore FS)_{SHEAR} = \frac{42.5\ [kpsi]}{1.13\ [kpsi]}$$ ← τ_y ← $\tau_{xy,max}$

$$\boxed{FS)_{SHEAR} = 39.8\ [-].}$$

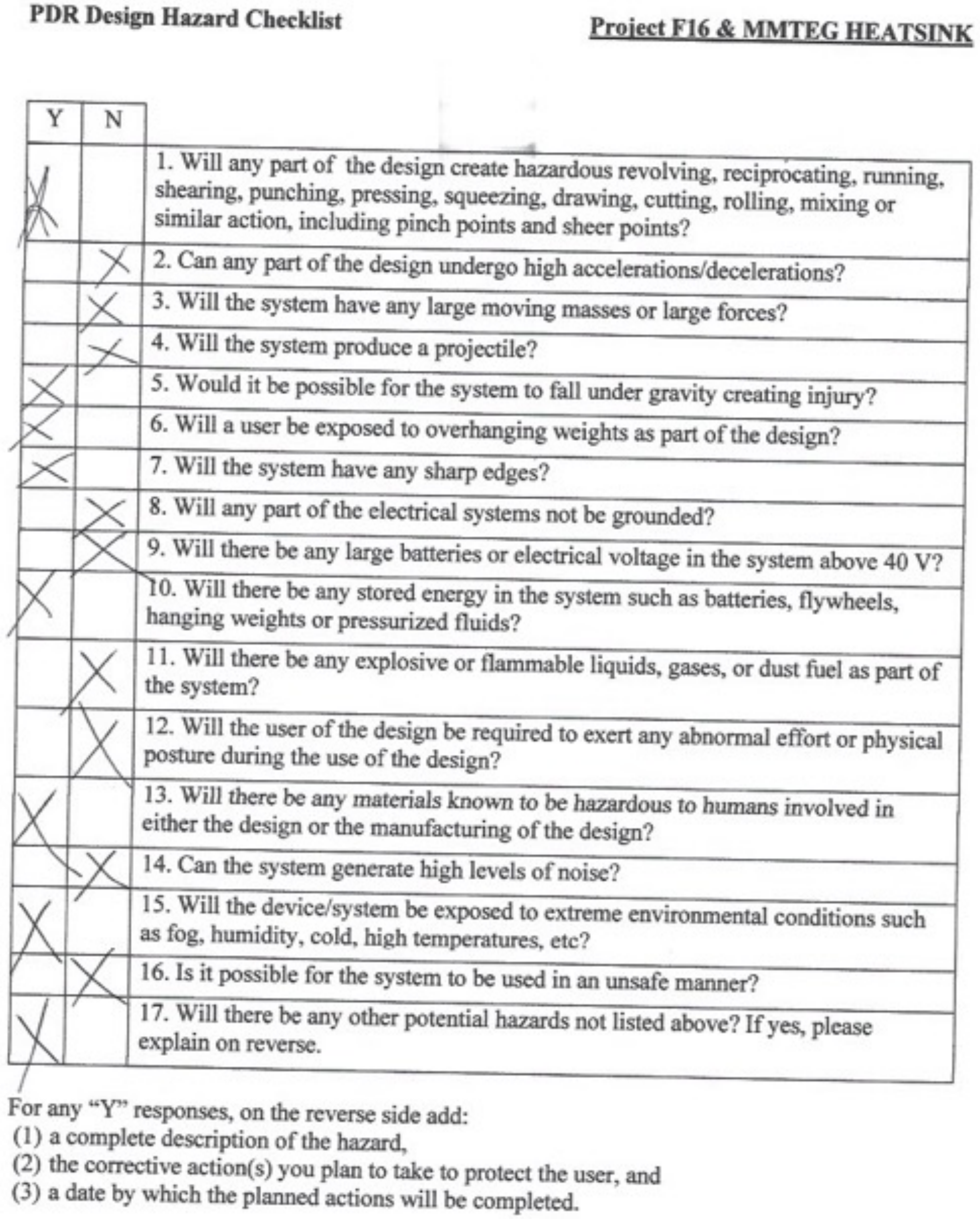
→ PLENTY SUFFICIENT.

Appendix D – Failure Modes & Effects Analysis

F16 - FMEA

System / Function	Potential Failure Mode	Potential Effects of the Failure Mode	Severity	Potential Causes of the Failure Mode	Current Preventitive Activities	Occurence	Current Detection Activities	Detection	RPN	Recommended Action(s)	Responsibility & Target Completion Date	Action Results				
												Actions Taken	Sensitivity	Occurrence	Detection	RPN
Maintain cold side temperature	Thermal performance degradation	Decreased heat sink performance	4	Lack of wind	Designing for passive convection	10	Thermal tests in varying conditions	2	80	Design for still air condtions. Assume worst case scenario	Peyton N. 1/20/22	ANSYS® heat transfer coefficients corresponded to natural convection	4	4	2	32
		Not enough energy produced	8	Insufficient number of fins	Fin density tradeoff study	2	Thermal analysis in Ansys	2	32							
Attach to combustion chamber	Heatsink detaches from combustion chamber	No energy produced	8	Insufficient pressure on TEG	Plans to create a installation torque spec	2	Run heat sink for 2 week test	4	64							
Opperate in remote location	Short lifetime	Frequent servicing required	5	Weather and environment degrade systm	Selecting materials with weather resistance	4	Creating an overview of operating locations	5	100	Specificy a service interval	Kadin F. 2/20/21		5	3	3	45
Scalable Design	Difficult to manufacture on assembly line	GTI cannot meeting quantity quota	5	Assembly lines cannot efficiently produce product	Design CAD features can be milled, extruded, and stamped	5	Evaluate designs using past manufacturing experience	4	100	Talk with sponsor and professors about design for manufacturing	Alec S. 3/17/22		5	3	3	45
Minimize Cost	Expensive	Prohibitive cost to GTI MMTEG system	6	Excessively expensive components selected	Simplify design iterations where possible	6	Check component costs on McMaster / Grainger etc	2	72							
Easy Instalation	Hazardous instalation	Injures worker	9	a) Sharp fins b) Cause burns	a) Include deburing and sanding in work instructions b) Round potentially sharp corners c) Heat dependent coating providing visual que	3	a) Visual Inspection. b) Caution warnings	3	81	Add deburing to manufacturing process, use thicker plates	Jack W. 1/25/22	Plate thickness matches that of existing design, which had no issues with worker related injuries	9	2	2	36

Appendix E – Hazard Checklist (Updated)

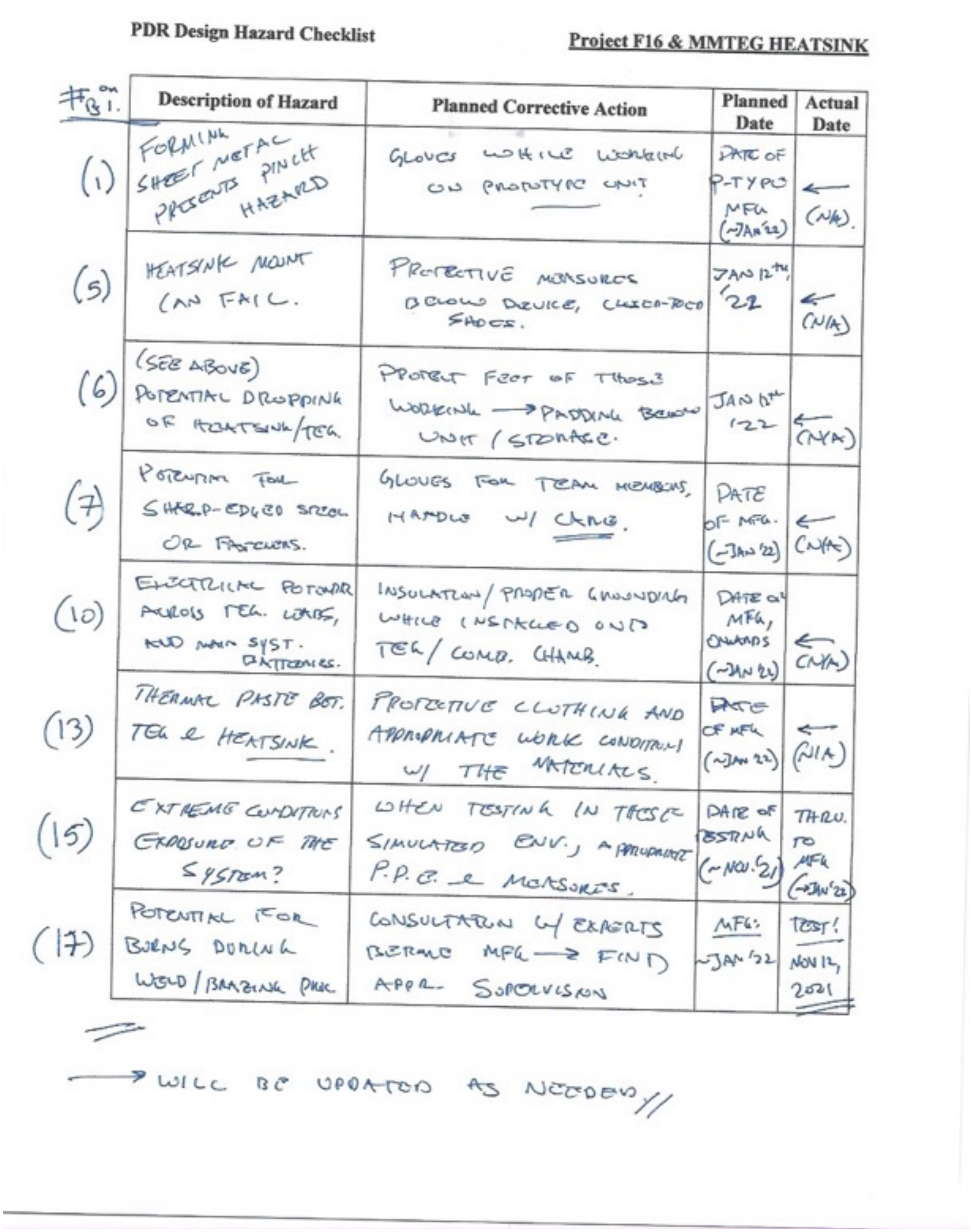


PDR Design Hazard Checklist

Project F16 & MMTEG HEATSINK

Y	N	
X		1. Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?
	X	2. Can any part of the design undergo high accelerations/decelerations?
	X	3. Will the system have any large moving masses or large forces?
	X	4. Will the system produce a projectile?
X		5. Would it be possible for the system to fall under gravity creating injury?
X		6. Will a user be exposed to overhanging weights as part of the design?
X		7. Will the system have any sharp edges?
	X	8. Will any part of the electrical systems not be grounded?
	X	9. Will there be any large batteries or electrical voltage in the system above 40 V?
X		10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
	X	11. Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?
	X	12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
X		13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
	X	14. Can the system generate high levels of noise?
X		15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc?
	X	16. Is it possible for the system to be used in an unsafe manner?
X		17. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

For any "Y" responses, on the reverse side add:
(1) a complete description of the hazard,
(2) the corrective action(s) you plan to take to protect the user, and
(3) a date by which the planned actions will be completed.



PDR Design Hazard Checklist

Project F16 & MMTEG HEATSINK

# on B1.	Description of Hazard	Planned Corrective Action	Planned Date	Actual Date
(1)	FORMING SHEET METAL PRESENTS PINCH HAZARD	GLOVES WHILE WORKING ON PROTOTYPE UNIT	DATE OF P-TYPE MFG (~JAN '22)	← (N/A).
(5)	HEATSINK MOUNT CAN FAIL.	PROTECTIVE MEASURES BELOW DEVICE, CLOSED-TOED SHOES.	JAN 12TH, '22	← (N/A)
(6)	(SEE ABOVE) POTENTIAL DROPPING OF HEATSINK/TEG	PROTECT FEET OF THOSE WORKING → PADDING BELOW UNIT / STORAGE.	JAN 12TH '22	← (N/A)
(7)	POTENTIAL FOR SHARP-EDGED STEEL OR FASTENERS.	GLOVES FOR TEAM MEMBERS, HANDLE W/ CARE.	DATE OF MFG. (~JAN '22)	← (N/A)
(10)	ELECTRICAL POTENTIAL ACROSS TEG. LEADS, AND MAIN SYST. BATTERIES.	INSULATION/PROPER GROUNDING WHILE INSTALLED ONTO TEG/COMB. CHAMB.	DATE OF MFG, ONWARDS (~JAN '22)	← (N/A)
(13)	THERMAL PASTE BET. TEG & HEATSINK.	PROTECTIVE CLOTHING AND APPROPRIATE WORK CONDITIONS W/ THE MATERIALS.	DATE OF MFG (~JAN '22)	← (N/A)
(15)	EXTREME CONDITIONS EXPOSURE OF THE SYSTEM?	WHEN TESTING IN THESE SIMULATED ENV., APPROPRIATE P.P.E. & MEASURES.	DATE OF TESTING (~NOV. '21)	THRU. TO MFG (~JAN '22)
(17)	POTENTIAL FOR BURNS DURING WELD/BRAZING PHASE	CONSULTATION W/ EXPERTS BEFORE MFG → FIND APPR. SUPERVISION	MFG: ~JAN '22	TEST! NOV 12, 2021

→ WILL BE UPDATED AS NEEDED //

Updates to Hazard Checklist since January 2022

Description of Hazard	Planned Corrective Action	Planned Date	Actual Date
End-milling the components such as base	Use training from techs to make it a safer assembly process	February 2022	Training taken place at 2 8 2022
Heat from copper during milling process	Prevent excessive touch of workpiece during milling operations and use good amount of coolant / appropriate cooling tim	February 2022	February 2022
Heat from copper components during testing	Use gloves and other protective clothing / PPE gear to prevent any burning of team members	Spring Quarter 2022	

Appendix F – Manufacturing Plan

Heat Pipe A

1. Establish the x as positive to the right, y as positive upward, and z as positive off the table
2. Start on one end, move a distance of 1.71” and bend the pipe 52.89° clockwise.
3. Move a distance of 0.68” and establish that as the new horizontal datum.
4. Bend the heat pipe to an angle of 37.11° clockwise from the new datum.
5. Rotate the heat pipe so that the z direction is to the right, y direction is directly up, and the negative x axis is off of the table
6. Move a distance of 0.68” from the bend going into the table and create a bend of 122.11° clockwise.
7. Lastly, rotate the heat pipe until the positive z is directed to the right, positive x direction is straight down, and negative y direction off of the table.
8. Using the pipe bender, create a 115.39° bend off the 1.71” in the counterclockwise direction.

Heat Pipe B

1. Establish the x as positive to the right, y as positive upward, and z as positive off the table
2. Start on one end, move a distance of 1.71” and bend the pipe 45.61° clockwise.
3. Move a distance of 0.38” and establish that as the new horizontal datum.
4. Bend the heat pipe to an angle of 44.39° clockwise from the new datum.
5. Rotate the heat pipe so that the z direction is to the right, y direction is directly up, and the negative x axis is off of the table
6. Move a distance of 0.38” from the bend going into the table and create a bend of 169.73° clockwise.
7. Lastly, rotate the heat pipe until the positive z is directed to the right, positive x direction is straight down, and negative y direction off of the table.
8. Using the pipe bender, create a 169.51° bend off the 1.71” in the counterclockwise direction.

Heat Pipe C

1. Establish the x as positive to the right, y as positive upward, and z as positive off the table
2. Start on one end, move a distance of 1.71” and bend the pipe 54.61° clockwise.
3. Move a distance of 0.84” and establish that as the new horizontal datum.
4. Bend the heat pipe to an angle of 35.39° clockwise from the new datum.
5. Rotate the heat pipe so that the z direction is to the right, y direction is directly up, and the negative x axis is off of the table
6. Move a distance of 0.84” from the bend going into the table and create a bend of 117.08° clockwise.
7. Lastly, rotate the heat pipe until the positive z is directed to the right, positive x direction is straight down, and negative y direction off of the table.
8. Using the pipe bender, create a 109.96° bend off the 1.71” in the counterclockwise direction.

Base

1. Face the top entire block.
2. Using a 4 flute end mill, make a groove with depth of 0.125” extending a distance of 0.250” from either side of center line that extends along the entire length of 1.76”.

3. Flip the piece so the 0.880” by 0.49” face is visible.
4. Using a 6mm drill bit, drill through holes with center locations of 0.145”, 0.435”, and 0.725” to the +X and -X directions. All the holes have a vertical center location of 0.2”.
5. Flip the part so that the -Z face is in the +Z direction.
6. Using a 0.25” drill bit, drill a hole in the center to a depth of 0.04”.
7. Using the same 0.25” drill bit and create a groove out to the end
8. Flip the part so that the full length groove is facing vertically off the work table.
9. Using a 0.11” drill bit, drill 6 holes at a distance of 0.40” from either side of the centerline until they punch through to the other side. The holes are symmetrical about both the horizontal and vertical centerlines. The horizontal distance from the vertical centerline to the center of the first hole is 0.145”. The distance from the vertical centerline to the center of the second hole is 0.435”. The distance from the vertical centerline to the center of the third hole is 0.725”.
10. Using a 45-degree chamfering mill, mill a chamfer on the top and bottom vertical edges with a z distance of 0.125”.
11. Face the current surface to a surface finish of 16.

Steel Bar (Crossbar)

1. Face the top and bottom face
2. Use a 4 flute end mill, mill out a depth of 0.125” from the center of the piece to a distance of 0.89”.
3. Flip the part over.
4. Using the same 4 flute end mill, starting from each side, mill a depth of 0.1” for a distance of 0.80”.
5. Using a 0.27” drill bit, drill a through hole at a distance of 0.350” from the edge along the horizontal center line of the part.

Heat Fins

1. Waterjet (includes creating the 2D .dxf file, bringing the stock to Mustang 60, requesting service)
2. Deburr the exterior edges
3. Deburr the inside of the holes using a deburring scraper

Interface Block

1. With the underside of the part facing upwards, use the 1 inch drill to create a hole 1.75 inches in depth along the center line 1.650 inches from the center.
2. Using the holes from Step 1, create grooves for the rest of the 2” dimension, a distance of 0.35”.
3. Using a 0.27” drill bit, drill a through hole at the same locations as the 1” holes in step 1.
4. Flip the block over and face mill it to 16 surface finish (finish all over)

5. Using a 0.25” drill bit, drill a hole of depth 0.0625” in the exact center of the part.
6. Using the hole from Step 5, create a groover perpendicular to the line that connects the two center points of the 0.27” holes.

Assembly Plan

1. Slide Heat Pipe A into the first hole on the copper base plate on both sides. Fill any empty space with thermal paste.

2. Slide Heat Pipe B into the third hole on the copper base plate on both sides. Fill any empty space with thermal paste.
3. Slide Het Pipe C into the fifth hole on the copper base plate on both sides. Fill any empty space with thermal paste.
4. Insert set screws into the 12 top holes using a drill.
5. Insert the thermocouples in the slot on the test stand base and cover any exposed area with thermal paste.
6. Place the TEG in between the copper base with heat pipes and set screws inserted and the test stand base.
7. Place the cross bar in the slot on the pipe base.
8. Using the bolt, secure a washer, then spring, then another washer between the crossbar and the head of the bolt.
9. In the 1.75” depth holes on the test stand base, insert a spring, then washer, then nut (in order from the top of the heat sink to the bottom of the heat sink)
10. Torque the bolt using a wrench until the TEG has 100 psi across it.
11. Repeat Steps 8-11 for the other bolt on the other side of the crossbar.
12. Lastly, insert the heat fins on the heat pipes at a spacing of ????.

Subsystem	Comp onent	Purchase (P) Modify (M) Build (B)	Raw Materials Needed to make/modify the part (only M & B)	Where/how procured?	Equipment and Operations anticipate using to make the component	Key limitations of this operation places on any parts made from it
Prototype						
Heat Dissipation Subsystem	Heat Pipes	M	Round with Sintered Wick, 6mm OD, 250mm Long	McMaster Carr, purchased through Cal Poly Pro Card. Part number: 3874N23	6 mm pipe bender, from the Mustang 60 Machine shop (on Cal Poly campus). No soft jaws needed.	Minimum bend radius = 3* heat pipe diameter. Minimum bend radius = 18 mm.
	Base	M	Multipurpose 110 Copper Bar 1/2" Thick, 2" Wide	McMaster Carr, purchased through Cal Poly Pro Card. Part number: 8964K42	Manual mill to create shaped part per CAD. 1 setup needed, using vice jaws. Deburring after milling.	Set screw hole depth limited by the distance from the the top of the heat pipe holes to the upper surface (0.1894 in)
	Steel Bar	M	Tight-Tolerance Hardened 4140 Alloy Steel Bar 1/2" Thick, 1/2" Wide	McMaster Carr, purchased through GTI. Part number: 8892K59	Manual mill to create shaped part per CAD. 1 setup needed, using vice jaws. Deburring after milling.	n/a
	Thermal Compound	P	n/a	McMaster Carr, purchased through GTI. Part number: 3715N12	n/a	n/a
	Set Screws	P	n/a	McMaster Carr, purchased through GTI. Part number: 90669A189	n/a	n/a
	Heat Fins	B	Corrosion-Resistant 3000 Series Aluminum Sheet 0.0200" Thick	McMaster Carr, purchased through GTI. Part number: 8973K286	Water jet, from Mustang 60 Machine shop (on Cal Poly campus). Final thickness of 0.02 in and dimensions of 6" by 6".	Lead time to use water jet. Preparing 2D .dxt file and requesting service (shop website)
Mounting subsystem	Interface block	M	Easy-to-Machine Multipurpose 304 Stainless Steel Sheet 4" x 4", 2" Thick	McMaster Carr, purchased through GTI. Part number: 6620K312	Manual mill to create shaped part per CAD. 1 setup needed, using vice jaws. Deburring after milling.	Minimum depth of notch on upper side is dictated by thickness of thermocouples (0.0625")
	Nuts	P	n/a	McMaster Carr, purchased through GTI. Part number: 90499A805	n/a	n/a
	TEG	Given	n/a	Provided by GTI	n/a	n/a
	Springs	P	n/a	McMaster Carr, purchased through GTI. Part number: 9657K487	n/a	n/a
	Washer	P	n/a	McMaster Carr, purchased through GTI. Part number: 91525A416	n/a	n/a
	Mounting Bolts	P	n/a	McMaster Carr, purchased through GTI. Part number: 92196A342	n/a	n/a

Appendix G – Team F16 Relevant Manufacturing Drawings

1000 – Top Level Assembly

- **1000E** – Exploded View of Top Level Assembly

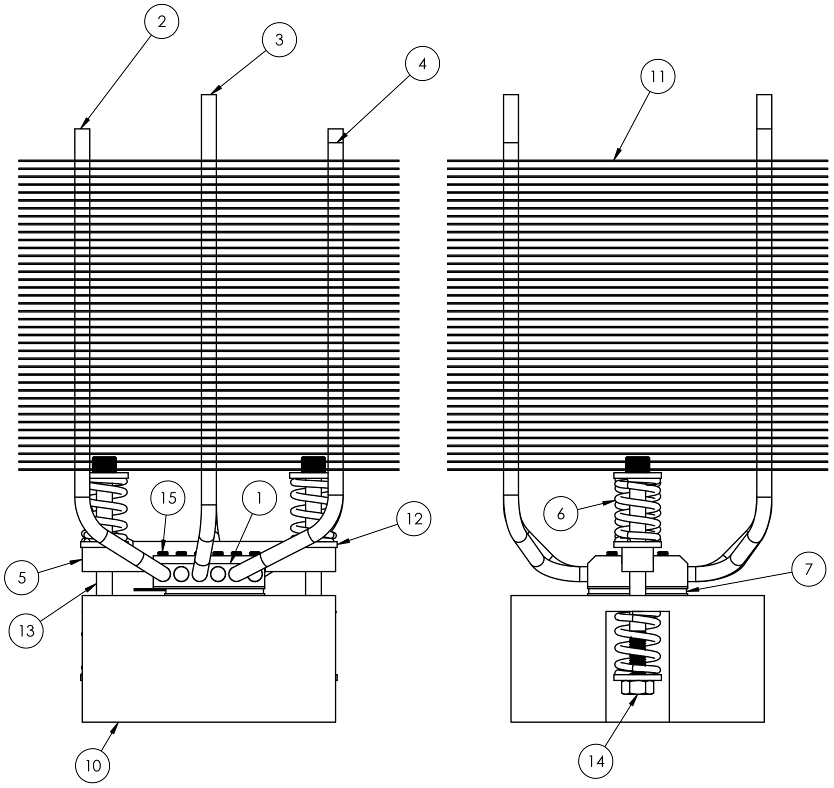
1100 – Heat Sink Subassembly

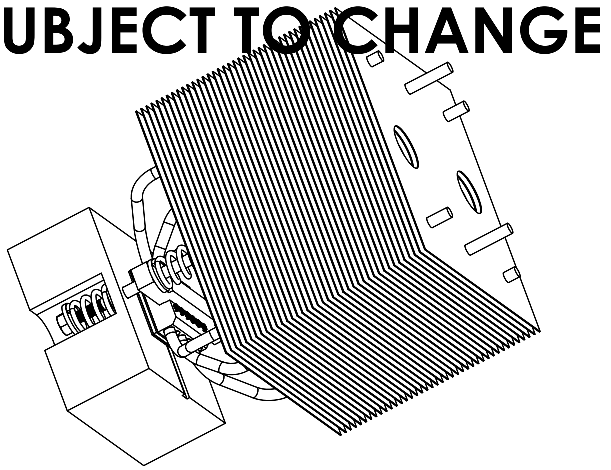
- **1100E** – Exploded View of Heat Sink Subassembly
- **1101** – Heat Sink Base
- **1102** – Heat Pipe A
- **1103** – Heat Pipe B
- **1104** – Heat Pipe C
- **1105** – Heat Fin
- **1106** – Set Screw

1200 – Heat Sink Test Jig Subassembly

- **1200E** – Exploded View of Heat Sink Test Jig Subassembly
- **1201** – Test Jig Base **1202** – Crossbar
- **1203** – Spring
- **1204** – 1⁄4-28 Bolt
- **1205** – Oversized Washer **1206** – 1⁄4-28 Nut

DRAFT - SUBJECT TO CHANGE





ITEM NO.	PART NUMBER	DESCRIPTION	McMaster PN	McMaster Stock PN	QTY.
1	1101	6 Pipe Base		8964K42	1
2	1102	Heat Pipe A		3874N23	2
3	1103	Heat Pipe B		3874N23	2
4	1104	Heat Pipe C		3874N23	2
5	1202	Crossbar		8892K59	1
6	1203	Spring	9657K487		4
7	1207	TEG			1
8	n/a				1
9	n/a				1
10	1201	Test Stand Base			1
11	1105	Heat Fin			40
12	1205	Washer	91525A416		6
13	1204	Bolt	92196A342		2
14	1206	Nut	90499A805		2
15	1106	Set Screw	90669A189		12

Cal Poly Mechanical Engineering TEAM F16	SENIOR PROJECT		TOP ASSEMBLY		Drwn. By: KADIN FELDIS
	1000		1/25/22		Drwn. By: PEYTON NIENABER

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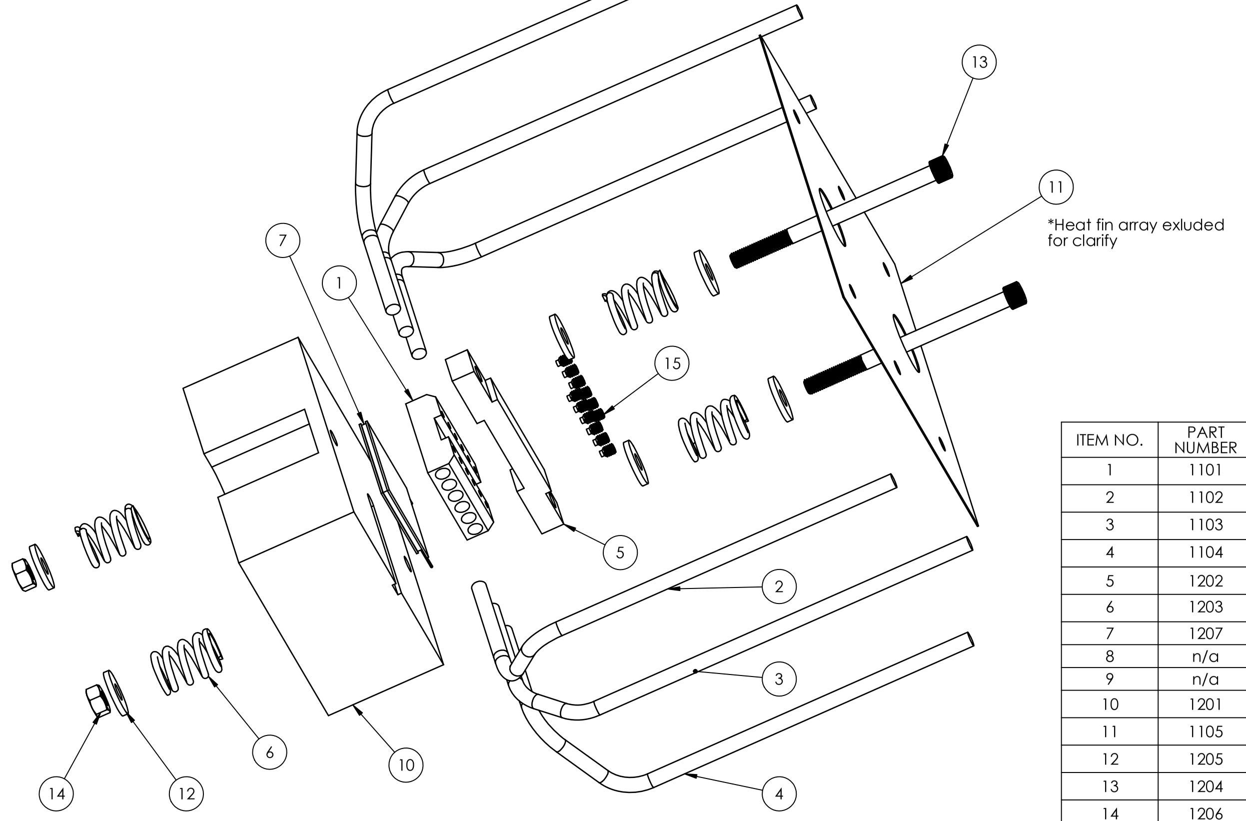

*Heat fin array exluded for clarify

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	1101	6 Pipe Base	1
2	1102	Heat Pipe A	2
3	1103	Heat Pipe B	2
4	1104	Heat Pipe C	2
5	1202	Crossbar	1
6	1203	Spring	4
7	1207	TEG	1
8	n/a		1
9	n/a		1
10	1201	Test Stand Base	1
11	1105	Heat Fin	1
12	1205	Washer	6
13	1204	Bolt	2
14	1206	Nut	2
15	1106	Set Screw	12

Cal Poly Mechanical Engineering TEAM F16	SENIOR PROJECT		ASSEMBLY EXPLODED VIEW		Drwn. By: KADIN FELDIS
	1000E		1/26/22		Chkd. By: PEYTON NIENABER

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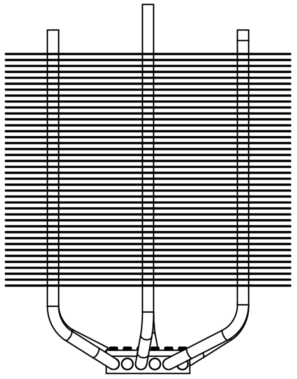

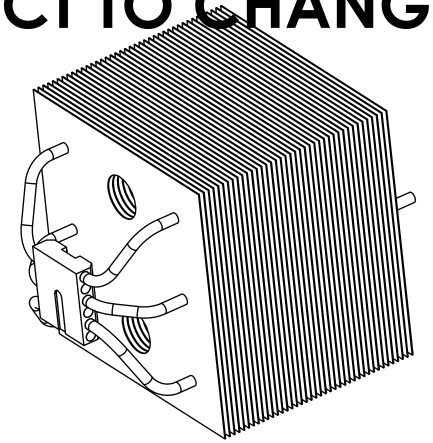

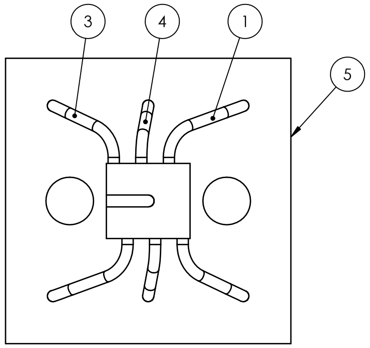

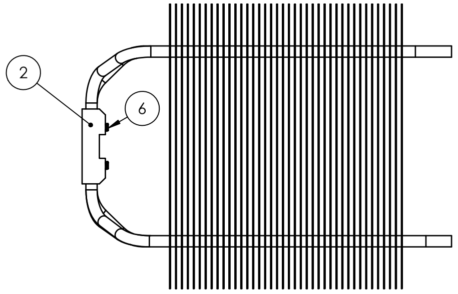

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	1104	Heat Pipe C	2
2	1101	6 Pipe Base	1
3	1102	Heat Pipe A	2
4	1103	Heat Pipe B	2
5	1105	Heat Fin	40
6	1106	Set Screw	12

Cal Poly Mechanical Engineering	SENIOR PROJECT		HEAT SINK		Drwn. By: KADIN FELDIS
TEAM F16	1100		1/26/22		Chkd. By: PEYTON NIENABER

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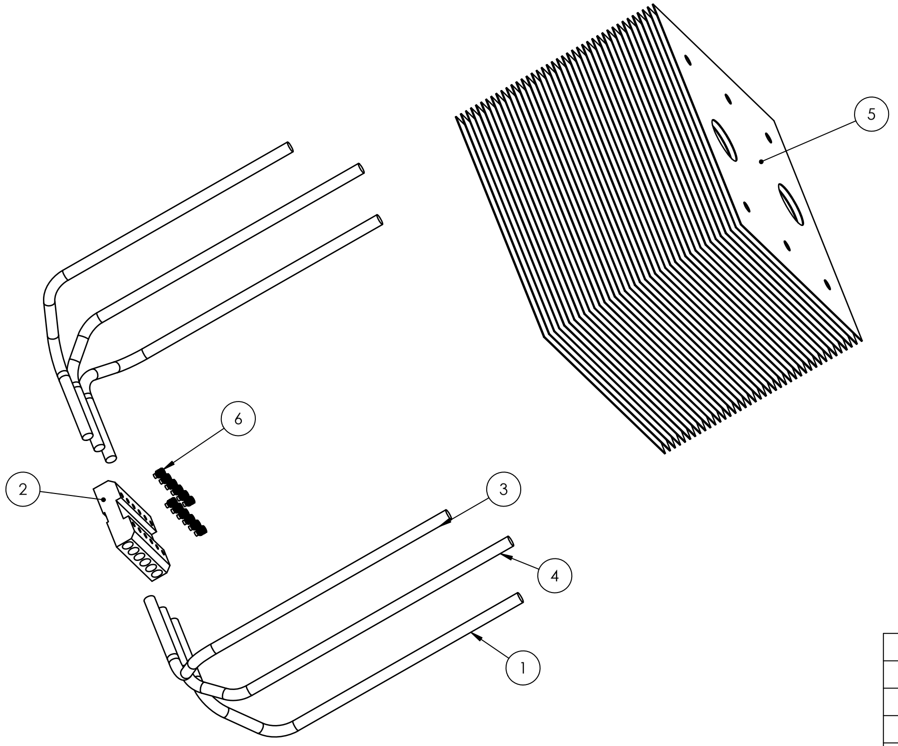

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	1104	Heat Pipe C	2
2	1101	6 Pipe Base	1
3	1102	Heat Pipe A	2
4	1103	Heat Pipe B	2
5	1105	Heat Fin	40
6	1106	Set Screw	12

Cal Poly Mechanical Engineering TEAM F16	SENIOR PROJECT		HEAT SINK EXPLODED VIEW		Drwn. By: KADIN FELDIS
	1100E		1/27/22		Chkd. By: PEYTON NIENABER

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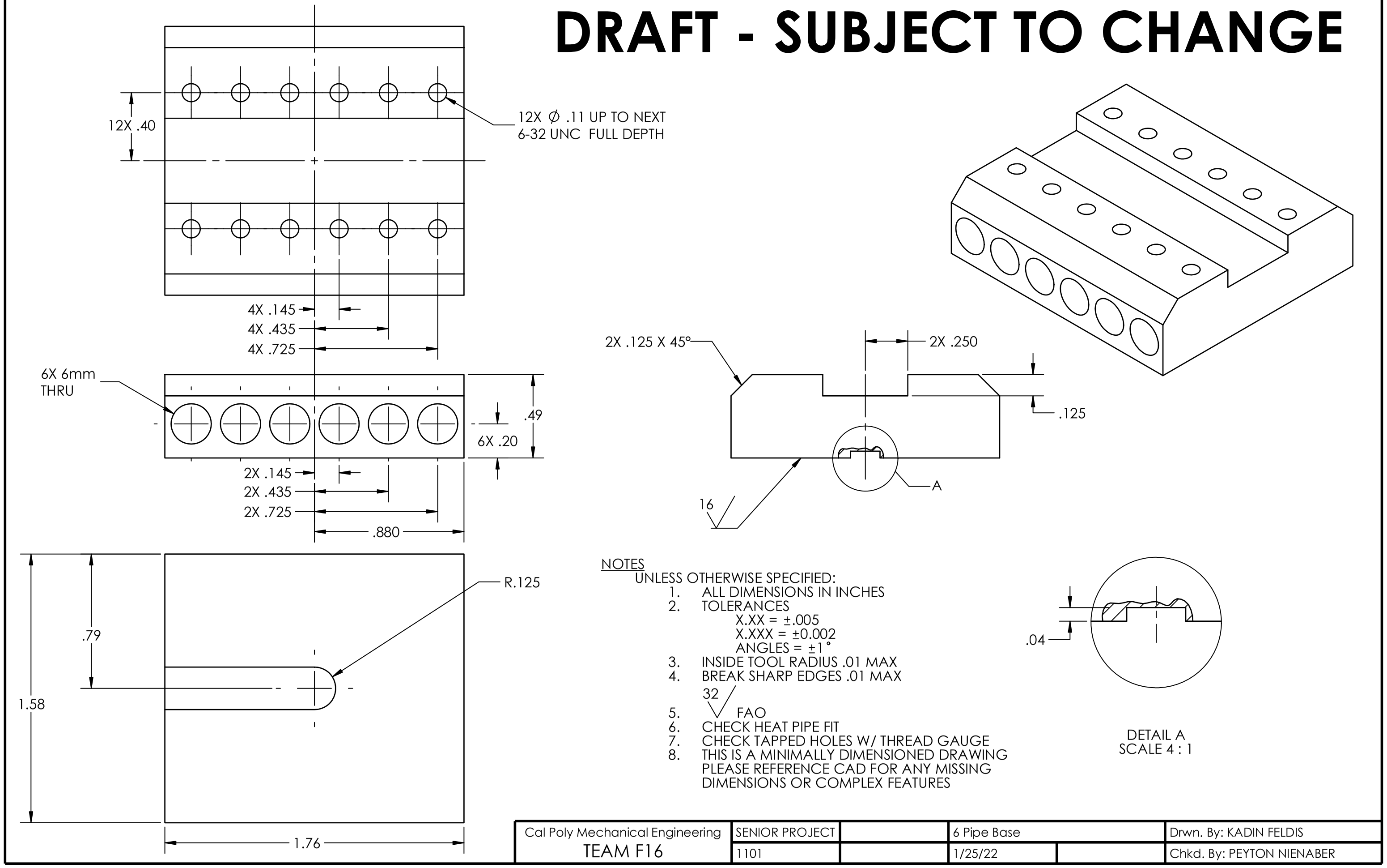
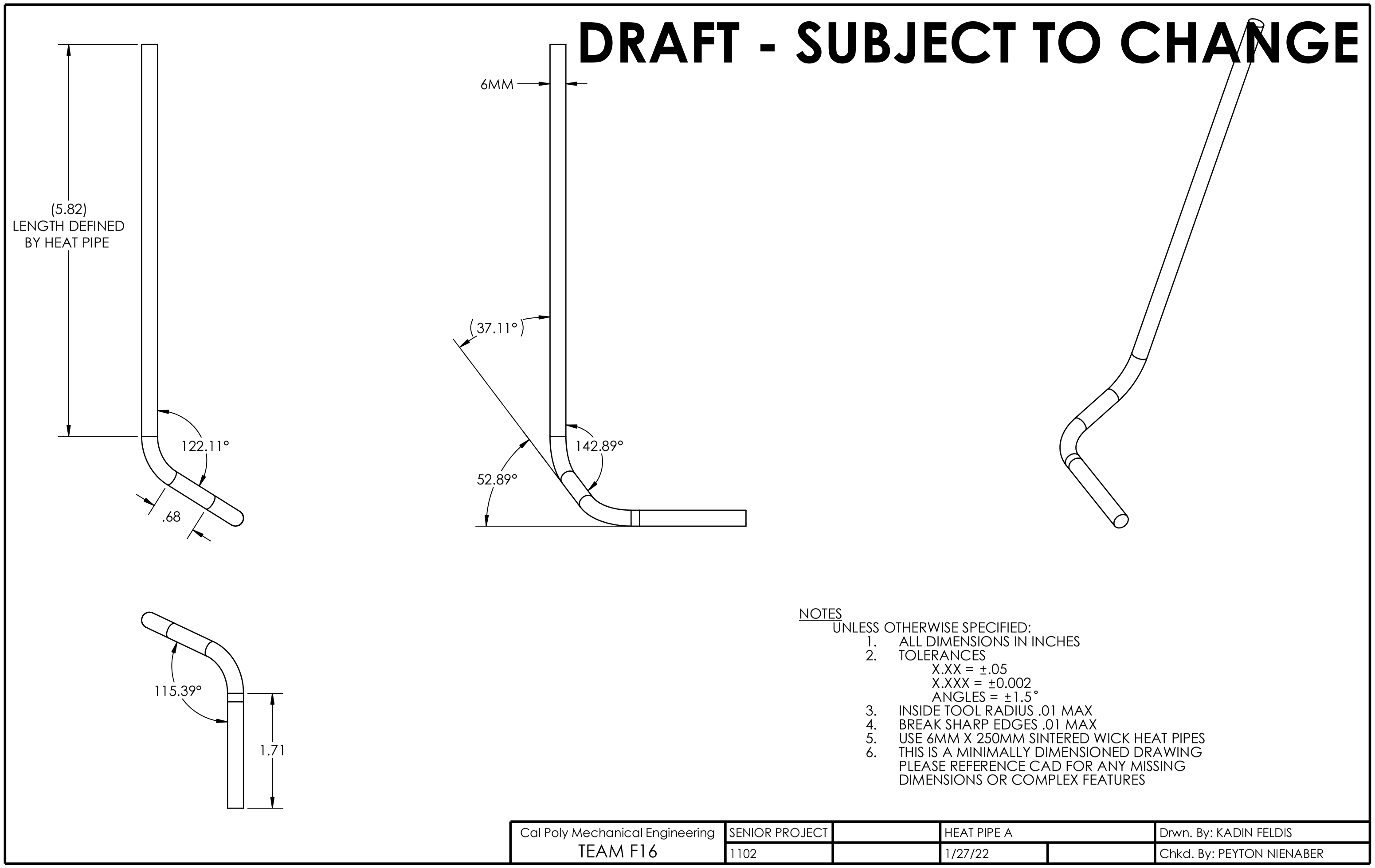


NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMENSIONS IN INCHES
2. TOLERANCES
X.XX = ±.005
X.XXX = ±0.002
ANGLES = ±1°
3. INSIDE TOOL RADIUS .01 MAX
4. BREAK SHARP EDGES .01 MAX
5. 32 FAO
6. CHECK HEAT PIPE FIT
7. CHECK TAPPED HOLES W/ THREAD GAUGE
8. THIS IS A MINIMALLY DIMENSIONED DRAWING PLEASE REFERENCE CAD FOR ANY MISSING DIMENSIONS OR COMPLEX FEATURES

Cal Poly Mechanical Engineering TEAM F16	SENIOR PROJECT		6 Pipe Base		Drwn. By: KADIN FELDIS
	1101		1/25/22		Chkd. By: PEYTON NIENABER

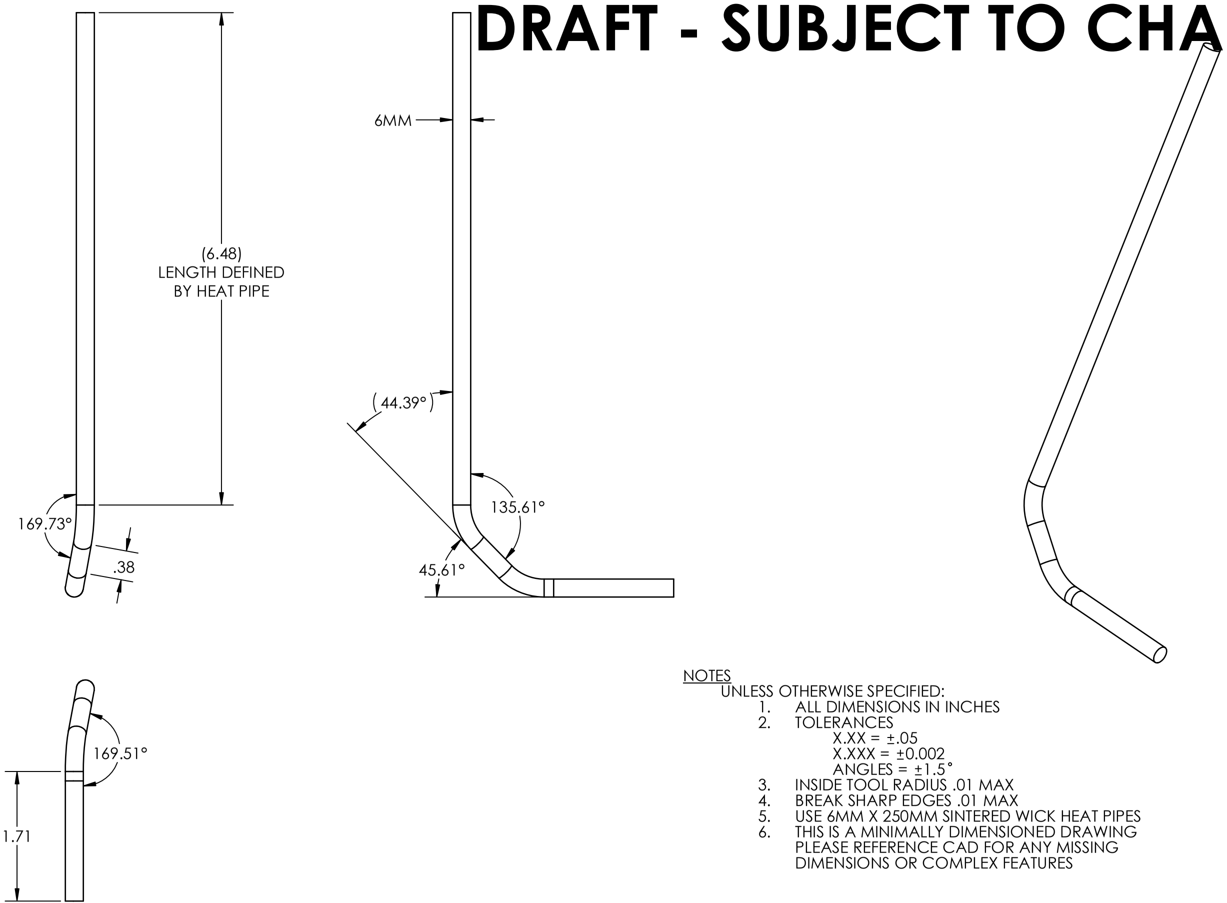
DRAFT - SUBJECT TO CHANGE



NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMENSIONS IN INCHES
2. TOLERANCES
X.XX = ±.05
X.XXX = ±0.002
ANGLES = ±1.5°
3. INSIDE TOOL RADIUS .01 MAX
4. BREAK SHARP EDGES .01 MAX
5. USE 6MM X 250MM SINTERED WICK HEAT PIPES
6. THIS IS A MINIMALLY DIMENSIONED DRAWING
PLEASE REFERENCE CAD FOR ANY MISSING
DIMENSIONS OR COMPLEX FEATURES

Cal Poly Mechanical Engineering TEAM F16	SENIOR PROJECT		HEAT PIPE A		Drwn. By: KADIN FELDIS
	1102		1/27/22		Chkd. By: PEYTON NIENABER

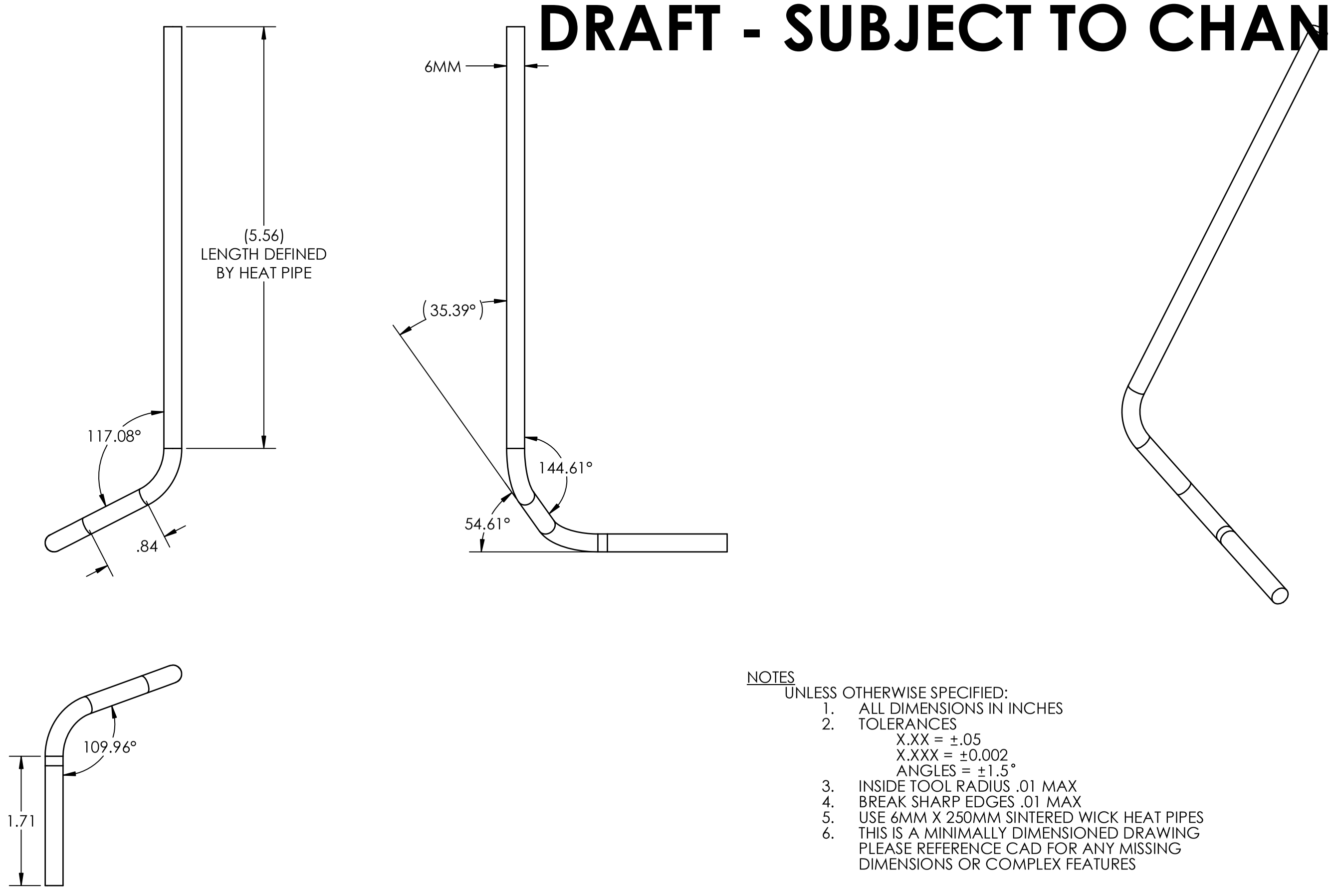
DRAFT - SUBJECT TO CHANGE



NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMENSIONS IN INCHES
2. TOLERANCES
    X.XX = ±.05
    X.XXX = ±0.002
    ANGLES = ±1.5°
3. INSIDE TOOL RADIUS .01 MAX
4. BREAK SHARP EDGES .01 MAX
5. USE 6MM X 250MM SINTERED WICK HEAT PIPES
6. THIS IS A MINIMALLY DIMENSIONED DRAWING PLEASE REFERENCE CAD FOR ANY MISSING DIMENSIONS OR COMPLEX FEATURES

Cal Poly Mechanical Engineering TEAM F16	SENIOR PROJECT		HEAT PIPE B		Drwn. By: KADIN FELDIS
	1103		1/27/22		Chkd. By: PEYTON NIENABER

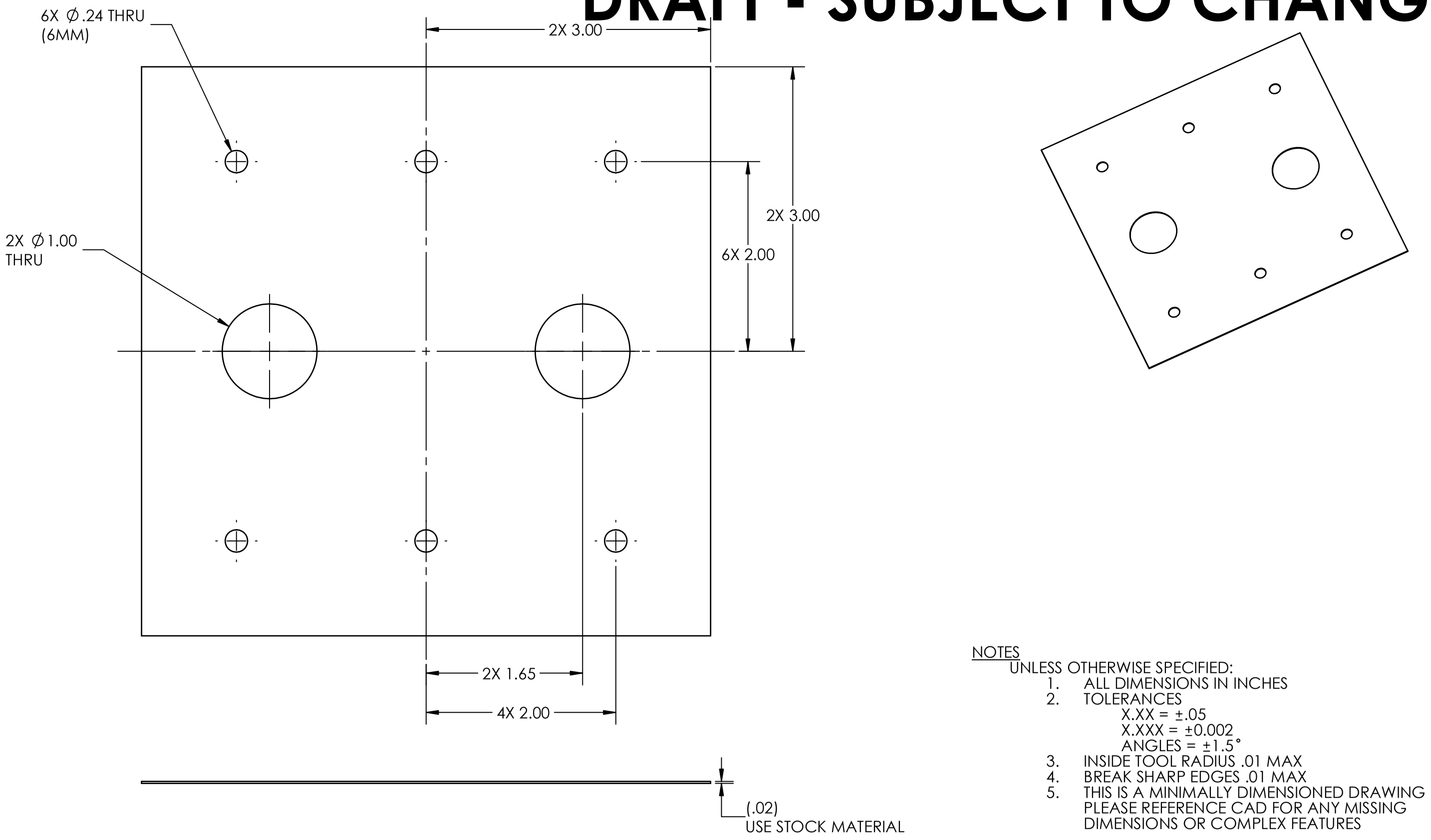
DRAFT - SUBJECT TO CHANGE



NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMENSIONS IN INCHES
2. TOLERANCES
    X.XX = ±.05
    X.XXX = ±0.002
    ANGLES = ±1.5°
3. INSIDE TOOL RADIUS .01 MAX
4. BREAK SHARP EDGES .01 MAX
5. USE 6MM X 250MM SINTERED WICK HEAT PIPES
6. THIS IS A MINIMALLY DIMENSIONED DRAWING
PLEASE REFERENCE CAD FOR ANY MISSING
DIMENSIONS OR COMPLEX FEATURES

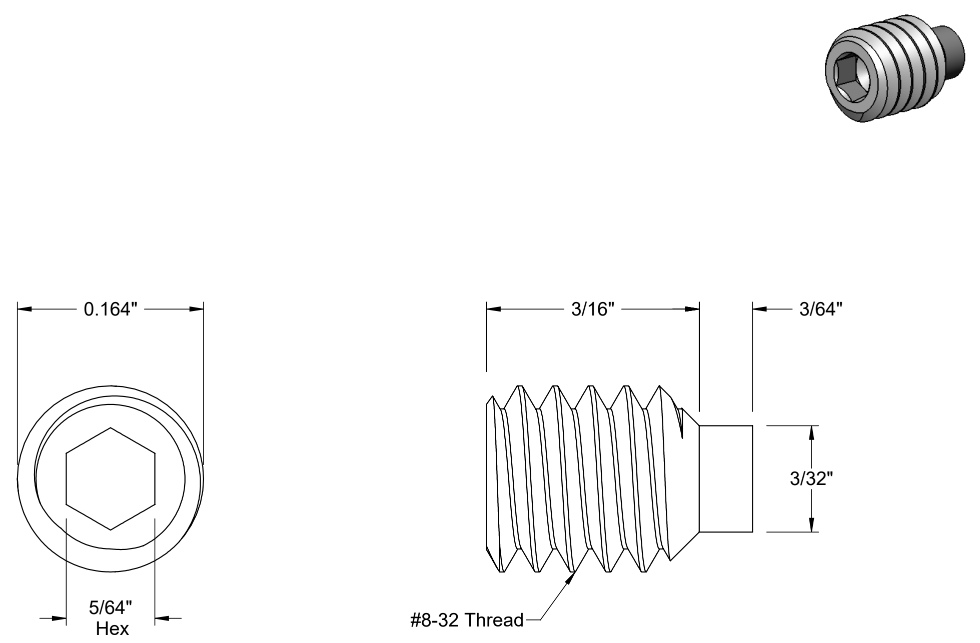
Cal Poly Mechanical Engineering TEAM F16	SENIOR PROJECT		HEAT PIPE C		Drwn. By: KADIN FELDIS
	1104		1/27/22		Chkd. By: PEYTON NIENABER

DRAFT - SUBJECT TO CHANGE



NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMENSIONS IN INCHES
2. TOLERANCES
    X.XX = ±.05
    X.XXX = ±0.002
    ANGLES = ±1.5°
3. INSIDE TOOL RADIUS .01 MAX
4. BREAK SHARP EDGES .01 MAX
5. THIS IS A MINIMALLY DIMENSIONED DRAWING PLEASE REFERENCE CAD FOR ANY MISSING DIMENSIONS OR COMPLEX FEATURES

Cal Poly Mechanical Engineering TEAM F16	SENIOR PROJECT		HEAT PIPE C		Drwn. By: KADIN FELDIS
	1104		1/27/22		Chkd. By: PEYTON NIENABER



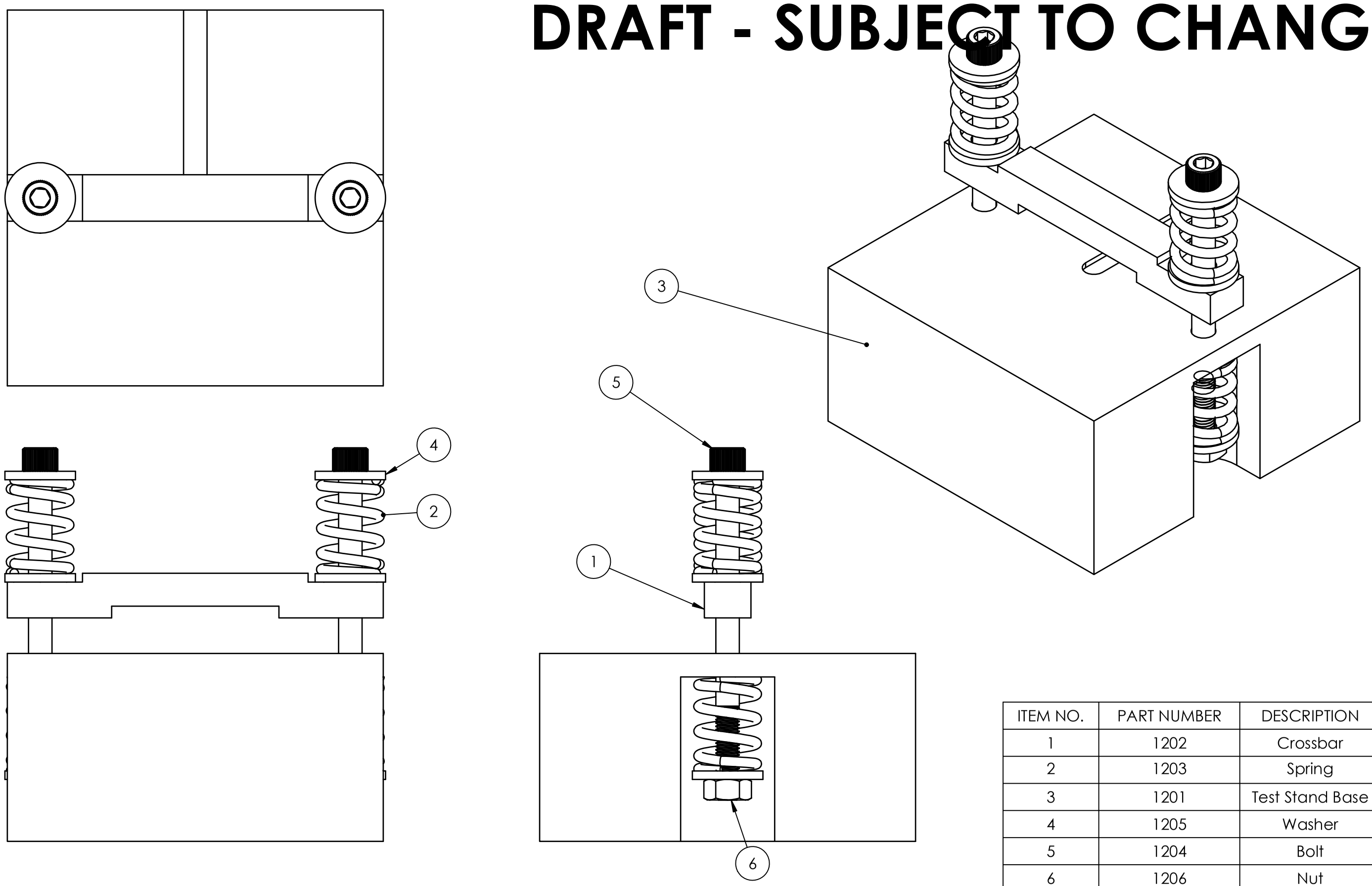
McMASTER-CARR® CAD

PART NUMBER **1106**

http://www.mcmaster.com

18-8 Stainless Steel
Brass-Tip Set Screws

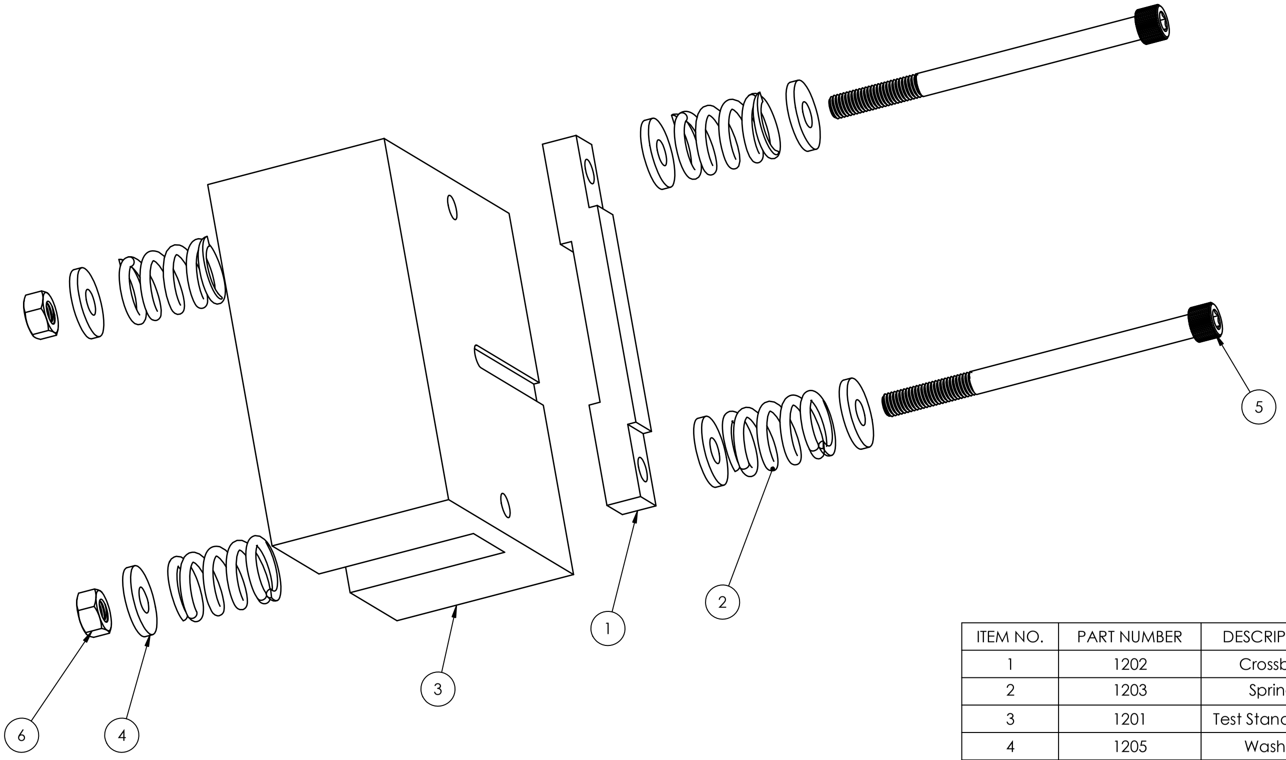
DRAFT - SUBJECT TO CHANGE



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	1202	Crossbar	1
2	1203	Spring	4
3	1201	Test Stand Base	1
4	1205	Washer	6
5	1204	Bolt	2
6	1206	Nut	2

Cal Poly Mechanical Engineering TEAM F16	SENIOR PROJECT		TEST JIG		Drwn. By: KADIN FELDIS
	1200		1/26/22		Chkd. By: PEYTON NIENABER

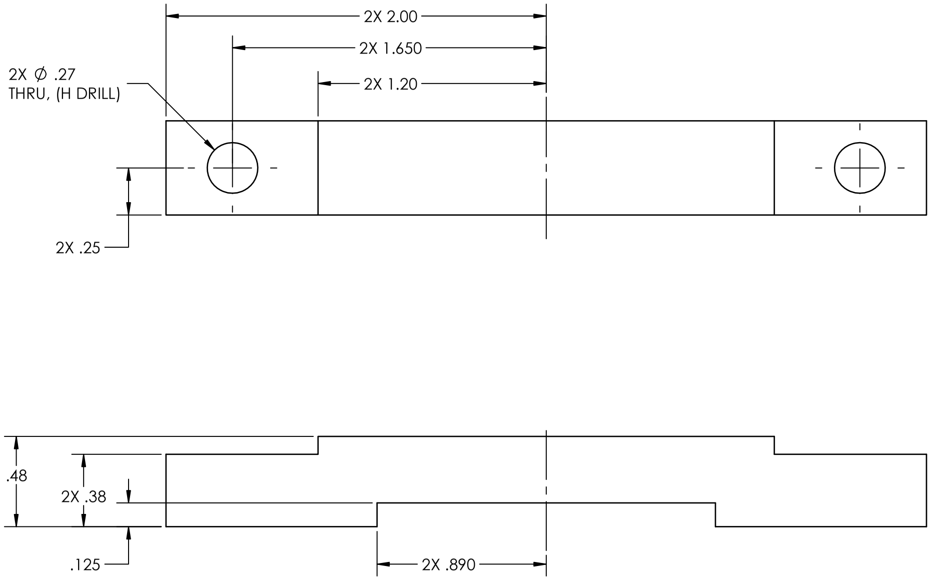
DRAFT - SUBJECT TO CHANGE

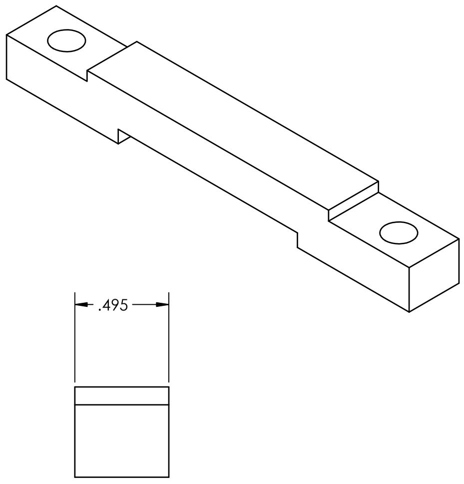


ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	1202	Crossbar	1
2	1203	Spring	4
3	1201	Test Stand Base	1
4	1205	Washer	6
5	1204	Bolt	2
6	1206	Nut	2

Cal Poly Mechanical Engineering TEAM F16	SENIOR PROJECT		TEST JIG EXPLODED VIEW		Drwn. By: KADIN FELDIS
	1200E		1/26/22		Chkd. By: PEYTON NIENABER

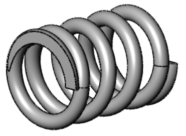
DRAFT - SUBJECT TO CHANGE

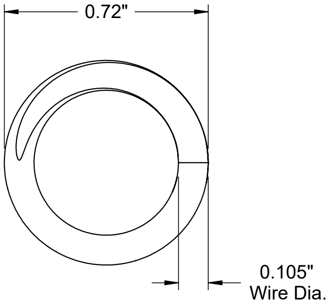


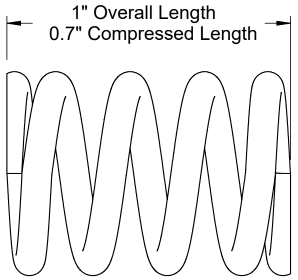


NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMENSIONS IN INCHES
2. TOLERANCES
    X.XX = ±.005
    X.XXX = ±0.002
    ANGLES = ±1°
3. INSIDE TOOL RADIUS .01 MAX
4. BREAK SHARP EDGES .01 MAX
5. 32√ FAO
6. CHECK 1/4-28 BOLT CLEARANCE FIT
7. CHECK FIT WITH HEATSINK BASE
8. THIS IS A MINIMALLY DIMENSIONED DRAWING PLEASE REFERENCE CAD FOR ANY MISSING DIMENSIONS OR COMPLEX FEATURES

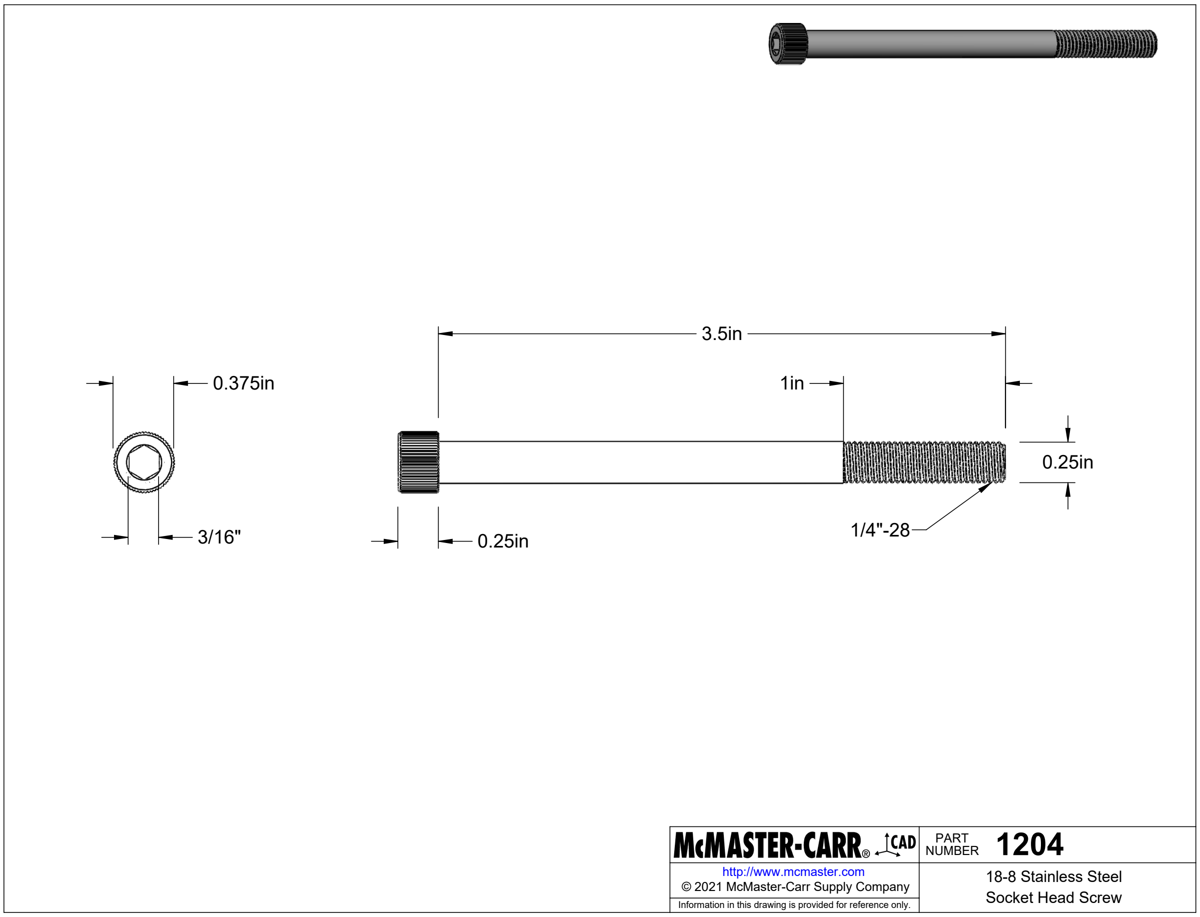
Cal Poly Mechanical Engineering TEAM F16	SENIOR PROJECT		CROSSBAR		Drwn. By: KADIN FELDIS
	1202		1/25/22		Chkd. By: PEYTON NIENABER

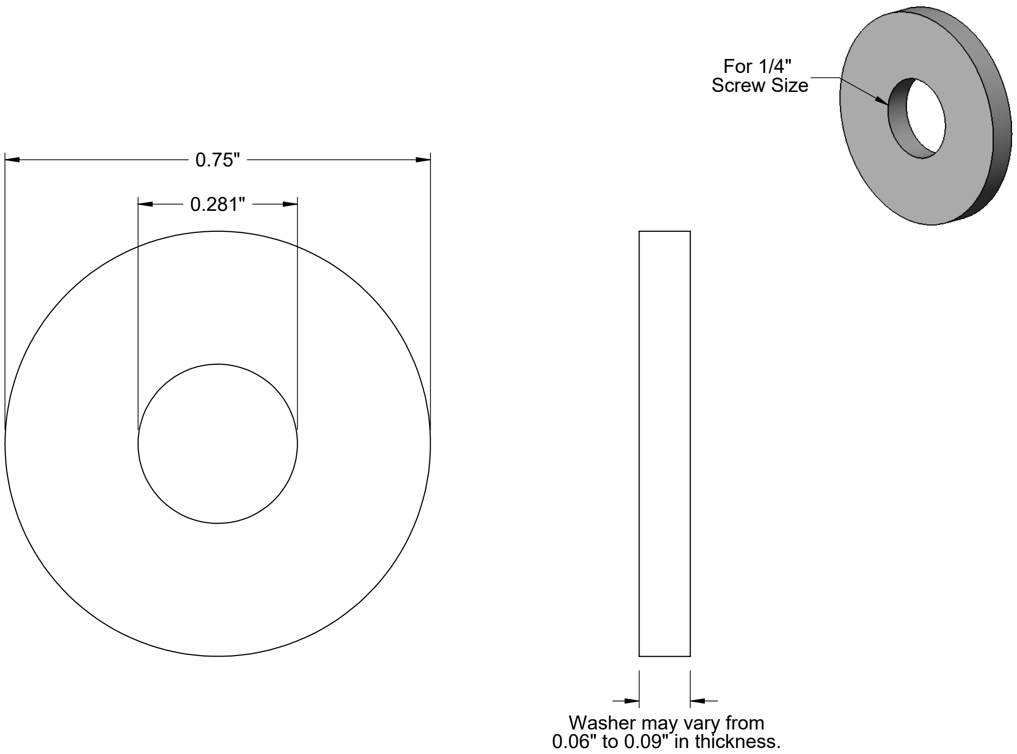






McMASTER-CARR® CAD	PART NUMBER	**1203**
http://www.mcmaster.com © 2021 McMaster-Carr Supply Company	Compression Spring	
Information in this drawing is provided for reference only.		

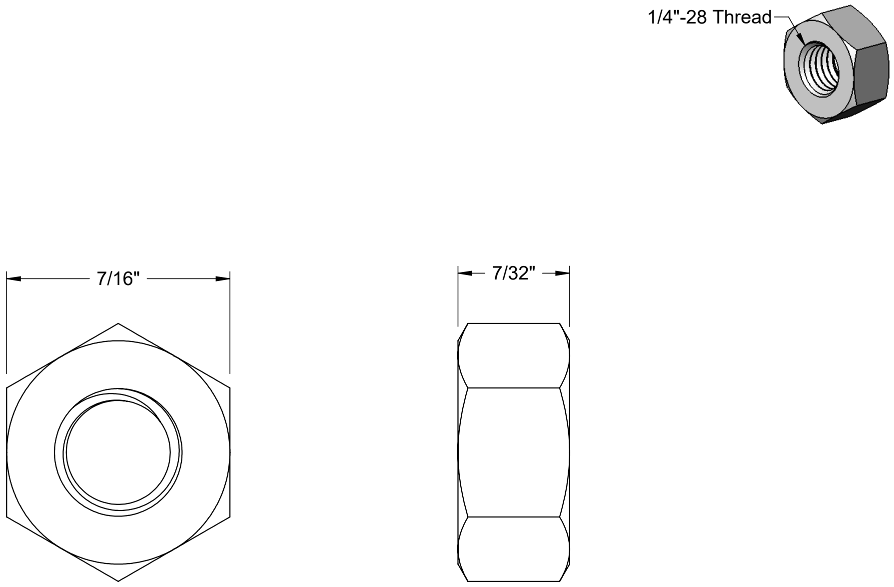

0.375in
3/16"
3.5in
1in
0.25in
0.25in
1/4"-28
McMASTER-CARR
CAD
PART NUMBER
1204
http://www.mcmaster.com
© 2021 McMaster-Carr Supply Company
Information in this drawing is provided for reference only.
18-8 Stainless Steel
Socket Head Screw



For 1/4" Screw Size

Washer may vary from 0.06" to 0.09" in thickness.

McMASTER-CARR® CAD	PART NUMBER	**1205**
http://www.mcmaster.com	316 Stainless Steel Washer	



McMASTER-CARR® CAD

PART NUMBER **1206**

http://www.mcmaster.com

High-Strength
Steel Hex Nut

Appendix H – Design Verification Plan

DVP&R - Design Verification Plan (Team F16)

Project: Cal Poly Design Team F16, GTI MMTEG | Sponsor: Gas Technology Institute (rep Abdelallah Ahmed) | Edit Date: 1/27/22

TEST PLAN										TEST RESULTS	
Test #	Specification	Test Description	Measurements	Acceptance Criteria	Required Facilities/Equipment	Parts Needed	Responsibility	TIMING		Numerical Results	Notes on Testing
								Start date	Finish date		
1	TEG temperature difference (indoor "room conditions")	-Test will be conducted indoors, preferably away from any direct sources of solar or other radiation -Attach test fixture ("design verification prototype") to 1000 [W] duty cycle-modulated hot plate via mounting defined in CAD geometry -Turn on hot plate and allow steel block to reach steady state temperature (dependent on ambient conditions -record initial temperatures on "hot" and "cold" side of TEG, as well as ambient -Allow system to reach steady state... when measurements plateau (changes between 1s time increments drop below 5% of nominal -plot response -repeat this process twice and average results -Will serve as nominal / "control" performance baseline against which other more dynamic condition tests can be evaluated	1) Thermocouple probe inserted into steel base to approximate the "HOT" side of TEG temperature 2) Thermocouple probe inserted into slot in copper base to approximate TEG "cold side" temperature	steady state "Cold side" temperature of TEG < 100 degC for 55 [W] heat input from block. Some linear extrapolation may be necessary based on the steady state that the system finds	-Design Verification prototype -Hot plate or burner capable of consistent 1000 [W] output over duty cycle modulation -Acess to power for said hot plate -Two thermocouples to measure hot and cold side temperatures of TEG, respectively. (FOR TEST #1 ONLY… an indoor environment with little interruptions)	Full Design Verification prototype (see relevant BoM)	Jack	5/1/22			
2	TEG temperature difference (outdoor "sunlit" conditions)	-Repeat test as in #1. -Conduct in "typical" sunlight blue skies day. record ambient conditions via photo and measurement of ambient temperature, etc. Reference tabulated values of solar radiation versus atmospheric conditions to evaluate performance	*See test #1*	*See test #1*	-See test #1 -Outdoor setting that testing can be reliably conducted without disturbance -Minimal wind and sunny conditions with minimal clouds	*See row #1*	Jack	5/1/22			
3	TEG temperature difference ("fouled" heatsink, outdoor "sunlit" conditions)	-Repeat test as in #1. -Install in similar / same (if possible) ambient conditions as test #2. -Coat heatsink in dust that would be encountered after several months of use in an arid environment. Possible application method includes collecting fine dirt and spraying it onto heatfins by use of compressed air	*See test #1*	*See test #1*	-See test #2 -Dirt that can be used to "foul" the heatsink -Compressed air or other applicator of dirt	*See row #1*	Jack	5/1/22			
4	TEG temperature difference (outdoor "overcast" conditions)	-Repeat test as in #1. -Conduct in "overcast" day. Measure conditions in similar fashion to #2.	*See test #1*	*See test #1*	-See test #1 -Outdoor setting that testing can be reliably conducted without disturbance -Minimal wind and sunny conditions with overcast conditions	*See row #1*	Jack	5/5/22			

Complete these columns when you conduct the tests.

DVP&R - Design Verification Plan (Team F16)

Project: Cal Poly Design Team F16, GTI MMTEG
Sponsor: Gas Technology Institute (rep Abdelallah Ahmed)
Edit Date: 1/27/22

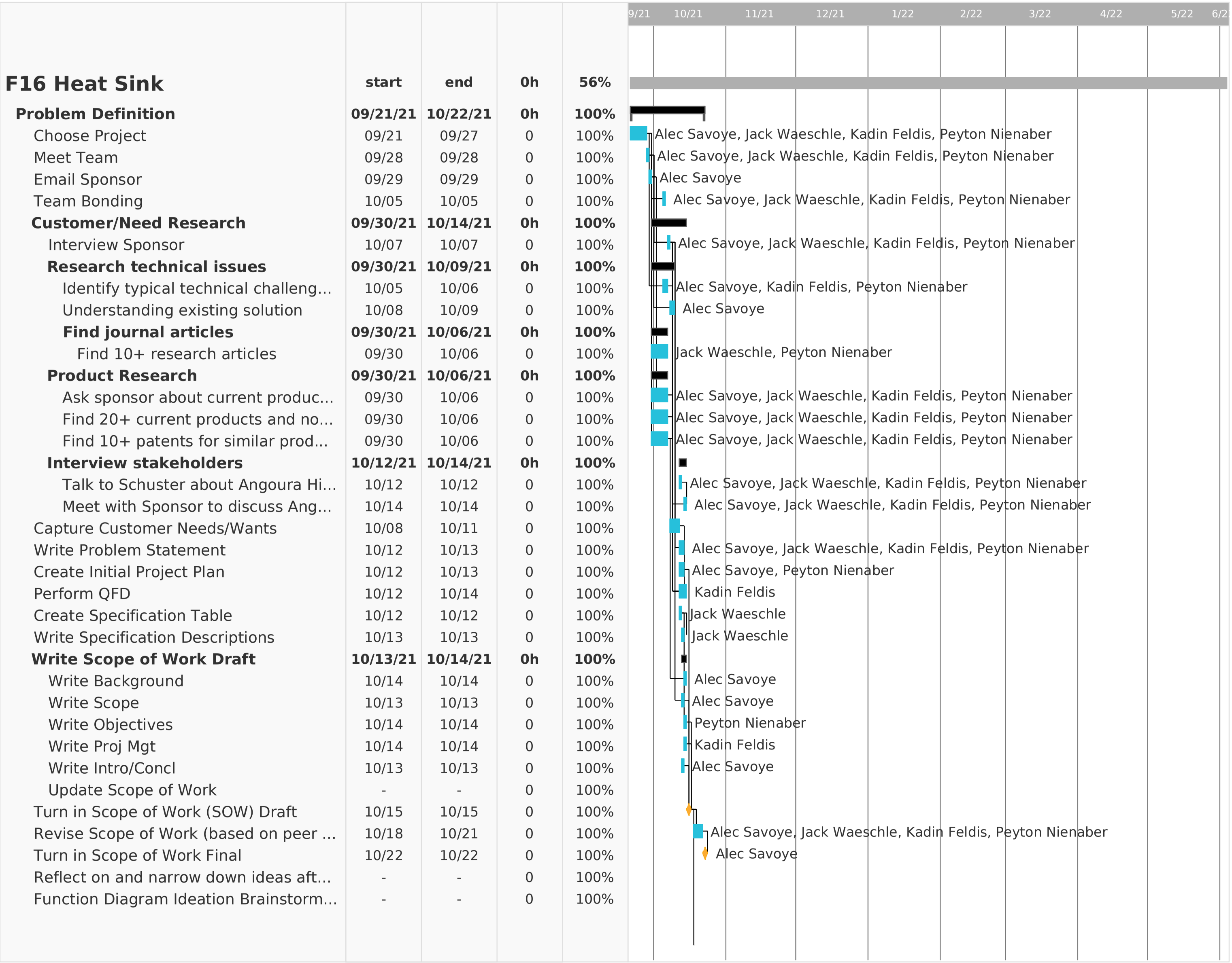
TEST PLAN										TEST RESULTS	
Test #	Specification	Test Description	Measurements	Acceptance Criteria	Required Facilities/Equipment	Parts Needed	Responsibility	TIMING		Numerical Results	Notes on Testing
								Start date	Finish date		
5	TEG temperature difference ("fouled" heatsink, outdoor "overcast" conditions)	-Repeat test as in #1. -Install in similar / same (if possible) ambient conditions as test #4. -"Foul" heatsink with method similar / same (if possible) to #3.	*See test #1*	*See test #1*	-See test #4 -Dirt that can be used to "foul" the heatsink -Compressed air or other applicator of dirt	*See row #1*	Jack	5/5/22			
6	TEG temperature difference (outdoor "overnight" conditions)	-Repeat test as in #1. -Conduct outdoors, at night, with no effects of solar radiation. Ambient temperature in the range of 30-45 degrees fahrenheit preferable.	*See test #1*	*See test #1*	-See test #1 -Outdoor setting that testing can be reliably conducted without disturbance -Minimal wind and clear skies nighttime conditions	*See row #1*	Jack	5/5/22			
7	TEG temperature difference ("fouled", outdoor "overnight" conditions)	-Repeat test as in #1. -Replicate with similar / same (if possible) ambient conditions to test #6. -"foul" heatsink with method similar / same (if possible) to #3.	*See test #1*	*See test #1*	-See test #6 -Dirt that can be used to "foul" the heatsink -Compressed air or other applicator of dirt	*See row #1*	Jack	5/5/22			
8	TEG temperature difference ("WINDY", indoor "room conditions")	-Repeat test as in #1. -Apply steady 5 [m/s] airflow parallel to heat fins as part of ambient conditions.	*See test #1*	*See test #1*	-See test #1 -Windy conditions of 5 m/s or around there… at least consistent so some approximation can be made	*See row #1*	Jack	5/5/22			

DVP&R - Design Verification Plan (Team F16)

Project:	Cal Poly Design Team F16, GTI MMTEG	Sponsor:	Gas Technology Institute (rep Abdelallah Ahmed)	Edit Date:	1/27/22

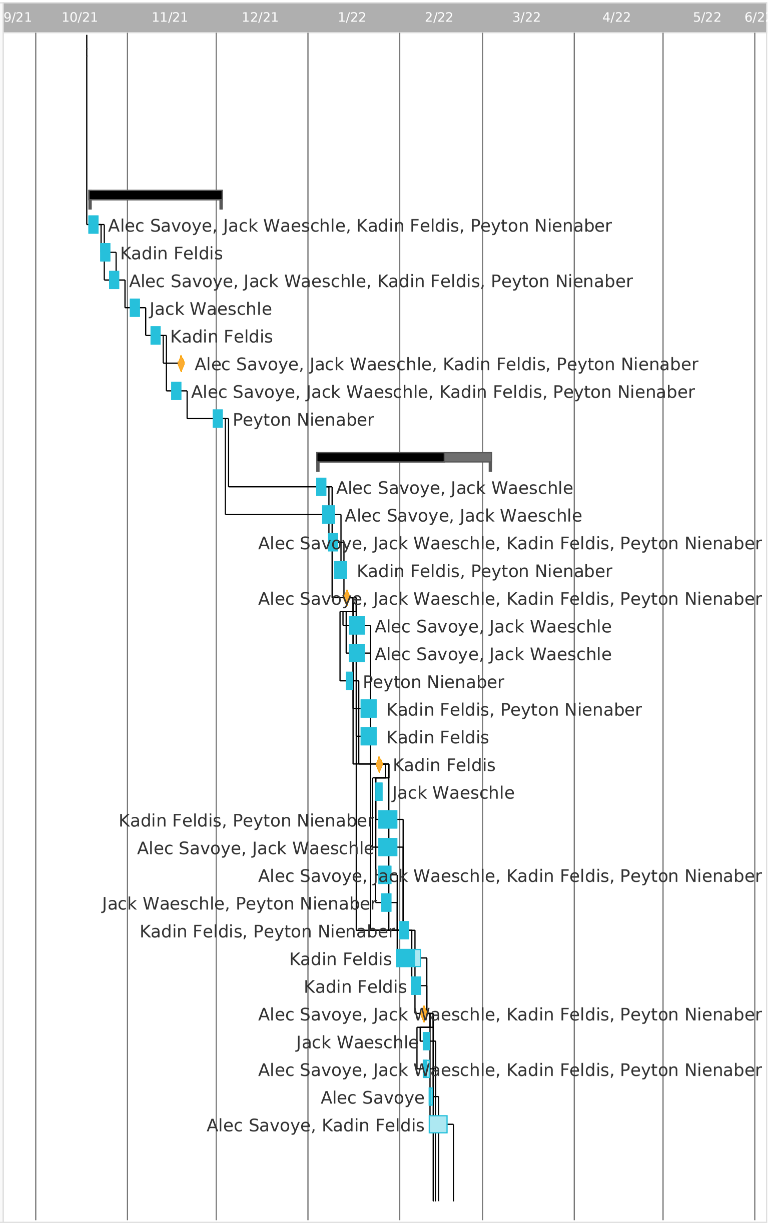
TEST PLAN										TEST RESULTS	
Test #	Specification	Test Description	Measurements	Acceptance Criteria	Required Facilities/Equipment	Parts Needed	Responsibility	TIMING		Numerical Results	Notes on Testing
								Start date	Finish date		

Appendix I – TeamGantt® Gantt Chart

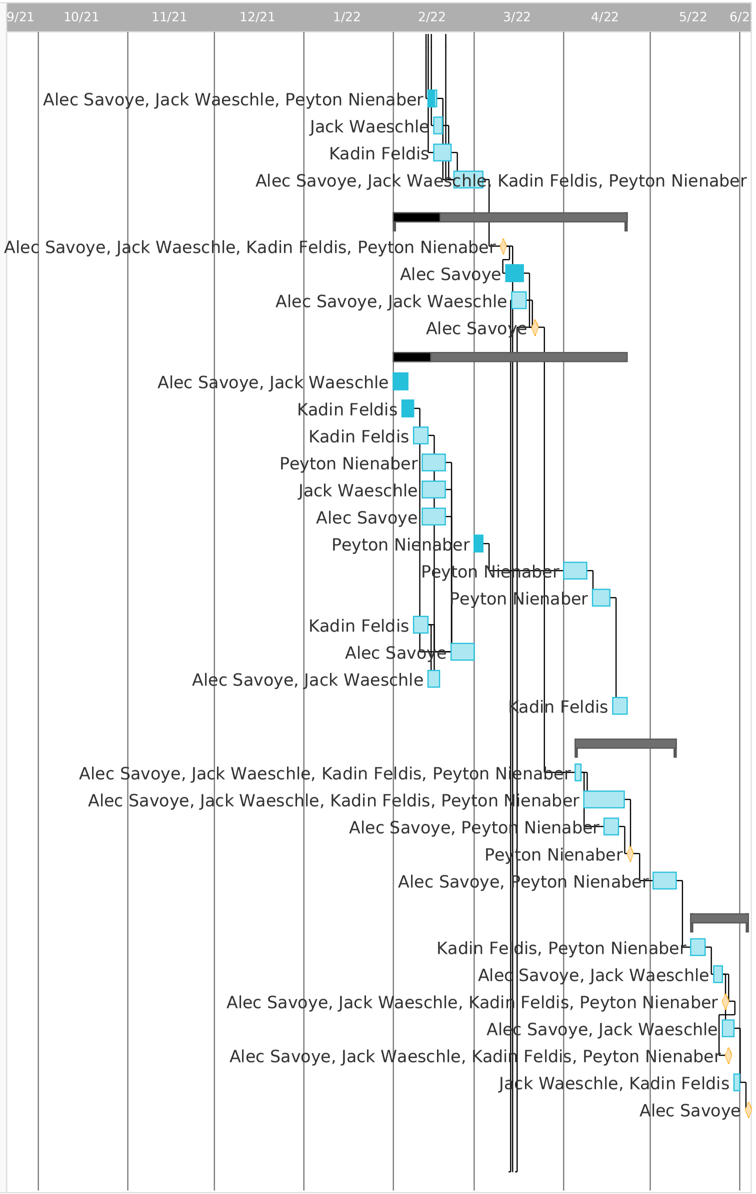


F16 Heat Sink	start	end	0h	56%	
Problem Definition	**09/21/21**	**10/22/21**	**0h**	**100%**	
Choose Project	09/21	09/27	0	100%	Alec Savoye, Jack Waeschle, Kadin Feldis, Peyton Nienaber
Meet Team	09/28	09/28	0	100%	Alec Savoye, Jack Waeschle, Kadin Feldis, Peyton Nienaber
Email Sponsor	09/29	09/29	0	100%	Alec Savoye
Team Bonding	10/05	10/05	0	100%	Alec Savoye, Jack Waeschle, Kadin Feldis, Peyton Nienaber
Customer/Need Research	**09/30/21**	**10/14/21**	**0h**	**100%**	
Interview Sponsor	10/07	10/07	0	100%	Alec Savoye, Jack Waeschle, Kadin Feldis, Peyton Nienaber
Research technical issues	**09/30/21**	**10/09/21**	**0h**	**100%**	
Identify typical technical challeng...	10/05	10/06	0	100%	Alec Savoye, Kadin Feldis, Peyton Nienaber
Understanding existing solution	10/08	10/09	0	100%	Alec Savoye
Find journal articles	**09/30/21**	**10/06/21**	**0h**	**100%**	
Find 10+ research articles	09/30	10/06	0	100%	Jack Waeschle, Peyton Nienaber
Product Research	**09/30/21**	**10/06/21**	**0h**	**100%**	
Ask sponsor about current produc...	09/30	10/06	0	100%	Alec Savoye, Jack Waeschle, Kadin Feldis, Peyton Nienaber
Find 20+ current products and no...	09/30	10/06	0	100%	Alec Savoye, Jack Waeschle, Kadin Feldis, Peyton Nienaber
Find 10+ patents for similar prod...	09/30	10/06	0	100%	Alec Savoye, Jack Waeschle, Kadin Feldis, Peyton Nienaber
Interview stakeholders	**10/12/21**	**10/14/21**	**0h**	**100%**	
Talk to Schuster about Angoura Hi...	10/12	10/12	0	100%	Alec Savoye, Jack Waeschle, Kadin Feldis, Peyton Nienaber
Meet with Sponsor to discuss Ang...	10/14	10/14	0	100%	Alec Savoye, Jack Waeschle, Kadin Feldis, Peyton Nienaber
Capture Customer Needs/Wants	10/08	10/11	0	100%	
Write Problem Statement	10/12	10/13	0	100%	Alec Savoye, Jack Waeschle, Kadin Feldis, Peyton Nienaber
Create Initial Project Plan	10/12	10/13	0	100%	Alec Savoye, Peyton Nienaber
Perform QFD	10/12	10/14	0	100%	Kadin Feldis
Create Specification Table	10/12	10/12	0	100%	Jack Waeschle
Write Specification Descriptions	10/13	10/13	0	100%	Jack Waeschle
Write Scope of Work Draft	**10/13/21**	**10/14/21**	**0h**	**100%**	
Write Background	10/14	10/14	0	100%	Alec Savoye
Write Scope	10/13	10/13	0	100%	Alec Savoye
Write Objectives	10/14	10/14	0	100%	Peyton Nienaber
Write Proj Mgt	10/14	10/14	0	100%	Kadin Feldis
Write Intro/Concl	10/13	10/13	0	100%	Alec Savoye
Update Scope of Work	-	-	0	100%	
Turn in Scope of Work (SOW) Draft	10/15	10/15	0	100%	
Revise Scope of Work (based on peer ...	10/18	10/21	0	100%	Alec Savoye, Jack Waeschle, Kadin Feldis, Peyton Nienaber
Turn in Scope of Work Final	10/22	10/22	0	100%	Alec Savoye
Reflect on and narrow down ideas aft...	-	-	0	100%	
Function Diagram Ideation Brainstorm...	-	-	0	100%	

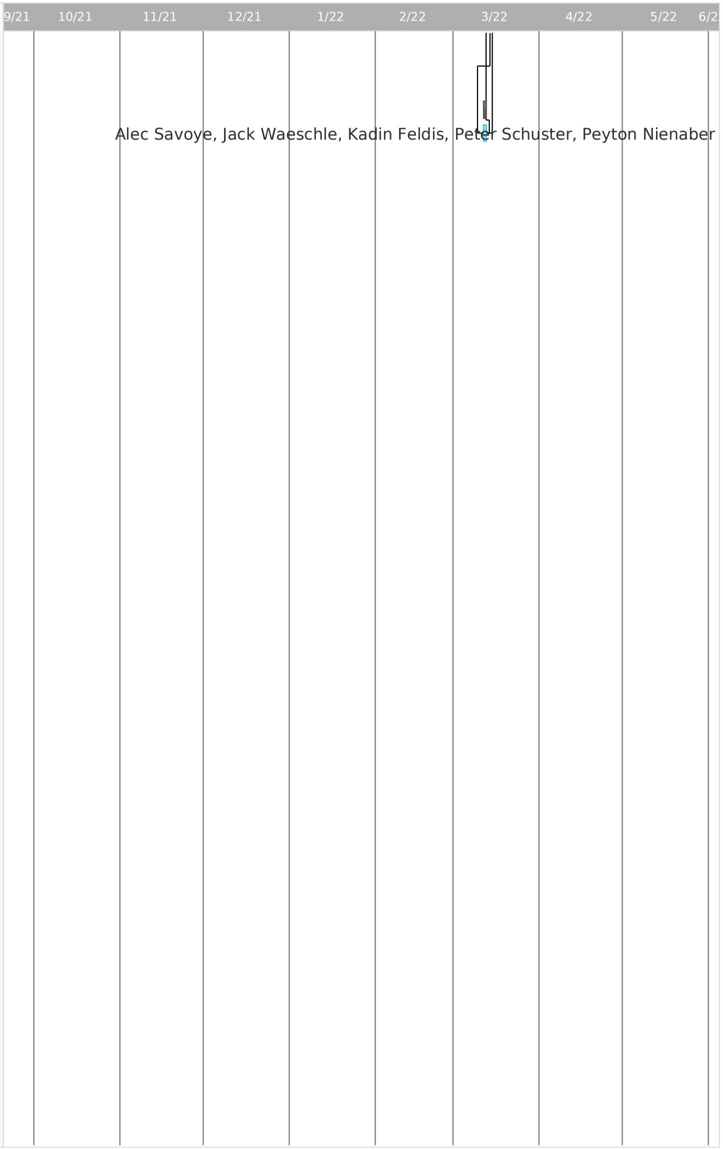
Pugh Matrix	-	-	0	100%
Top Ideas Description	-	-	0	100%
Create Concept Prototype Plan	-	-	0	100%
Concept Generation & Selection	**10/19/21**	**12/02/21**	**0h**	**100%**
Ideation Models	10/19	10/21	0	100%
Pairwise & Decision Matrix	10/23	10/25	0	100%
Modeling & Refinement	10/26	10/28	0	100%
Selection Analysis: CAD	11/02	11/04	0	100%
Concept Communication: Prototype	11/09	11/11	0	100%
Preliminary Design Review Presentati...	11/18	11/18	0	100%
Preliminary Design Review Report	11/16	11/18	0	100%
FMEA	11/30	12/02	0	100%
Detailed Design & Analysis	**01/04/22**	**03/03/22**	**0h**	**73%**
Design Analysis Round 1 (Heat Pipes)	01/04	01/06	0	100%
Meet with Pascual for design advice	01/06	01/09	0	100%
Further Testing - w/ Sponsor (per AA)	01/08	01/10	0	100%
Design Updates Round 1 (Heat Pipes)	01/10	01/13	0	100%
Interim Design Review (IDR)	01/13	01/13	0	100%
Design Analysis Round 2 (Base)	01/15	01/19	0	100%
Design Analysis Round 2 (Heat Fins)	01/15	01/19	0	100%
Design for still air (FMEA)	01/14	01/15	0	100%
Design Updates Round 2 (Base)	01/19	01/23	0	100%
Design Updates Round 2 (Heat Fins)	01/19	01/23	0	100%
Yellow Tag Cert for Kadin	01/24	01/24	0	100%
Use Thicker plates (FMEA)	01/24	01/25	0	100%
Finalize Design Based on Rnds 1 & 2	01/25	01/30	0	100%
Create Final Thermal Model	01/25	01/30	0	100%
Order Parts	01/25	01/28	0	100%
iBOM	01/26	01/28	0	100%
Manufacturing Plan and Drawings	02/01	02/03	0	100%
Build Structural Prototype (Base + Pi...	01/31	02/07	0	75%
Drawing/Spec Package	02/05	02/07	0	100%
Critical Design Review Presentation	02/08	02/08	0	100%
Design Tool Updates	02/09	02/10	0	100%
CDR Final Revisions	02/09	02/10	0	50%
Submit Critical Design Review to SPO...	02/11	02/11	0	50%
Fin Analysis/Updates Round 3	02/11	02/16	0	0%



Yellow Tag Cert For All Members	02/13	02/15	0	75%
Safety Review and Risk Assessment	02/15	02/17	0	0%
Add service interval (FMEA)	02/15	02/20	0	0%
VP Build Days	02/22	03/03	0	0%
Manufacturing	**02/01/22**	**04/22/22**	**0h**	**20%**
Manuf & Test Review	03/10	03/10	0	0%
Talk to sponsor about manufacturing ...	03/12	03/17	0	100%
Experimental Design	03/14	03/18	0	0%
Verification Prototype Sign-Off	03/21	03/21	0	0%
Actual Manufacturing	**02/01/22**	**04/22/22**	**0h**	**16%**
Laser cutting wooden jig heat fins	02/01	02/05	0	100%
Milling the Copper Base	02/04	02/07	0	100%
Milling the crossbar	02/08	02/12	0	0%
Bending Heat Pipe A	02/11	02/18	0	0%
Bending Heat Pipe B	02/11	02/18	0	0%
Bending Heat Pipe C	02/11	02/18	0	0%
Reaching out to Dakota for waterjet...	03/01	03/03	0	100%
Creating a dxf file for the heat fins ...	04/01	04/08	0	0%
Waterjet cutting	04/11	04/16	0	0%
Milling Test Stand Base	02/08	02/12	0	0%
Assembling the heat pipe and copp...	02/21	02/28	0	0%
Assembling the test stand base and...	02/13	02/16	0	0%
Attaching the heat fins to the rest of...	04/18	04/22	0	0%
Testing	**04/05/22**	**05/09/22**	**0h**	**0%**
Test Procedures - Late Stage	04/05	04/06	0	0%
VP Build - Late Stage	04/08	04/21	0	0%
Testing - Late Stage	04/15	04/19	0	0%
DVPR Sign-Off	04/23	04/23	0	0%
Testing - Final Verification	05/02	05/09	0	0%
Project Wrap-up	**05/15/22**	**06/03/22**	**0h**	**0%**
Write FDR Report	05/15	05/19	0	0%
Create Expo Poster	05/23	05/25	0	0%
Final Design Review (FDR)	05/26	05/26	0	0%
Clean out workspaces	05/26	05/29	0	0%
EXPO DAY !	05/27	05/27	0	0%
Complete Checklist	05/30	05/31	0	0%
Submit FDR to Sponsor	06/03	06/03	0	0%



Misc	**03/12/22**	**03/12/22**	**0h**	**0%**
Senior Exam	03/12	03/12	0	0%
Admin	-	-	0	0%
Project	-	-	0	0%
Other	-	-	0	0%
Finalize All Paperwork for LA Trip	-	-	0	100%
Follow Up w/ Sponsor After Meeting in...	-	-	0	100%
Update Gantt Chart	-	-	0	100%
FMEA	-	-	0	100%
Team Bonding - Bike Night	-	-	0	100%
Team Feedback	-	-	0	100%
Team Contract Update 2	-	-	0	100%
Sync w/ Sponsor After Break	-	-	0	100%



PART IV -FINAL DESIGN REVIEW

MMTEG Heatsink Design
Sponsor: Gas Technology Institute

Sponsor Contact: Abdellah Ahmed
aahmed@gti.energy

Project Members: *Team F16*

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Peyton Nienaber
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Mechanical Engineering Department
California Polytechnic State University
San Luis Obispo
June 3rd, 1345

Table of Contents

1. Design Updates

Upon completion of our Critical Design Review (CDR) we had yet to optimize the fin array. The following subsection is an overview our final design choices and optimization techniques. See Appendix A for more context and details of previous trade studies that aided in selecting a base design and heat pipe configuration.

1.1. Heat Fin Trade Study

After completing the heat fin design and quantifying the thermal conductivity of the heat pipes we moved on to the design of the heat fin array. The heat fin array was optimized using an iterative convergence study. The iterative convergence study used both 1D and 3D models. Up to this point, a generic convection coefficient was utilized in ANSYS® for 3D simulations. This approach loses its effectiveness in the heat fin spacing study because a constant convection coefficient would simply show more fins with tighter spacing as always preferable. In order to create an effective study, we wrote an EES® script to predict convection coefficient in a vertical channel (1D model). The EES® code for this model is included in Appendix B. To start the study, we guessed an average fin temperature. The resulting convection coefficient was used in the ANSYS® simulation, here we assumed that this convection coefficient applies across every surface and resulted in a new average fin array temperature. That average temperature was plugged back into the 1D model to complete the loop. This process was repeated until the convection coefficient stopped changing significantly. Finally, an average cold side base temperature was pulled from the 3D simulation and served as a datapoint. See Appendix C for an exhaustive breakdown of these simulations and results. A visual aid to understand this process is provided in Figure 1, below:

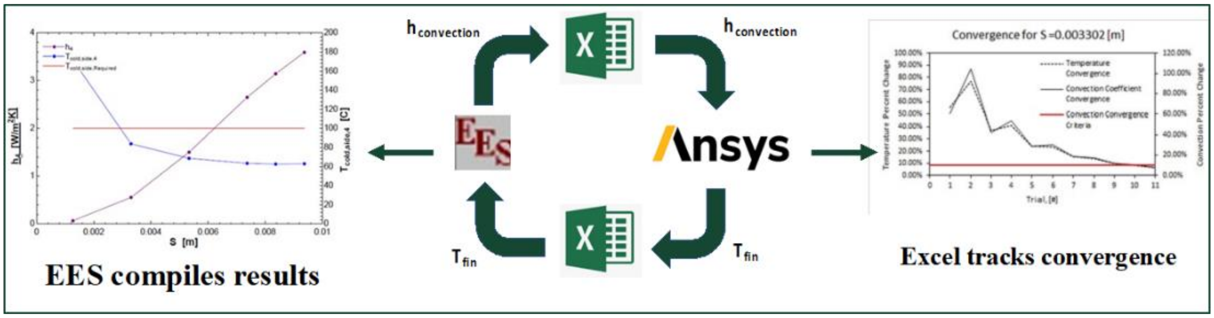


Figure 1. Thermal simulation iteration and convergence cycle.

The iterative study was run for four separate configurations of the heatsink. We varied the thermal conductivity of the heat pipes, the size of the heat fins, and different fin spacings (fin counts). The purpose of these variations was to select an optimal fin size, an optimal fin spacing, and to evaluate the sensitivity of the system to small changes.

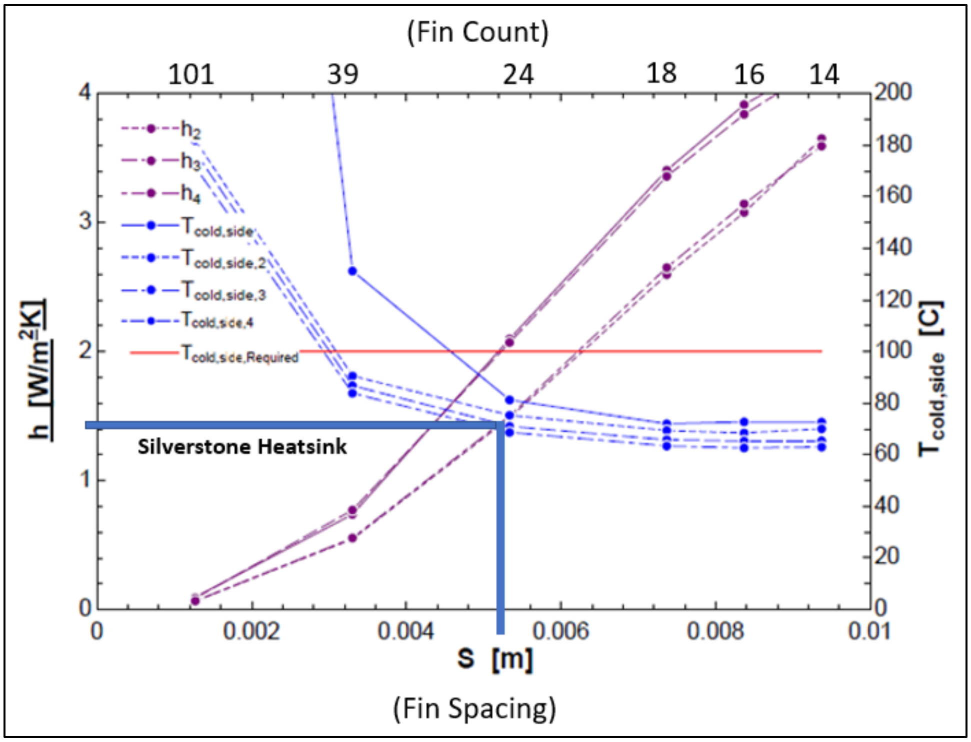


Figure 2. Thermal simulation results summary with datapoint for Silverstone Heatsink highlighted as a verification datapoint. Between 14 and 18 fins appears to be the optimal range for passive convection in our case.

This system was designed to operate with passive convection. Looking at Figure 2 above you can see that there is a stable region between approximately 14 and 18 fins. This is the region of lowest predicted cold side temperature. In that region there is a relatively low sensitivity to fin spacing, heat pipe thermal conductivity, and heat fin size. This is advantageous because it shows us that the design is robust enough to perform within specification despite inevitable variation in factors such as heat pipe thermal conductivity that will come with mass production. The Silverstone heatsink provided by GTI was used as an order of magnitude sanity check to verify this model. As you can see, based on the thick blue lines, the Silverstone heatsink lies on the predicted performance curve for the 24 fins (the approximate number of fins on the Silverstone heatsink). Interestingly the Silverstone heatsink performance falls on the transition region where passive convection starts to trend towards poor performance. This is likely because the Silverstone heatsink is designed to operate under passive or active convection conditions and selecting a design point closer to the aforementioned transition provides better performance during active convection.

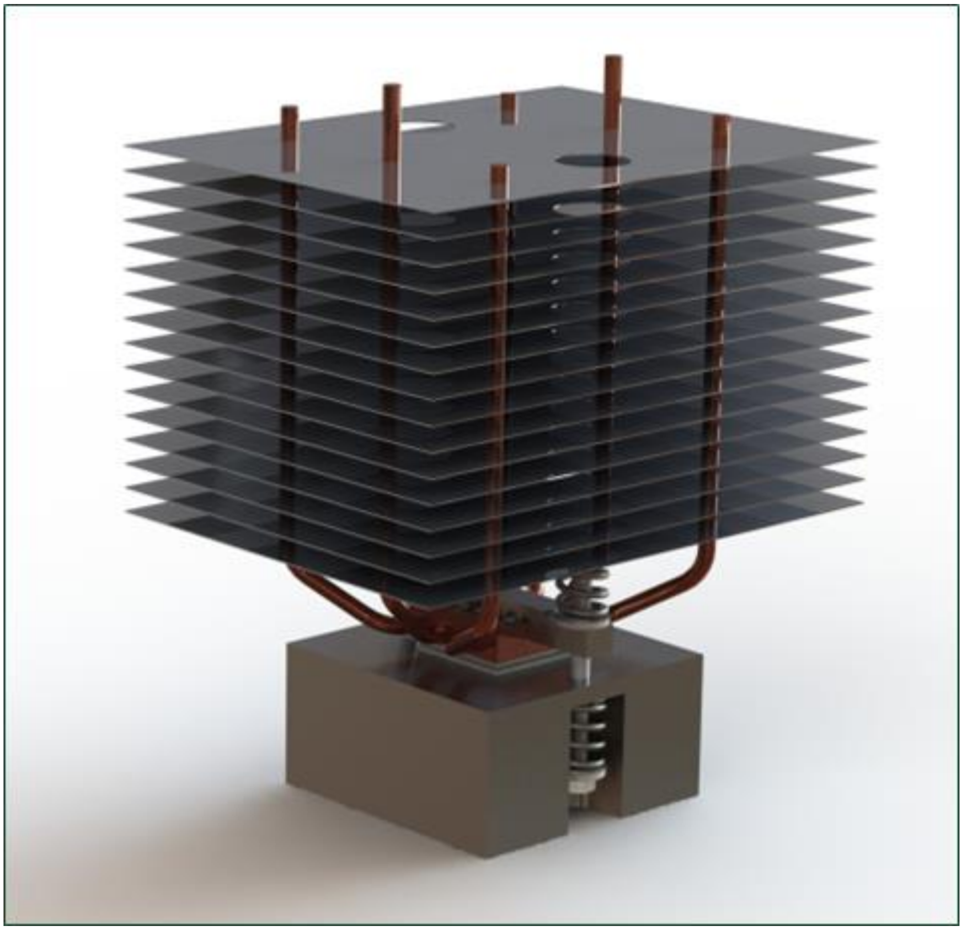


Figure 3. 16 evenly spaced fins selected for our verification prototype. The final CAD model including accurate fin count and spacing is pictured here.

Figure 3 above shows the heatsink design with the optimized 16 fin array. It is worth noting that our final verification prototype only features 13 fins due to manufacturing constraints, but we still met performance criteria. This indicates that 16 fins might be over engineered and GTI could consider reducing the fin count in the future in order to save money when moving to large scale manufacturing and implementation of this design.

2. Manufacturing

The following section goes into detail explaining the final manufacturing processes involved in producing the verification prototype. These were driven by the Manufacturing Plan, drafted earlier this year, which can found in Appendix D. As with the structural prototype, all of this work was performed by hand, and so components were frequently checked against full-size drawings. These can be found in Appendix E. Details on components purchased for the heatsink prototype can be found in Appendix F with the Bill of Materials.

Certain delays were expected and encountered due to the high demand and relatively low availability of the BridgePort® manual mills. These were taken in stride, and manufacturing was kept on schedule by ordering parts early and remaining in close contact with shop personnel. We relied on our Gantt Chart (Appendix G) to keep track of progress on this. Utilizing the structural prototype within the final verification prototype did help accelerate our manufacturing process by reducing the parts and shop time involved. Another important consideration was safety of team members during this work. A breakdown of potential hazards is included in Appendix H.

To decide what shapes would be easiest to punch and best for soldering, test tokens were made. These test tokens were 1 in squares that were waterjet cut to be a variety of shapes (circles, ovals, crosses, and triangles). These tokens were then used in the fin bending jig and test soldered. This aspect of the design process allowed for the best shape and size to be chosen without needing to cut the full fin array for multiple hole designs.

The fin bending jig functioned by aligning a punch that could then be driven through a smaller hole cut by the waterjet in the fin, creating a flared hole in the process, more on that in this section. The size of the waterjet hole in the fins was determined after experimenting with the test tokens.

Initial attempts to solder the test tokens onto a spare heat pipe revealed that a soldering iron was not going to prove sufficient heat input to the contact area. A small propane plumber’s torch was substituted, and it proved to be far more effective. See Figure 4, below, for a view of these initial trials.

Figure 4. Kadin doing initial soldering test with a test token. All test tokens on the heat pipe were different shapes and sizes.

Selecting a soldering process allowed us to finalize the holes on the heat fin design. The next step was to produce the fins that would be soldered into the array. We decided to use the waterjet to cut the fins since it is relatively easy to use and had a short queue. Figure 5 shows one run of the water jetting process:

Figure 5. Water jet cutting heat fins from aluminum sheet.

After our fin spacing and sizing analysis was complete, we exported the 3D models of heat fins as DXF files. That DXF file was used to water jet our fins out of a four-foot square sheet of aluminum. Tabs were used to prevent the heat fins from moving as they were cut. Small tabs in the material were easy to break by hand after cutting was completed. These tabs had to be upsized to prevent fins from physically falling through the stock and getting pulled into the waterjet wash bin.

The next challenge was ensuring good soldering action when attaching the heat fins to the heat pipes. Figure 6, below, shows the design of a special jig designed and used for this purpose:

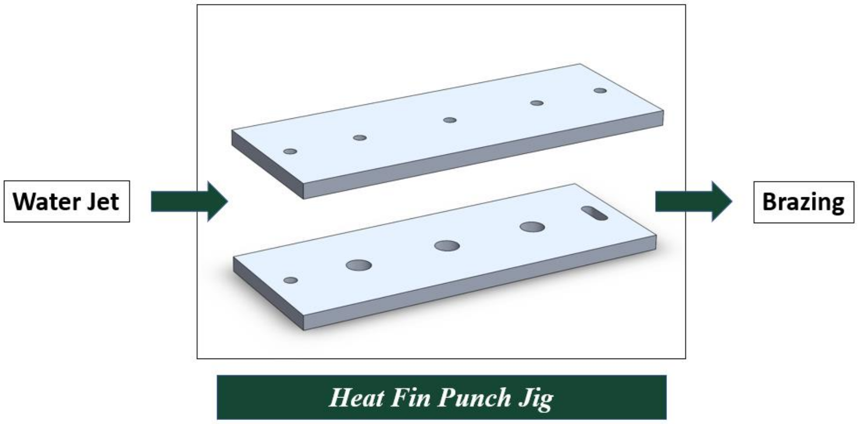


Figure 6. Heat fin punch jig.

To improve the quality of our soldering joints we designed a heat fin punch jig that produces flared holes in our heat fins. These flares provide more material contact area for each joint and create an appropriately sized hole to insure proper capillary action when soldering. Figure 7 shows the jig in use, below:

Figure 7. Peyton using the fin bending jig to flare a hole in a fin prior to soldering.

After all of the heat fins were cut and punched, we started the soldering process to join each heat fin to each heat pipe in a way that creates the most thermal conductivity between the two. Wooden jigs, as pictured on the left and righthand sides of the heatsink in Figure 8, below, were laser cut to help us set the correct fin spacing and hold each fin in place as we soldered.

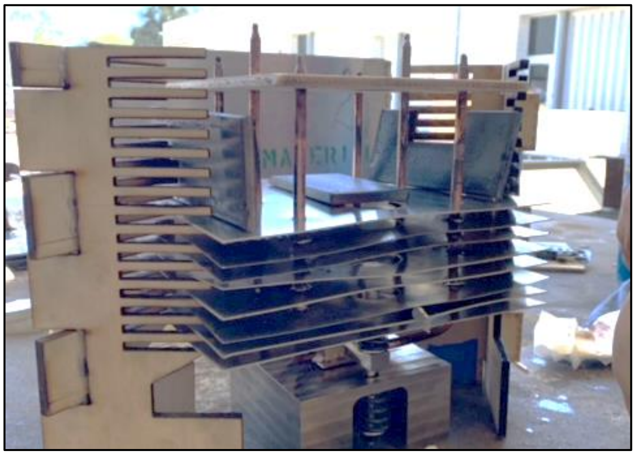


Figure 8. Heat fins are being soldered to heat pipes. Wooden jigs pictured on left and righthand sides.

As can be seen in Figure 8, the unpredictable heat output of a blowtorch led to some fin warping. The warping is a bit unsightly, but the heatsink still performed well and met our performance requirements. Once the design is moved into a refined manufacturing environment, we expect to achieve more parallel fins which will only improve performance.

Figure 9. Limitations of wooden jigs.

Although we soaked our wooden jigs in water before soldering, we had issues with unplanned spontaneous combustion (USC) with both our fin support jigs and our heat pipe alignment jigs as seen in Figure 9. To avoid future USC, we recommend aluminum or steel jigs.

During soldering, joints became more successful as more fins were added. We believe this is because the amount of heat pipe remaining decreased as the number of fins below increased, meaning the temperature maxima on the heat pipe occurred closer to the location of the joint, allowing us to successfully solder before the flux burned and fouled the surface of the heat pipe. Additionally, it was observed that the temperature of the steel test base approached ambient conditions as the number of fins increased as the heatsink was successfully operating as a heatsink. With initial fins, the base became too hot to touch.

One challenge we ran into while soldering the fins was towards the end of the processes and the potential for burning the heat pipes. On the final few fins, we started to notice the heat pipes burning green which indicated the heat pipes were actually starting to melt. This was because of there were less fins and heat pipe area to dissipate the heat. We started to become concerned about the possibility of the heat pipes bursting so we stopped soldering at the 13th fin. If a brazing oven or a different avenue was used, this most likely would not have been a problem.

3. Design Verification

After successfully manufacturing the Verification Prototype, we conducted a series of tests to confirm its performance was sufficiently within spec. See Appendix I for a tabulated form of this process (“Design Verification Plan”). Our testing covered the two book-end cases for ambient conditions – cold nighttime (ideal) and sunlit daytime (worst case). We achieved our specification of less than 100 °C cold side temperature for a heat input of at least 50 W in both scenarios. For more details on the design of the test jig, see previous team documentation and Appendix J for component testing details.

It should be noted that the following procedures were based on initial Failure Modes and Effects Analysis (Appendix K), performed earlier on in conjunction with the sponsor. A detailed breakdown of each test procedure is included in Appendix L.

Before deriving any major design conclusions from the results of these tests, it’s important to acknowledge the nuances of the experimental setup. The first is inherently flawed since it runs on a duty cycle once it makes it to a final temperature. This meant that the steady state temperature was not actually at steady state but rather followed a sinusoidal trajectory. The burner also does not have specific labels for the heat flux input but rather has a dial with unknown power measurements. This meant that unless the dial was set to the max, there was limited consistency between the settings each time. Additionally, our large steel test base acted as a good thermal mass to help even out the heat input, but also introduced a new challenge of reaching steady state in a timely manner. Our transient response in testing was approximately 100 minutes. Installed on the combustion chamber, we expect the transient portion of operation to be much shorter, as the aluminum combustion chamber has much less thermal mass than our steel test base.

In addition to our final verification prototype tests, we completed intermediate testing during manufacturing such as determining heat pipe thermal conductivity. This was used to verify assumptions used in our ANSYS® models that drove our design choices. These results can be found in the CDR document.

The uncertainty on these tests was mostly due to precision in the measurement tools, the variability of the measurements due to the thermocouple values changing with the slightest of ambient conditions. The variability of the temperature and the slight changes that could occur between the time of the test and when the values were recorded, was mitigated by the values being photographed at the same time and then recorded from that photo. While this decreased the error significantly, there is still error to be accounted for due to the slight delay in measurement. Data was collected via an Excel spreadsheet in order to ensure ease of collection and easy visualization. We learned during the testing process that adding the thermal mass at the bottom of the testing apparatus made for a longer time to reach steady state. Additionally, using two different kinds of thermocouples created changes in how we measured the data and ensured that they were measured at the same time. If we were to do more testing in the future, we would have reduced the size of the base and used the smaller version of the thermocouples to allow for a faster time to steady state as well as consistent measurement tools.

Please see the Design Verification Prototype Report (DVPR) for more details on the tests as well as the test procedures to see how they were completed in a safe, efficient, and result oriented way. At this stage in testing, most design choices have been made from engineering judgement and research into similar fields.

Table 1. Facilities and equipment requirements/procurement.

#	Description	Source	Method to Obtain
1	Hot plate and Prototype	Team equipment	Source from team
2	Testing area	Kadin Feldis’s Garage	Confirmation with Kadin and roommates
3	Thermocouples	Stan Beebe	Email Hans Mayer

To run these tests, we created the setup seen in Figure 10 using the materials found in Table 1. Within these tests, we used four thermocouples to measure the temperature and four distinct locations. This data along with manufacturing data sheets allowed us to determine the performance of our heatsink when compared to the specifications we were tasked to reach.

Figure 10. Test setup for nighttime ambient conditions. The bolt cutters and locally sourced diorite rock were critical to ensure test fixture stability.

In order to determine if the heatsink performed to specification, we ran a test during the daytime and nighttime where we placed thermocouples at the bottom of the TEG, top of the TEG, and first fin, and final fin. The raw data sheet of the thermocouple readout temperatures can be found in Appendix M. Plots of the temperatures at a certain location on the heatsink as a function of time for the nighttime and daytime can be Figure 11 and Figure 12 respectively.

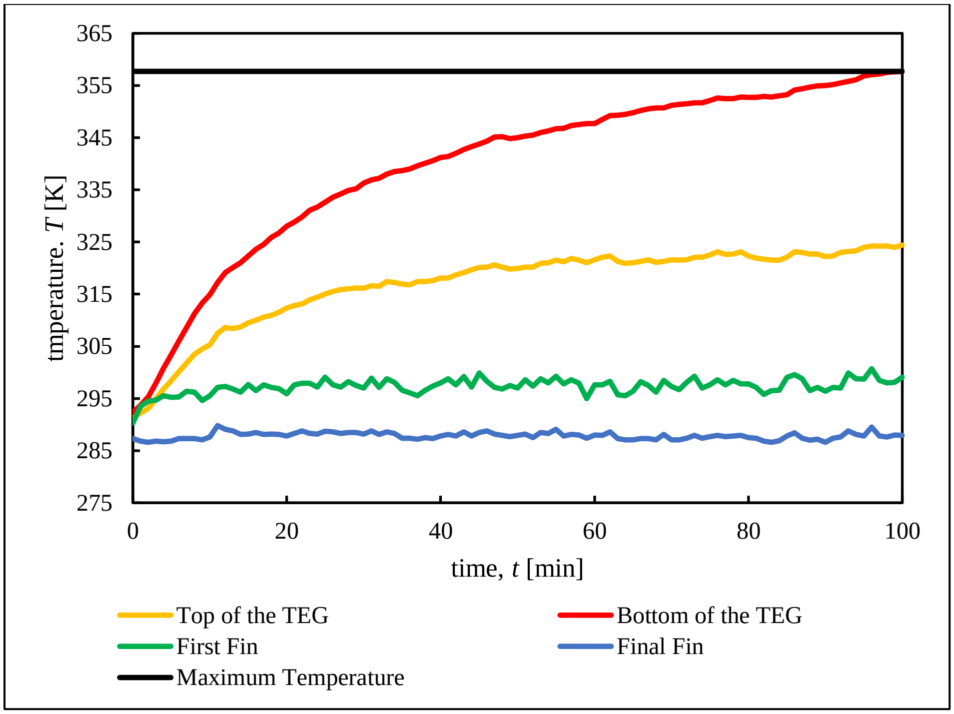


Figure 11. Temperature values, in K, for the nighttime test during the transient and eventual steady state portions.

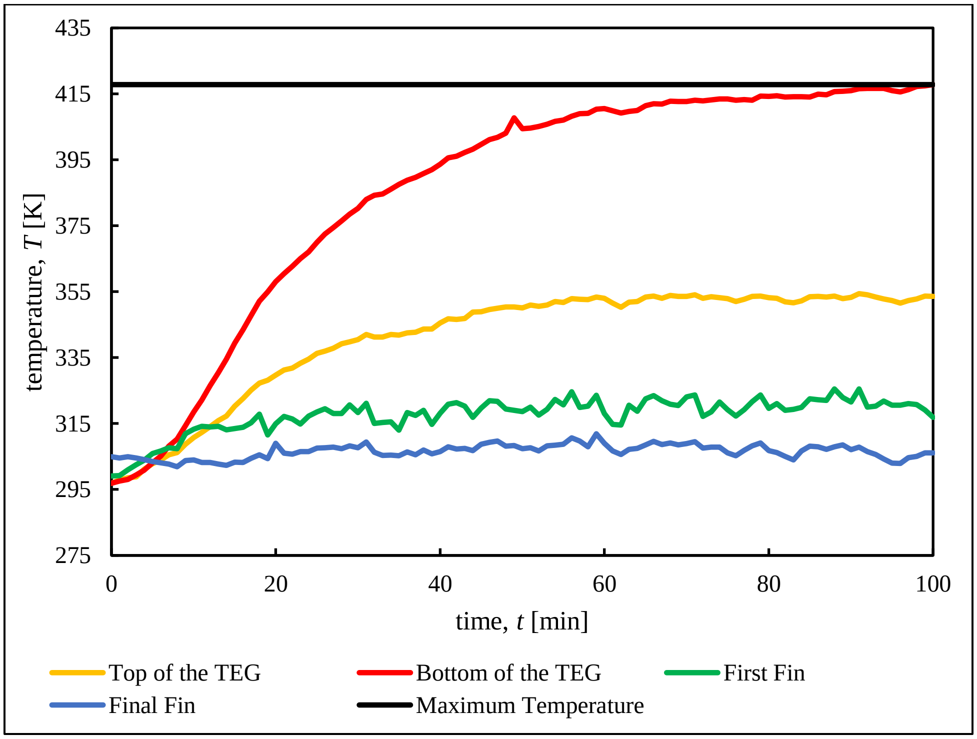


Figure 12. Temperature values, in K, for the daytime test during the transient and eventual steady state portions.

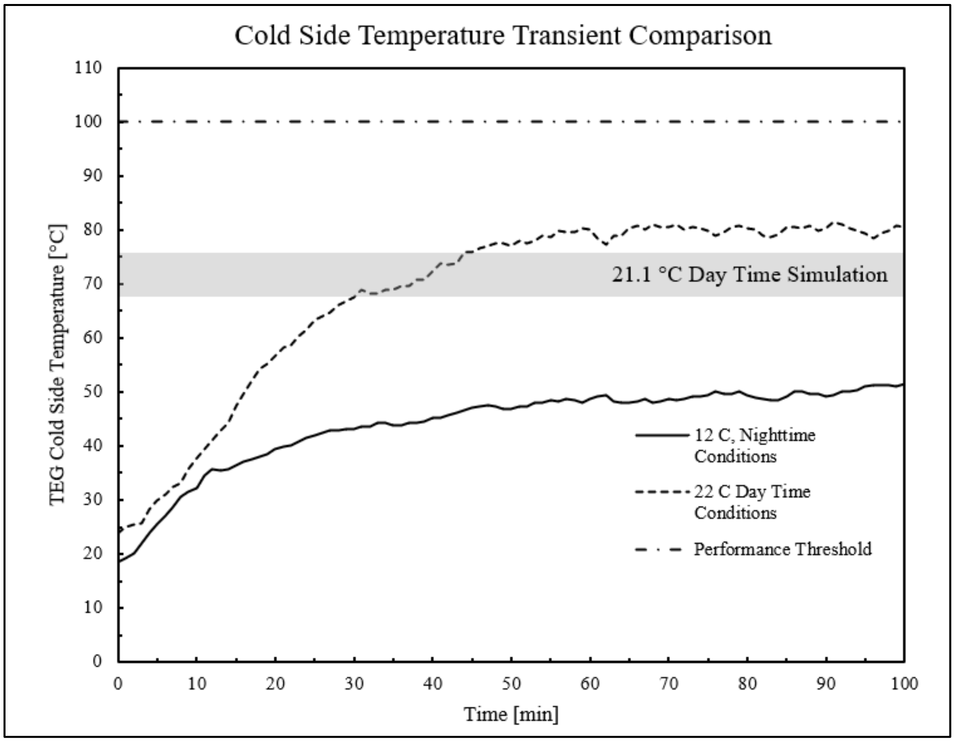
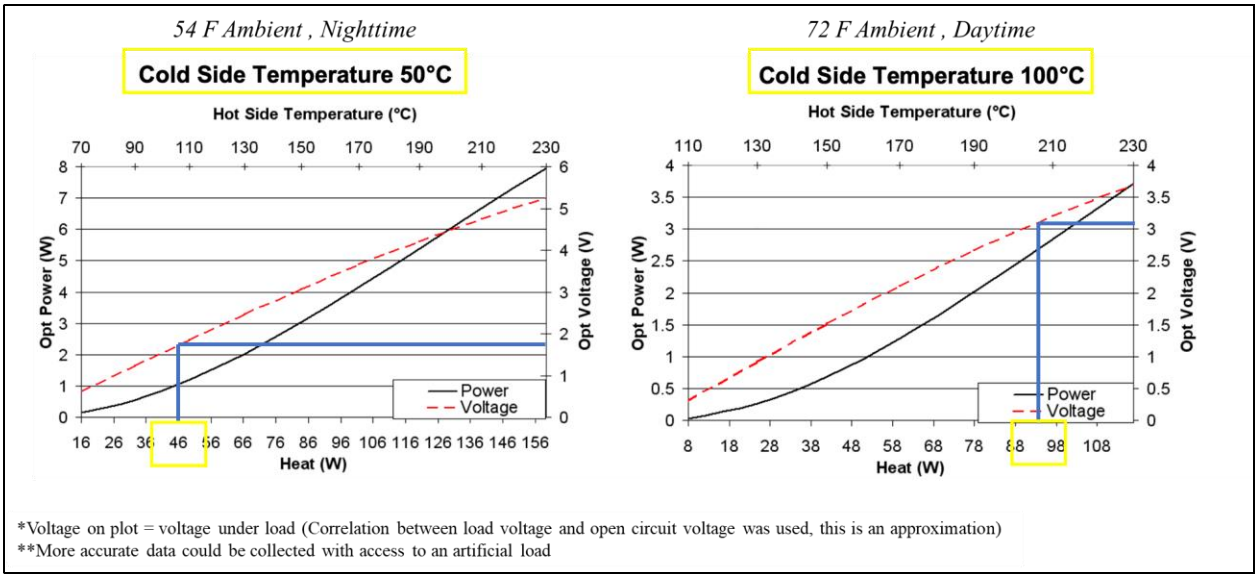


Figure 13. Final results and simulation comparison.

A set of two final tests were conducted to verify the performance of our verification prototype. Both tests, one conducted during the day and one at night, exceeded performance requirements set by GTI. As you can see from the Figure 13, the simulation predicted performance region was relatively close to the observed experimental performance with corresponding environmental inputs.



*Voltage on plot = voltage under load (Correlation between load voltage and open circuit voltage was used, this is an approximation)
**More accurate data could be collected with access to an artificial load

Figure 14. Analysis of Manufacturer datasheet to determine the input power.

Because we did not have access to the perfect test equipment some inputs and outputs of our final test are approximations. First, we did not have a load cell to accurately measure the under-load performance of the TEG. In order to complete the test, we measured open circuit voltage and correlated open circuit voltage to optimum voltage using information from the TEG manufacturer datasheet, see Appendix N and Figure 14 above. The result is a certain level of uncertainty in the actual heat input for each test. Our approximations show a heat input of 46 for the nighttime test and 95 for the daytime test highlights in Figure 14 above.

Data collection was completed via Excel and all uncertainty analysis was done through small sample analysis at steady state. The following equations were used for the uncertainty analysis and error propagation, where s is the standard deviation and n is the number of trials.

$$R = \frac{ts}{\sqrt{n}}$$

$$u_{xm} = \sqrt{B^2 + P^2 + R^2}$$

In order to calculate the repeatability uncertainty and subsequent t value, we assumed a 95% confidence interval. The bias, B, was calculated by the subtracting the ambient from the initial reading. The precision was given by half of the resolution and was consistent across all of the thermocouple readings.

Error propagation was calculated by the equations below.

$$U_{R,x_i} = \frac{R\left(x_i + U_{x_i}\right) - R\left(x_i + U_{x_i}\right)}{2}$$

$$U_R = \pm\left({U_{R,x_1}}^2 + {U_{R,x_2}}^2 + \cdots\right)^{1/2}$$

For the best-case scenario test, where the heatsink was ran at night, the following uncertainties were determined in Table 2.

Table 2. Best-case uncertainty analysis overview.

Thermocouple Location	Top of TEG	Bottom of TEG	First Fin	Final Fin
Repeatability	0.218	0.537	0.430	0.205
Bias	0.416	1.316	-0.683	-3.683
Precision	0.05	0.05	0.05	0.05
Uncertainty [K]	0.472	1.423	0.808	3.689

The final error propagation ended up being 7.78x10^{-3}.

For the worst-case scenario test, where the heatsink was ran during daytime the following uncertainties were determined in Table 3.

Table 3. Worst-case uncertainty analysis overview.

Thermocouple Location	Top of TEG	Bottom of TEG	First Fin	Final Fin
Repeatability	0.277	0.567	0.813	0.626
Bias	5.916	5.916	8.116	13.916
Precision	0.05	0.05	0.05	0.05
Uncertainty [K]	5.923	5.944	8.157	13.930

The final error propagation ended up being 3.19×10^{-2}.

Some challenges we ran into while testing were the duty cycle and changing ambient conditions. The duty cycle was a constant problem with our testing since it meant that there was not a constant heat input into the system. This in turn meant that our heat input followed a vaguely sinusoidal trend and could be considered added error. Additionally, the tests were completed in nonconstant ambient conditions where the wind, temperature, and humidity were not held constant. This could have created additional error but were neglected since the system when implemented would have the variety of conditions.

During the testing process, we learned that measuring ambient conditions throughout is a great way to avoid additional error as well as monitor how the system is behaving. We also learned that having the correct equipment is important and can make a large difference in the quality of measurements. One example of this was obtaining 0.0045” diameter thermocouples that allowed us to measure the temperature on the hot and cold sides of the TEG without creating a large air gap. These thermocouples were much more precise, accurate, and reacted faster to temperature changes.

4. Discussion and Recommendations

Throughout the project, we learned that there were a lot of different aspects that needed to be optimized and realized the manufacturing was going to be a huge hurdle. At the start of the project, we thought the design of the heatsink was going to be a large heat transfer problem, but it ended up being so much more. While there was some heat transfer, there was also tons of optimization for cost, trade studies, and manufacturing. One thing that surprised us all a lot was the sheer amount of manufacturing and what kind as well. Compared to other teams that used 3D printers and the laser cutter for all manufacturing, we used pipe benders, manual mills, brazing equipment, and more.

If we were continuing to work on this project, we would want to do more testing with a heatsink that had fewer fins to see if a less overly engineered design would perform just as well. We would also want to talk more with GTI about their implementation of the design and see if it is possible to only have the system run at night, to improve efficiency. The current system exceeds the intended specifications for thermal performance and costs more than intended. Because of that, we would change the design to have less fins to lessen how over-spec it is and decrease the cost. Another way to decrease the cost would be to source the materials from places the specialize in high volume consumers.

Manufacturing wise, we wish we would have begun the manufacturing process sooner since we were under tight deadlines while working efficiently all winter quarter. This however was not an option because of the class deliverable timeline and the fact that our project did not fit the typically senior project schedule. More manufacturing time could only have been obtained by fundamentally changing how the senior design series is.

For high volume production, we recommend using a CNC tube bender for the heat pipes, CNC manufacturing for the copper base, automated heat fin dimpling process, and perhaps a brazing oven for the soldering the fins to the heat pipes. While this would be a large upfront cost, it would lead to so much less time manufacturing and decreased costs in the long run. As stated above, it would also be beneficial to purchase supplies from some other place than McMaster Carr since their prices are much higher compared to a large-scale business. When using our prototype, we recommend making sure there is limited dirt or other debris on it to avoid additional thermal resistance. Additionally, it is important to ensure that the TEG is intact and functioning since high temperatures and pressure have the potential for the TEG to fail.

We strongly advise future engineers and maintenance technicians to verse themselves in the User Manual, provided in Appendix O.

5. Conclusion

In an effort to decrease the environmental impact from existing natural gas infrastructure, the Gas Technology Institute asked our team to design a new heatsink to bolster the operation of a thermo-electric generator valve control system. The goal was to design a heatsink that works with the existing GTI system and can be produced at scale. Cal Poly Senior Project Team F16 gladly accepted the challenge and took the project from ideation to final design. Our final verification prototype shows performance that exceeds the requirements provided by our sponsor. As GTI moves forward with our design we recommend reducing the number and/or size of the fins to reduce cost at scale while maintaining required performance.

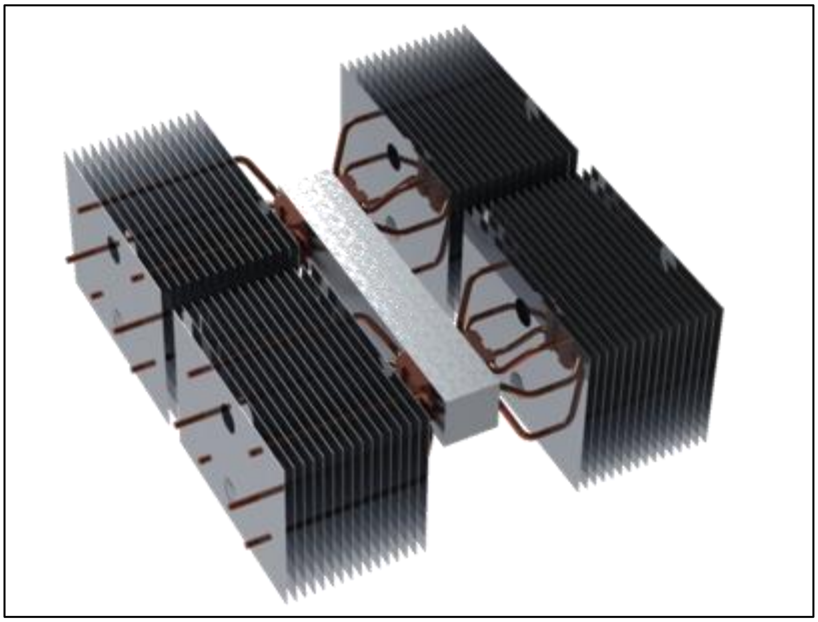


Figure 15. Final configuration of the heat sink with the combustion chamber.

Figure 15 above shows a possible 4 heatsink configuration on GTI's combustion chamber. It is possible to mount the heatsinks vertically or to reduce the spacing between heatsinks as required by the system. Additional heatsinks can be added should GTI choose to extend the combustion chamber.

The only things we would want to change in our design if we had to do this again would be to reduce the number of fins since currently the design is over-engineered. This would again decrease the cost of the heatsink, but still perform below the thermal specifications that were provided with as long as the number of fins wasn't reduced too much. One other thing that we would want to change would be where raw materials were bought from since McMaster Carr was quite expensive.

In final, our current design exceeds the specifications given by GTI; however, in future iterations we advise a reduction in the number of fins to decrease the cost since the thermal performance was significantly above specification.

Team F16 was grateful to join GTI in working on this project. We hope that it goes on to make a difference in creating a cleaner natural gas industry in the United States.

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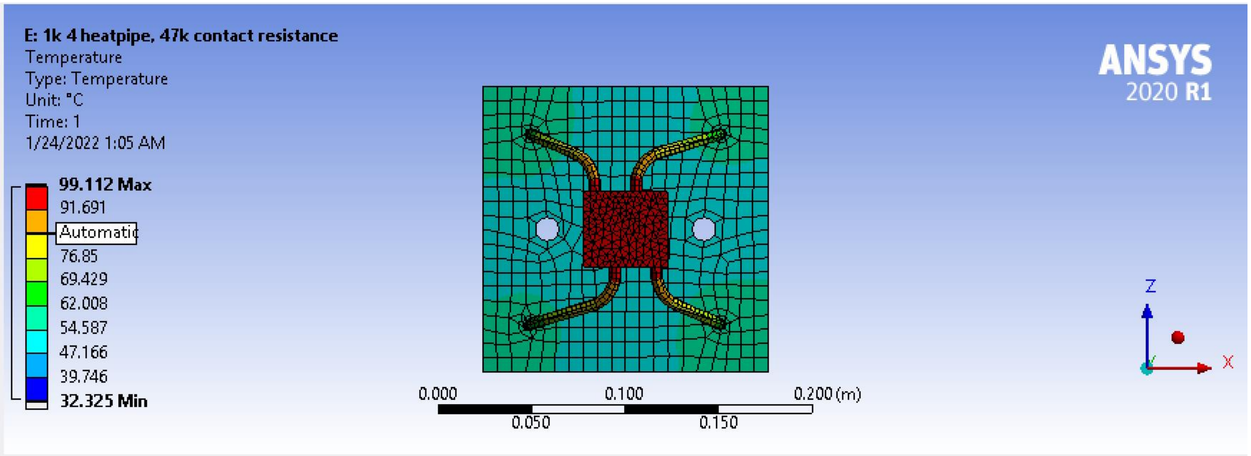
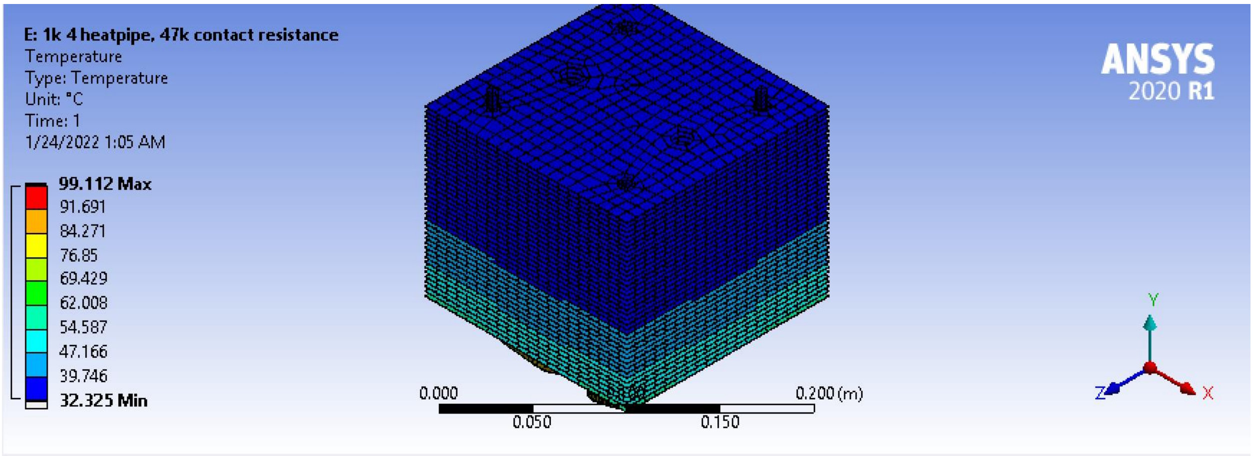
Appendices

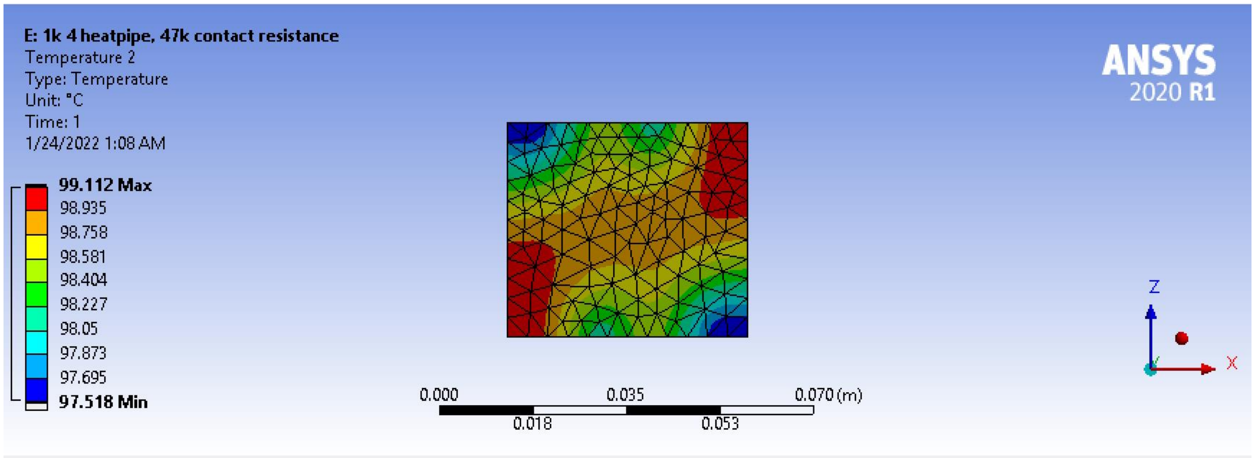
A. Supplementary Simulation Results
B. EES® Script – 1D Convection Coefficient
C. Thermal Simulation Iteration and Results Documentation
D. Manufacturing Plan
E. Relevant Manufacturing Drawings
F. Bill of Materials and Team Budget
G. Gantt Chart
H. Hazards Checklist
I. Design Verification Plan
J. Hand-Calculations for Normal and Shear Stress Loading on Crossbar
K. Failure Modes and Effects Analysis
L. Test Procedures
M. Experimental Raw Data
N. Teg Manufacturer Datasheet
O. User Manual

Appendix A - Supplementary Simulation Results

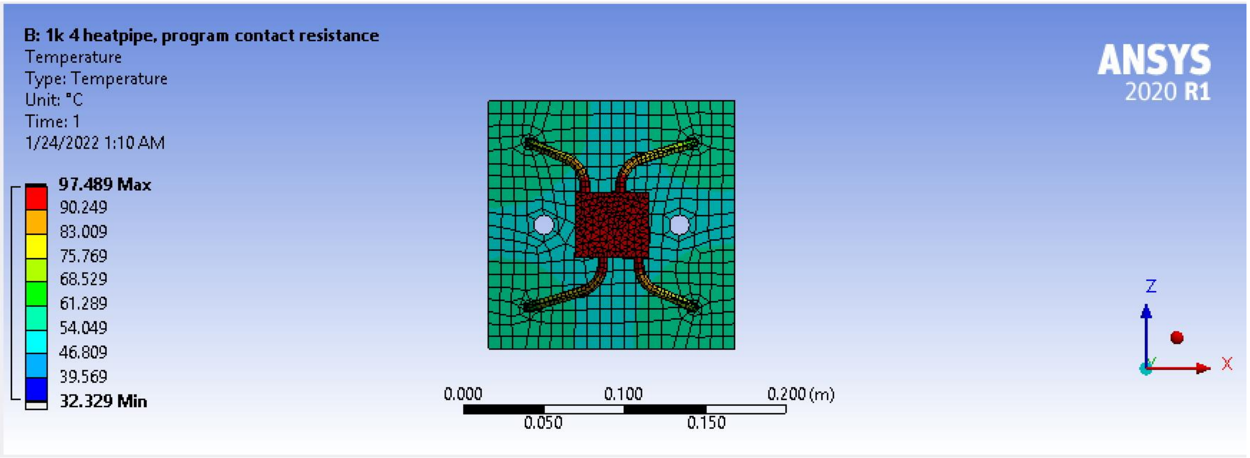
1k 4 heatpipe 47k contact resistance







1k 4 heatpipe program contact resistance



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Unit: °C
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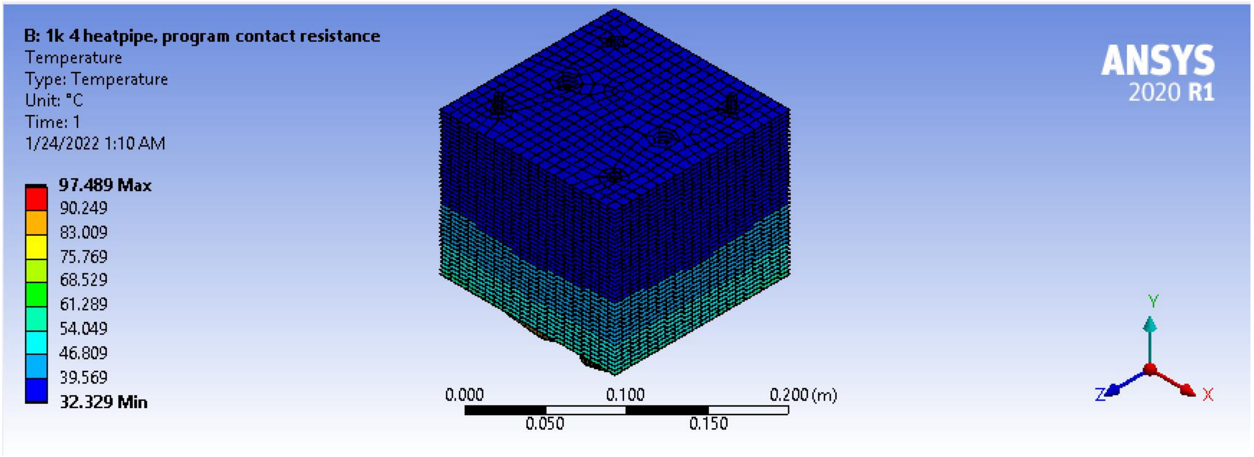

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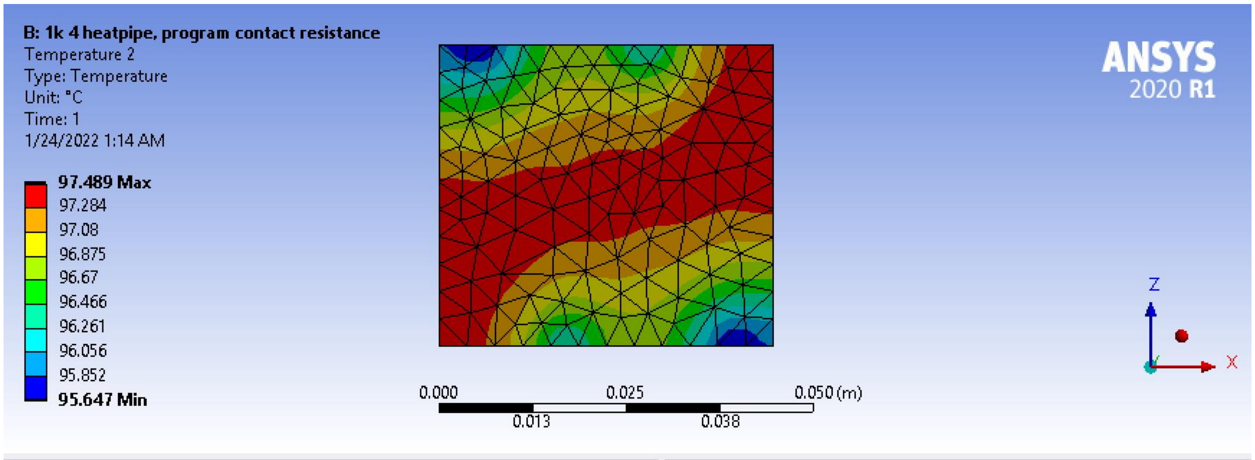

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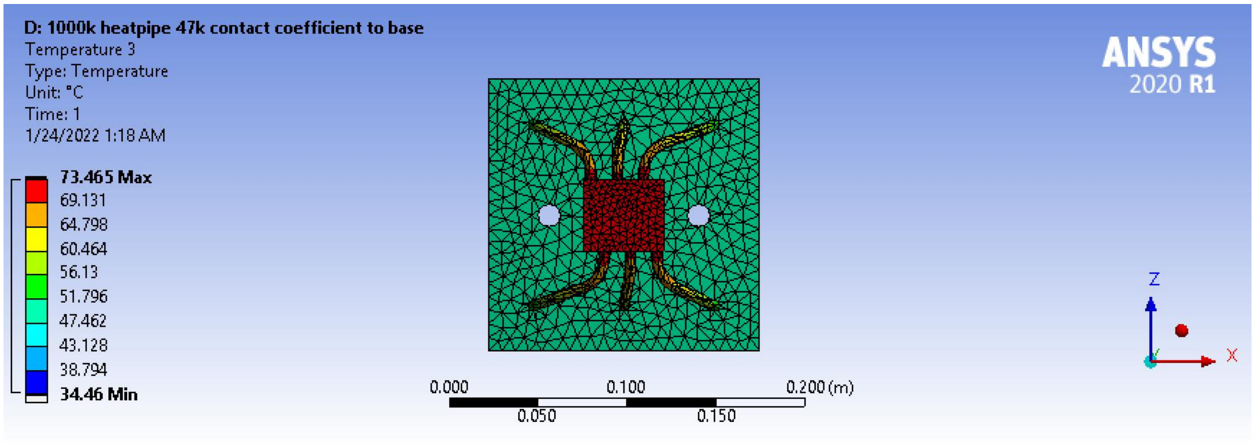
Temperature 2
Type: Temperature
Unit: °C
Time: 1
1/24/2022 1:14 AM

1k conductivity heatpipes 47k contact 6 heatpipes



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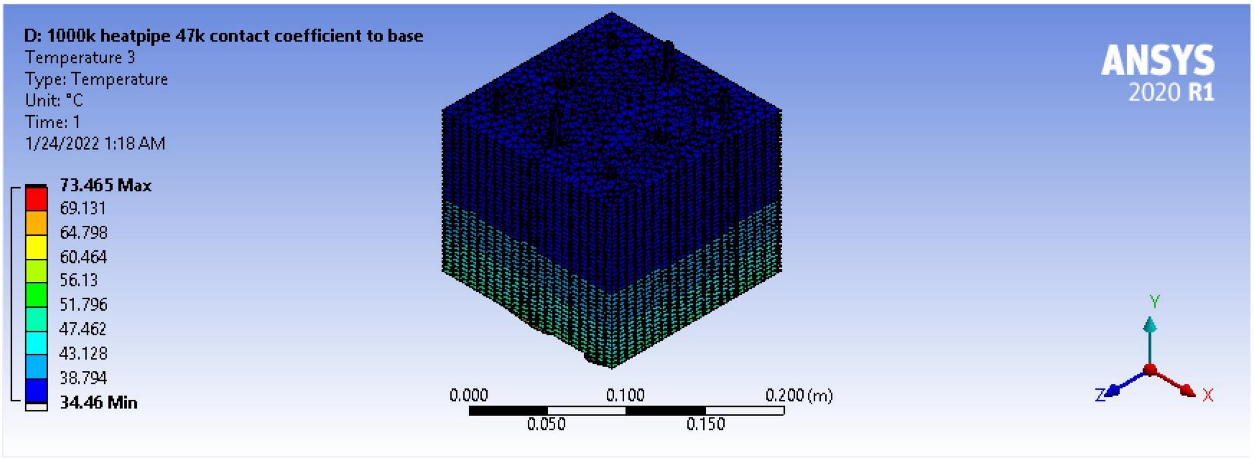

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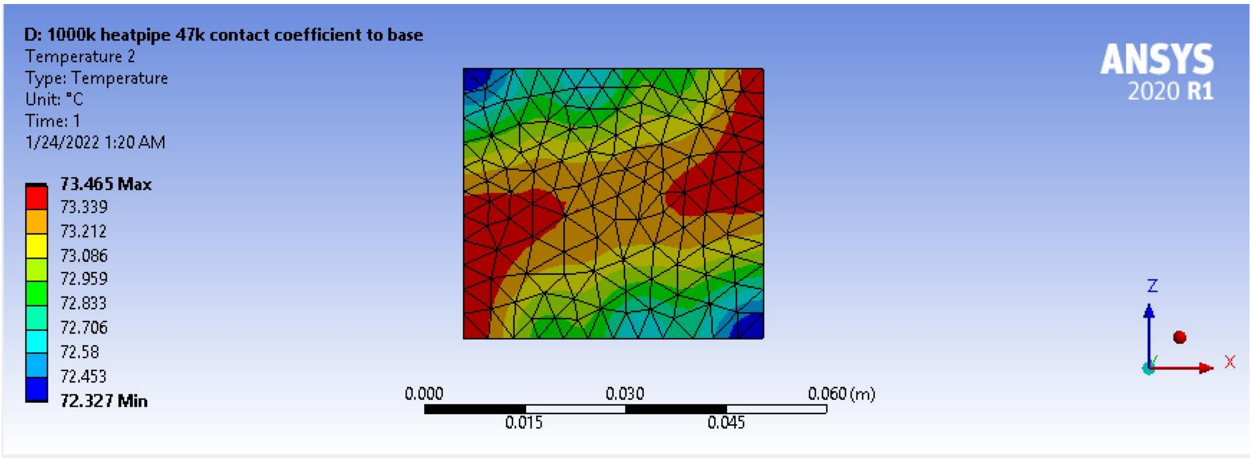

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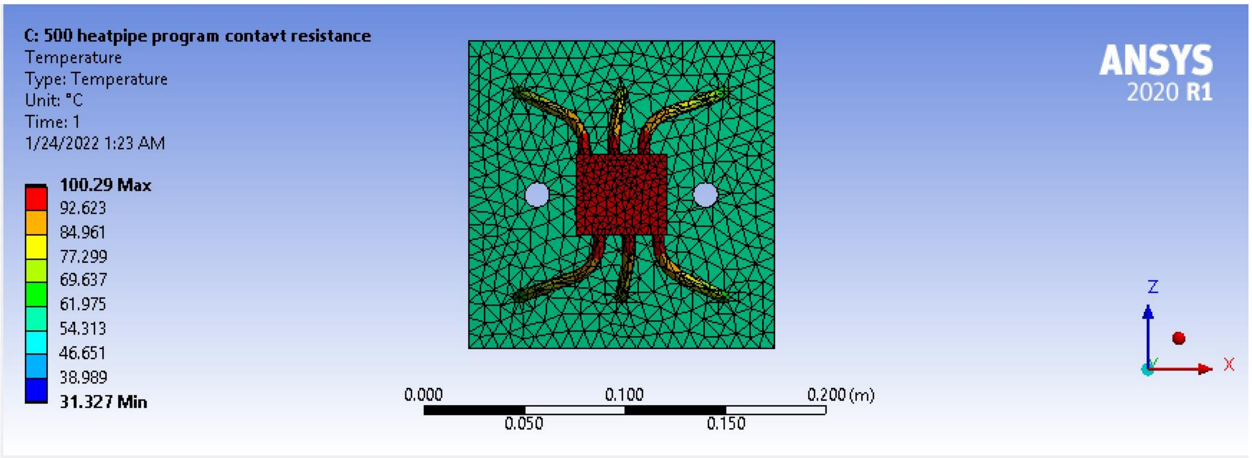
500 conductivity heatpipes 47k contact 6 heatpipes


C: 500 heatpipe program contavt resistance
Temperature
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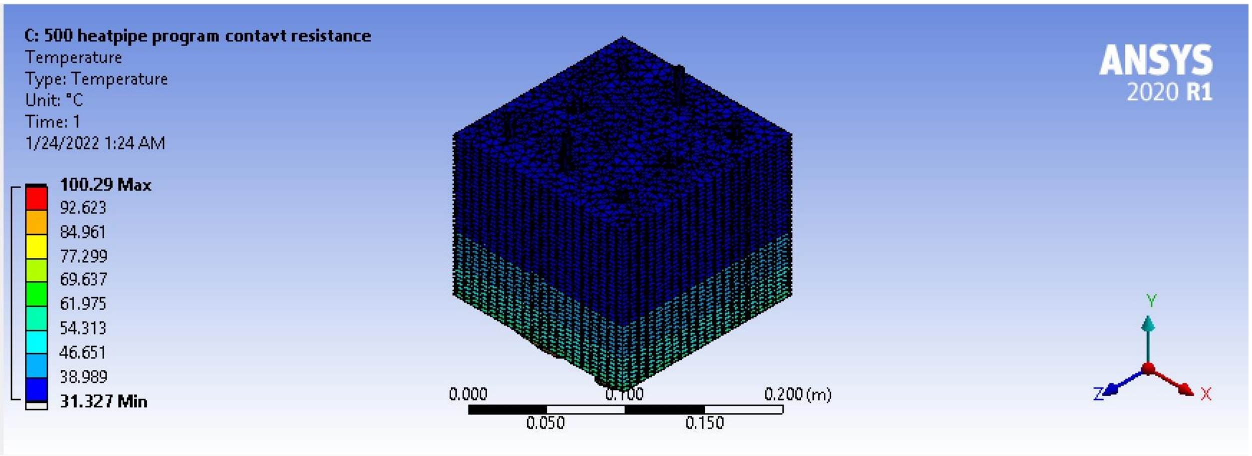
100.29 Max
92.623
84.961
77.299
69.637
61.975
54.313
46.651
38.989
31.327 Min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Temperature
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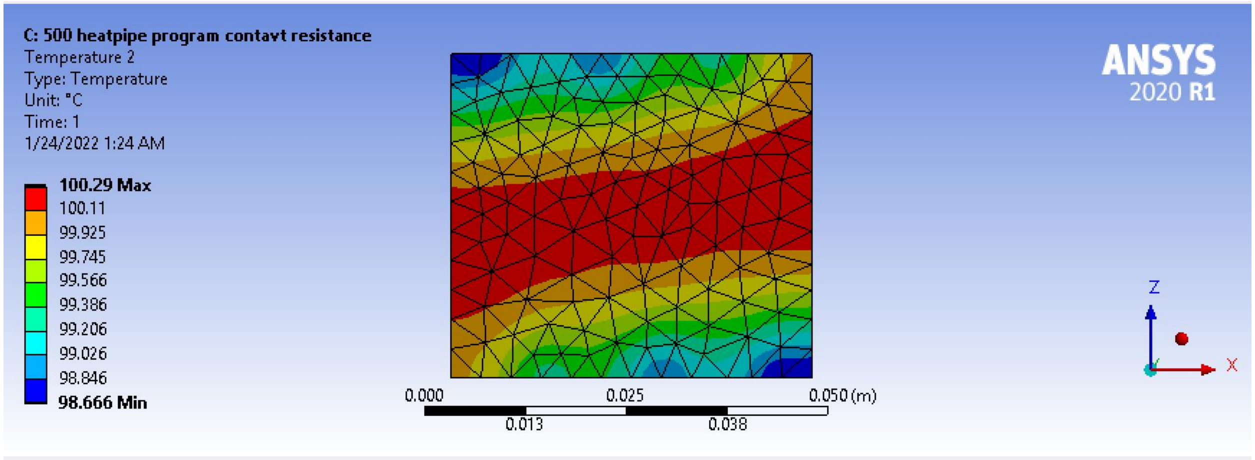
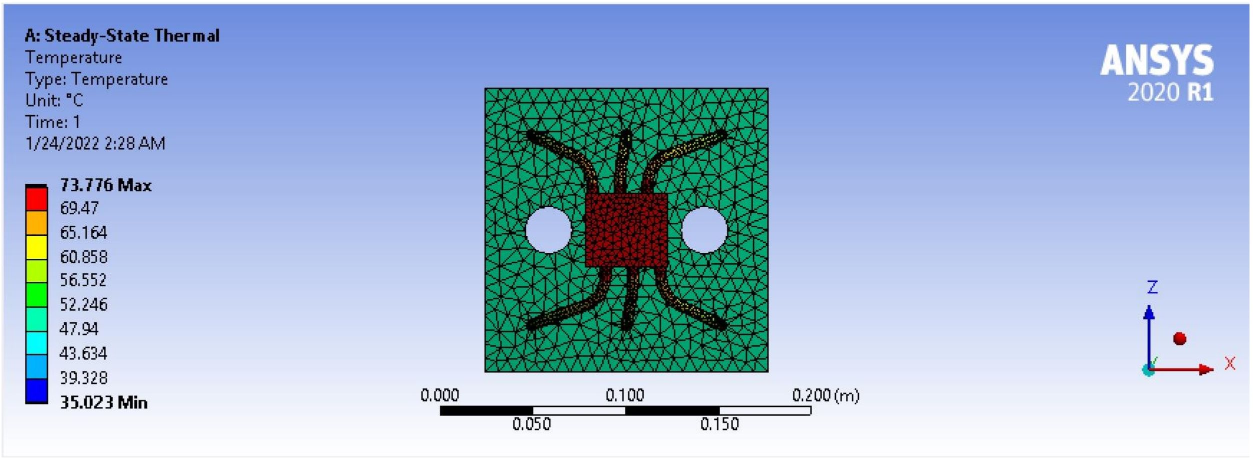
Unit: °C
Time: 1
1/24/2022 1:24 AM

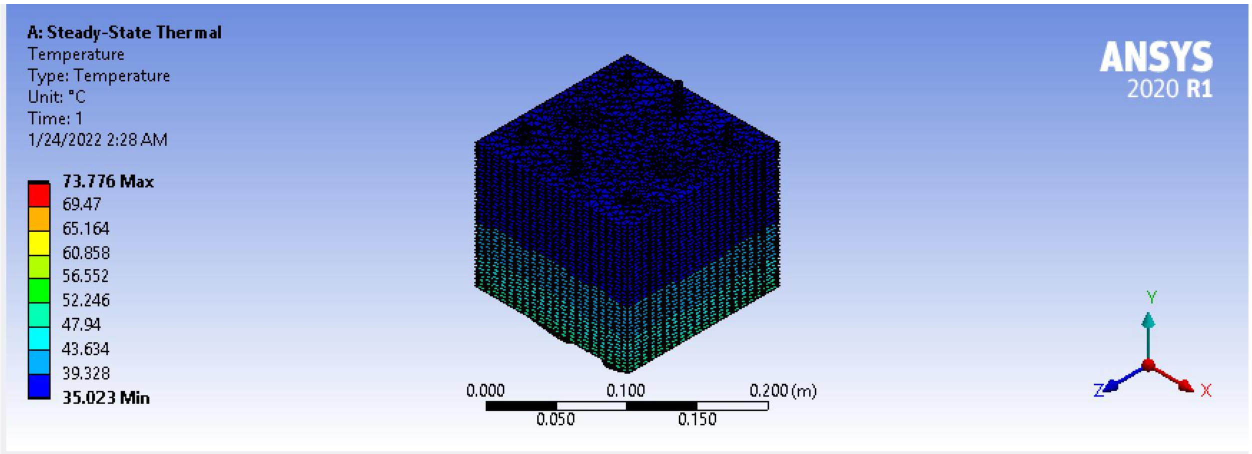
100.29 Max
92.623
84.961
77.299
69.637
61.975
54.313
46.651
38.989
31.327 Min

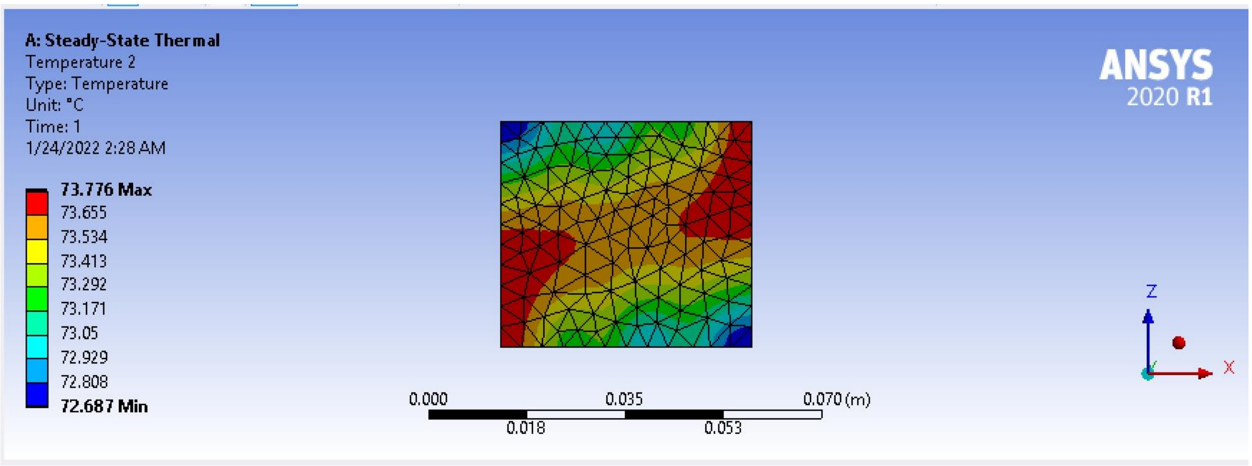

C: 500 heatpipe program contavt resistance
Temperature 2
Type: Temperature
Unit: °C
Time: 1
1/24/2022 1:24 AM

100.29 Max
100.11
99.925
99.745
99.566
99.386
99.206
99.026
98.846
98.666 Min

1k heatpipe conductance 47k contact heatpipes 6 pipes AND larger holes for DFMA consideration







Appendix B - EES Script - 1D Convection Coefficient

```
// Team F16 - Fin Spacing & Count Optimization

g = 9.81 [m/s^2]

// ---------------------- 1000 W/m-K ----------------------------->

//T_s = 100 [C] // Average surface temperature of all heat fins, pulled from Ansys
T_infinity = 22 [C] // Ambient temperature
P = 101.3 [kPa] // Ambient pressure
L = 0.1524 [m] // Channel Length, 6in
// S Spacing of the channel

Fluid$ = 'air'
Call fc_vertical_channel(Fluid$, T_s, T_infinity, P, L, S : h, Nusselt, Ra) //6in w/ 1000W/m-K

//Number_fins = 5

//T_cold_side = 100 [C]

T_cold_side_Required = 100 [C]

L_2 = 0.2032 [m] // Channel Length, 8in

Call fc_vertical_channel(Fluid$, T_s_2, T_infinity, P, L_2, S : h_2, Nusselt_2, Ra_2) //8in w/ 1000W/m-K

//T_s_2 = 100 [C]

//T_cold_side_2 = 100 [C]

// ---------------------- 1307 W/m-K ----------------------------->

//T_s_3 = 100 [C]

Call fc_vertical_channel(Fluid$, T_s_3, T_infinity, P, L, S : h_3, Nusselt_3, Ra_3) //6in w/ 1307W/m-K

//T_cold_side_3 = 1 [C]

//T_s_4 = 100 [C]

Call fc_vertical_channel(Fluid$, T_s_4, T_infinity, P, L_2, S : h_4, Nusselt_4, Ra_4) //8in w/ 1307W/m-K

//T_cold_side_4 = 1 [C]
```

$g = 9.81 \quad [m/s^2]$

$T_\infty = 22 \quad [C]$

$P = 101.3 \quad [kPa]$

$L = 0.1524 \quad [m]$

Fluid\$ = 'Air'

Call $\mathbf{fc}_{vertical,channel}\left(Fluid\$, T_s , T_\infty , P , L , S : h , Nusselt , Ra \right)$

$T_{cold,side,Required} = 100 \quad [C]$

$L_2 = 0.2032 \quad [m]$

Call $\mathbf{fc}_{vertical,channel}$ $\left(Fluid\$, T_{s,2} , T_{\infty} , P , L_2 , S : h_2 , Nusselt_2 , Ra_2\right)$

Call $\mathbf{fc}_{vertical,channel}$ $\left(Fluid\$, T_{s,3} , T_{\infty} , P , L , S : h_3 , Nusselt_3 , Ra_3\right)$

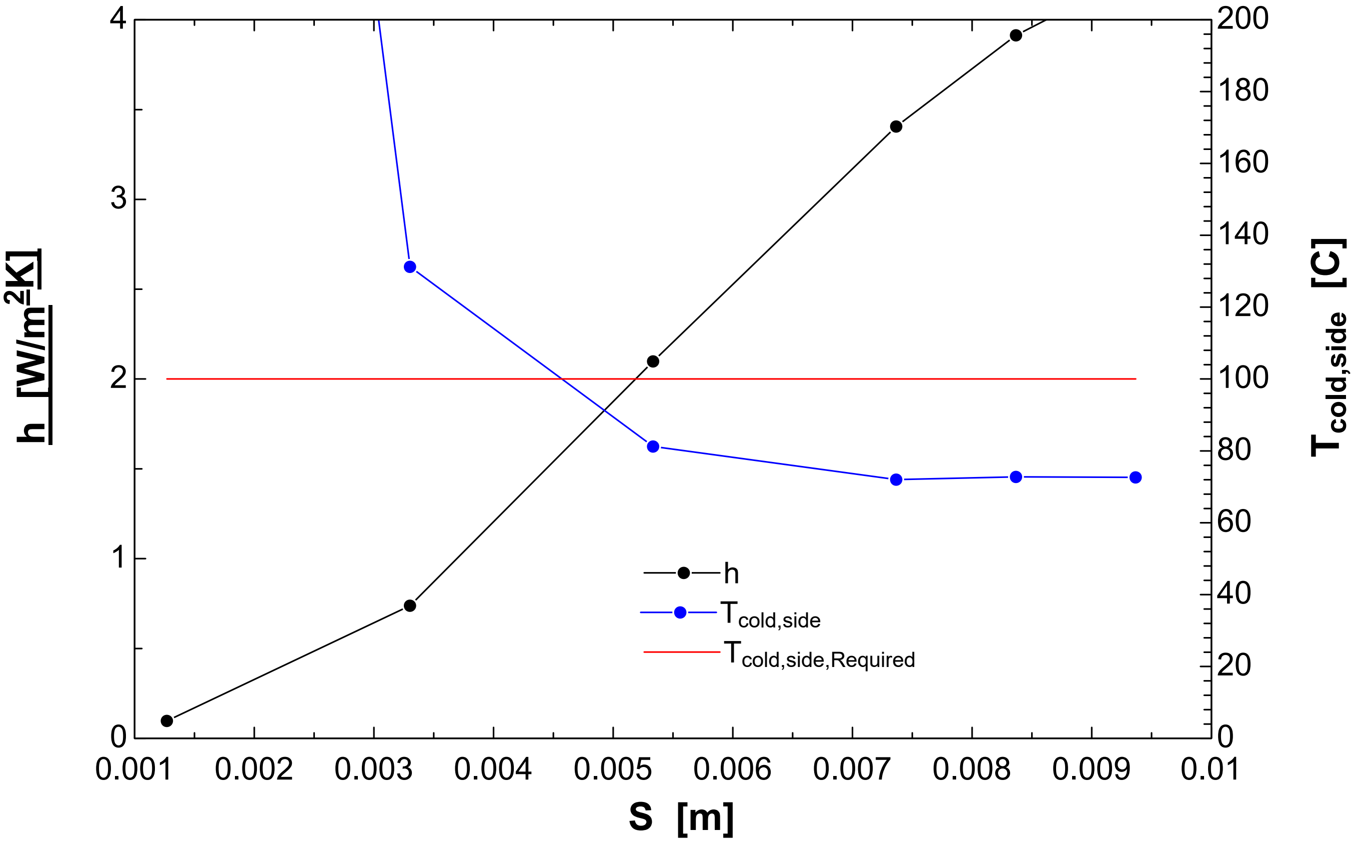
Call $\mathbf{fc}_{vertical,channel}$ $\left(Fluid\$, T_{s,4} , T_{\infty} , P , L_2 , S : h_4 , Nusselt_4 , Ra_4\right)$

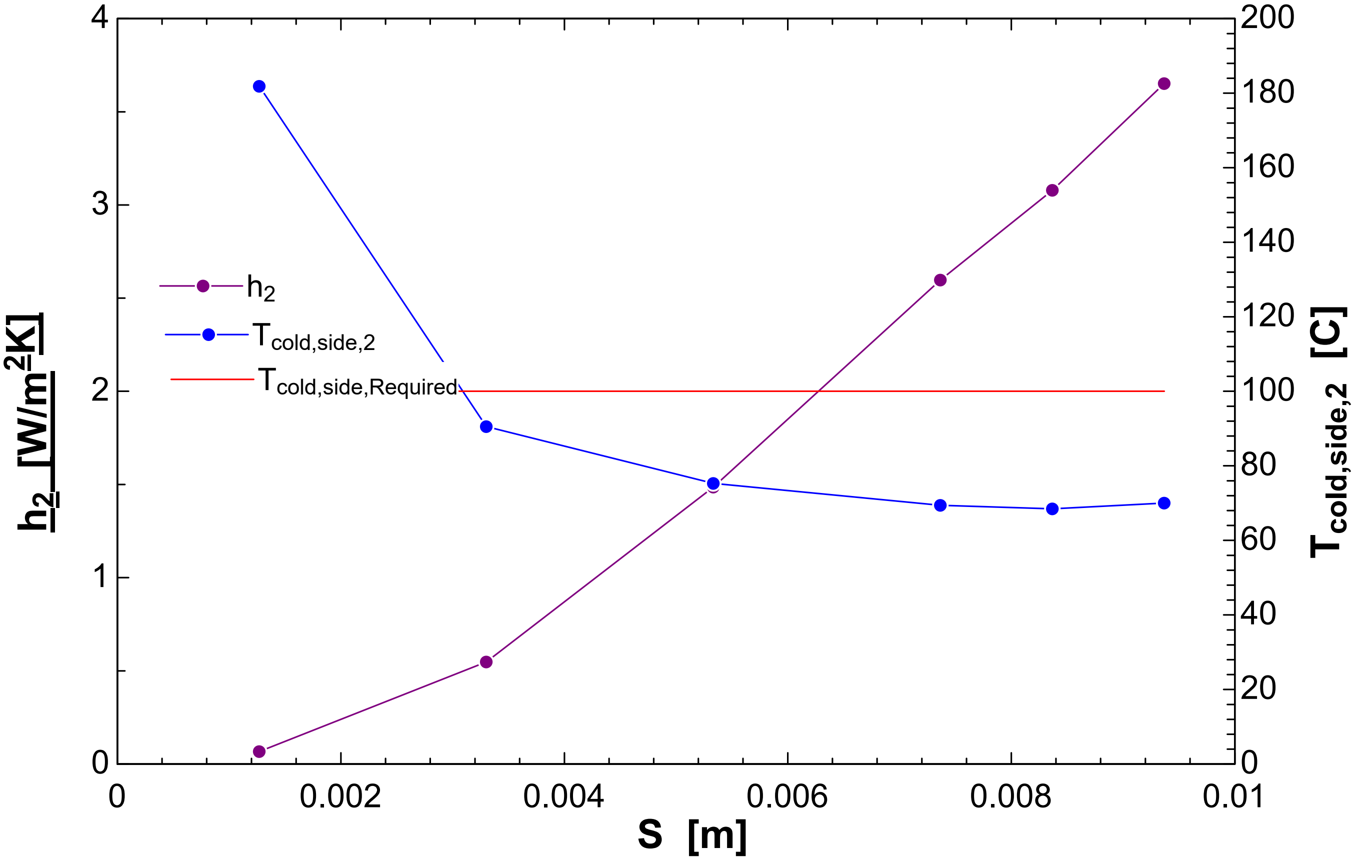
Parametric Table: Table

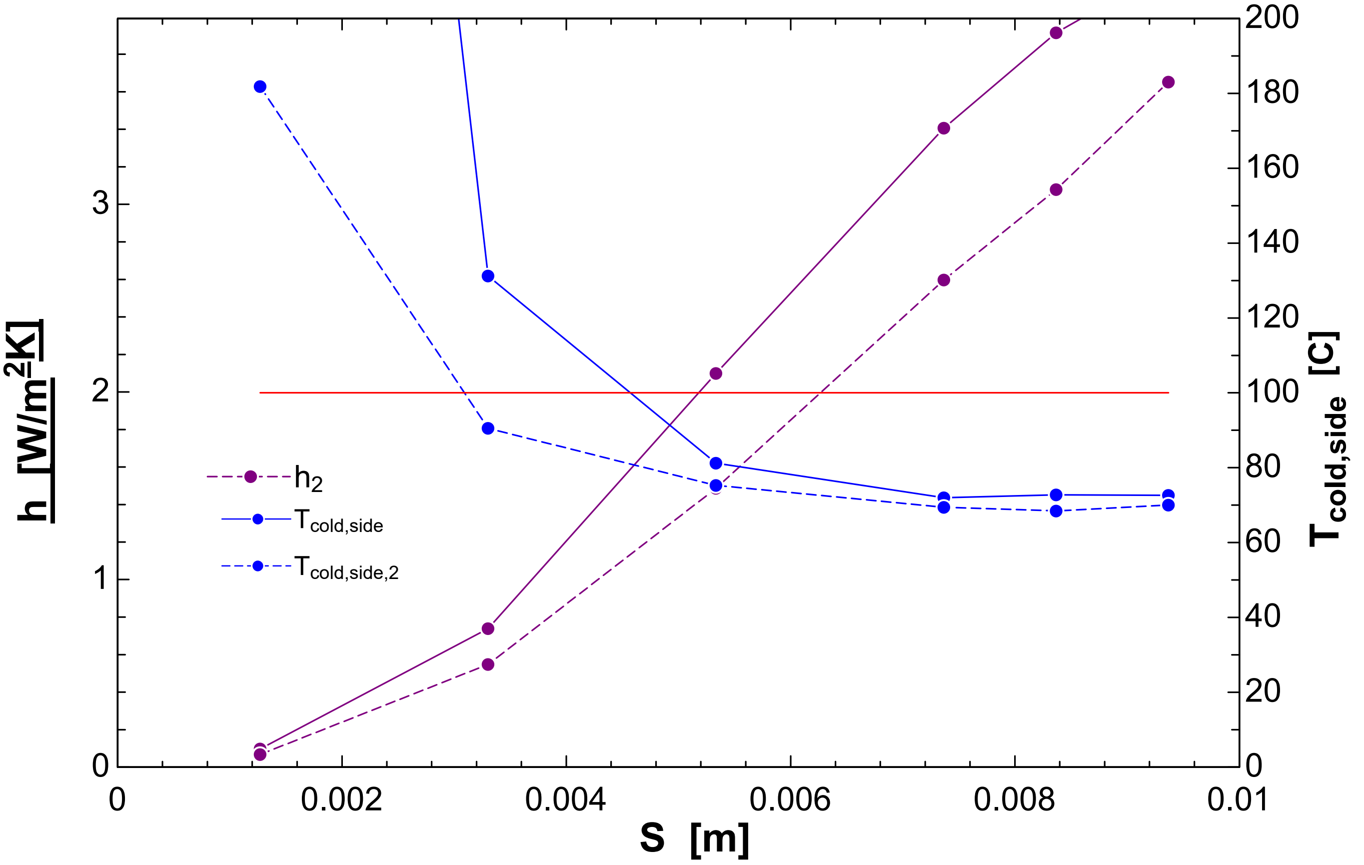
	S [m]	h [W/m2-K]	h_2 [W/m2-K]	h_3 [W/m2-K]	h_4 [W/m2-K]	L [m]	L_2 [m]	T_s [C]	$T_{s,2}$ [C]	$T_{s,3}$ [C]
Run 1	0.00127	*0.09682*	*0.06708*	*0.08991*	*0.06657*	*0.1524*	*0.2032*	310	148.2	150.1
Run 2	0.003302	*0.7384*	*0.5477*	*0.7713*	*0.5551*	*0.1524*	*0.2032*	57.97	57.47	60.04
Run 3	0.005334	*2.098*	*1.487*	*2.071*	*1.502*	*0.1524*	*0.2032*	45.08	43.08	44.69
Run 4	0.007366	*3.406*	*2.597*	*3.358*	*2.652*	*0.1524*	*0.2032*	40.01	37.65	39.55
Run 5	0.008367	*3.914*	*3.078*	*3.839*	*3.145*	*0.1524*	*0.2032*	39.83	36.84	39.07
Run 6	0.009368	*4.254*	*3.651*	*4.216*	*3.593*	*0.1524*	*0.2032*	39.79	38.51	39.37

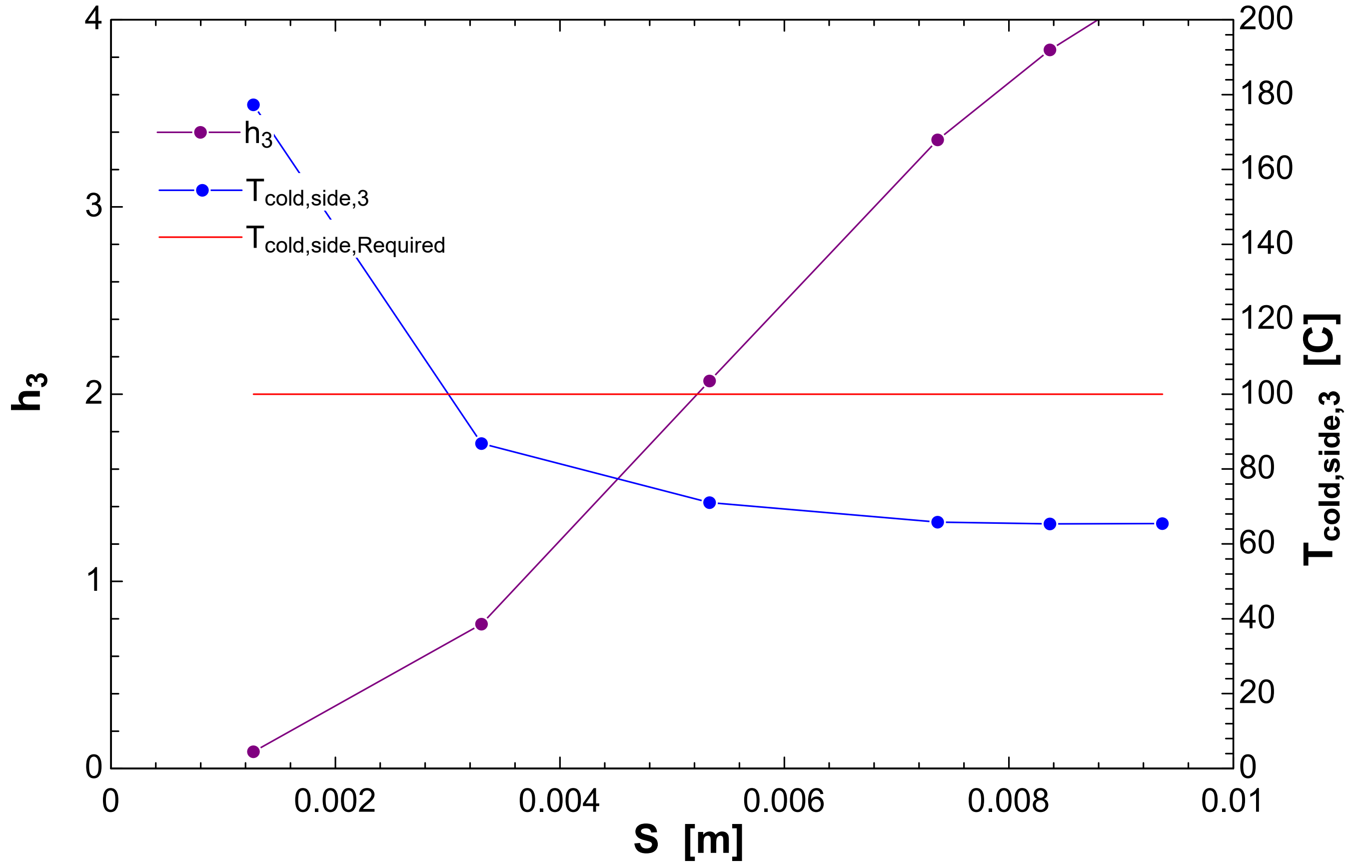
Parametric Table: Table

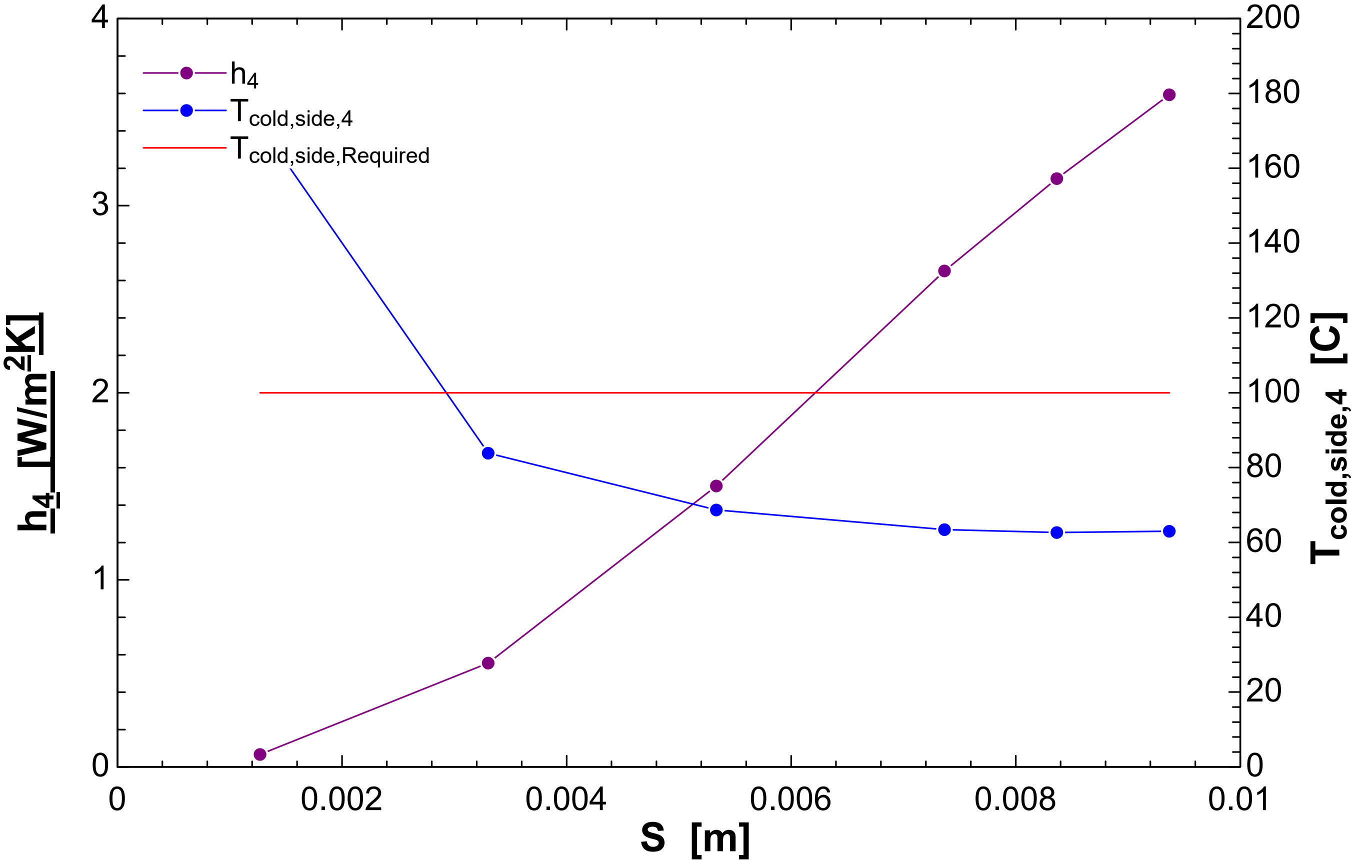
	$T_{s,4}$ [C]	$Number_{fins}$	$T_{cold,side}$ [C]	$T_{cold,side,2}$ [C]	$T_{cold,side,3}$ [C]	$T_{cold,side,4}$ [C]	$T_{cold,side,Required}$ [C]
Run 1	145.5	101	663	181.9	177.3	171.5	*100*
Run 2	58.08	39	131.2	90.53	86.79	83.87	*100*
Run 3	43.34	24	81.24	75.29	71.04	68.69	*100*
Run 4	38.16	18	71.99	69.42	65.83	63.41	*100*
Run 5	37.45	16	72.76	68.45	65.32	62.67	*100*
Run 6	37.9	14	72.64	70.04	65.44	62.97	*100*

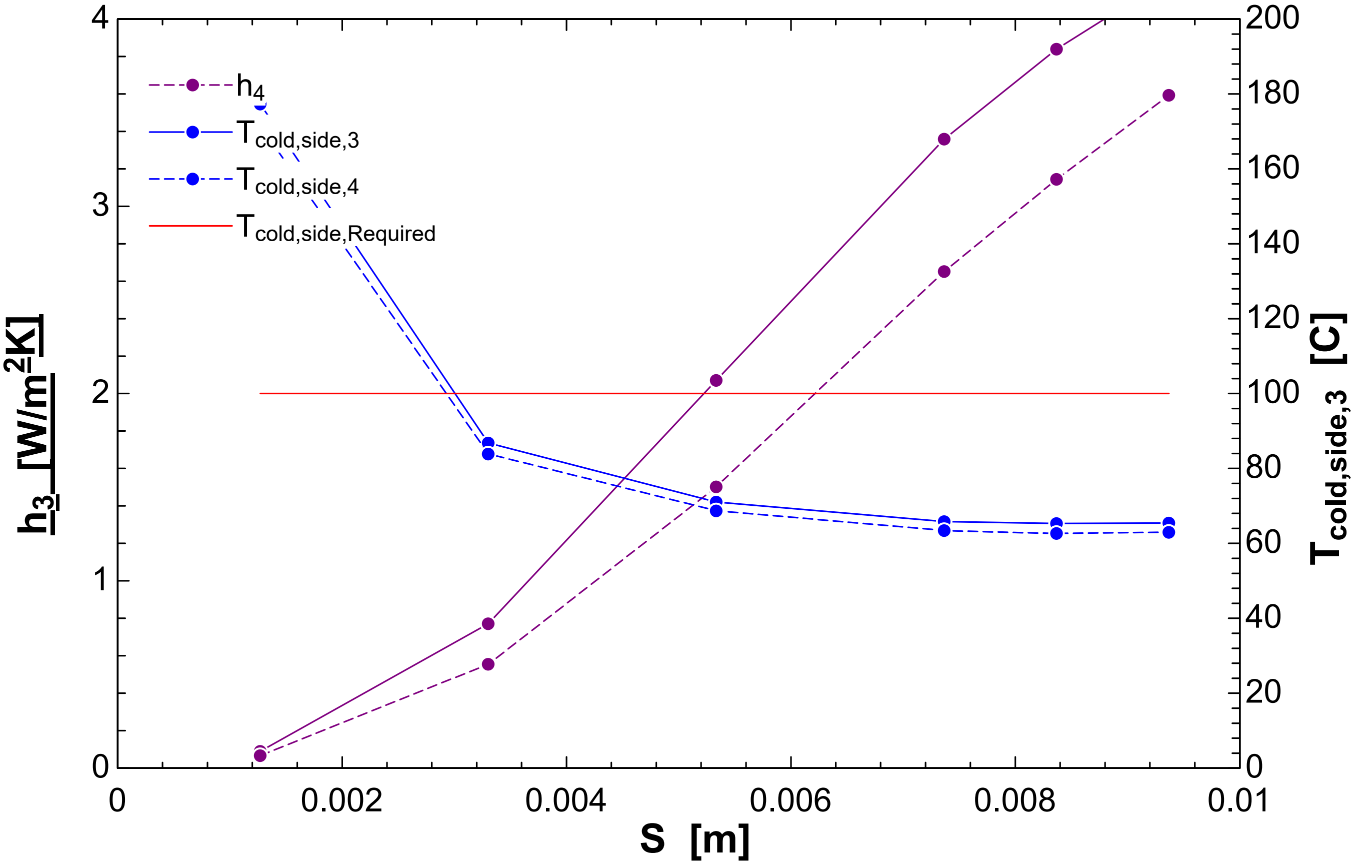

h [W/m²K]
S [m]
T cold,side [C]
h
T cold,side
T cold,side,Required
0
1
2
3
4
0.001
0.002
0.003
0.004
0.005
0.006
0.007
0.008
0.009
0.01
0
20
40
60
80
100
120
140
160
180
200

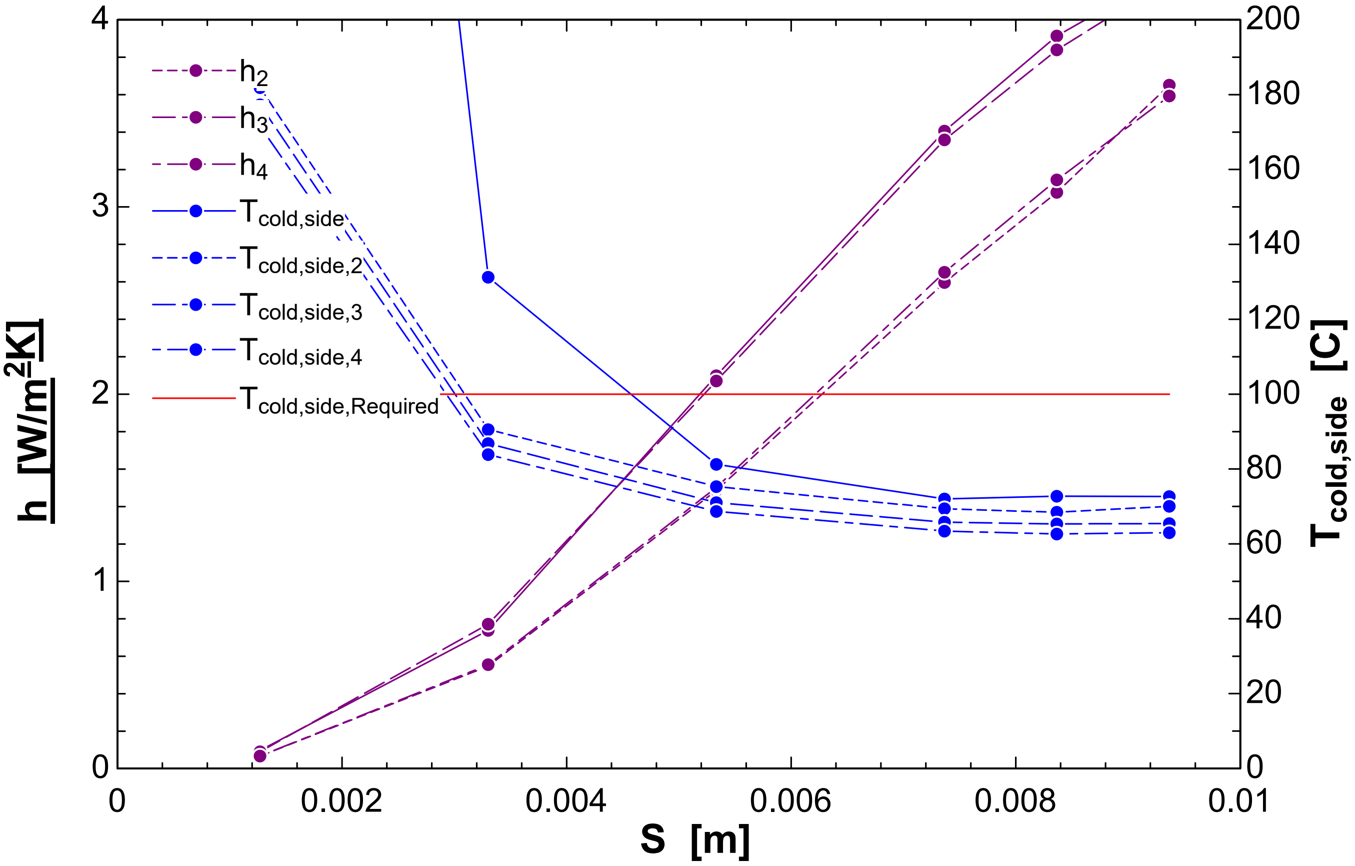

h2 [W/m²K]
S [m]
T cold,side,2 [C]
h2
T cold,side,2
T cold,side,Required
0
1
2
3
4
0
0.002
0.004
0.006
0.008
0.01
0
20
40
60
80
100
120
140
160
180
200


h [W/m²K]
0
1
2
3
S [m]
0
0.002
0.004
0.006
0.008
0.01
T cold,side [C]
0
20
40
60
80
100
120
140
160
180
200
h2
T cold,side
T cold,side,2


h3
Tcold,side,3
Tcold,side,Required
h3
Tcold,side,3 [C]
S [m]
0
0.002
0.004
0.006
0.008
0.01
0
1
2
3
4
0
20
40
60
80
100
120
140
160
180
200


h4
Tcold,side,4
Tcold,side,Required
h4 [W/m2K]
Tcold,side,4 [C]
S [m]
0
0.002
0.004
0.006
0.008
0.01
0
1
2
3
4
0
20
40
60
80
100
120
140
160
180
200


h_4
$T_{cold,side,3}$
$T_{cold,side,4}$
$T_{cold,side,Required}$
h_3 [W/m^{2}K]
0
1
2
3
4
$T_{cold,side,3}$ [C]
0
20
40
60
80
100
120
140
160
180
200
S [m]
0
0.002
0.004
0.006
0.008
0.01


h_2
h_3
h_4
T_cold,side
T_cold,side,2
T_cold,side,3
T_cold,side,4
T_cold,side,Required
h [W/m²K]
0
1
2
3
4
T_cold,side [C]
0
20
40
60
80
100
120
140
160
180
200
S [m]
0
0.002
0.004
0.006
0.008
0.01

Appendix C - Thermal Simulation Iteration and Results Documentation

Heat Fin Trade Study – Senior Project Group F16

Purpose:

This trade study was conducted to determine heat fin spacing and quantity. Inputs for this trial are based on best practices and the results of our structural prototype test.

Method:

This solution uses an iteration approach with both Ansys and Engineering Equation Solver (EES). First, a fin average temperature of 100C is assumed for every case. Then a convection coefficient is calculated for every fin spacing, fin size, and heat pipe thermal conductivity case. Those convection coefficients are plugged into Ansys – which contains a 3d thermal model of the heatsink – and new average fin temperatures are calculated for every case. Those average fin temperatures are then plugged back into the EES model to calculate a new convection coefficient. This process is repeated until the solution converges. We define convergence as less than ten percent different in values of convection coefficient between two consecutives runs of any case. Once a converged convection heat transfer coefficient has been obtained for each case that coefficient is used to calculate a TEG or heatsink base cold side temperature. This cold side temperature is the constraint for our design. The results of this study can be found in the tables and figures below.

Assumptions:

1) Radiation neglected
2) Convection coefficient is a vertical channel, semi-infinite width, and defined height
3) Convection coefficient applies to the entire model
4) Heat input through 1 face of the copper base only
5) Thermal contact resistance between heat pipes and the heatsink base as well as between the heat pipes and the heat fins is negligible
6) Thermal contact resistance between the TEG and the heatsink base in negligible
7) Convergence of thermal simulation convection coefficient is defined as less than 10 percent difference in convection coefficient value between two consecutive runs

Uncertainty Standards:

Put uncertainty information here for all following results

Naming Convention For EES

Name_1 -> Trial #1, 6x6in Fins with K=1000W/m-K for heat pipes

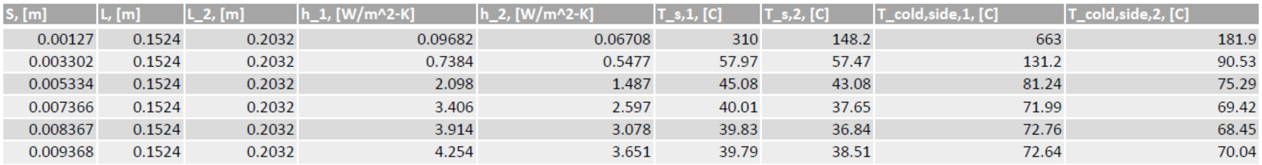
Name_2 -> Trail #2, 6x8in Fins with K=1000W/m-K for heat pipes

Name_3 -> Trial #3, 6x6in Fins with K=1307W/m-K for heat pipes

Name_4 -> Trial #4, 6x8in Fins with K=1307W/m-K for heat pipes

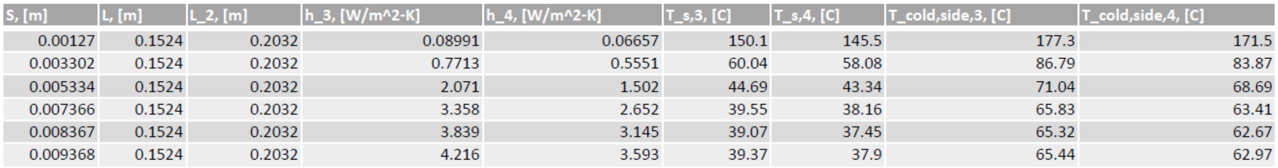
EES Results – Convection heat transfer coefficient Calculation

Table 1. EES Summary



S, [m]	L, [m]	L_2, [m]	h_1, [W/m^2-K]	h_2, [W/m^2-K]	T_s,1, [C]	T_s,2, [C]	T_cold,side,1, [C]	T_cold,side,2, [C]
0.00127	0.1524	0.2032	0.09682	0.06708	310	148.2	663	181.9
0.003302	0.1524	0.2032	0.7384	0.5477	57.97	57.47	131.2	90.53
0.005334	0.1524	0.2032	2.098	1.487	45.08	43.08	81.24	75.29
0.007366	0.1524	0.2032	3.406	2.597	40.01	37.65	71.99	69.42
0.008367	0.1524	0.2032	3.914	3.078	39.83	36.84	72.76	68.45
0.009368	0.1524	0.2032	4.254	3.651	39.79	38.51	72.64	70.04

Table 2. EES Summary



S, [m]	L, [m]	L_2, [m]	h_3, [W/m^2-K]	h_4, [W/m^2-K]	T_s,3, [C]	T_s,4, [C]	T_cold,side,3, [C]	T_cold,side,4, [C]
0.00127	0.1524	0.2032	0.08991	0.06657	150.1	145.5	177.3	171.5
0.003302	0.1524	0.2032	0.7713	0.5551	60.04	58.08	86.79	83.87
0.005334	0.1524	0.2032	2.071	1.502	44.69	43.34	71.04	68.69
0.007366	0.1524	0.2032	3.358	2.652	39.55	38.16	65.83	63.41
0.008367	0.1524	0.2032	3.839	3.145	39.07	37.45	65.32	62.67
0.009368	0.1524	0.2032	4.216	3.593	39.37	37.9	65.44	62.97

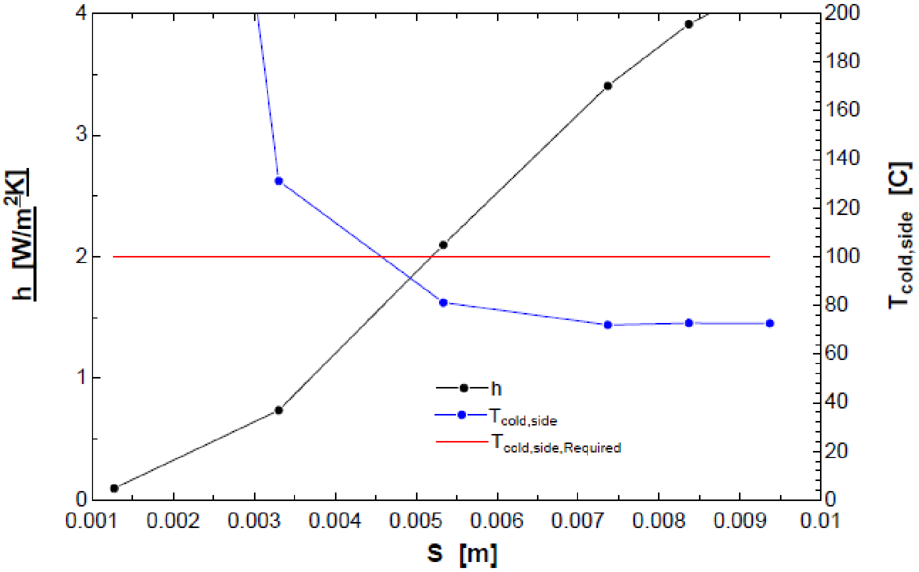


Figure 1. Trial #1

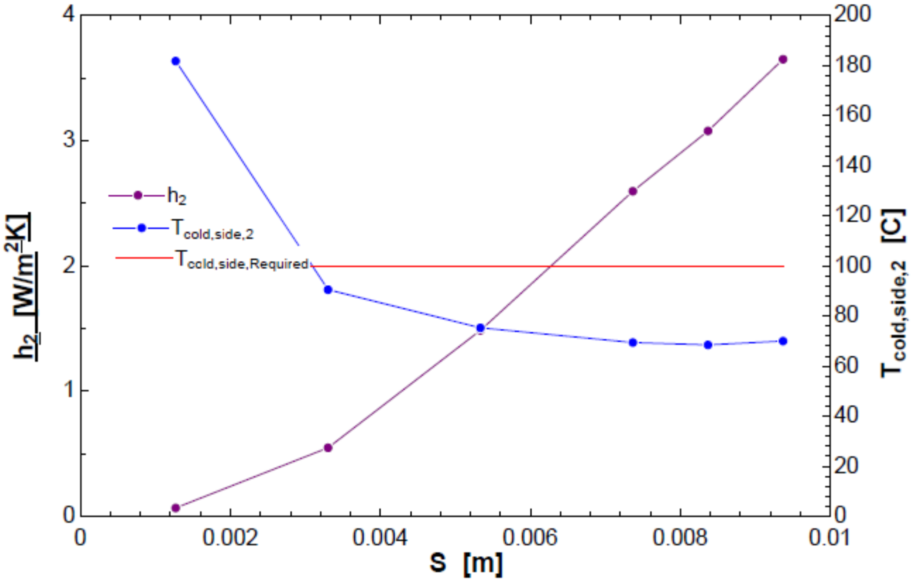


Figure 2. Trial #2

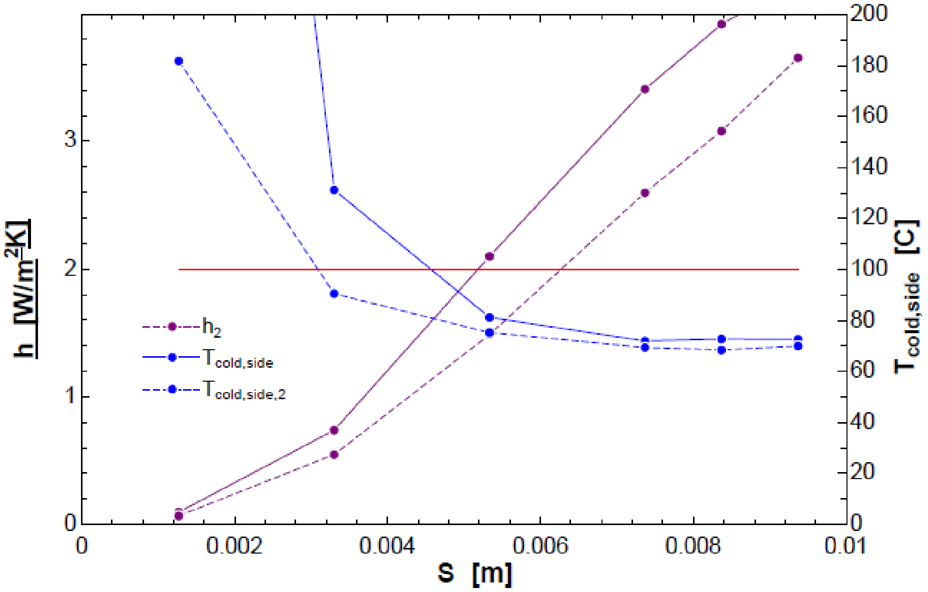


Figure 3. Trail #1 & Trial #2

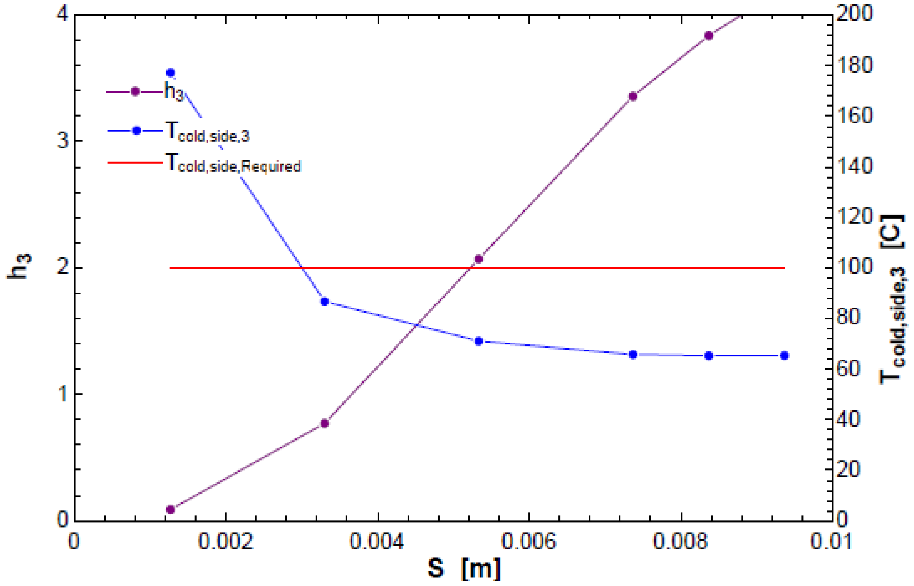


Figure 4. Trial #3

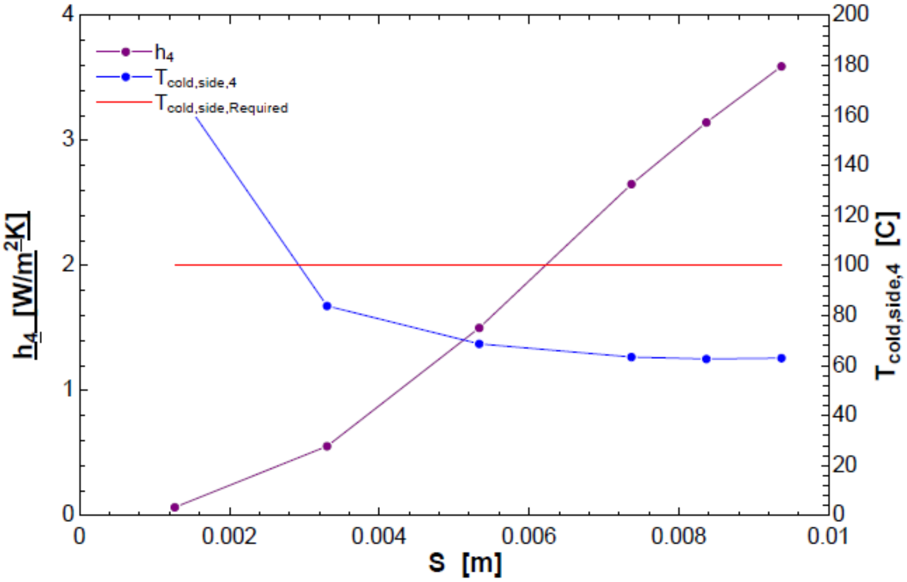


Figure 5. Trial #4

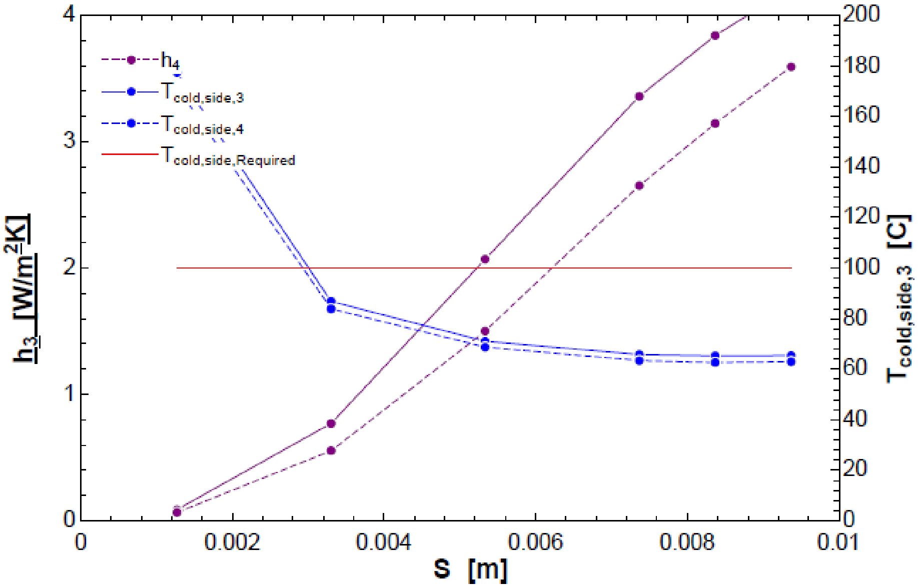


Figure 6. Trial #3 & Trial #4

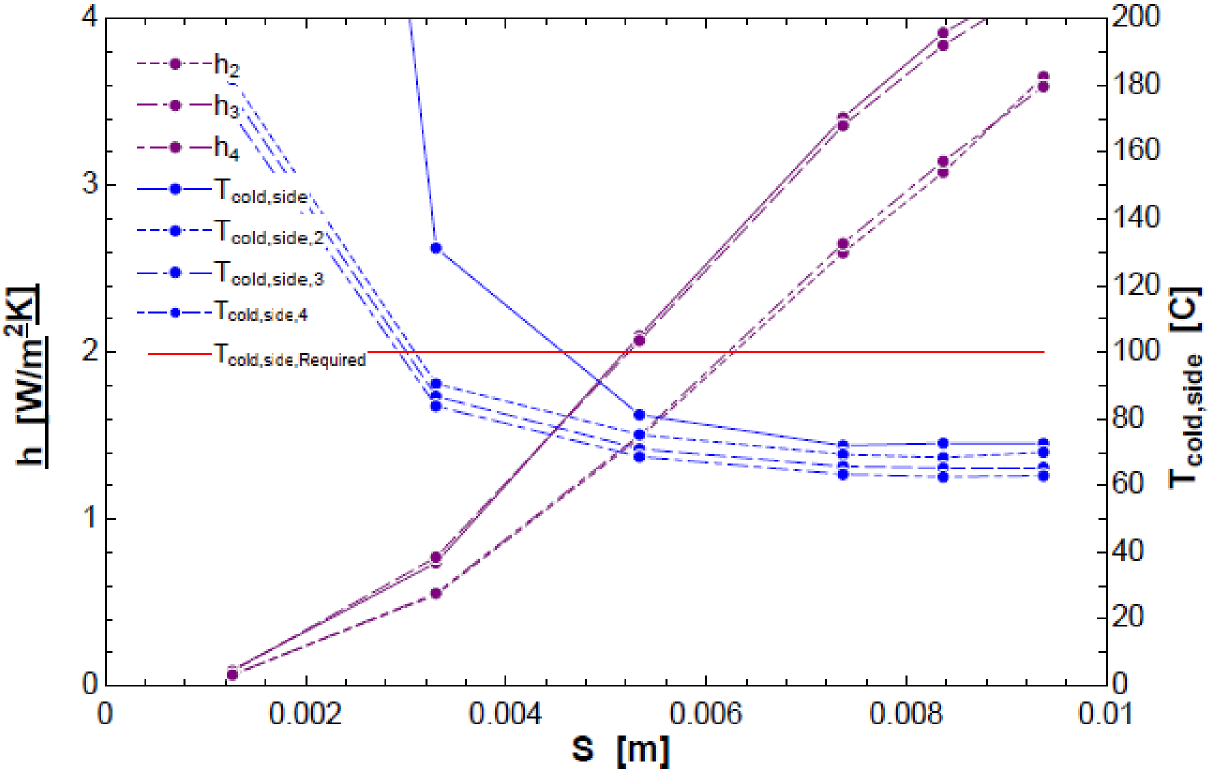


Figure 7. Trials #1 through #4.

Ansys & Excel Results – 3d thermal simulation models and convection coefficient convergence.

Summary of Simulation & Convergence Results

101 Fins | S = 0.05in = 0.00127m

6x6in Heat Fins

1000 W/m-K | “Configuration 1a”

Table 3. Iterative trials to obtain temperature convergence for a 6x6 inch fin with spacing of 0.00127 m and convection coefficient of 1000 W/m-K.

S = 0.00127 [m]			101 Fins	Config 1
Trial #	T_s, [C]	Delta T [%]	h, [W/m2-K]	Delta h %
	100	n/a	0.07154	n/a
1	413	313.00%	0.088	23.01%
2	333.3	19.30%	0.095	7.95%
3	310	6.99%	0.0968	1.89%

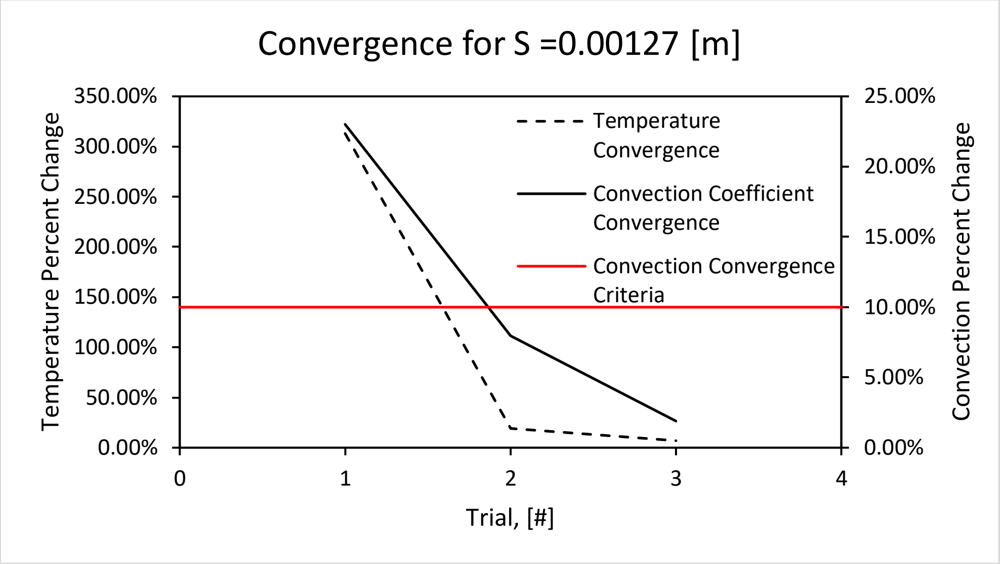


Figure 8. Convergence plot for S= 0.00127 m and a 6x6 inch heat fin with a convection coefficient of 1000 W/m-K.

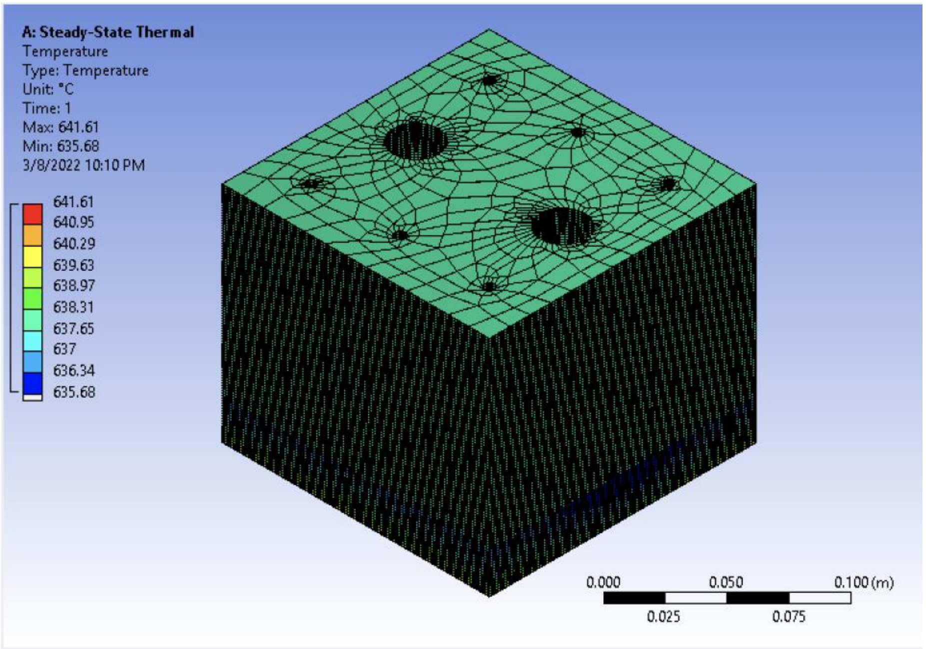


Figure 9. Fin array temperature gradient.

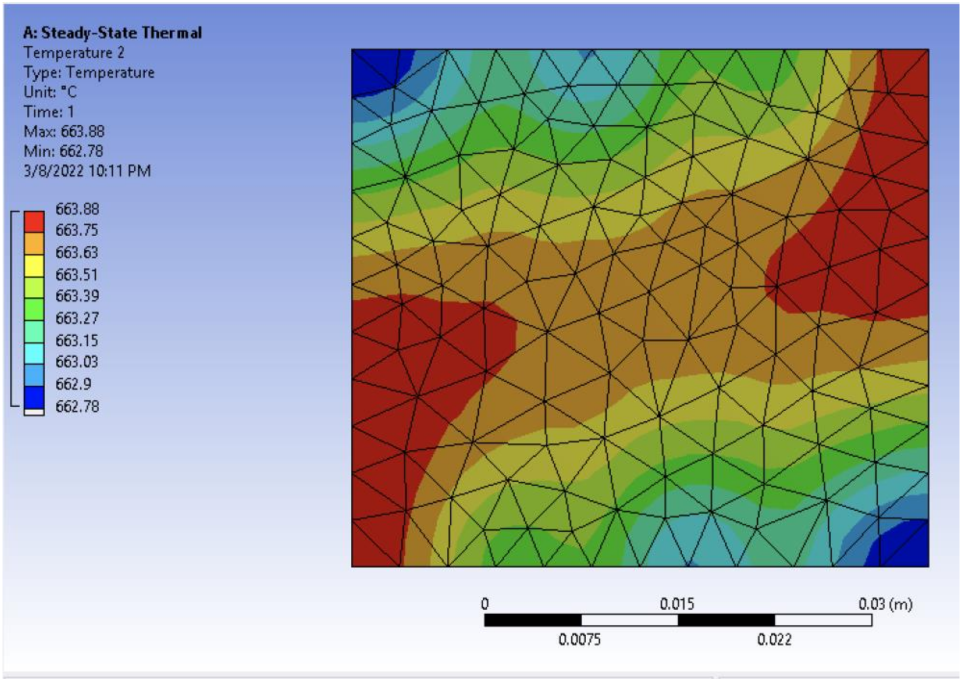


Figure 10. Copper base temperature gradient.

Average Base Temperature: 633 [C]

1307 W/m-K | "Configuration 1c"

Table 4. Iterative trials to obtain temperature convergence for a 6x6 inch fin with spacing of 0.00127 m and convection coefficient of 1307 W/m-K.

S = 0.00127 [m]			101 Fins	Config 1c
Trial #	T_s, [C]	Delta T %	h, [W/m2-K]	Delta h %
	310	n/a	0.09682	n/a
1	135.85	56.18%	0.08604	11.13%
2	150.12	10.50%	0.08991	4.50%
	Base Temp	177.3	C	

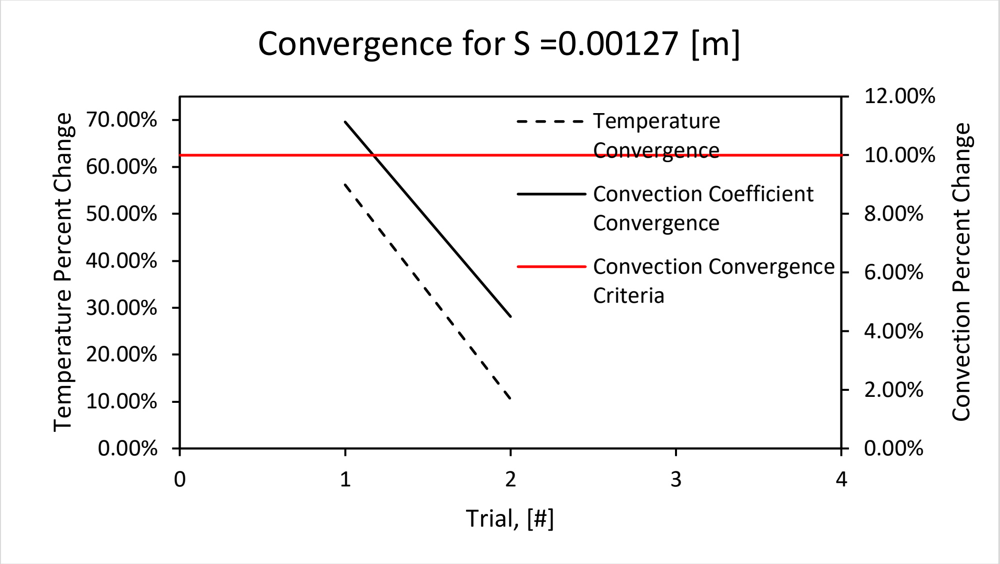


Figure 11. Convergence plot for S= 0.00127 m and a 6x6 inch heat fin with a convection coefficient of 1307 W/m-K.

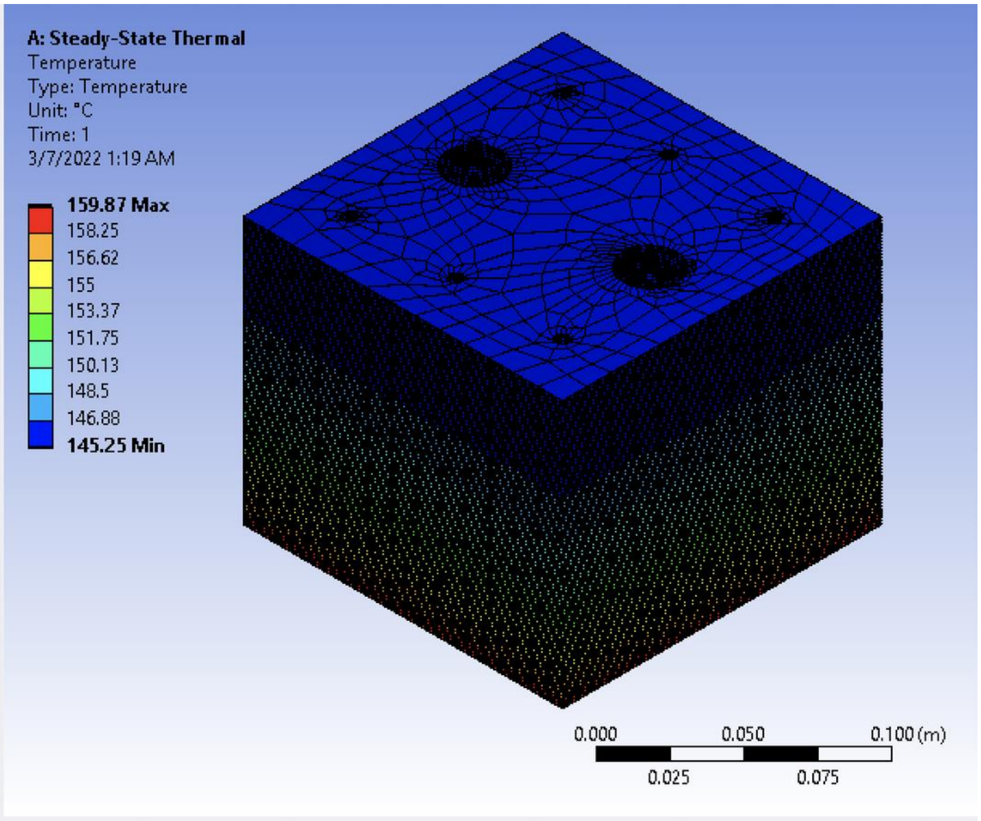


Figure 12. Fin array temperature gradient.

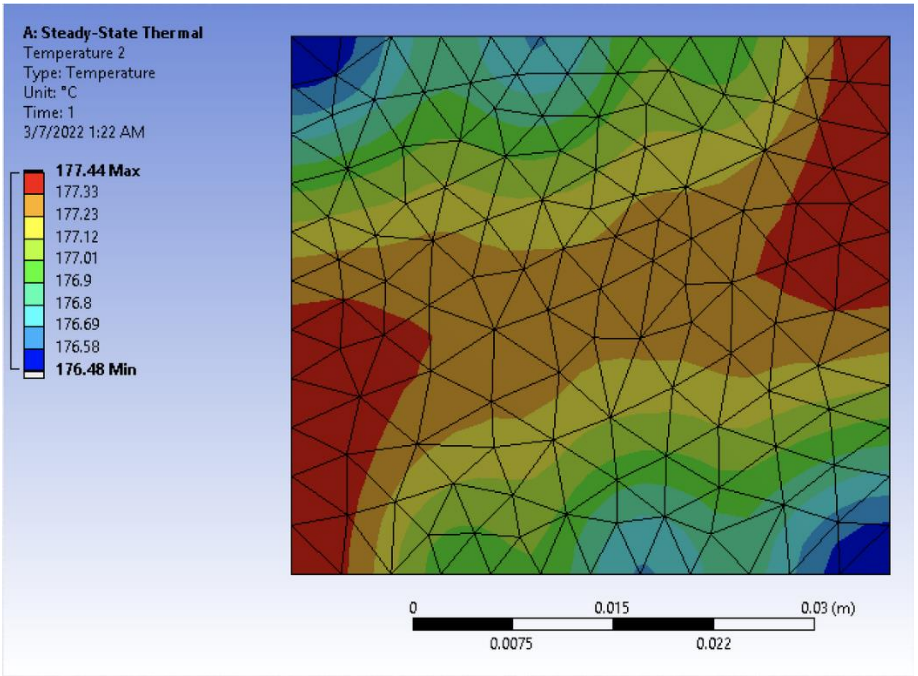


Figure 13. Copper base temperature gradient.

Average Base Temperature: 177.3 [C]

6x8in Heat Fins

1000 W/m-K | "Configuration 1b"

Table 5. Iterative trials to obtain temperature convergence for a 6x8 inch fin with spacing of 0.00127 m and convection coefficient of 1000 W/m-K.

S = 0.00127 [m]			101 Fins	Config 1b
Trial #	T_s, [C]	Delta T %	h, [W/m2-K]	Delta h %
	100	n/a	0.05365	n/a
1	174.62	74.62%	0.07098	32.30%
2	137.36	21.34%	0.06487	8.61%
3	148.22	7.91%	0.06708	3.41%

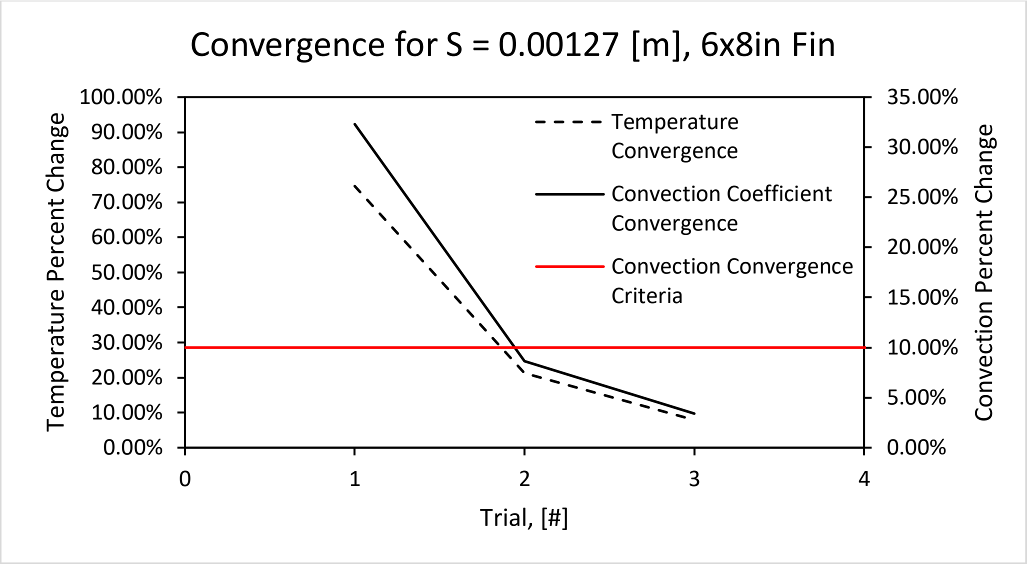


Figure 14. Convergence plot for S= 0.00127 m and a 6x8 inch heat fin with a convection coefficient of 1000 W/m-K.

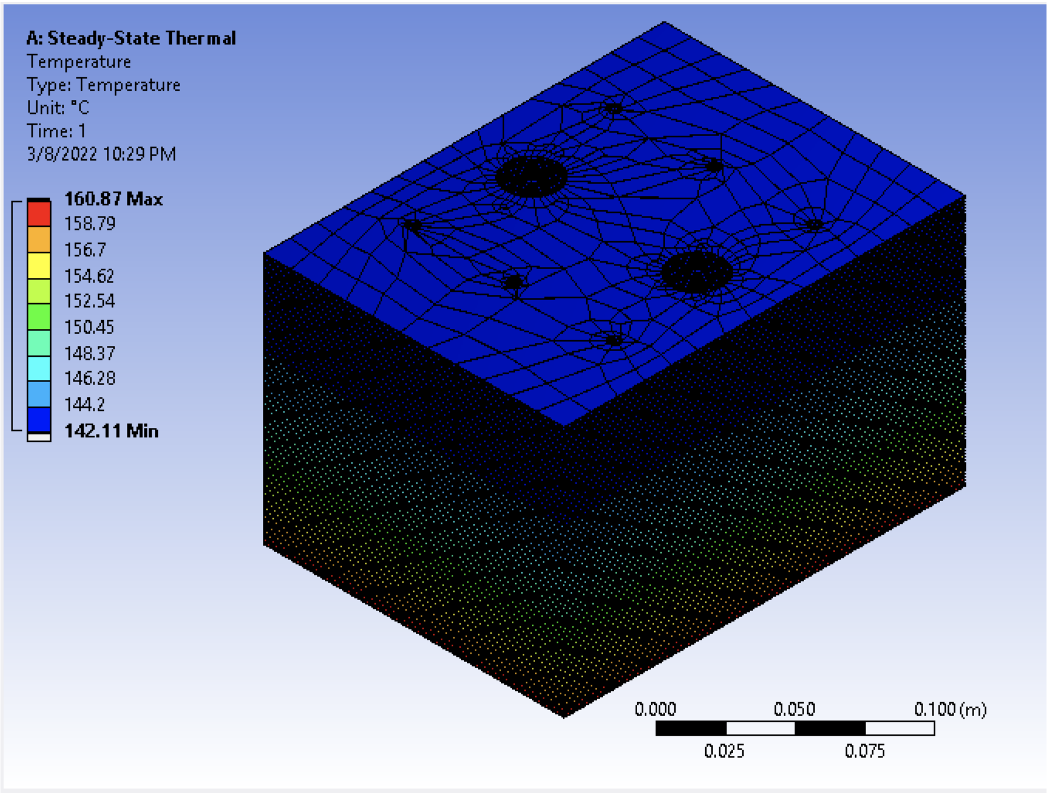


Figure 15. Fin array temperature gradient.

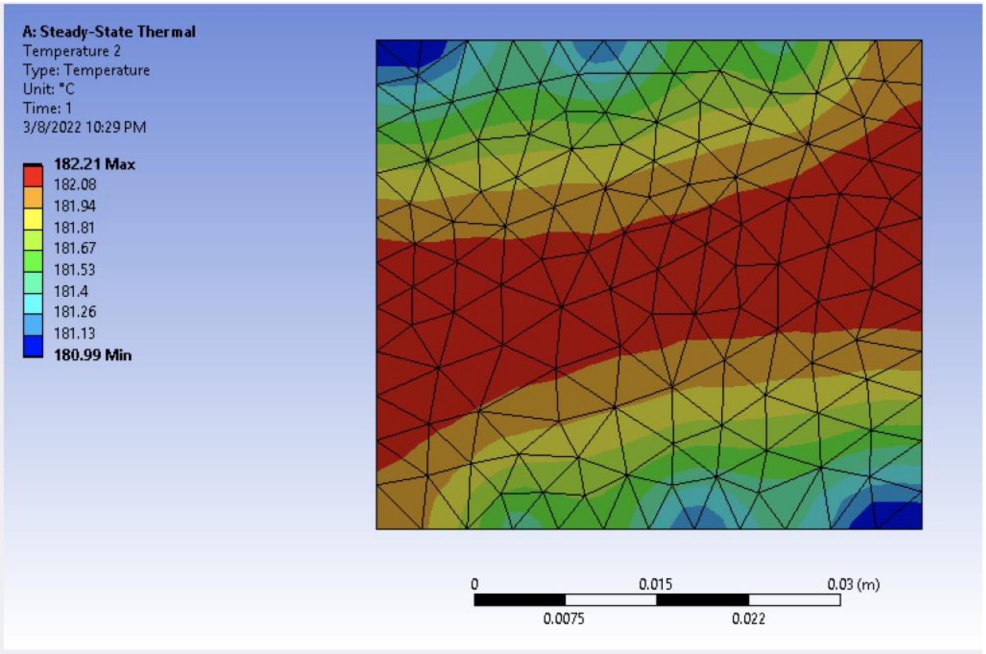


Figure 16. Copper base temperature gradient.

Average Base Temperature: 181.9 [C]

1307 W/m-K | “Configuration 1d”

Table 6. Iterative trials to obtain temperature convergence for a 6x68inch fin with spacing of 0.00127 m and convection coefficient of 1307 W/m-K.

S = 0.00127 [m]			101 Fins	Config 1d
Trial #	T_s, [C]	Delta T %	h, [W/m2-K]	Delta h %
	148.2	n/a	0.06708	n/a
1	144.08	2.78%	0.06629	1.18%
2	145.53	1.01%	0.06657	0.42%

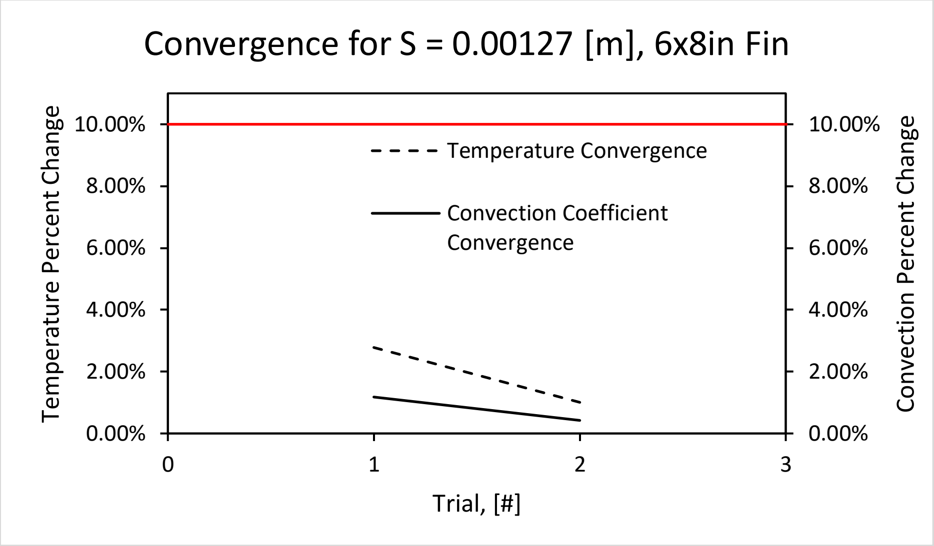


Figure 17. Convergence plot for S= 0.00127 m and a 6x8 inch heat fin with a convection coefficient of 1307 W/m-K.

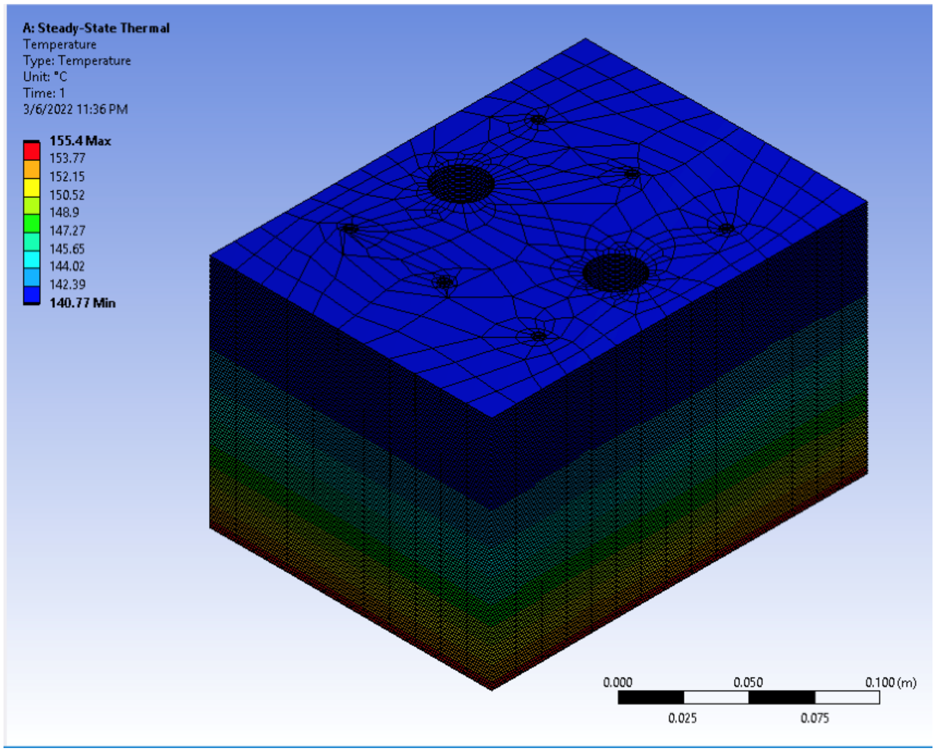


Figure 18. Fin array temperature gradient.

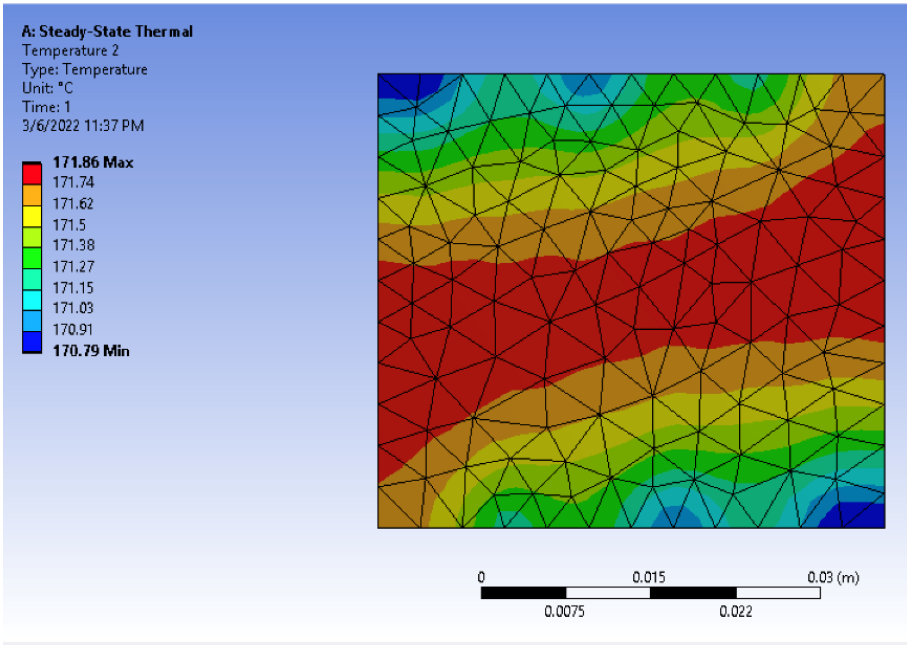


Figure 19. Copper base temperature gradient.

Average Base Temperature: 171.5 [C]

39 Fins | S = 0.12in = 0.00330m

6x6in Heat Fins

1000 W/m-K | “Configuration 2a”

Table 7. Iterative trials to obtain temperature convergence for a 6x6 inch fin with spacing of 0.003302 m and convection coefficient of 1000 W/m-K.

S = 0.003302 [m]			39 Fins	Config 2
Trial #	T_s, [C]	Delta T %	h, [W/m2-K]	Delta h %
	100	n/a	1.257	n/a
1	44.73	55.27%	0.505	59.82%
2	78.98	76.57%	1.034	104.75%
3	49.687	37.09%	0.5972	42.24%
4	70.14	41.16%	0.9197	54.00%
5	53.16	24.21%	0.6582	28.43%
6	65.65	23.50%	0.8562	30.08%
7	55.5	15.46%	0.6978	18.50%
8	63.16	13.80%	0.8192	17.40%
9	57	9.75%	0.7226	11.79%
10	61.74	8.32%	0.7976	10.38%
11	57.97	6.11%	0.7384	7.42%

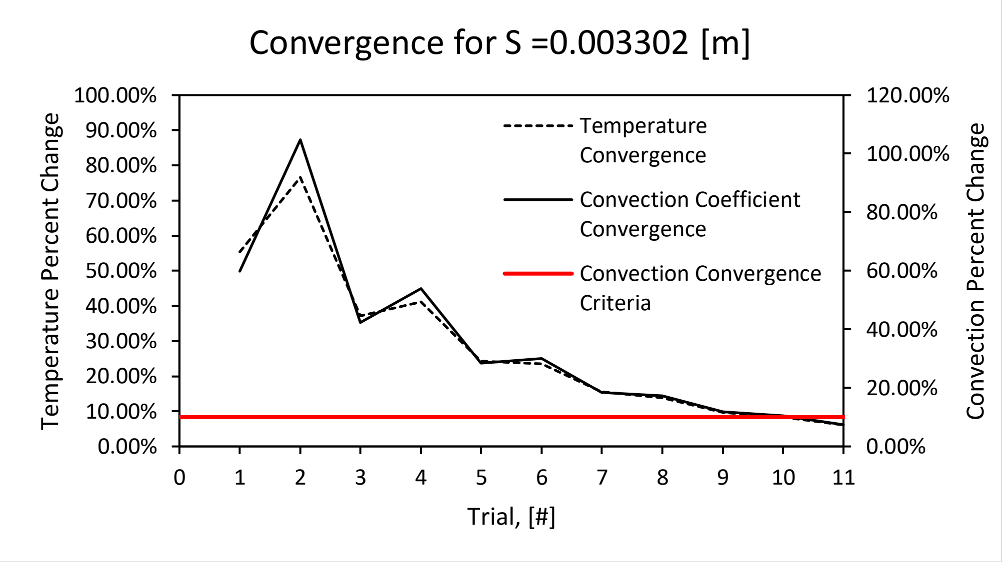


Figure 20. Convergence plot for S= 0.003302 m and a 6x6 inch heat fin with a convection coefficient of 1000 W/m-K.

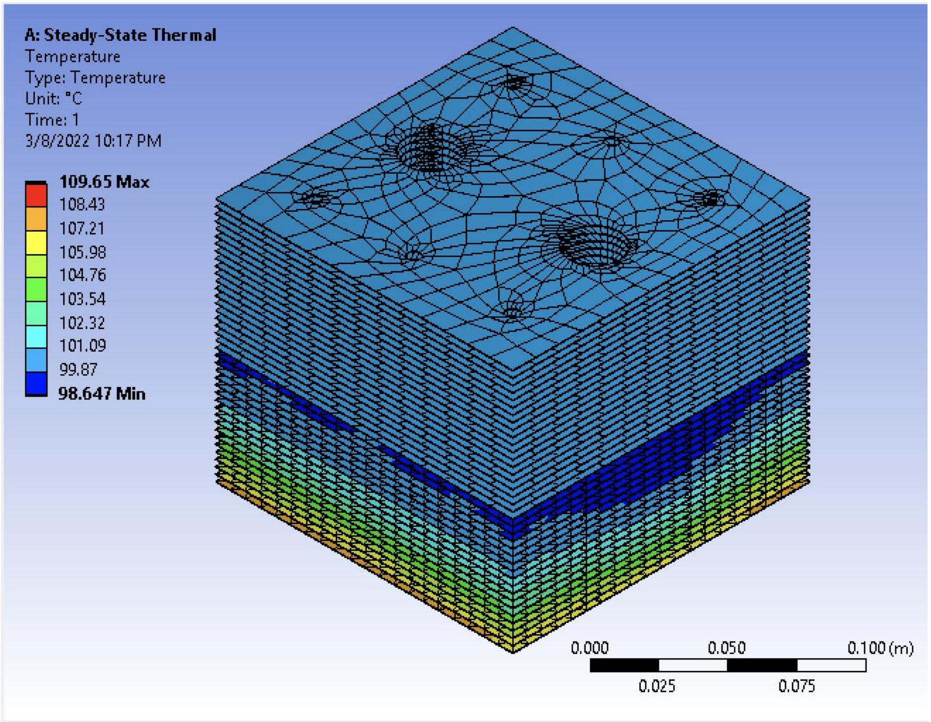


Figure 21. Fin array temperature gradient.

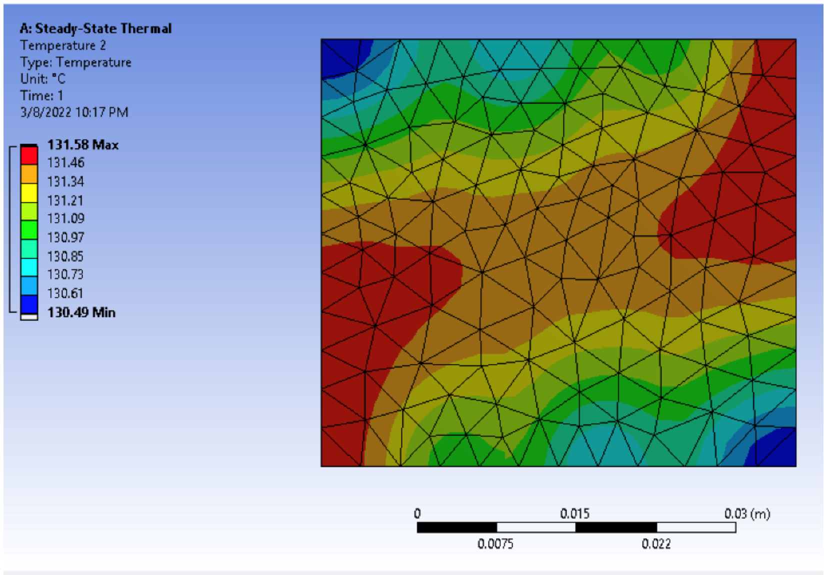


Figure 22. Copper base temperature gradient.

Average Base Temperature: 131.2 [C]

1307 W/m-K | “Configuration 2c”

Table 8. Iterative trials to obtain temperature convergence for a 6x6 inch fin with spacing of 0.003302 m and convection coefficient of 1307 W/m-K.

S = 0.003302 [m]			39 Fins	Config 2c
Trial #	T_s, [C]	Delta T %	h, [W/m2-K]	Delta h %
	57.97	n/a	0.7384	n/a
1	60.043	3.58%	0.7713	4.46%
	Base Temp	86.79	C	

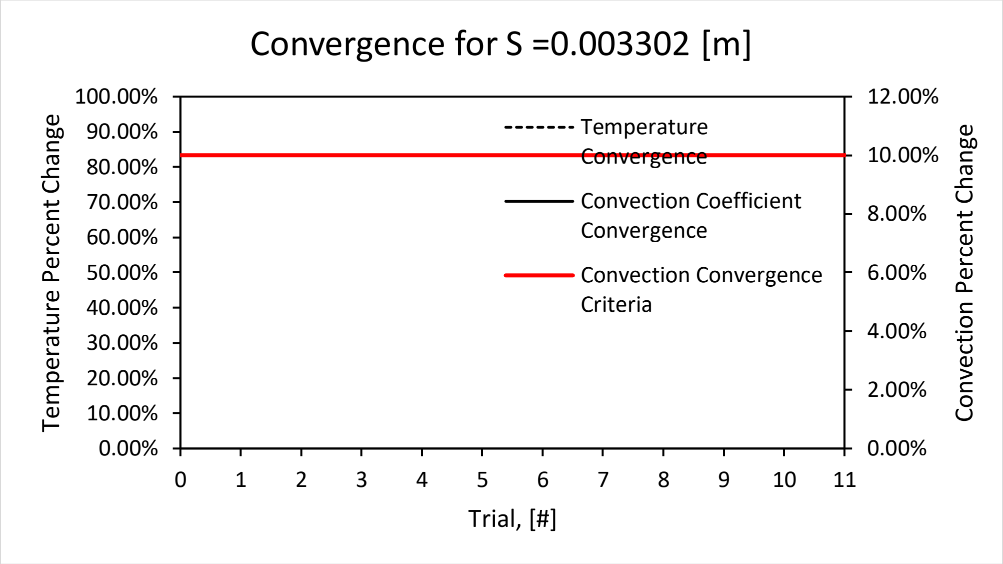


Figure 23. Convergence plot for S= 0.003302 m and a 6x6 inch heat fin with a convection coefficient of 1307 W/m-K.

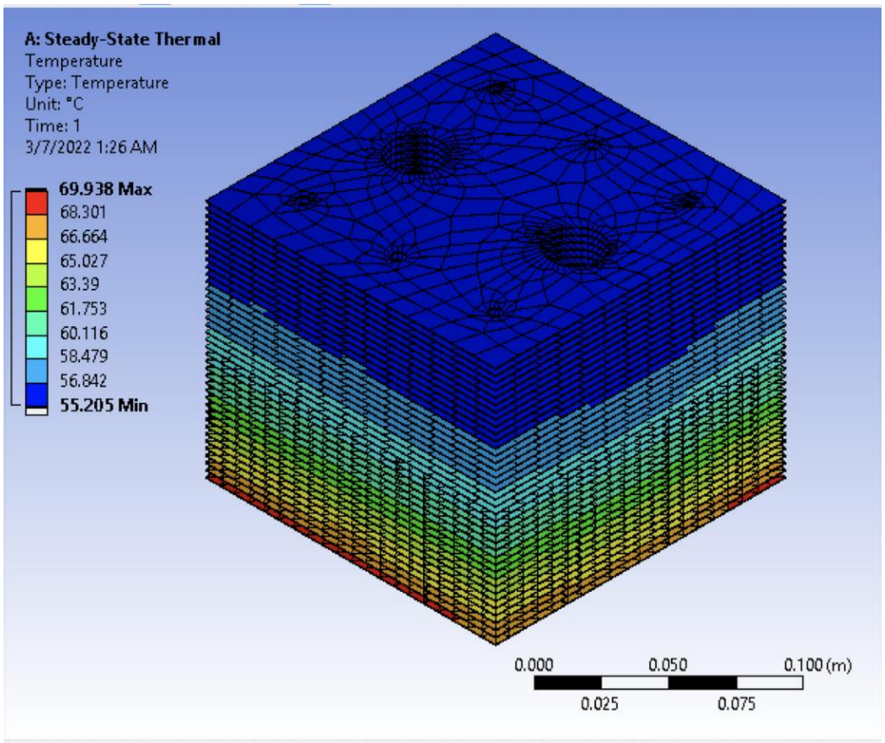


Figure 24. Fin array temperature gradient.

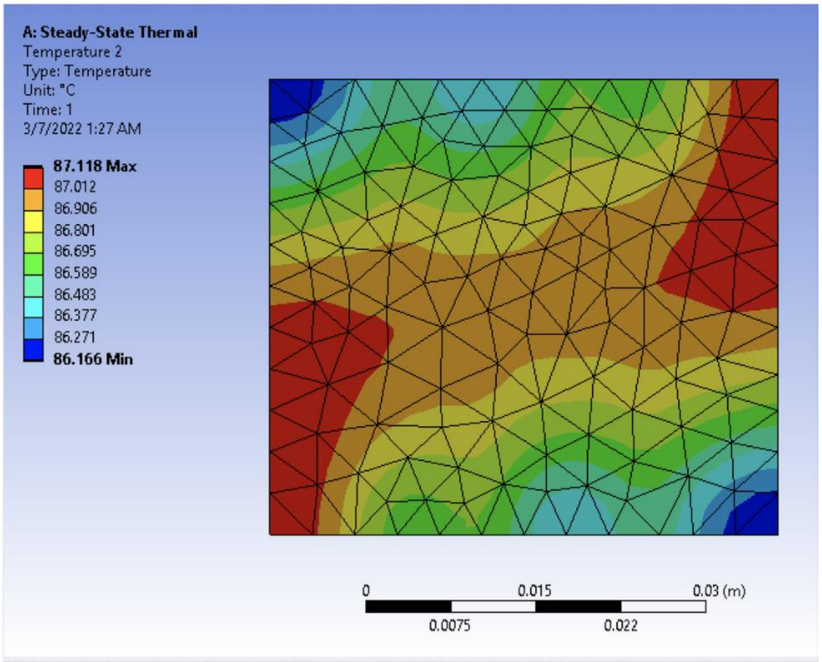


Figure 25. Copper base temperature gradient.

Average Base Temperature: 86.79 [C]

6x8in Heat Fins

1000 W/m-K | “Configuration 2b”

Table 9. Iterative trials to obtain temperature convergence for a 6x8 inch fin with spacing of 0.003302 m and convection coefficient of 1000 W/m-K.

S = 0.003302 [m]			39 Fins	Config 2b
Trial #	T_s, [C]	Delta T %	h, [W/m2-K]	Delta h %
	100	n/a	0.943	n/a
1	44.232	55.77%	0.3718	60.57%
2	78.439	77.34%	0.7708	107.32%
3	49.172	37.31%	0.441	42.79%
4	69.579	41.50%	0.684	55.10%
5	52.664	24.31%	0.4873	28.76%
6	65.055	23.53%	0.6356	30.43%
7	55.002	15.45%	0.5171	18.64%
8	62.572	13.76%	0.6078	17.54%
9	56.513	9.68%	0.5359	11.83%
10	61.148	8.20%	0.5914	10.36%
11	57.471	6.01%	0.5477	7.39%

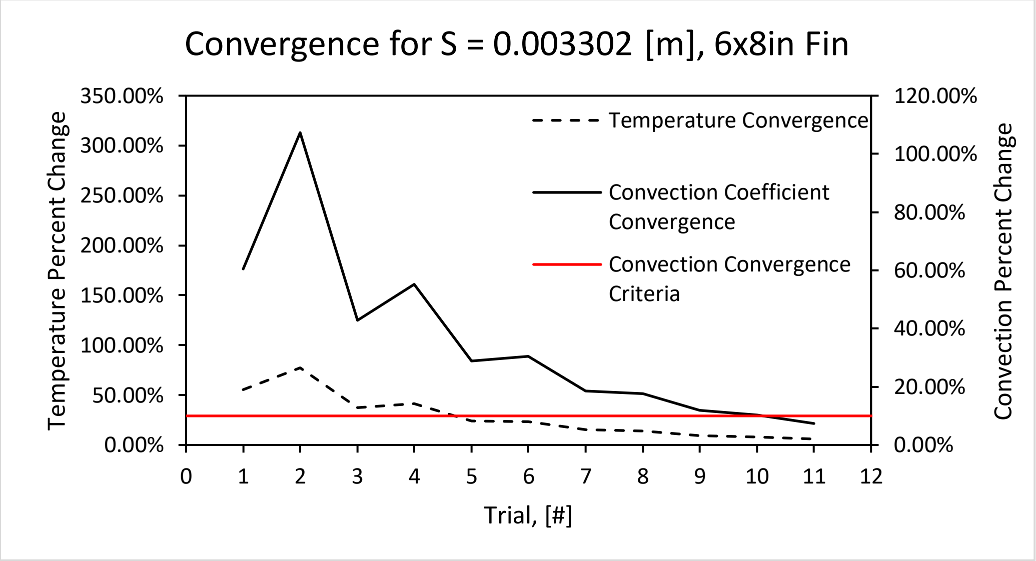


Figure 26. Convergence plot for S= 0.003302 m and a 6x8 inch heat fin with a convection coefficient of 1000 W/m-K.

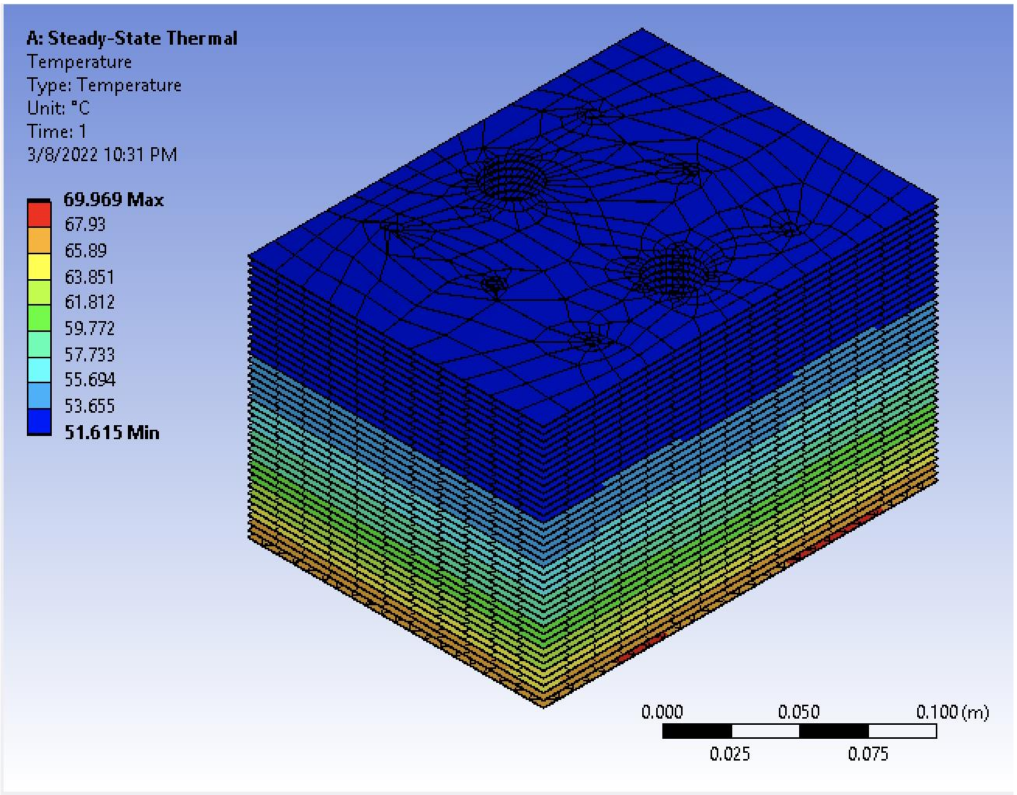


Figure 27. Fin array temperature gradient.

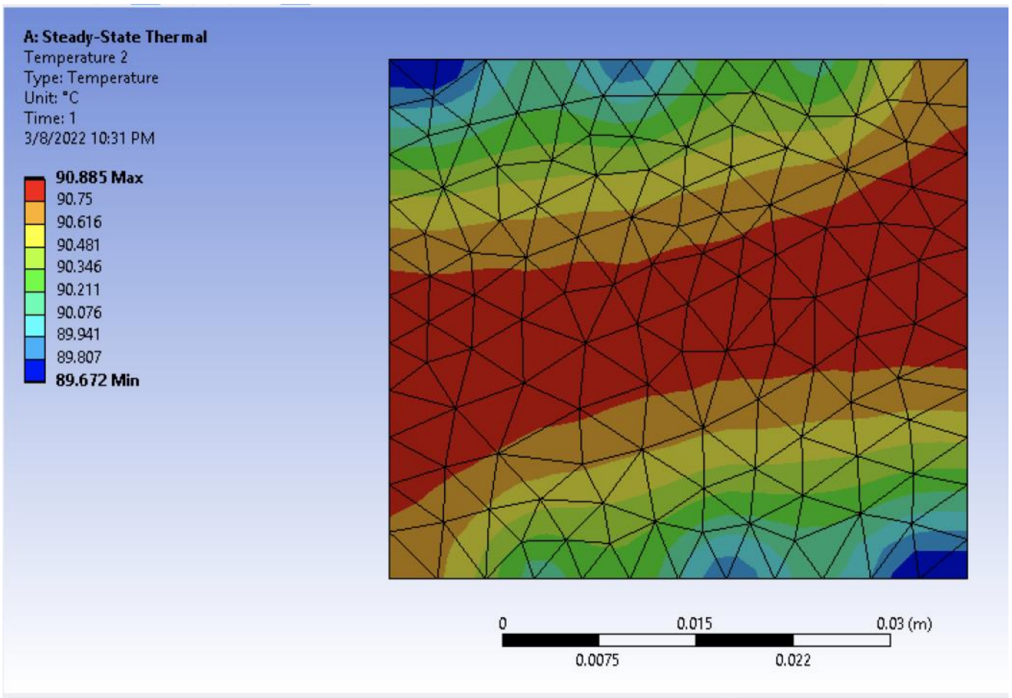


Figure 28. Copper base temperature gradient.

Average Base Temperature: 90.53 [C]

1307 W/m-K | "Configuration 2d"

Table 10. Iterative trials to obtain temperature convergence for a 6x8 inch fin with spacing of 0.003302 m and convection coefficient of 1307 W/m-K.

S = 0.003302 [m]			39 Fins	Config 2d
Trial #	T_s, [C]	Delta T %	h, [W/m2-K]	Delta h %
	57.47	n/a	0.5477	n/a
1	60.33	4.98%	0.5818	6.23%
2	58.083	3.72%	0.5551	4.59%

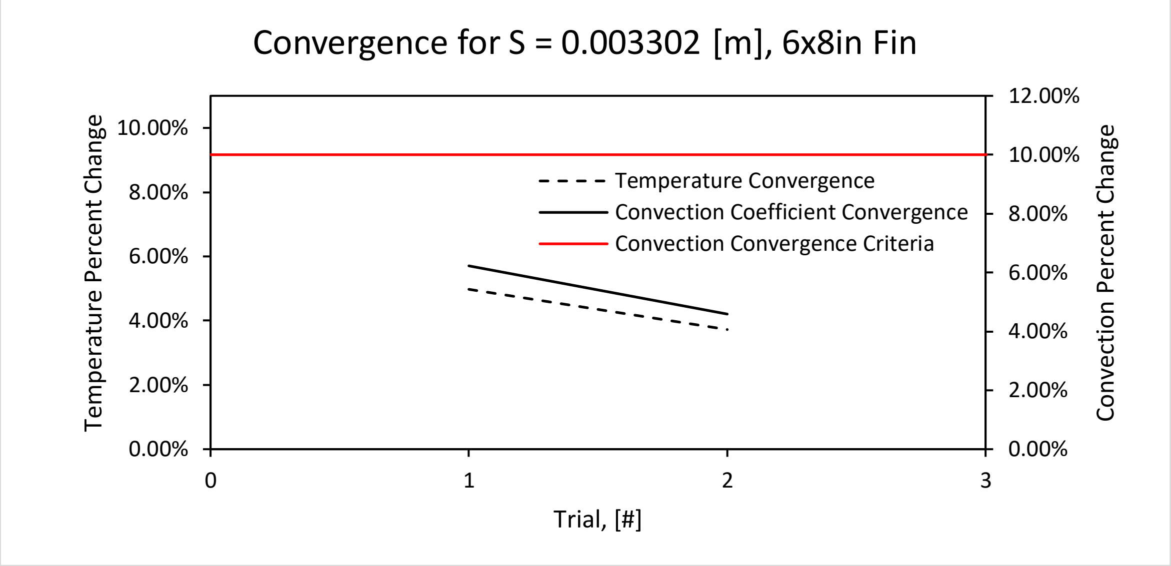


Figure 29. Convergence plot for S= 0.003302 m and a 6x8 inch heat fin with a convection coefficient of 1307 W/m-K.

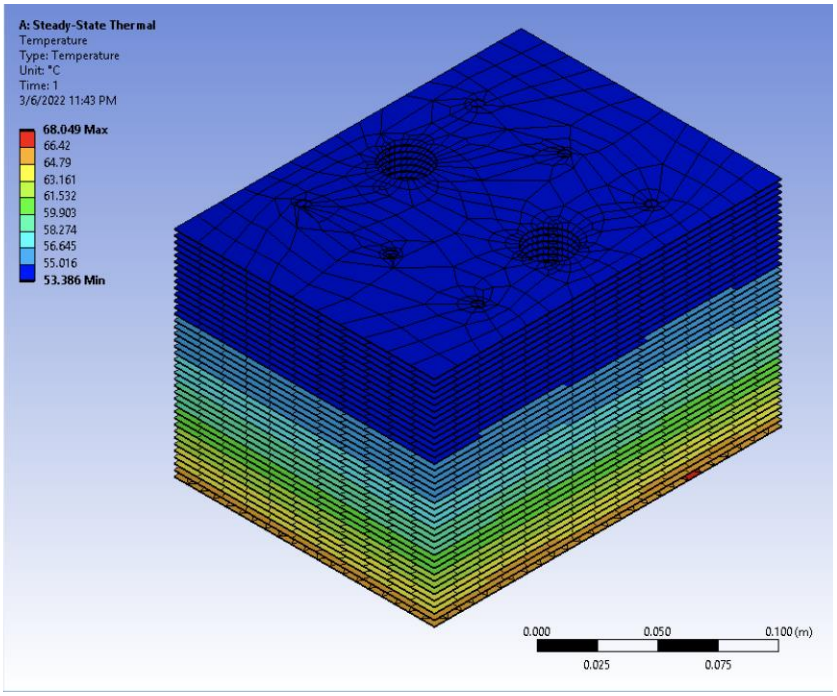


Figure 30. Fin array temperature gradient.

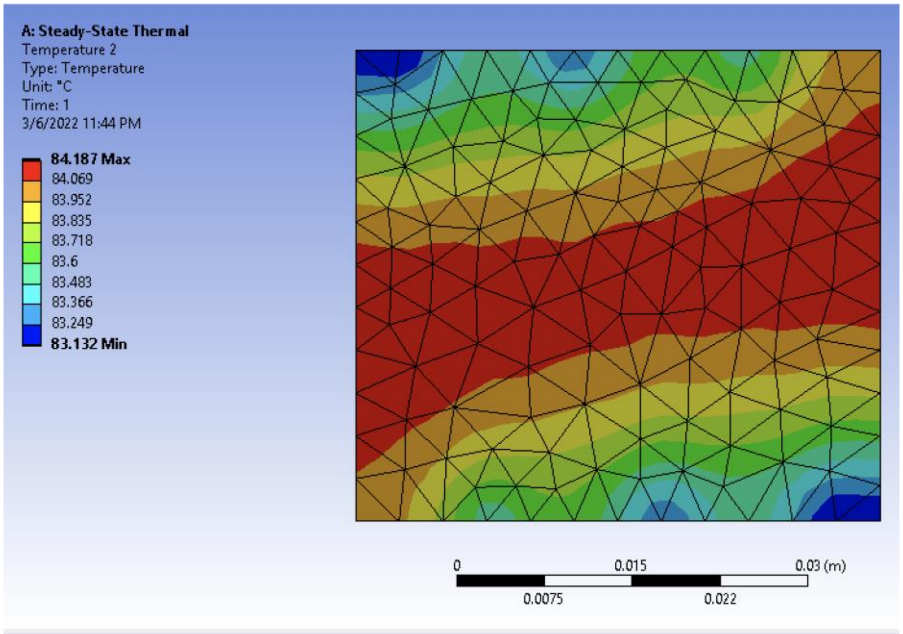


Figure 31. Copper base temperature gradient.

Average Base Temperature = 83.87 [C]

24 Fins | S = 0.21in = 0.00533m

6x6in Heat Fins

1000 W/m-K | “Configuration 3a”

Table 11. Iterative trials to obtain temperature convergence for a 6x6 inch fin with spacing of 0.00533 m and convection coefficient of 1000 W/m-K.

S = 0.005334 [m]			24 Fins	Config 3
Trial #	T_s, [C]	Delta T %	h, [W/m2-K]	Delta h %
	100	n/a	4.34	n/a
1	32	68.00%	1.013	76.66%
2	66.19	106.84%	3.274	223.20%
3	35.385	46.54%	1.323	59.59%
4	55.734	57.51%	2.765	108.99%
5	37.922	31.96%	1.543	44.20%
6	50.863	34.13%	2.482	60.86%
7	39.784	21.78%	1.697	31.63%
8	48.205	21.17%	2.313	36.30%
9	41.114	14.71%	1.803	22.05%
10	46.639	13.44%	2.208	22.46%
11	42.043	9.85%	1.875	15.08%
12	45.677	8.64%	2.141	14.19%
13	42.683	6.55%	1.923	10.18%
14	45.075	5.60%	2.098	9.10%

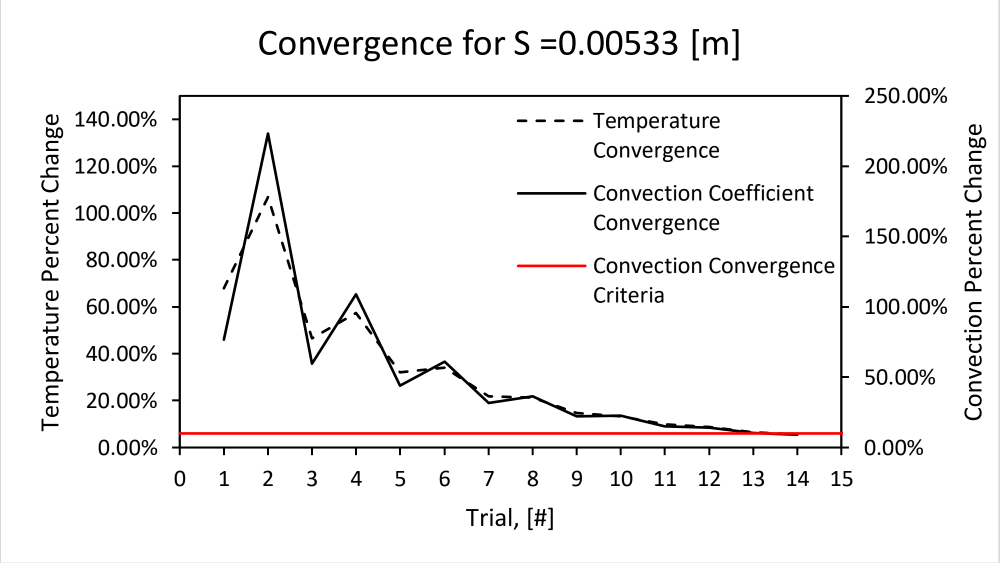


Figure 32. Convergence plot for S= 0.00533 m and a 6x6 inch heat fin with a convection coefficient of 1000 W/m-K.

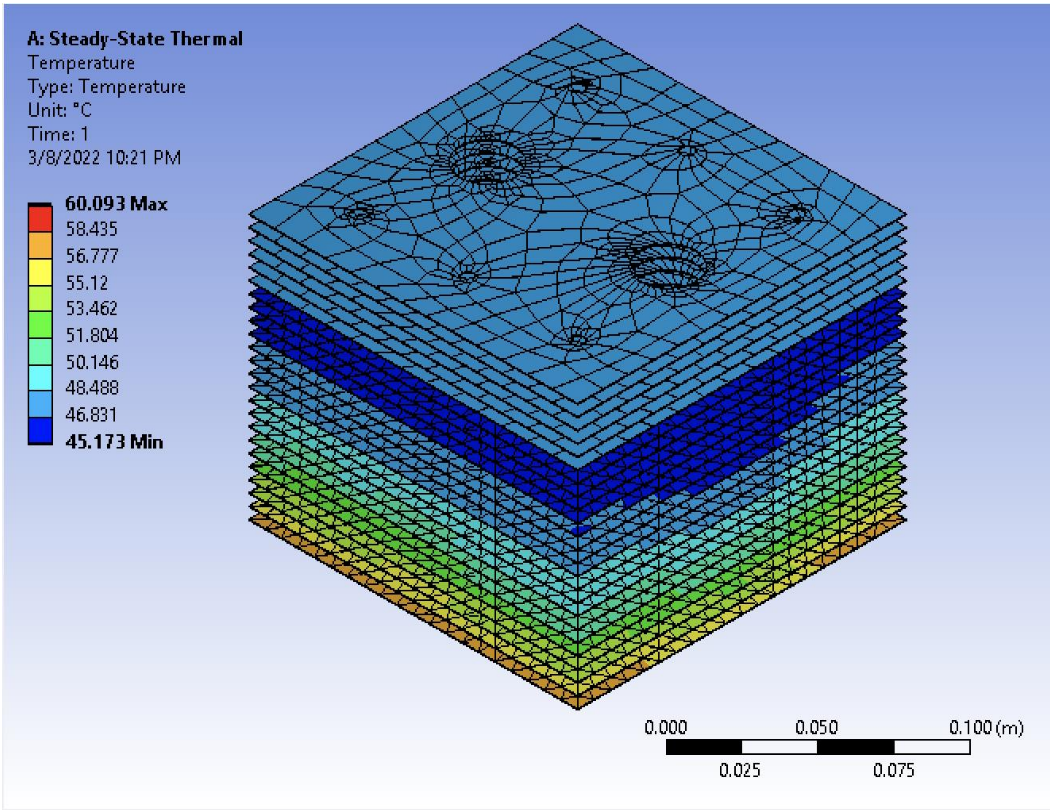


Figure 33. Fin array temperature gradient.

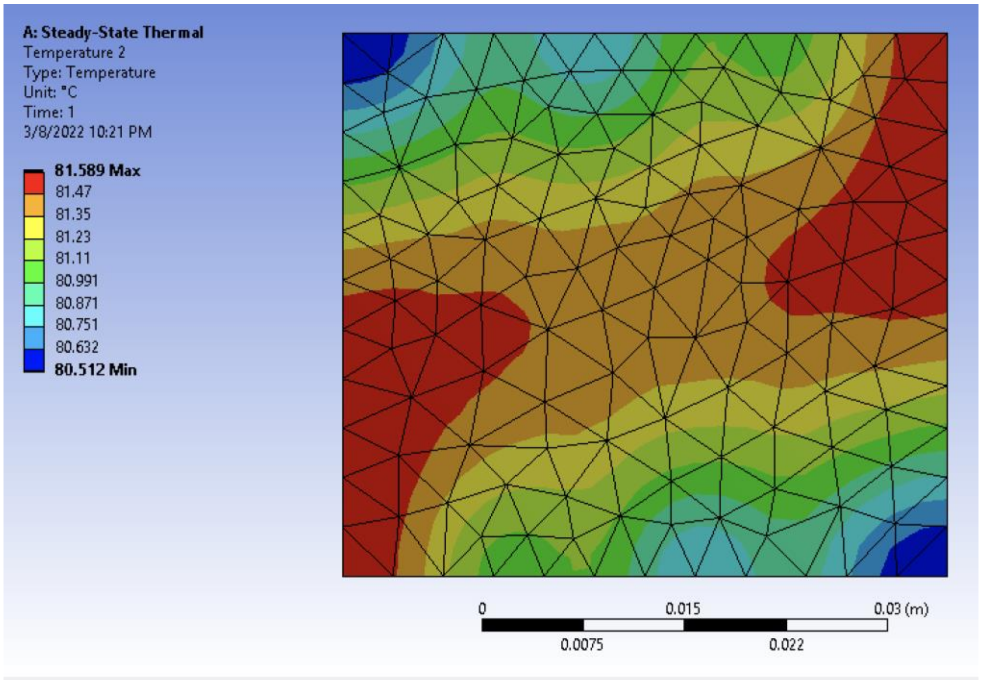


Figure 34. Copper base temperature gradient.

Average Base Temperature: 81.24 [C]

1307 W/m-K | “Configuration 3c”

Table 12. Iterative trials to obtain temperature convergence for a 6x6 inch fin with spacing of 0.00533 m and convection coefficient of 1307 W/m-K.

S = 0.005334 [m]			24 Fins	Config 3c
Trial #	T_s, [C]	Delta T %	h, [W/m2-K]	Delta h %
	45.08	n/a	2.098	n/a
1	43.221	4.12%	1.964	6.39%
2	44.689	3.40%	2.071	5.45%
	Base Temp	71.04	C	

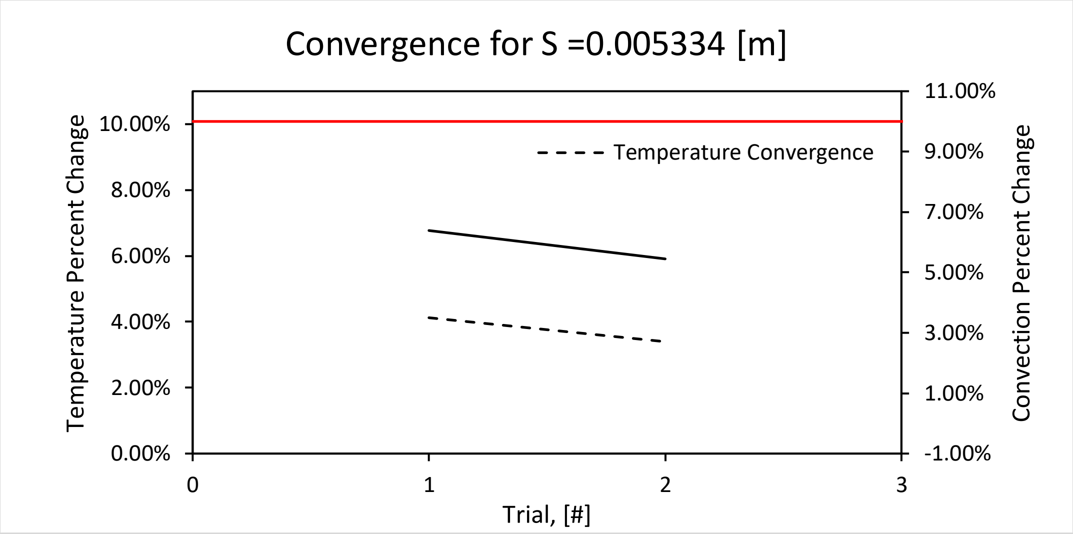


Figure 35. Convergence plot for S= 0.00533 m and a 6x6 inch heat fin with a convection coefficient of 1307 W/m-K.

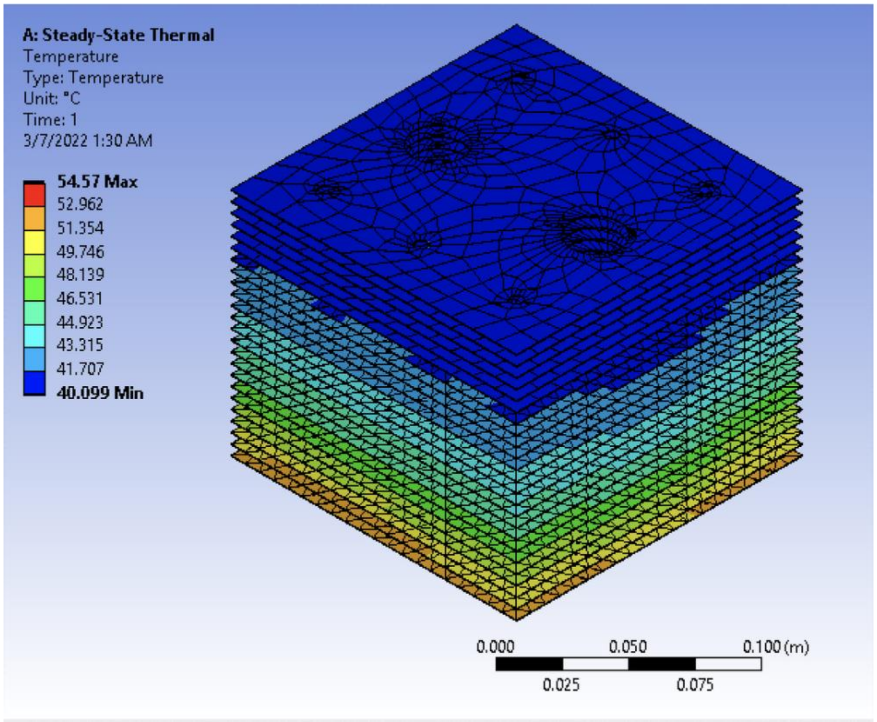


Figure 36. Fin array temperature gradient.

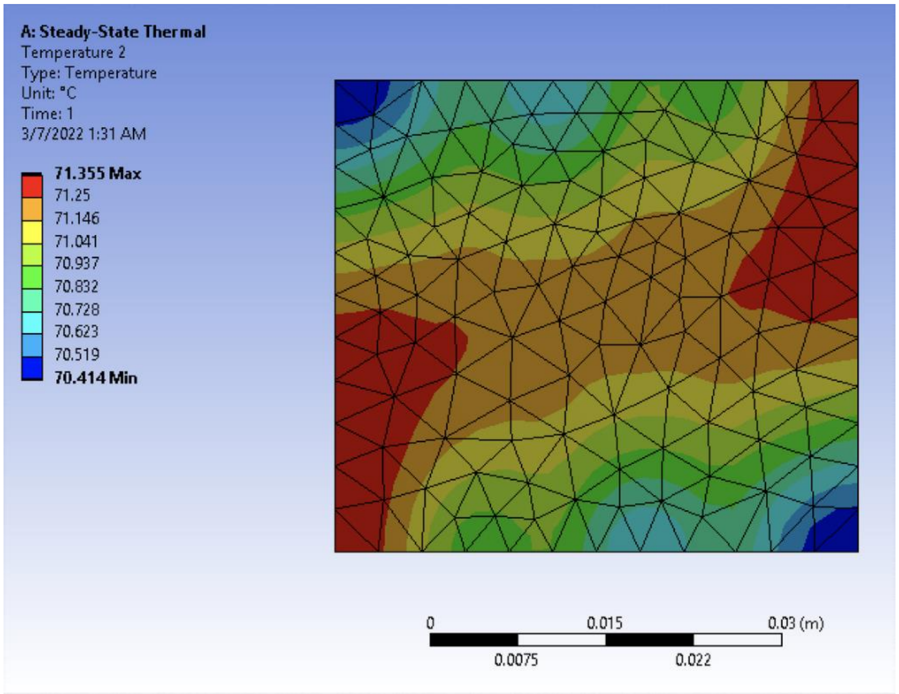


Figure 37. Copper base temperature gradient.

Average Base Temperature: 71.04 [C]

6x8in Heat Fins

1000 W/m-K | “Configuration 3b”

Table 13. Iterative trials to obtain temperature convergence for a 6x8 inch fin with spacing of 0.00533 m and convection coefficient of 1000 W/m-K.

S = 0.005334 [m]			24 Fins	Config 3b
Trial #	T_s, [C]	Delta T %	h, [W/m2-K]	Delta h %
	100	n/a	3.537	n/a
1	31.457	68.54%	0.7212	79.61%
2	68.765	118.60%	2.686	272.43%
3	34.49	49.84%	2.098	21.89%
4	38.02	10.23%	1.171	44.18%
5	50.774	33.55%	1.913	63.36%
6	39.579	22.05%	1.271	33.56%
7	48.503	22.55%	1.794	41.15%
8	40.751	15.98%	1.345	25.03%
9	47.041	15.44%	1.714	27.43%
10	41.631	11.50%	1.399	18.38%
11	46.071	10.67%	1.66	18.66%
12	42.272	8.25%	1.438	13.37%
13	45.416	7.44%	1.623	12.87%
14	42.736	5.90%	1.466	9.67%
15	44.967	5.22%	1.597	8.94%
16	43.076	4.21%	1.487	6.89%

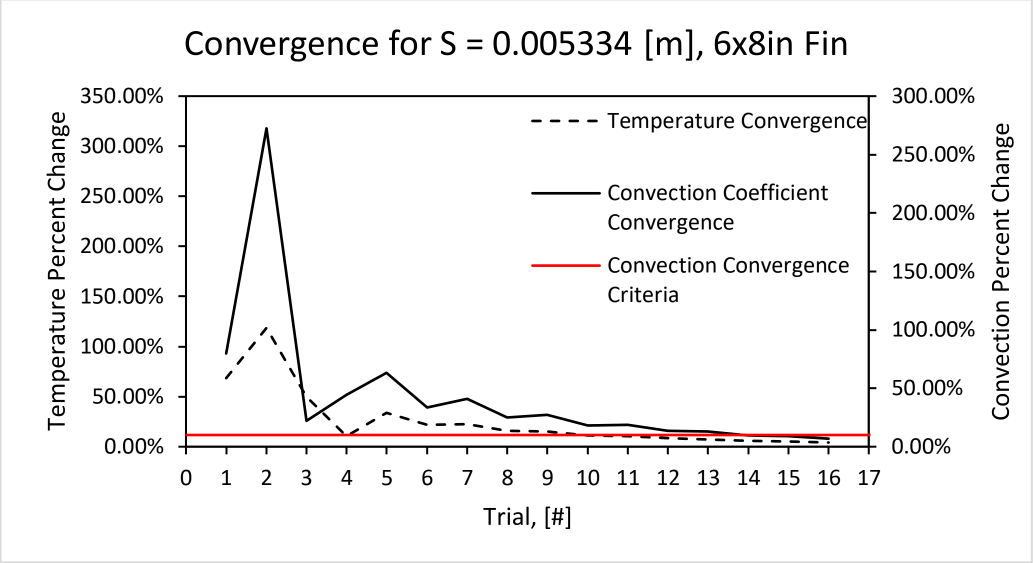


Figure 38. Convergence plot for S= 0.00533 m and a 6x8 inch heat fin with a convection coefficient of 1000 W/m-K.

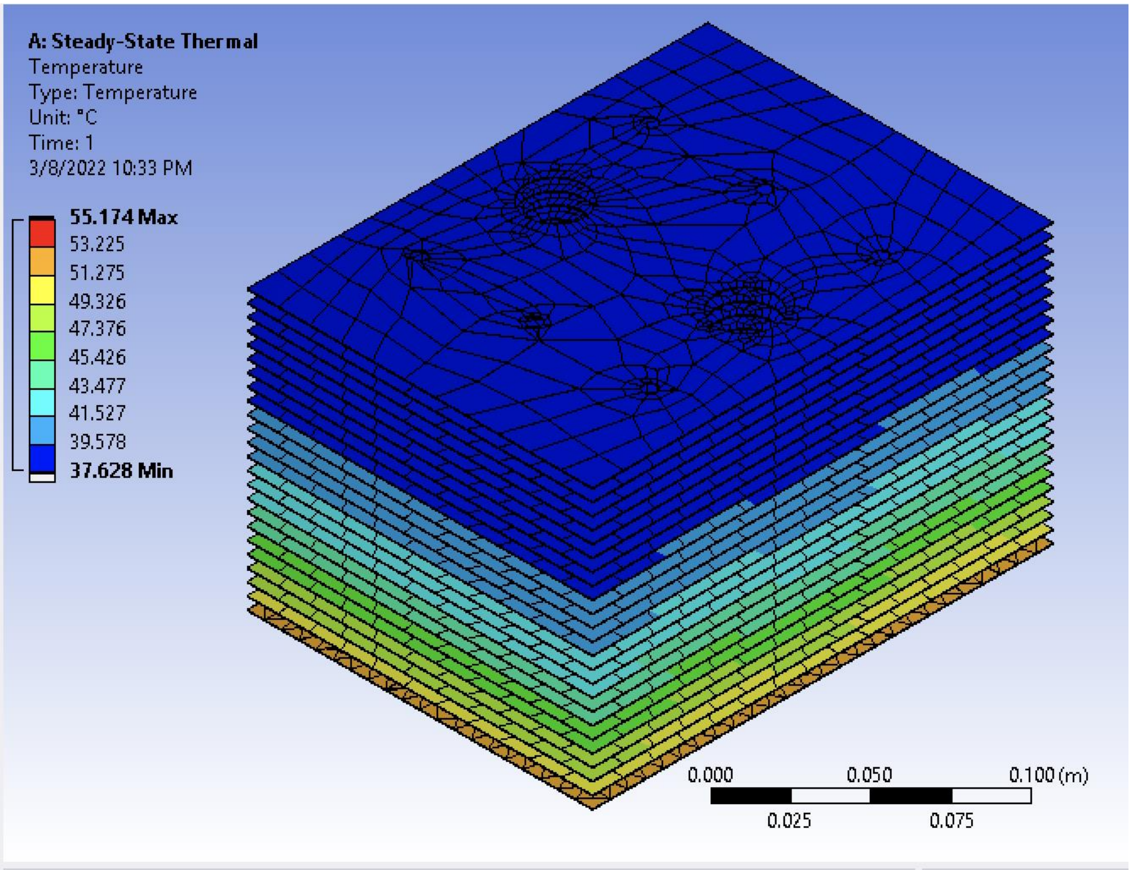


Figure 39. Fin array temperature gradient.

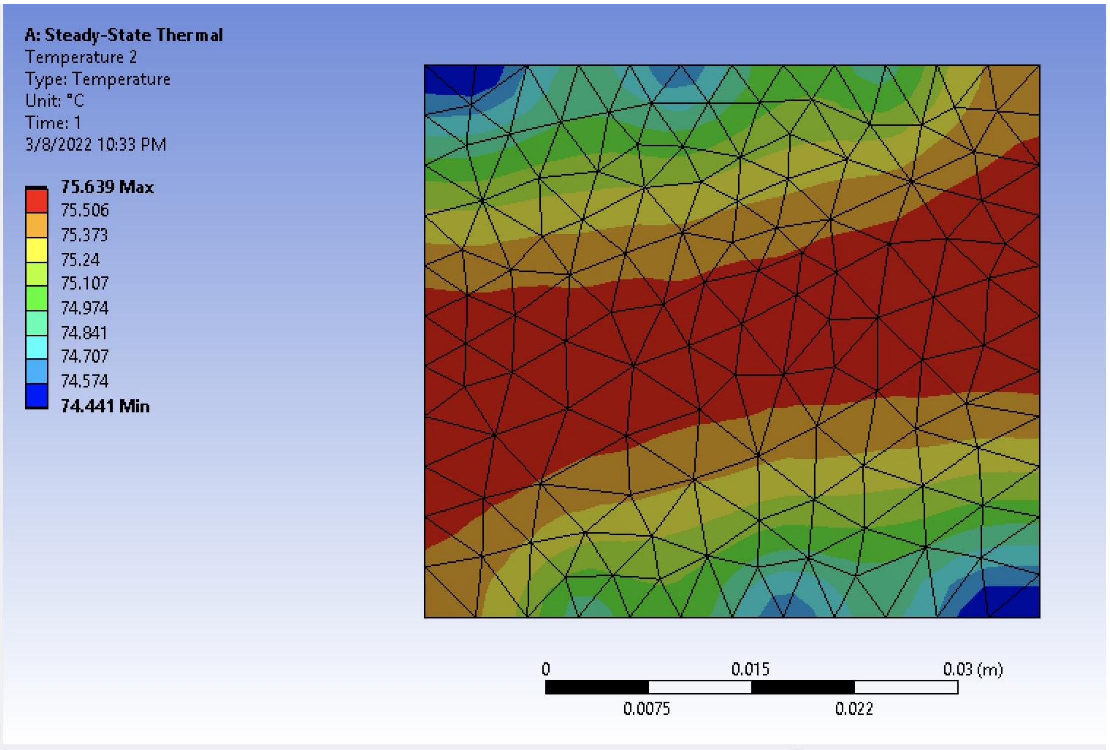


Figure 40. Copper base temperature gradient.

Average Base Temperature: 75.29 [C]

1307 W/m-K | “Configuration 3d”

Table 14. Iterative trials to obtain temperature convergence for a 6x8 inch fin with spacing of 0.00533 m and convection coefficient of 1307 W/m-K.

S = 0.005334 [m]			24 Fins	Config 3d
Trial #	T_s, [C]	Delta T %	h, [W/m2-K]	Delta h %
	43.08	n/a	1.487	n/a
1	44.686	3.73%	1.581	6.32%
2	43.335	3.02%	1.502	5.00%

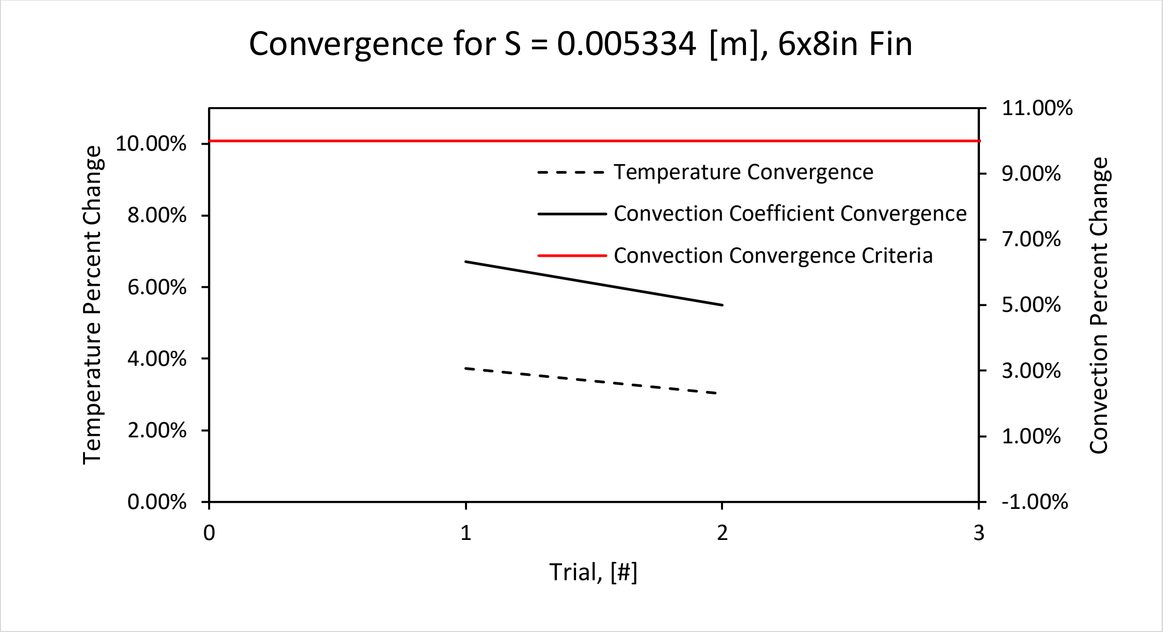


Figure 41. Convergence plot for S= 0.00533 m and a 6x8 inch heat fin with a convection coefficient of 1307 W/m-K.

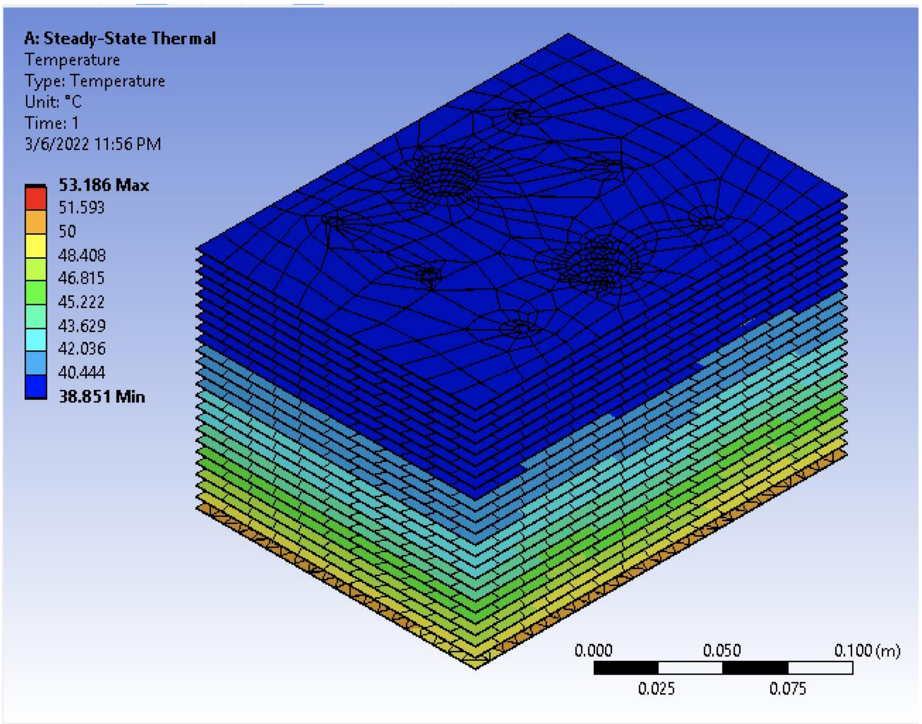


Figure 42. Fin array temperature gradient.

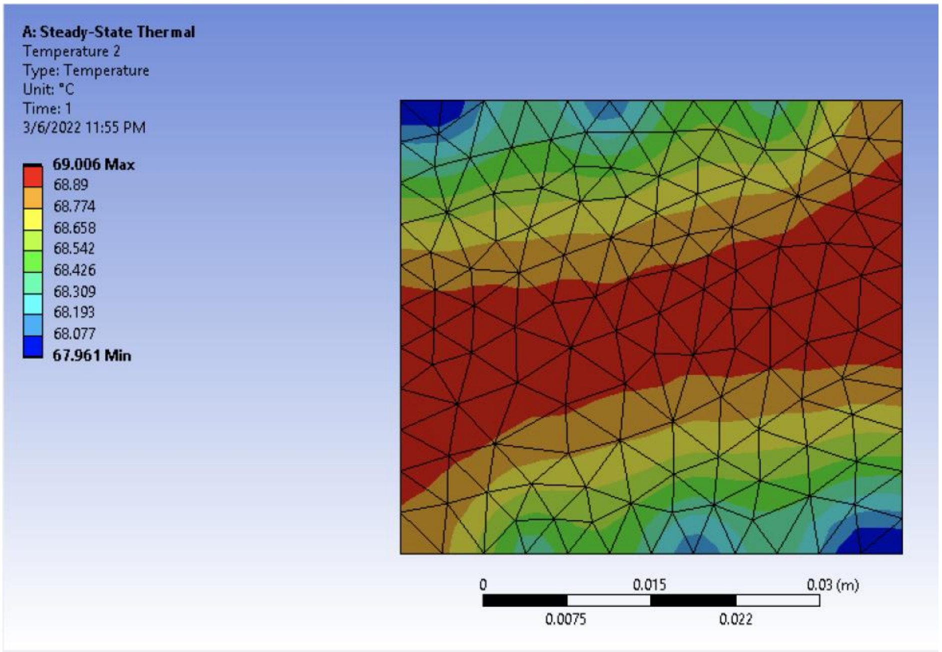


Figure 43. Copper base temperature gradient.

Average Base Temperature = 68.69 [C]

18 Fins | S = 0.29in = 0.00737m

6x6in Heat Fins

1000 W/m-K | “Configuration 4a”

Table 15. Iterative trials to obtain temperature convergence for a 6x6 inch fin with spacing of 0.00737 m and convection coefficient of 1000 W/m-K.

S = 0.007366 [m]			18 Fins	Config 4
Trial #	T_s, [C]	Delta T %	h, [W/m2-K]	Delta h %
	100	n/a	6.067	n/a
1	31.27	68.73%	2.239	63.10%
2	48.036	53.62%	4.087	82.54%
3	36.014	25.03%	2.951	27.80%
4	41.618	15.56%	3.563	20.74%
5	38.154	8.32%	3.207	9.99%
6	40.008	4.86%	3.406	6.21%
	38.924			

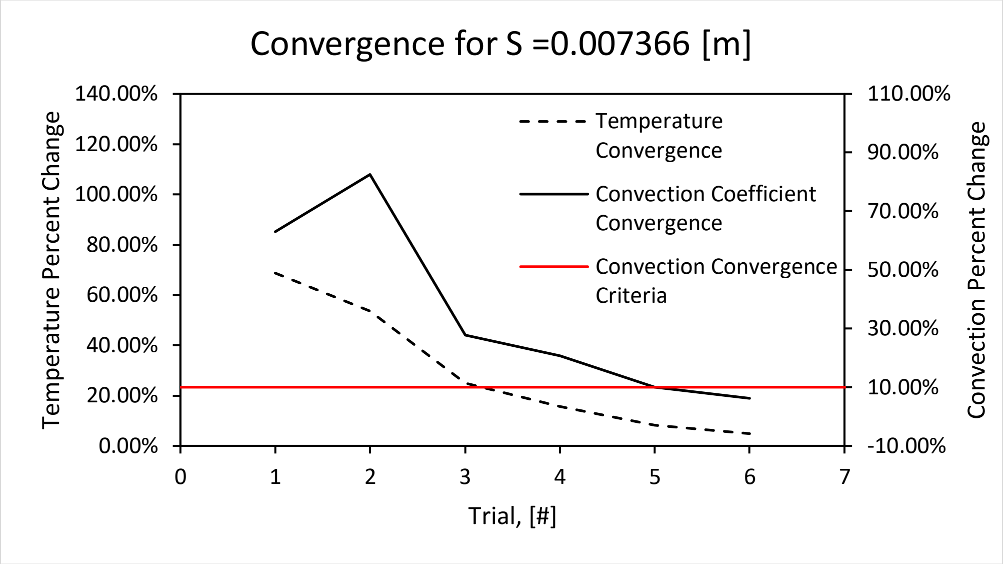


Figure 44. Convergence plot for S= 0.007366 m and a 6x6 inch heat fin with a convection coefficient of 1000 W/m-K.

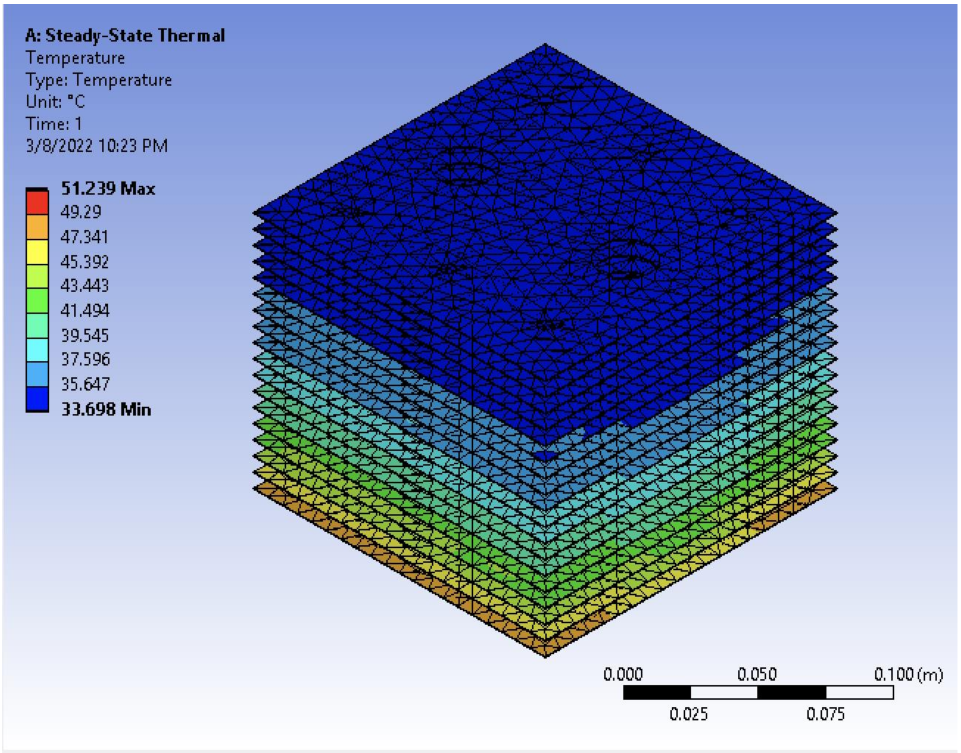


Figure 45. Fin array temperature gradient.

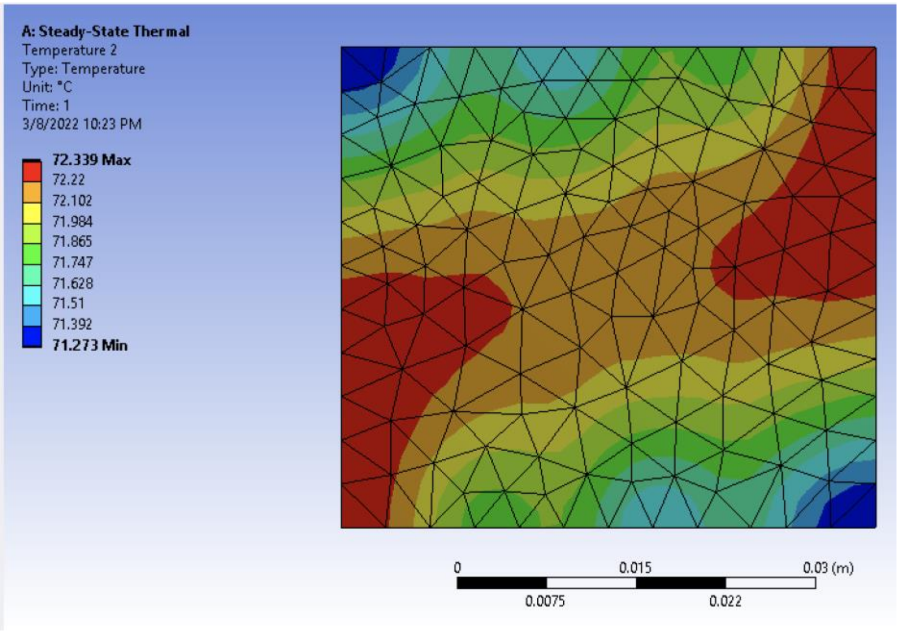


Figure 46. Copper base temperature gradient.

Average Base Temperature: 71.99 [C]

1307 W/m-K | "Configuration 4c"

Table 16. Iterative trials to obtain temperature convergence for a 6x6 inch fin with spacing of 0.00737 m and convection coefficient of 1307 W/m-K.

S = 0.007366 [m]			18 Fins	Config 4c
Trial #	T_s, [C]	Delta T %	h, [W/m2-K]	Delta h %
	40.01	n/a	3.406	n/a
1	38.973	2.59%	3.297	3.20%
2	39.55	1.48%	3.358	1.85%
	Base Temp	65.832	C	

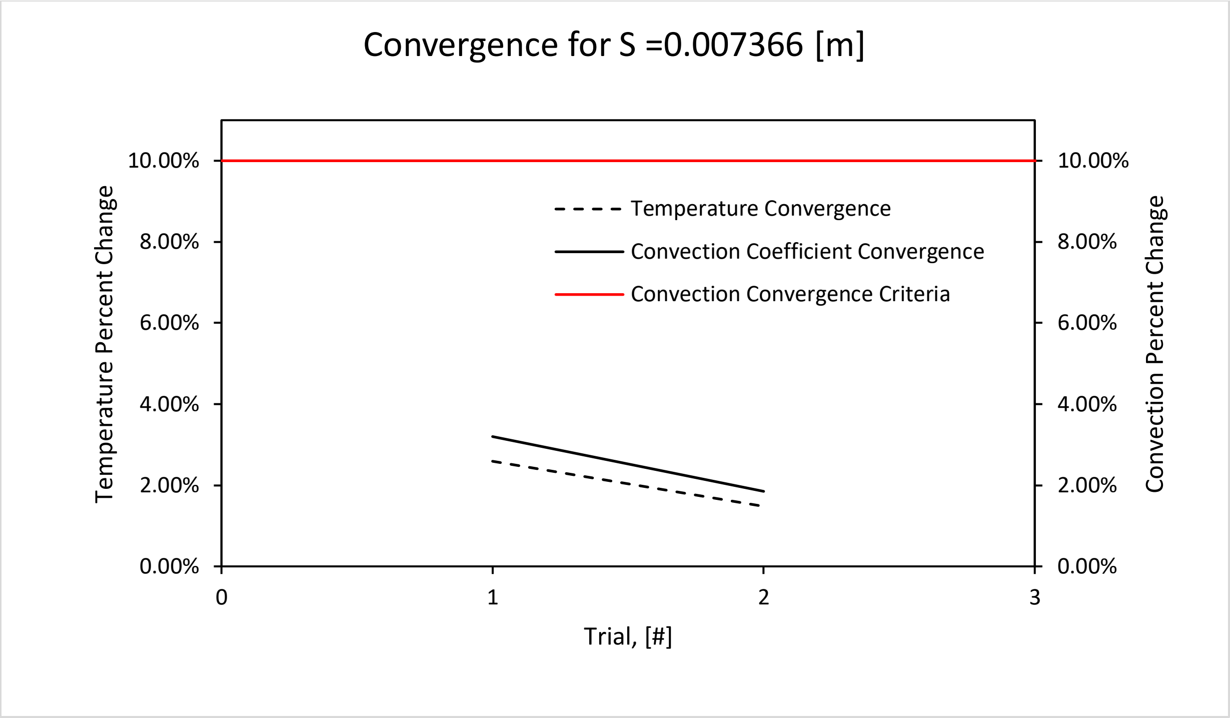


Figure 47. Convergence plot for S= 0.007366 m and a 6x6 inch heat fin with a convection coefficient of 1307 W/m-K.

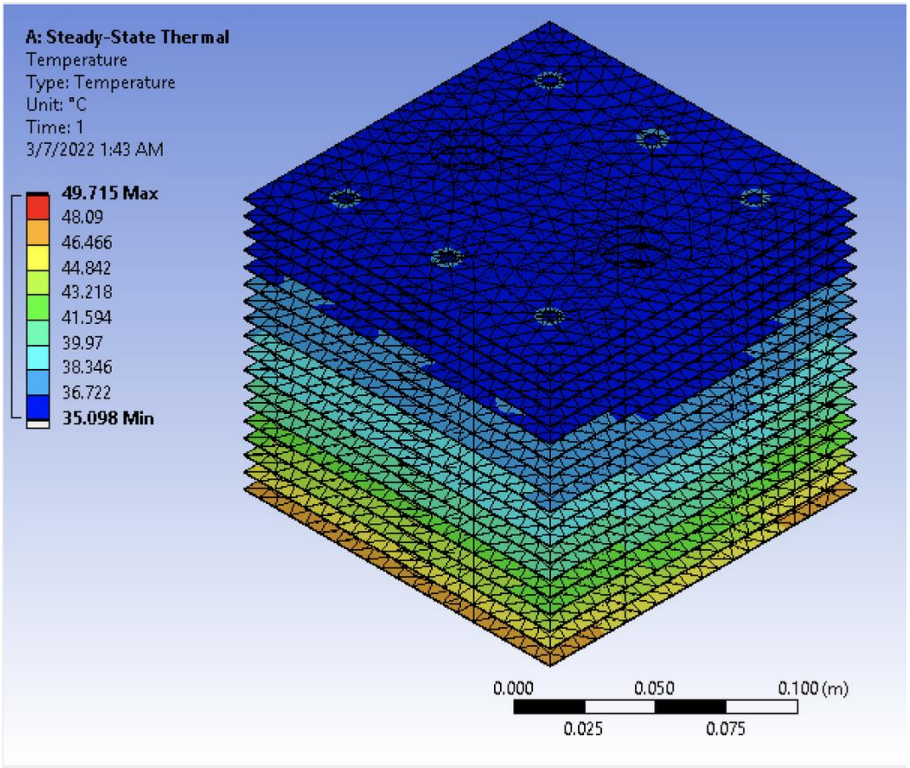


Figure 48. Fin array temperature gradient.

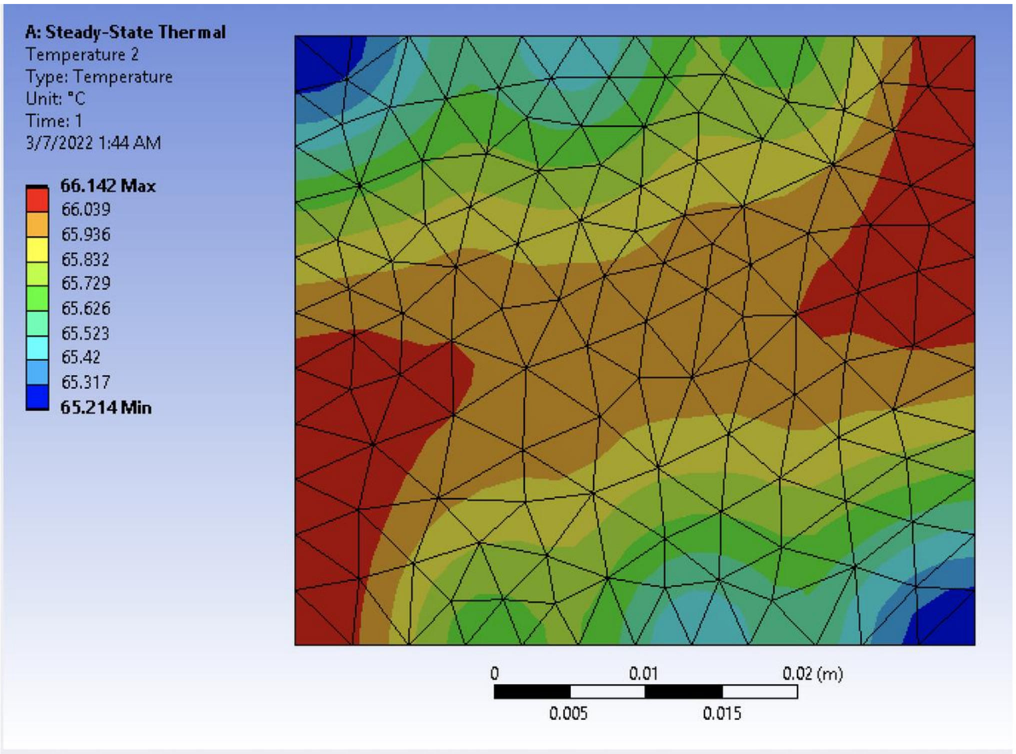


Figure 49. Copper base temperature gradient.

Average Base Temperature: 65.83 [C]

6x8in Heat Fins

1000 W/m-K | “Configuration 4b”

Table 17. Iterative trials to obtain temperature convergence for a 6x8 inch fin with spacing of 0.00737 m and convection coefficient of 1000 W/m-K.

S = 0.007366 [m]			18 Fins	Config 4b
Trial #	T_s, [C]	Delta T %	h, [W/m2-K]	Delta h %
	100	n/a	5.392	n/a
1	30.126	69.87%	1.589	70.53%
2	49.984	65.92%	3.616	127.56%
3	34.21	31.56%	2.189	39.46%
4	42.275	23.57%	3.044	39.06%
5	36.536	13.58%	2.473	18.76%
6	39.93	9.29%	2.83	14.44%
7	37.648	5.72%	2.597	8.23%

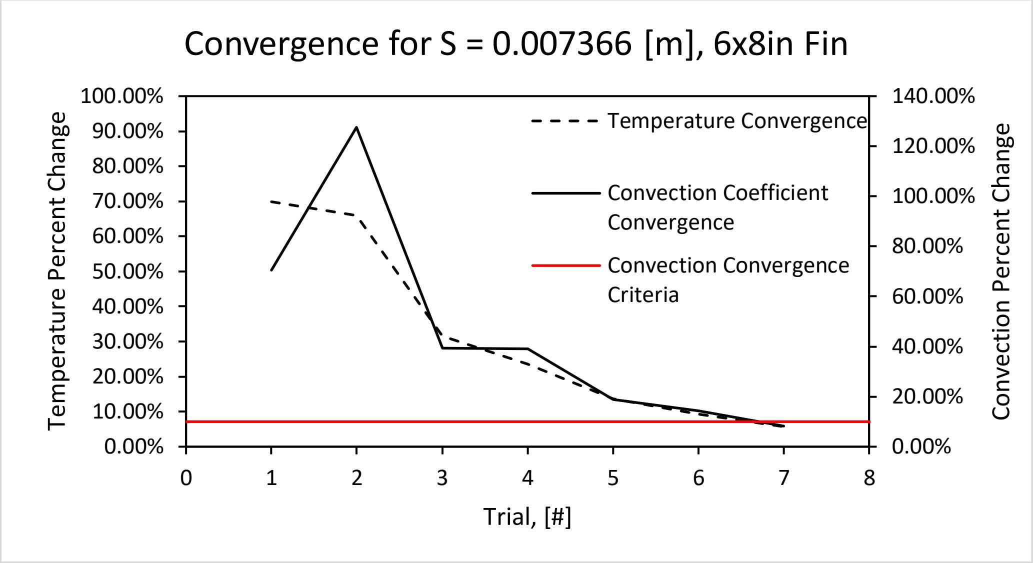


Figure 50. Convergence plot for S= 0.007366 m and a 6x8 inch heat fin with a convection coefficient of 1000 W/m-K.

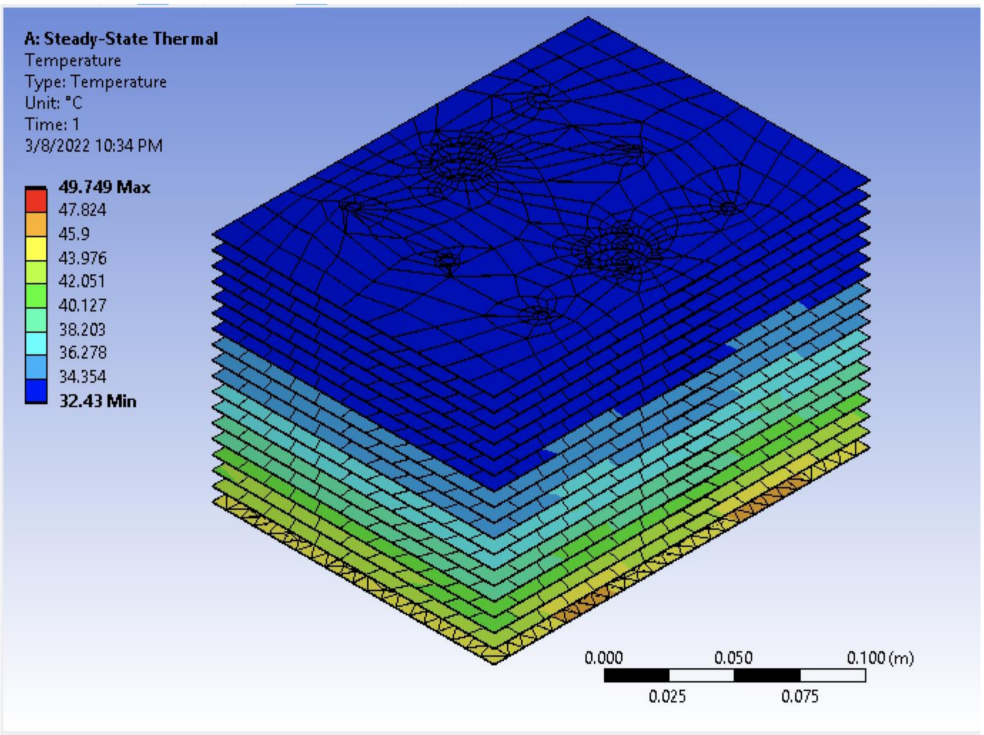


Figure 51. Fin array temperature gradient.

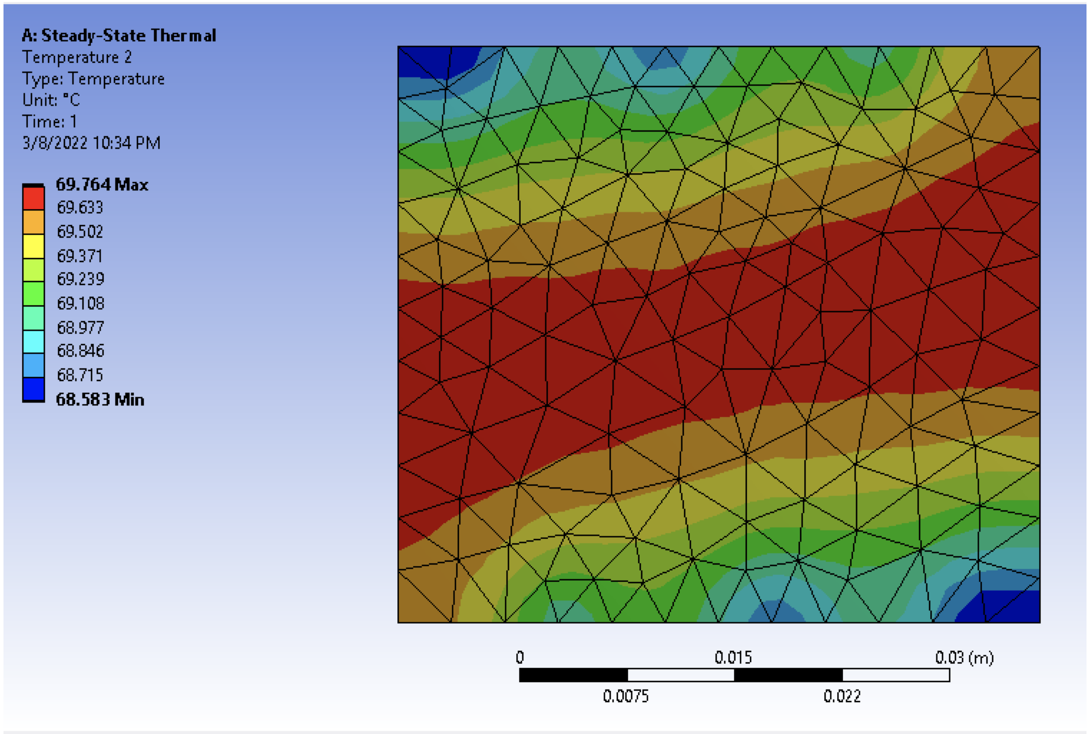


Figure 52. Copper base temperature gradient.

Average Base Temperature: 69.42 [C]

1307 W/m-K | “Configuration 4d”

Table 18. Iterative trials to obtain temperature convergence for a 6x8 inch fin with spacing of 0.00737 m and convection coefficient of 1307 W/m-K.

S = 0.007366 [m]			18 Fins	Config 4d
Trial #	T_s, [C]	Delta T %	h, [W/m2-K]	Delta h %
	37.65	n/a	2.597	n/a
1	39.128	3.93%	2.751	5.93%
2	38.16	2.47%	2.652	3.60%

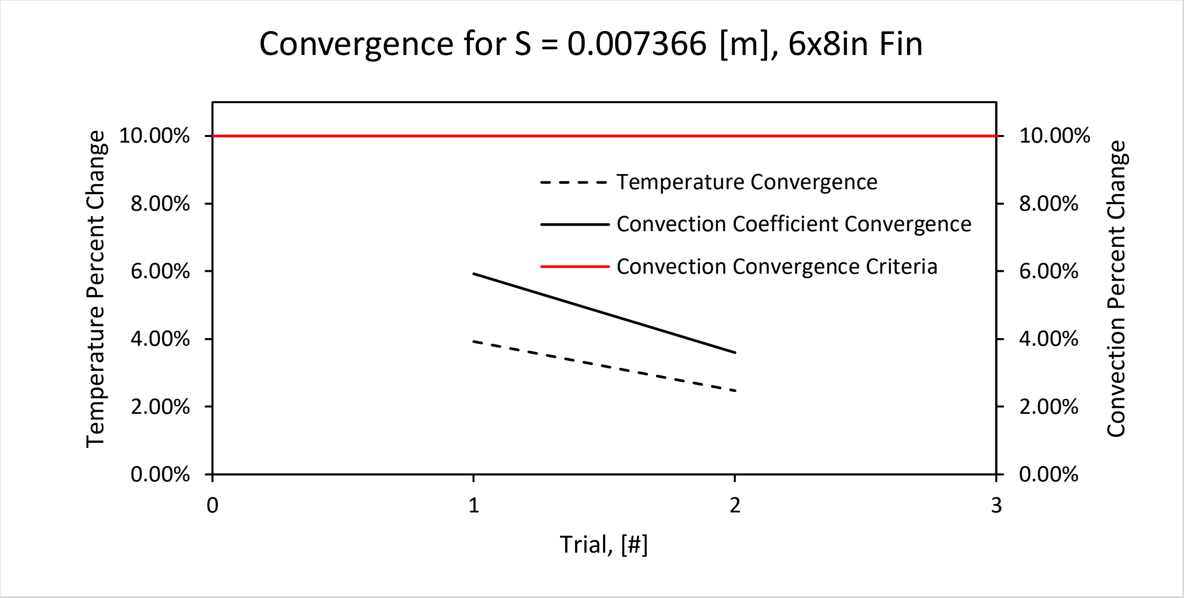


Figure 53. Convergence plot for S= 0.007366 m and a 6x8 inch heat fin with a convection coefficient of 1307 W/m-K.

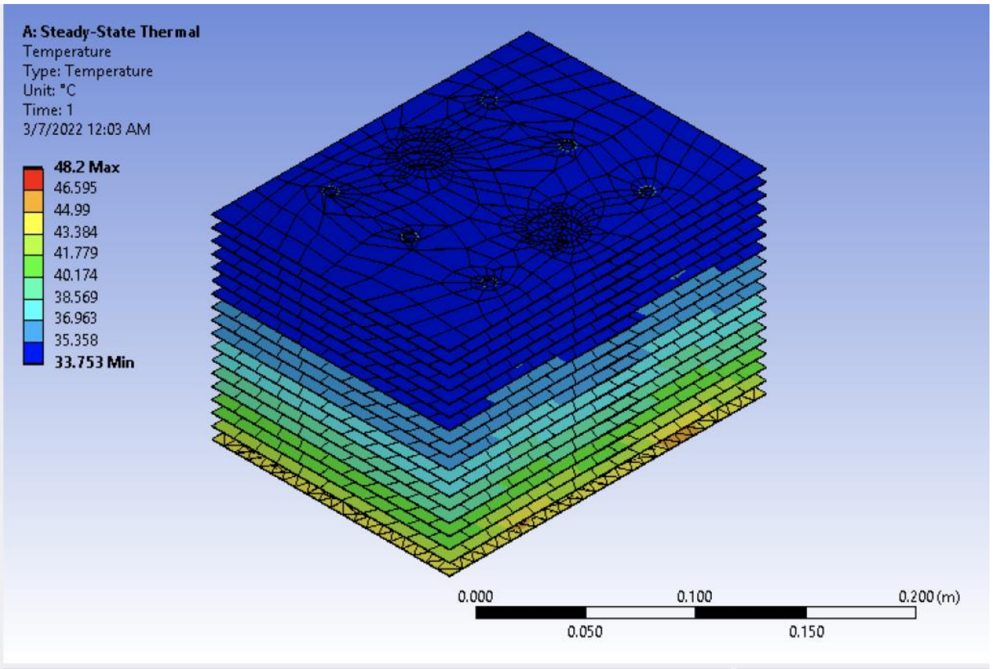
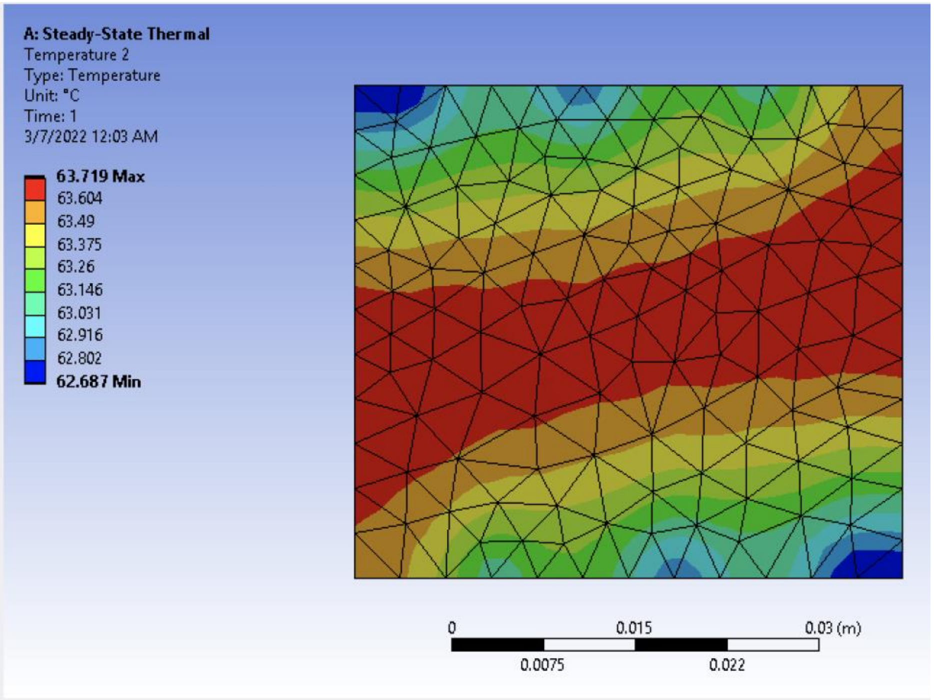


Figure 54. Fin array temperature gradient.



A: Steady-State Thermal
Temperature 2
Type: Temperature
Unit: °C
Time: 1
3/7/2022 12:03 AM

Figure 55. Copper base temperature gradient.

Average Base Temperature = 63.41 [C]

16 Fins | S = 0.33in = 0.00837m

6x6in Heat Fins

1000 W/m-K | "Configuration 5a"

Table 19. Iterative trials to obtain temperature convergence for a 6x6 inch fin with spacing of 0.00837 m and convection coefficient of 1000 W/m-K.

S = 0.008367 [m]			16 Fins	Config 5
Trial #	T_s, [C]	Delta T %	h, [W/m2-K]	Delta h %
	100	n/a	6.42	n/a
1	31.706	68.29%	2.884	55.08%
2	44.381	39.98%	4.303	49.20%
3	36.785	17.12%	3.593	16.50%
4	39.834	8.29%	3.914	8.93%

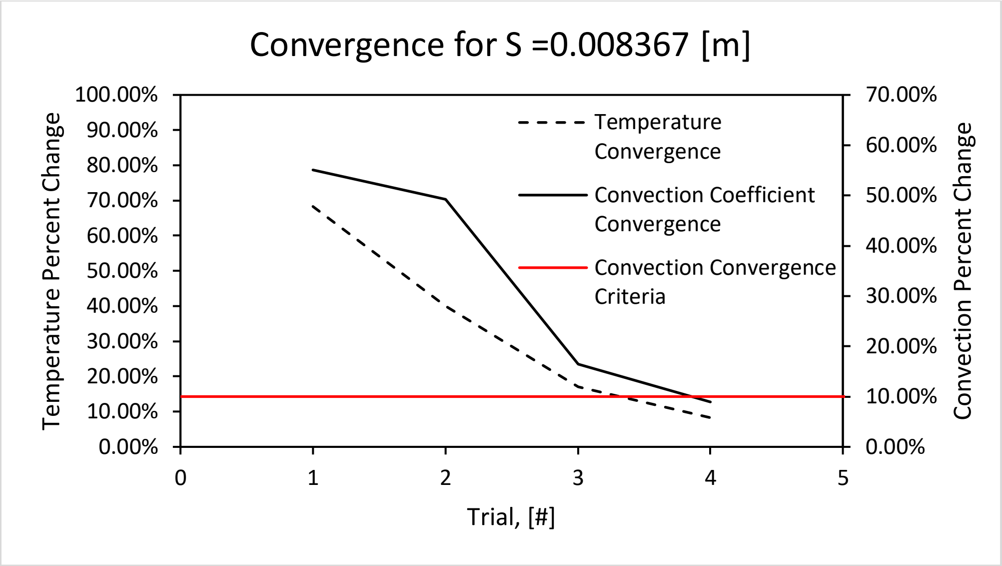


Figure 56. Convergence plot for S= 0.00837 m and a 6x6 inch heat fin with a convection coefficient of 1000 W/m-K.

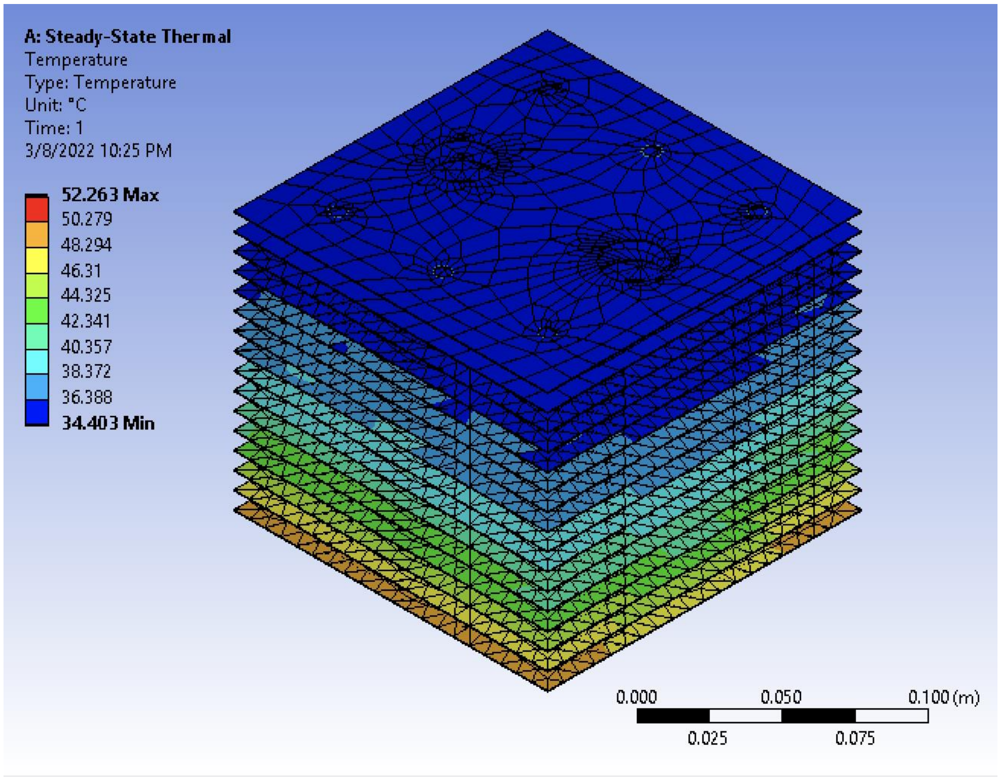


Figure 57. Fin array temperature gradient.

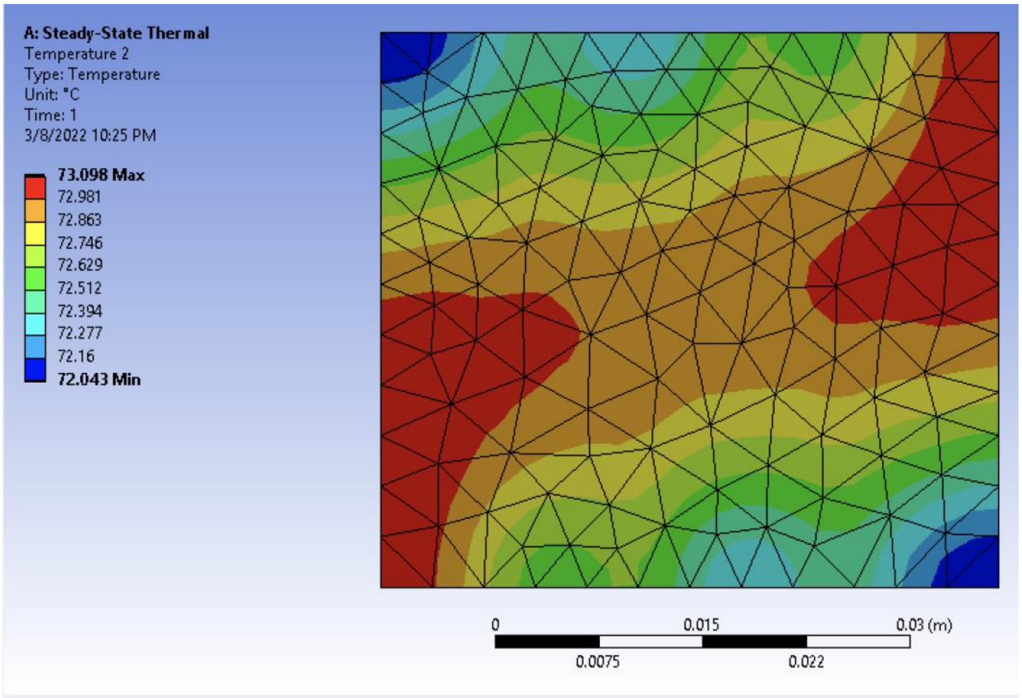


Figure 58. Copper base temperature gradient.

Average Base Temperature: 72.76 [C]

1307 W/m-K | "Configuration 5c"

Table 20. Iterative trials to obtain temperature convergence for a 6x6 inch fin with spacing of 0.00837 m and convection coefficient of 1307 W/m-K.

S = 0.008367 [m]			16 Fins	Config 5c
Trial #	T_s, [C]	Delta T %	h, [W/m2-K]	Delta h %
	39.83	n/a	3.914	n/a
1	38.444	3.48%	3.775	3.55%
2	39.069	1.63%	3.839	1.70%
	Base Temp	65.321	C	

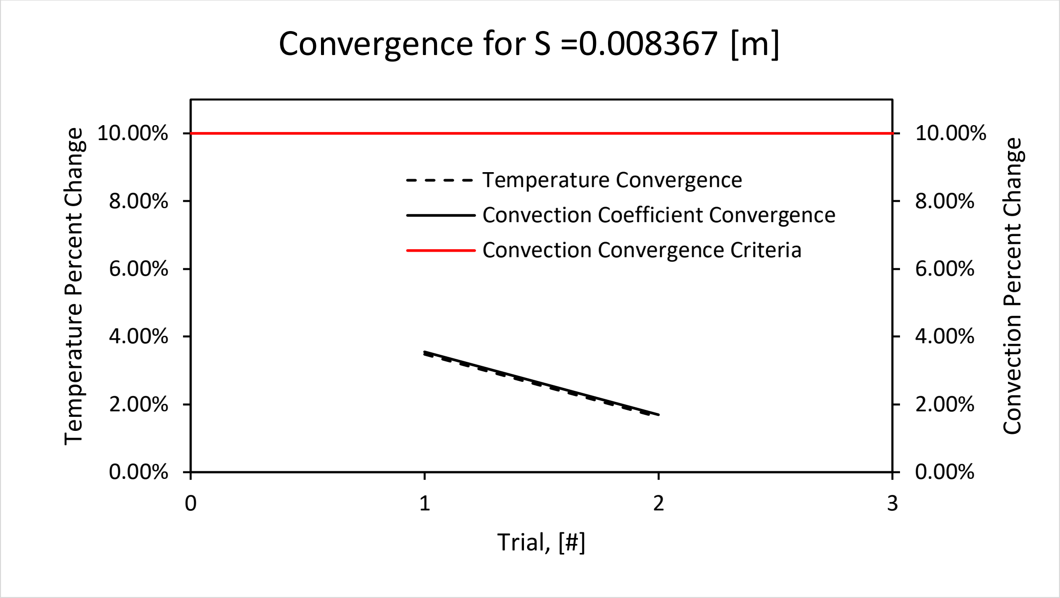


Figure 59. Convergence plot for S= 0.00837 m and a 6x6 inch heat fin with a convection coefficient of 1307 W/m-K.

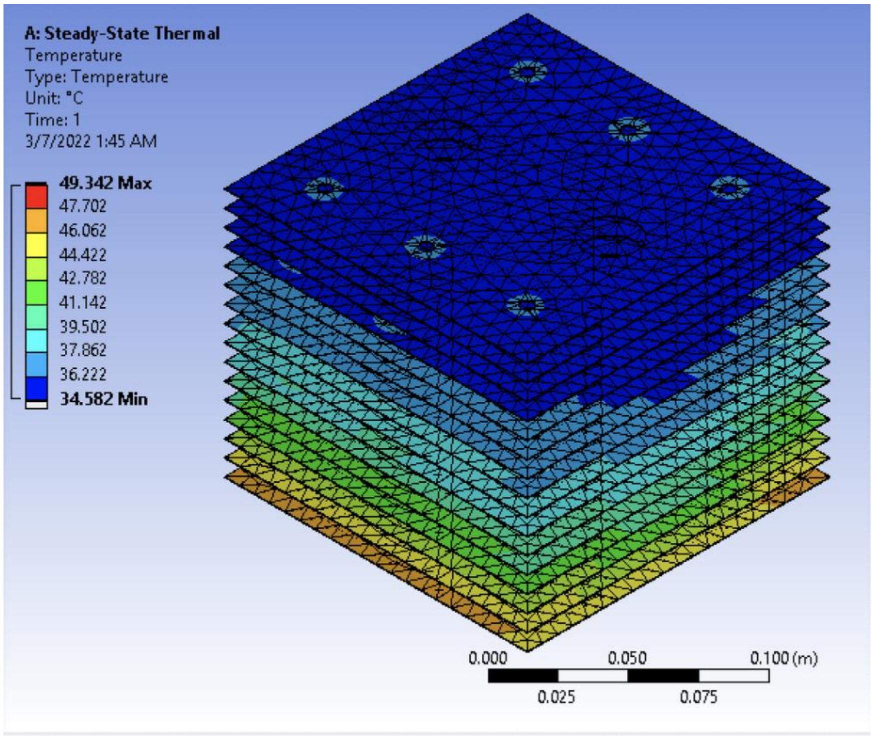


Figure 60. Fin array temperature gradient.

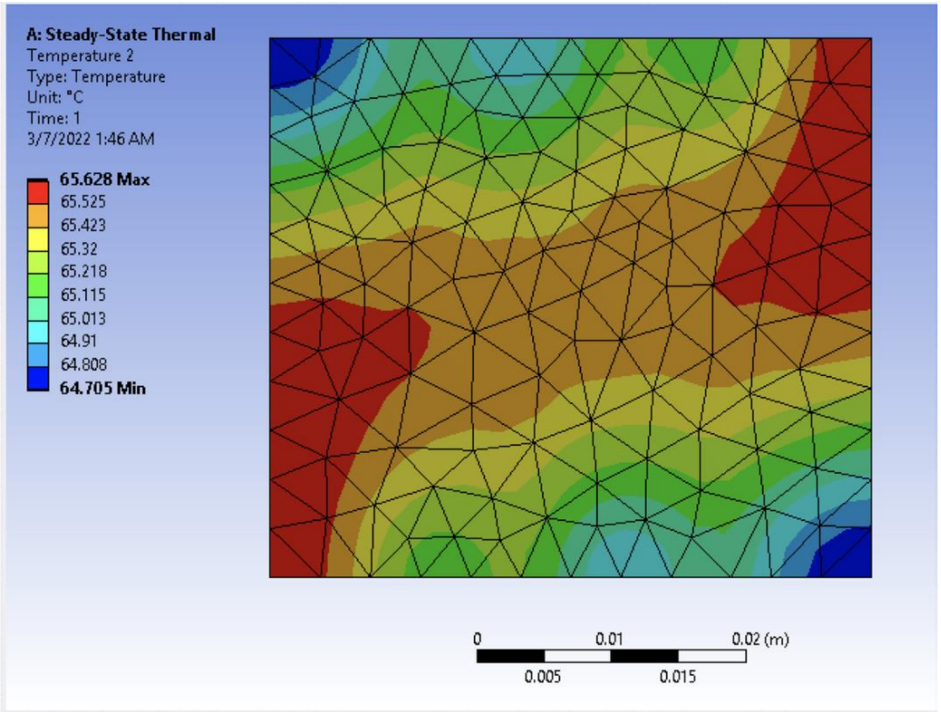


Figure 61. Copper base temperature gradient.

Average Base Temperature: 65.32 [C]

6x8in Heat Fins

1000 W/m-K | “Configuration 5b”

Table 21. Iterative trials to obtain temperature convergence for a 6x8 inch fin with spacing of 0.00837 m and convection coefficient of 1000 W/m-K.

S = 0.008367 [m]			16 Fins	Config 5b
Trial #	T_s, [C]	Delta T %	h, [W/m2-K]	Delta h %
	100	n/a	5.806	n/a
1	30.43	69.57%	2.177	62.50%
2	44.829	47.32%	3.795	74.32%
3	35.015	21.89%	2.863	24.56%
4	39.316	12.28%	3.334	16.45%
5	36.842	6.29%	3.078	7.68%

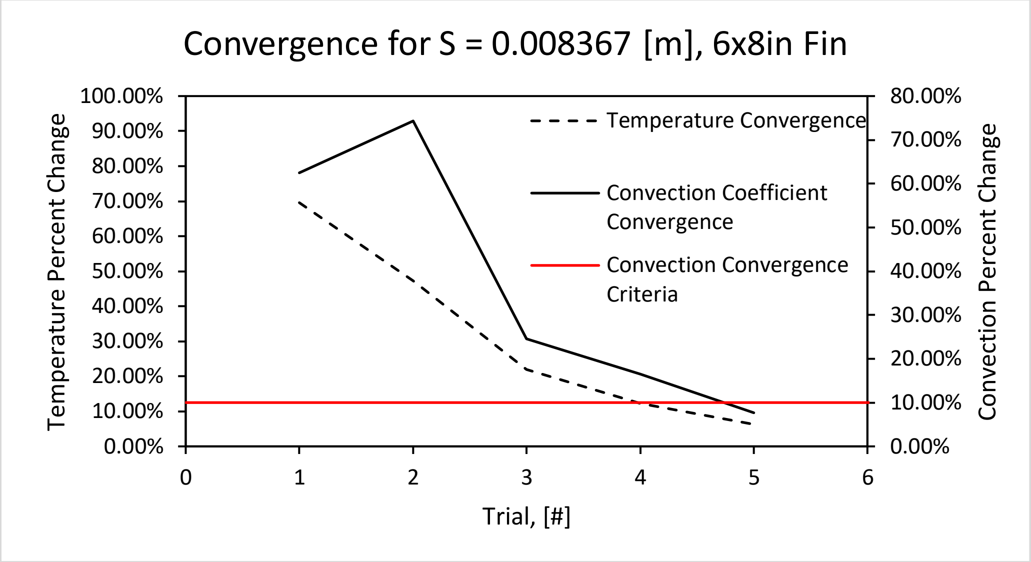


Figure 62. Convergence plot for S= 0.00837 m and a 6x8 inch heat fin with a convection coefficient of 1000 W/m-K.

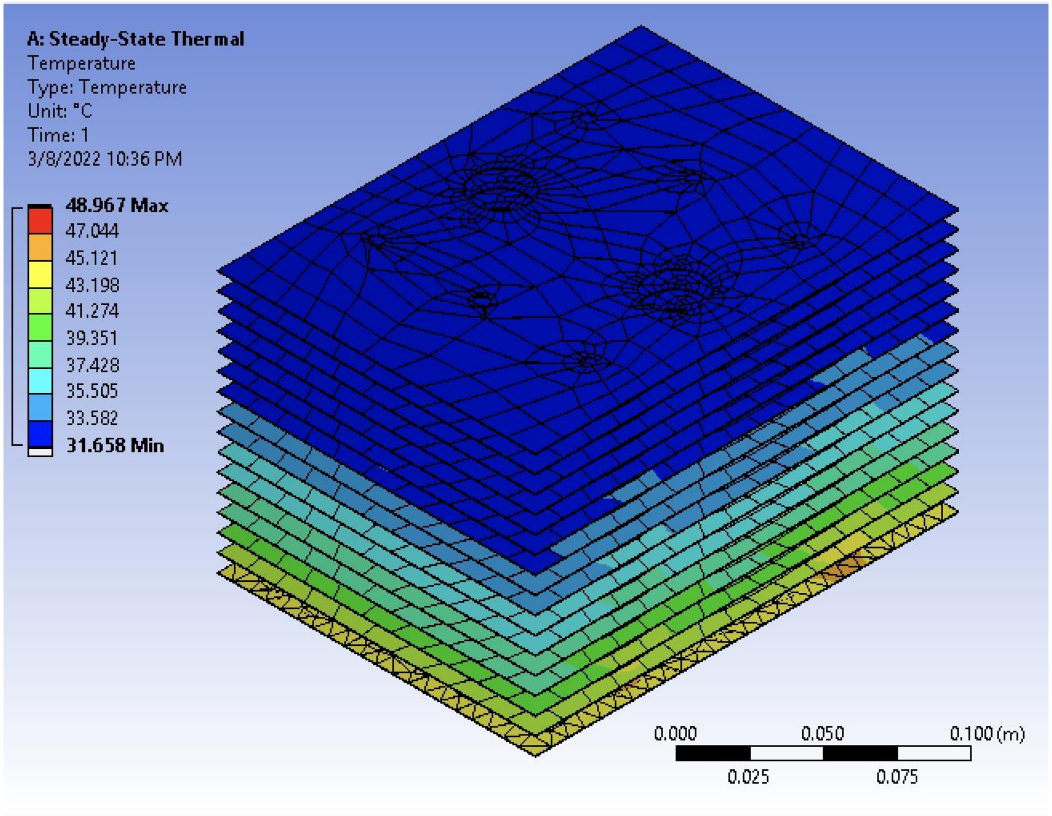


Figure 63. Fin array temperature gradient.

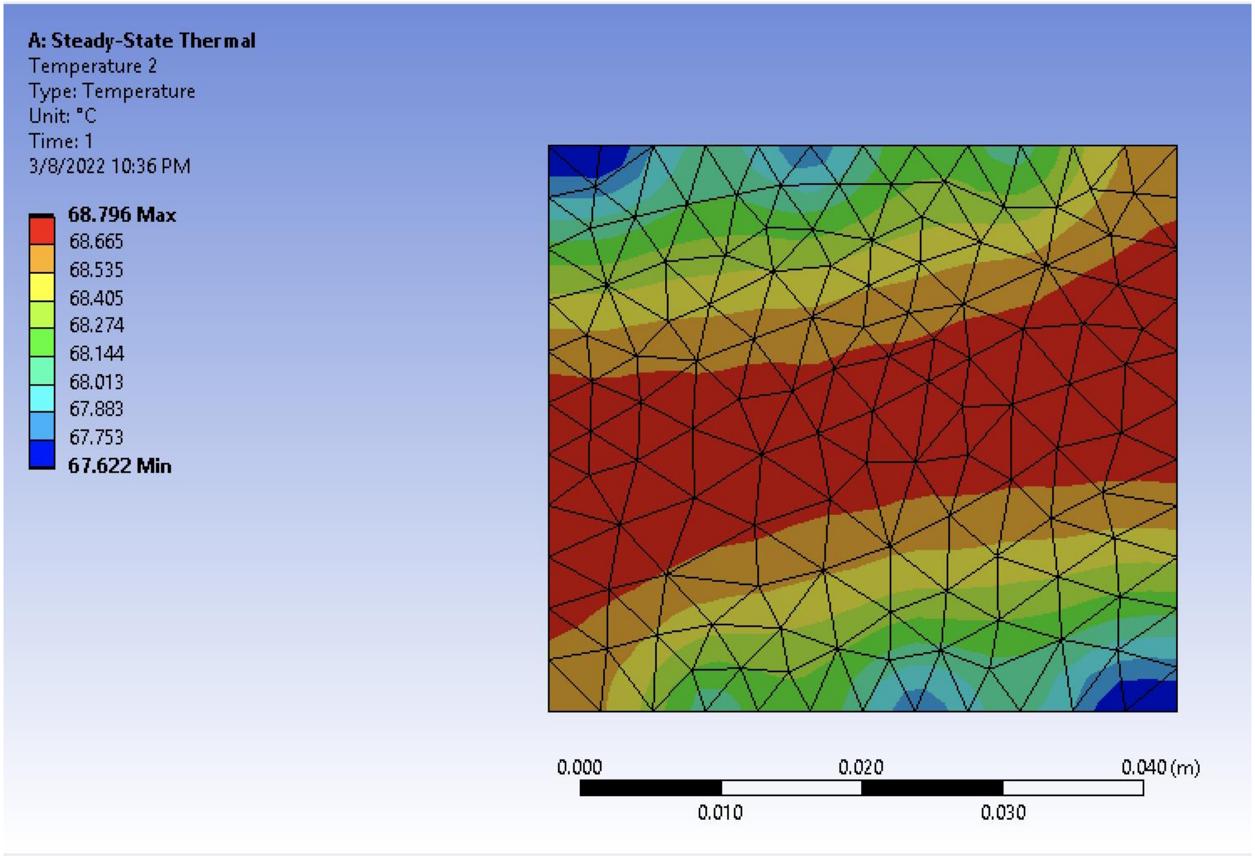


Figure 64. Copper base temperature gradient.

Average Base Temperature: 68.45 [C]

1307 W/m-K | "Configuration 5d"

Table 22. Iterative trials to obtain temperature convergence for a 6x8 inch fin with spacing of 0.00837 m and convection coefficient of 1307 W/m-K.

S = 0.008367 [m]			16 Fins	Config 5d
Trial #	T_s, [C]	Delta T %	h, [W/m2-K]	Delta h %
	36.84	n/a	3.078	n/a
1	38.16	3.58%	3.219	4.58%
2	37.45	1.86%	3.145	2.30%

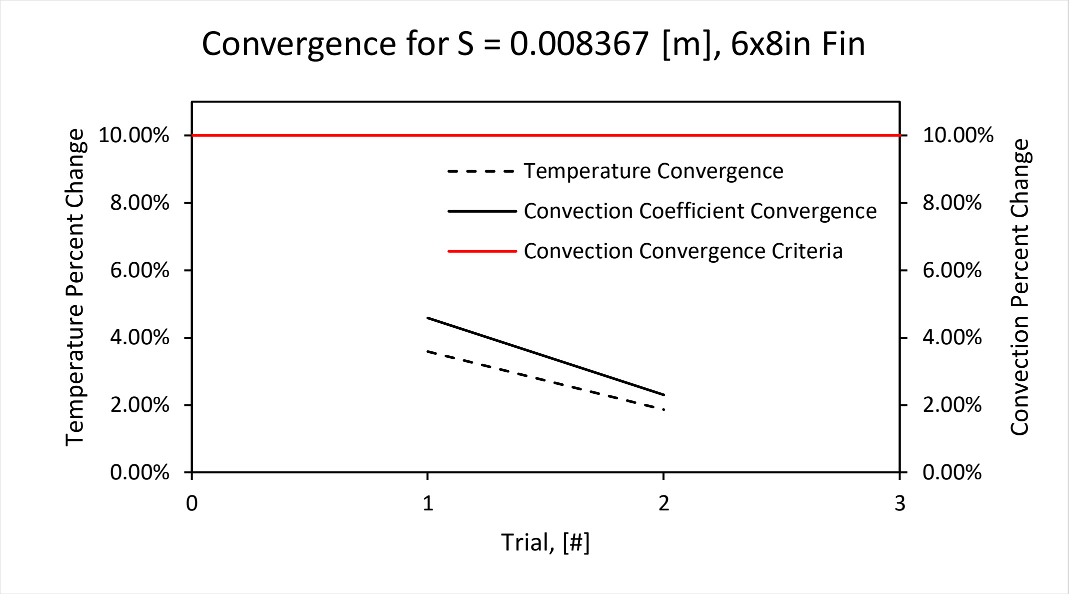


Figure 65. Convergence plot for S= 0.00837 m and a 6x8 inch heat fin with a convection coefficient of 1307 W/m-K.

Figure

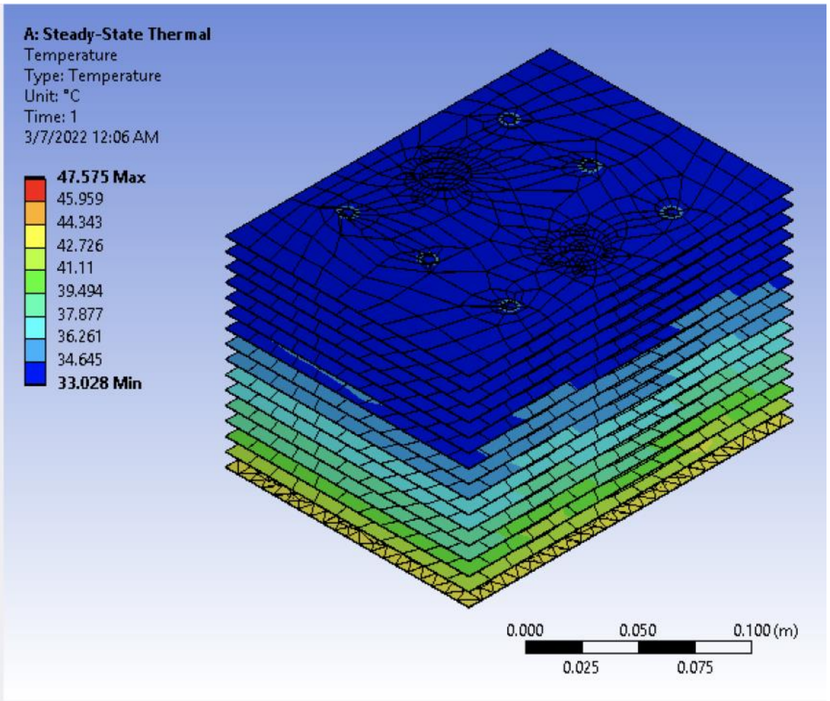


Figure 66. Fin array temperature gradient.

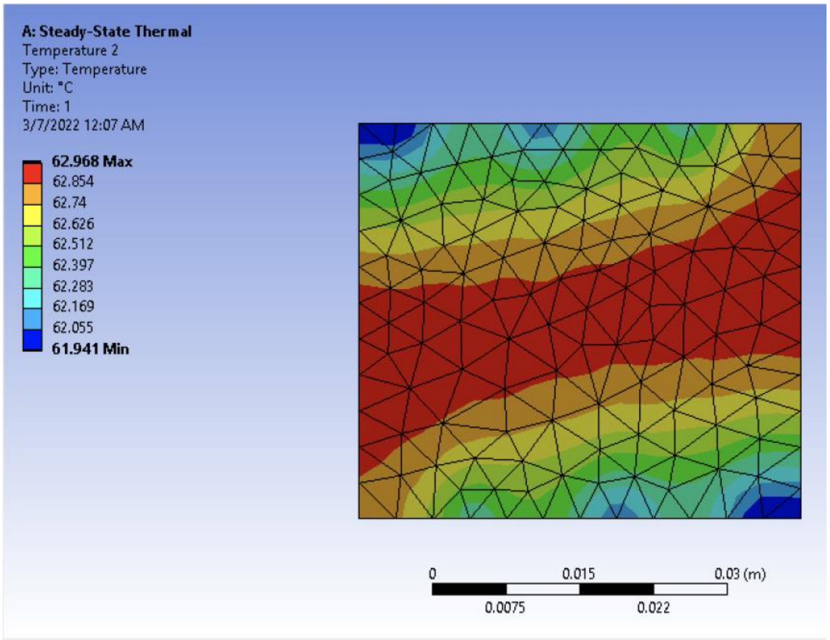


Figure 67. Copper base temperature gradient.

Average Base Temperature = 62.67 [C]

14 Fins | S = 0.37in = 0.00937m

6x6in Heat Fins

1000 W/m-K | "Configuration 6a"

Table 23. Iterative trials to obtain temperature convergence for a 6x6 inch fin with spacing of 0.00937 m and convection coefficient of 1000 W/m-K.

S = 0.009368 [m]			14 Fins	Config 6
Trial #	T_s, [C]	Delta T %	h, [W/m2-K]	Delta h %
	100	n/a	6.627	n/a
1	32.709	67.29%	3.454	47.88%
2	43.168	31.98%	4.53	31.15%
3	37.974	12.03%	4.084	9.85%
4	39.794	4.79%	4.254	4.16%

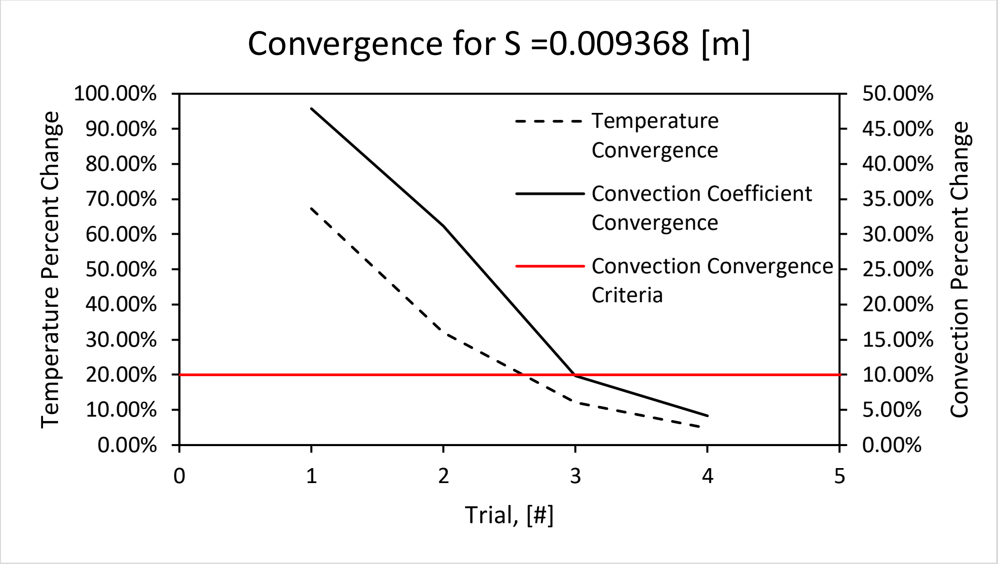


Figure 68. Convergence plot for S= 0.009368 m and a 6x6 inch heat fin with a convection coefficient of 1000 W/m-K.

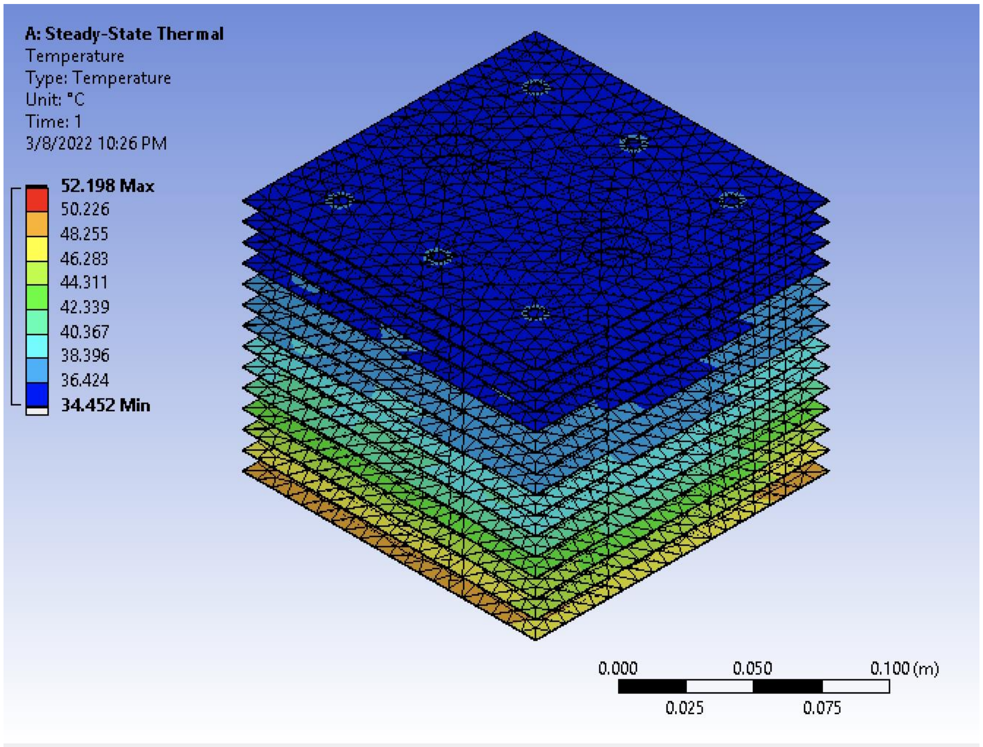


Figure 69. Fin array temperature gradient.

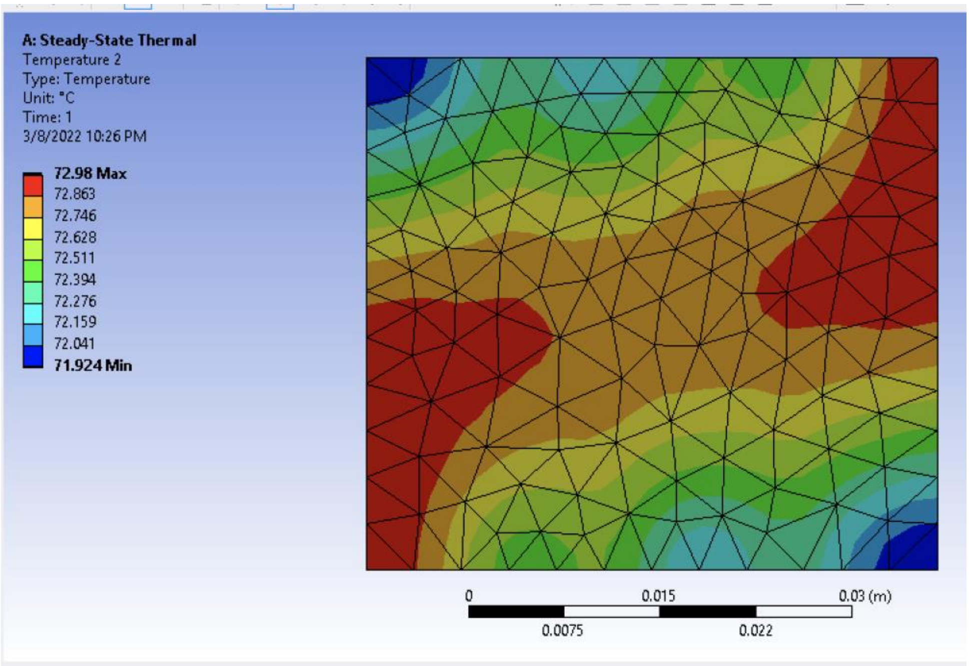


Figure 70. Copper base temperature gradient.

Average Base Temperature: 72.64 [C]

1307 W/m-K | “Configuration 6c”

Table 24. Iterative trials to obtain temperature convergence for a 6x6 inch fin with spacing of 0.00937 m and convection coefficient of 1307 W/m-K.

S = 0.009368 [m]			14 Fins	Config 6c
Trial #	T_s, [C]	Delta T %	h, [W/m2-K]	Delta h %
	39.79	n/a	4.254	n/a
1	39.114	1.70%	4.193	1.43%
2	39.372	0.66%	4.216	0.55%
	Base Temp	65.443	C	

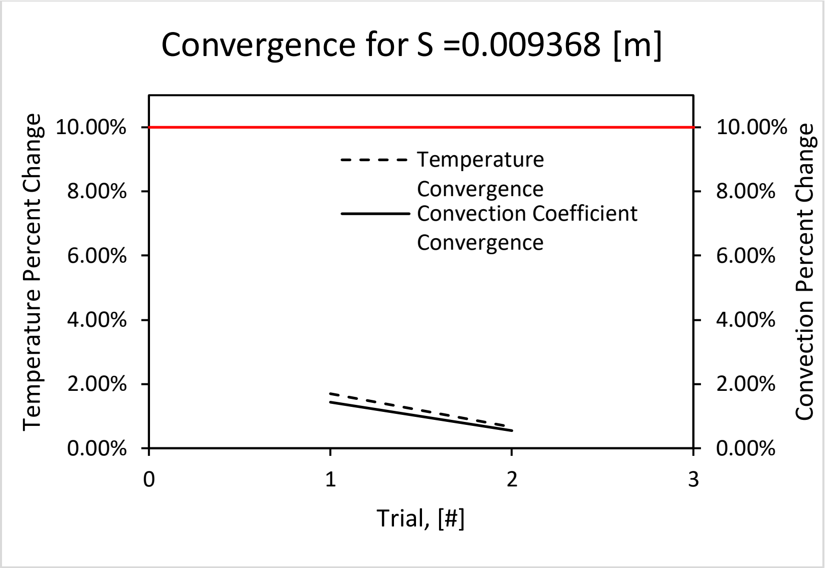


Figure 71. Convergence plot for S= 0.009368 m and a 6x6 inch heat fin with a convection coefficient of 1307 W/m-K.

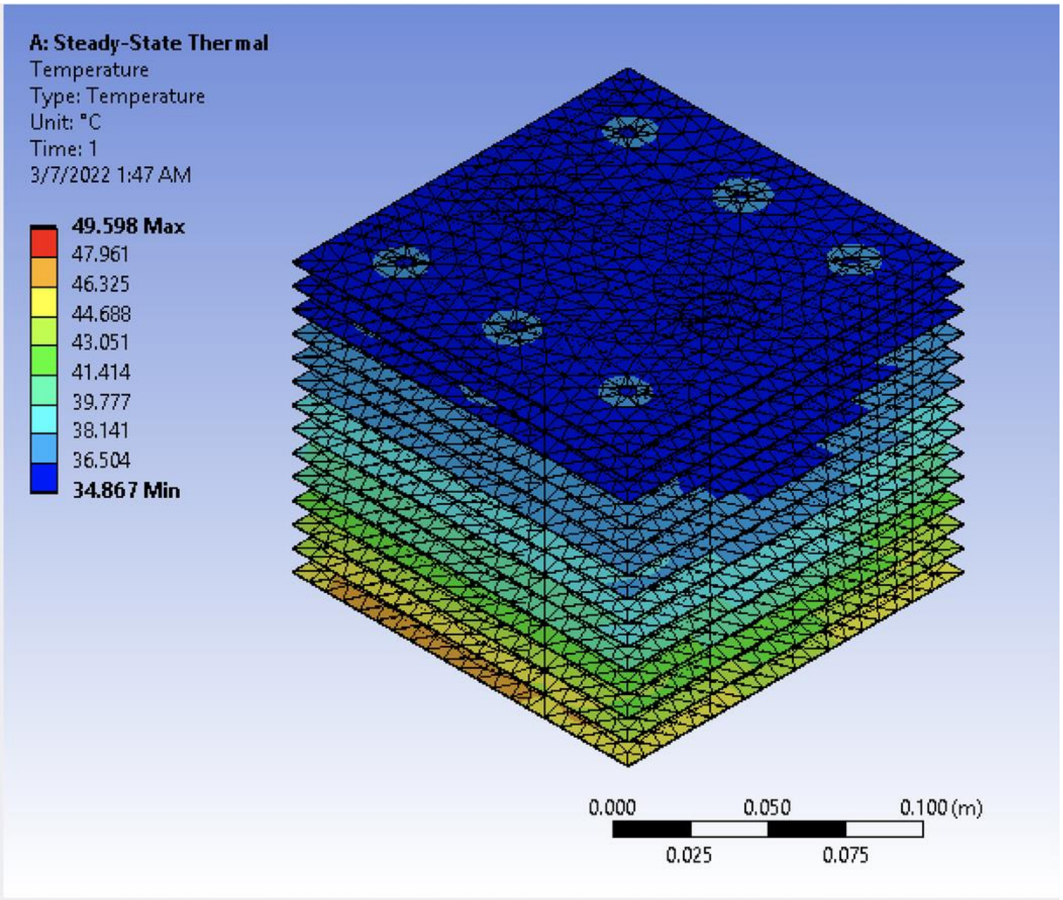


Figure 72. Fin array temperature gradient.

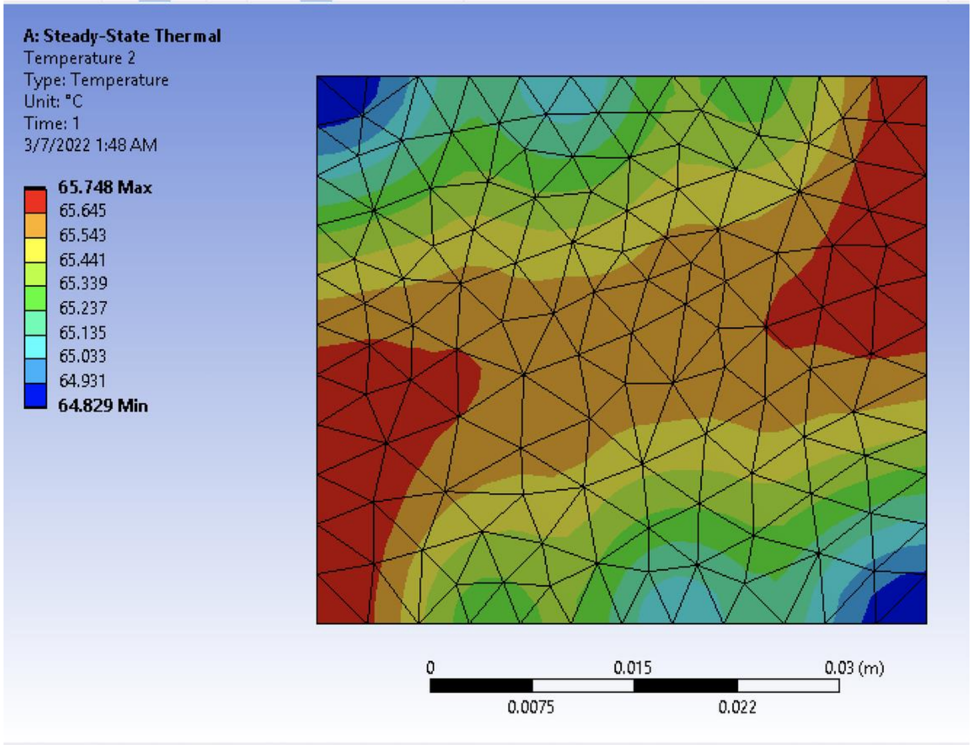


Figure 73. Copper base temperature gradient.

Average Base Temperature: 65.44 [C]

6x8in Heat Fins

1000 W/m-K | "Configuration 6b"

Table 25. Iterative trials to obtain temperature convergence for a 6x8 inch fin with spacing of 0.00937 m and convection coefficient of 1000 W/m-K.

S = 0.009368 [m]			14 Fins	Config 6b
Trial #	T_s, [C]	Delta T %	h, [W/m2-K]	Delta h %
	100	n/a	6.054	n/a
1	31.168	68.83%	2.749	54.59%
2	42.493	36.34%	3.986	45.00%
3	36.061	15.14%	3.403	14.63%
4	38.511	6.79%	3.651	7.29%

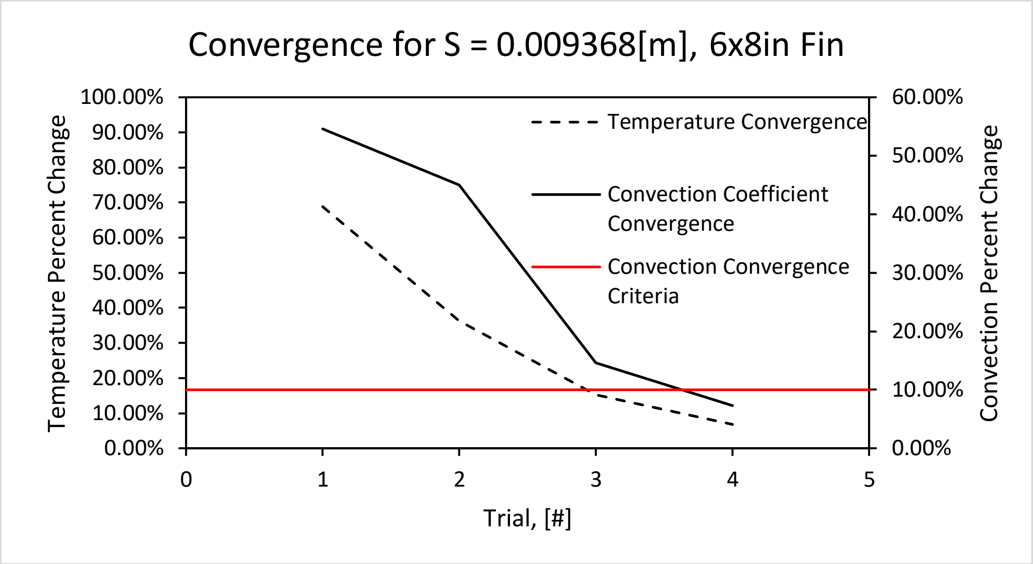


Figure 74. Convergence plot for S= 0.009368 m and a 6x8 inch heat fin with a convection coefficient of 1000 W/m-K.

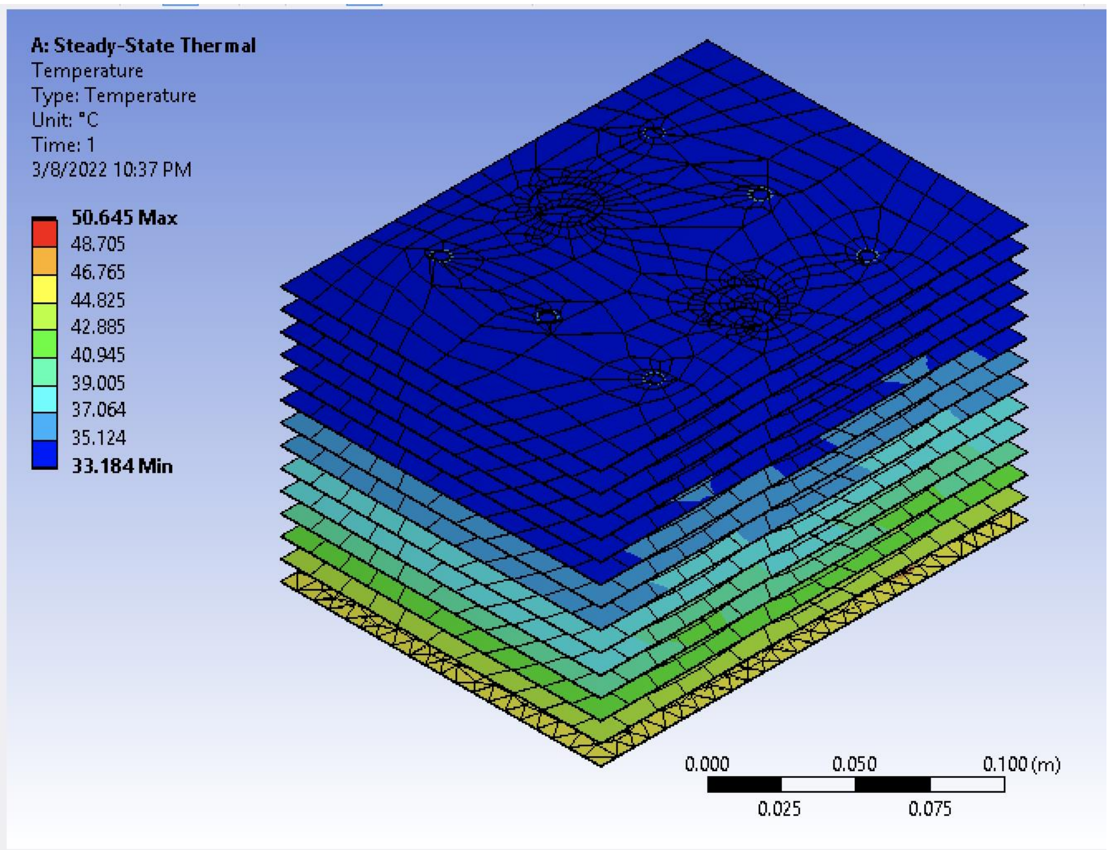


Figure 75. Fin array temperature gradient.

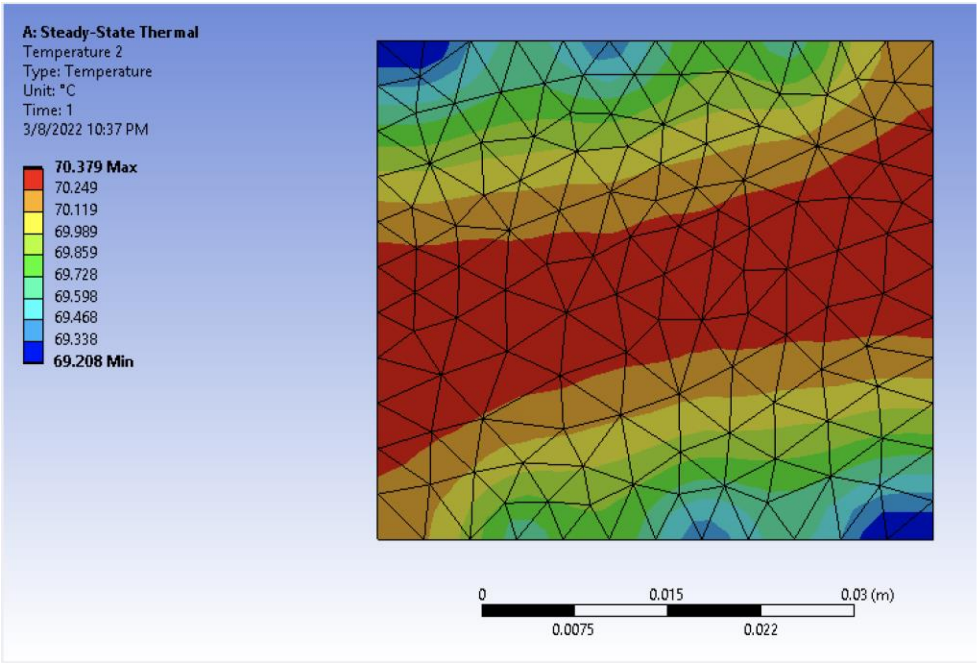


Figure 76. Copper base temperature gradient.

Average Base Temperature: 70.04 [C]

1307 W/m-K | "Configuration 6d"

Table 26. Iterative trials to obtain temperature convergence for a 6x8 inch fin with spacing of 0.00937 m and convection coefficient of 1307 W/m-K.

S = 0.009368 [m]			14 Fins	Config 6d
Trial #	T_s, [C]	Delta T %	h, [W/m2-K]	Delta h %
	38.51	n/a	3.651	n/a
1	37.45	2.75%	3.549	2.79%
2	37.902	1.21%	3.593	1.24%

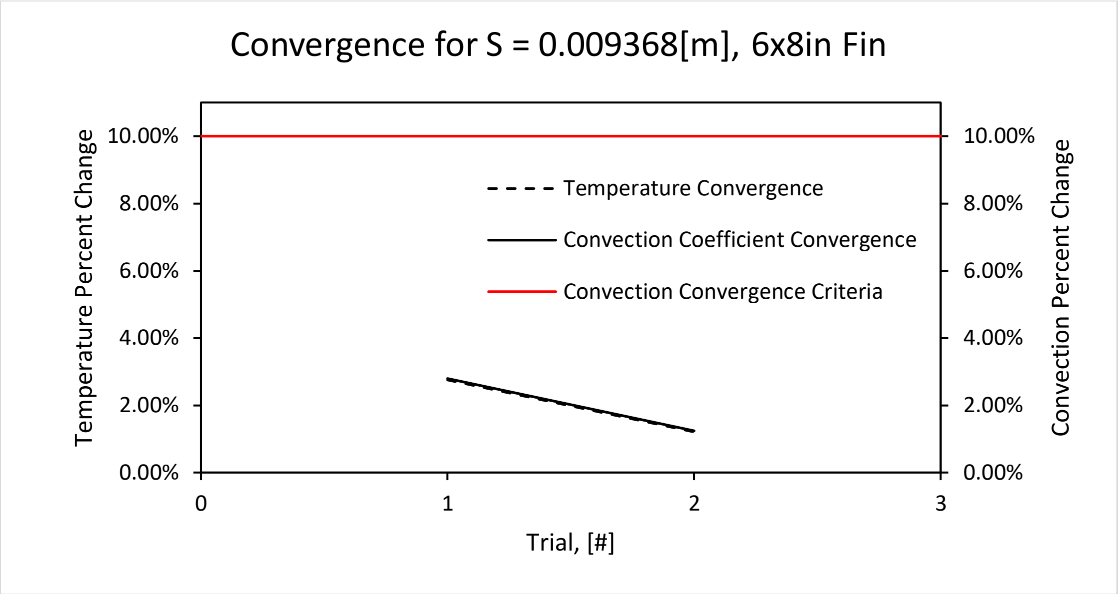


Figure 77. Convergence plot for S= 0.009368 m and a 6x8 inch heat fin with a convection coefficient of 1307 W/m-K.

Figure 

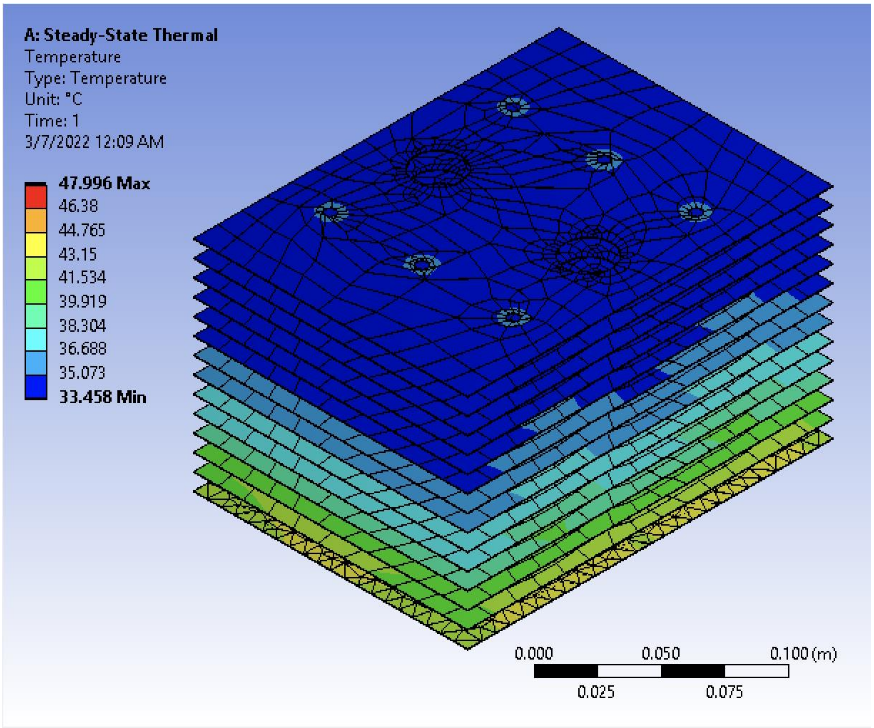


Figure 78. Fin array temperature gradient.

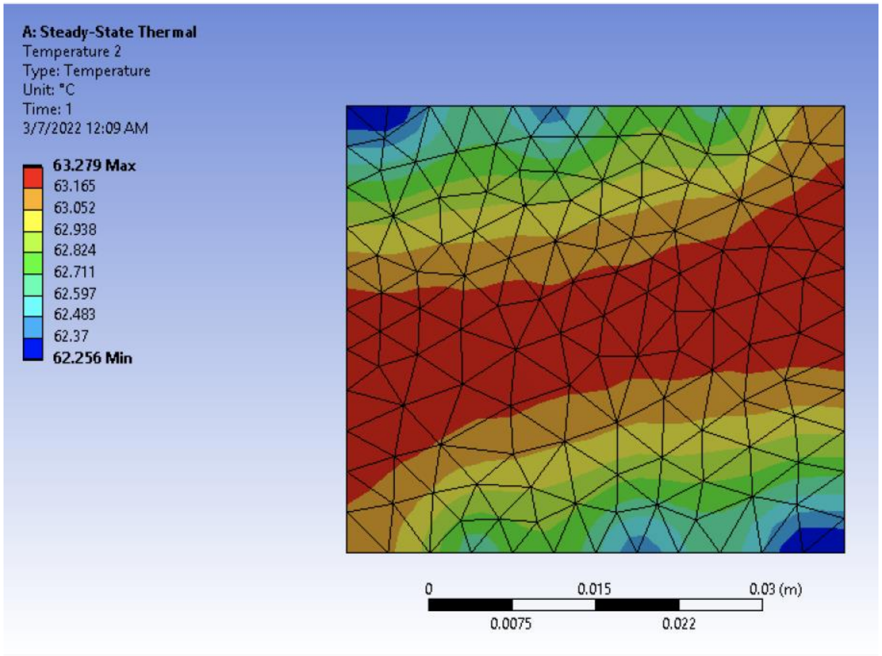


Figure 79. Copper base temperature gradient.

Average Base Temperature = 62.97 [C]

Appendix D - Manufacturing Plan

Subsystem	Component	Purchase (P) Modify (M) Build (B)	Raw Materials Needed to make/modify the part (only M & B)	Where/how procured?	Equipment and Operations anticipate using to make the component	Key limitations of this operation places on any parts made from it
Prototype						
Heat Dissipation Subsystem	Heat Pipes	M	Off the shelf heat pipes, diameter determined from ANSYS simulations	Purchased from McMasterCarr or local hardware store	Pipe / tube bender (might ask the shop techs for assistance, or puchase a tube bender specifically for small diameter pipes)	Min bend radius
	Heat Fins	B	Aluminum Sheet 6061	Purchased from McMasterCarr	Shear, water jet, or laser cut. Final thickness of 0.02 in.	Many processes are limited to 2d features
Mounting subsystem	Interface block	B	Block of Copper 110	Purchased from McMasterCarr or local hardware store	Mini mill in the Machine shop	Surface finish requirements on interface
	Mounting Bolts	P	n/a	Purchased from McMasterCarr or local hardware store	n/a	n/a
Manufacturing						
Heat Dissipation Subsystem	Heat Pipes	P	n/a	Custom order (GTIs choice)	CNC pipe / tube bender	Min bend radius
	Heat Fins	B	Aluminum 6061	Bulk purchase from a supplier (Metals Depot or Industrial Metal Supply)	Create tooling to stamp heat fins. Final thickness of 0.02 in.	Tooling cannot be modified easily after creation and has a high initial cost
Mounting subsystem	Interface block	B	Copper 110	Bulk purchase from a supplier (Metals Depot or Industrial Metal Supply)	Mill	Surface finish requirements on interface
	Mounting Bolts	P	n/a	Purchase in bulk from a supplier (GTIs choice)	n/a	n/a

Manufacturing Plan

Heat Pipe A

1. Establish the x as positive to the right, y as positive upward, and z as positive off the table
2. Start on one end, move a distance of 1.71” and bend the pipe 52.89° clockwise.
3. Move a distance of 0.68” and establish that as the new horizontal datum.
4. Bend the heat pipe to an angle of 37.11° clockwise from the new datum.
5. Rotate the heat pipe so that the z direction is to the right, y direction is directly up, and the negative x axis is off of the table
6. Move a distance of 0.68” from the bend going into the table and create a bend of 122.11° clockwise.
7. Lastly, rotate the heat pipe until the positive z is directed to the right, positive x direction is straight down, and negative y direction off of the table.
8. Using the pipe bender, create a 115.39° bend off the 1.71” in the counterclockwise direction.

Heat Pipe B

1. Establish the x as positive to the right, y as positive upward, and z as positive off the table
2. Start on one end, move a distance of 1.71” and bend the pipe 45.61° clockwise.
3. Move a distance of 0.38” and establish that as the new horizontal datum.
4. Bend the heat pipe to an angle of 44.39° clockwise from the new datum.
5. Rotate the heat pipe so that the z direction is to the right, y direction is directly up, and the negative x axis is off of the table
6. Move a distance of 0.38” from the bend going into the table and create a bend of 169.73° clockwise.
7. Lastly, rotate the heat pipe until the positive z is directed to the right, positive x direction is straight down, and negative y direction off of the table.
8. Using the pipe bender, create a 169.51° bend off the 1.71” in the counterclockwise direction.

Heat Pipe C

1. Establish the x as positive to the right, y as positive upward, and z as positive off the table
2. Start on one end, move a distance of 1.71” and bend the pipe 54.61° clockwise.
3. Move a distance of 0.84” and establish that as the new horizontal datum.
4. Bend the heat pipe to an angle of 35.39° clockwise from the new datum.
5. Rotate the heat pipe so that the z direction is to the right, y direction is directly up, and the negative x axis is off of the table
6. Move a distance of 0.84” from the bend going into the table and create a bend of 117.08° clockwise.
7. Lastly, rotate the heat pipe until the positive z is directed to the right, positive x direction is straight down, and negative y direction off of the table.
8. Using the pipe bender, create a 109.96° bend off the 1.71” in the counterclockwise direction.

Base

1. Face the top entire block.
2. Using a 4 flute end mill, make a groove with depth of 0.125” extending a distance of 0.250” from either side of center line that extends along the entire length of 1.76”.
3. Flip the piece so the 0.880” by 0.49” face is visible.

4. Using a 6mm drill bit, drill through holes with center locations of 0.145”, 0.435”, and 0.725” to the +X and -X directions. All the holes have a vertical center location of 0.2”.
5. Flip the part so that the -Z face is in the +Z direction.
6. Using a 0.25” drill bit, drill a hole in the center to a depth of 0.04”.
7. Using the same 0.25” drill bit and create a groove out to the end
8. Flip the part so that the full length groove is facing vertically off the work table.
9. Using a 0.11” drill bit, drill 6 holes at a distance of 0.40” from either side of the centerline until they punch through to the other side. The holes are symmetrical about both the horizontal and vertical centerlines. The horizontal distance from the vertical centerline to the center of the first hole is 0.145”. The distance from the vertical centerline to the center of the second hole is 0.435”. The distance from the vertical centerline to the center of the third hole is 0.725”.
10. Using a 45-degree chamfering mill, mill a chamfer on the top and bottom vertical edges with a z distance of 0.125”.
11. Face the current surface to a surface finish of 16.

Steel Bar (Crossbar)

1. Face the top and bottom face.
2. Use a 4 flute end mill, mill out a depth of 0.125” from the center of the piece to a distance of 0.89”.
3. Flip the part over.
4. Using the same 4 flute end mill, starting from each side, mill a depth of 0.1” for a distance of 0.80”.
5. Using a 0.27” drill bit, drill a through hole at a distance of 0.350” from the edge along the horizontal center line of the part.

Heat Fins

1. Waterjet (includes creating the 2D .dxf file, bringing the stock to Mustang 60, requesting service)
2. Deburr the exterior edges.
3. Deburr the inside of the holes using a deburring scraper.

Interface Block

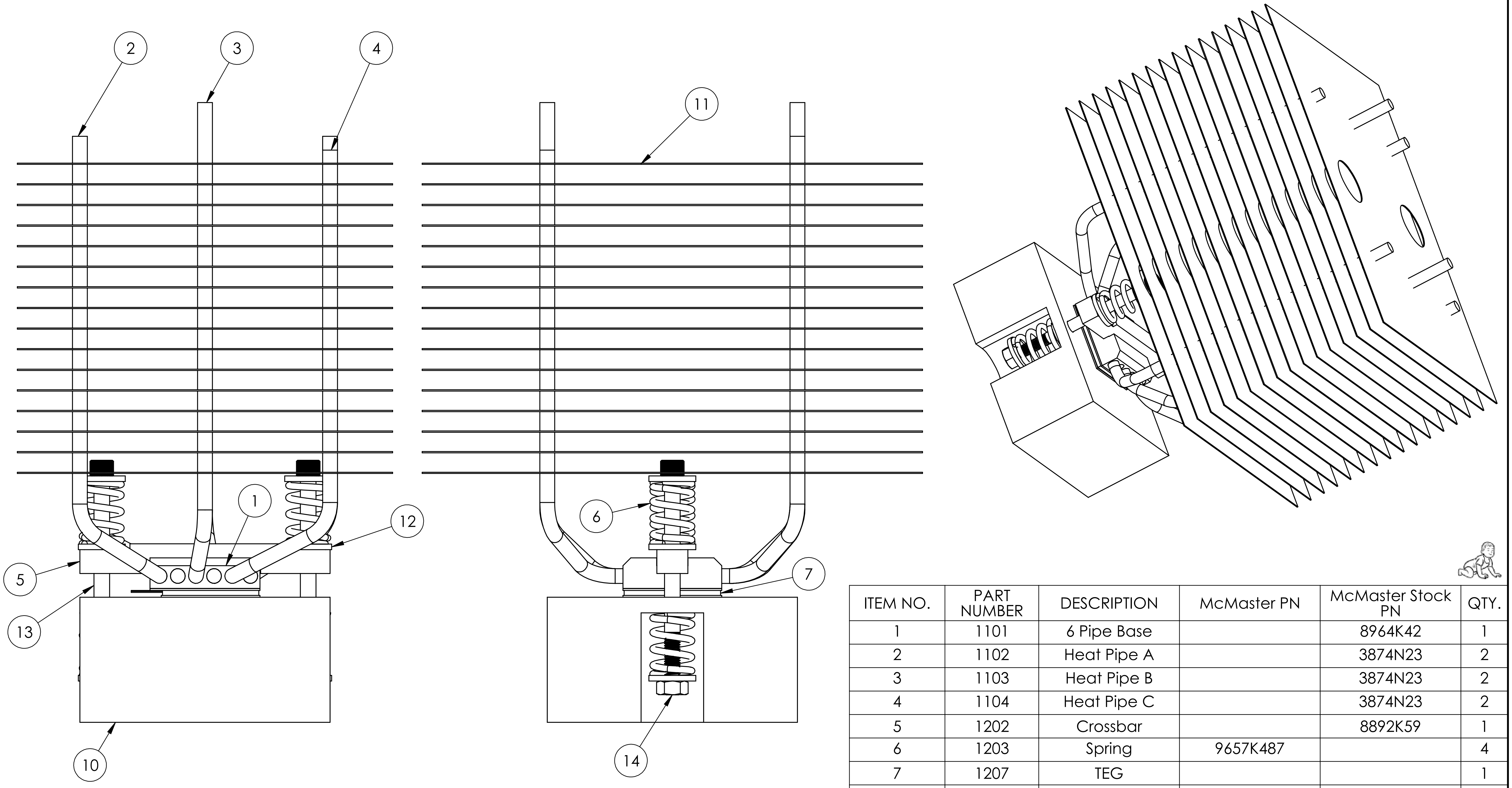
1. With the underside of the part facing upwards, use the 1 inch drill to create a hole 1.75 inches in depth along the center line 1.650 inches from the center.
2. Using the holes from Step 1, create grooves for the rest of the 2” dimension, a distance of 0.35”.
3. Using a 0.27” drill bit, drill a through hole at the same locations as the 1” holes in step 1.
4. Flip the block over and face mill it to 16 surface finish. (finish all over)
5. Using a 0.25” drill bit, drill a hole of depth 0.0625” in the exact center of the part.
6. Using the hole from Step 5, create a groover perpendicular to the line that connects the two center points of the 0.27” holes.

Assembly Plan

1. Slide Heat Pipe A into the first hole on the copper base plate on both sides. Fill any empty space with thermal paste.
2. Slide Heat Pipe B into the third hole on the copper base plate on both sides. Fill any empty space with thermal paste.

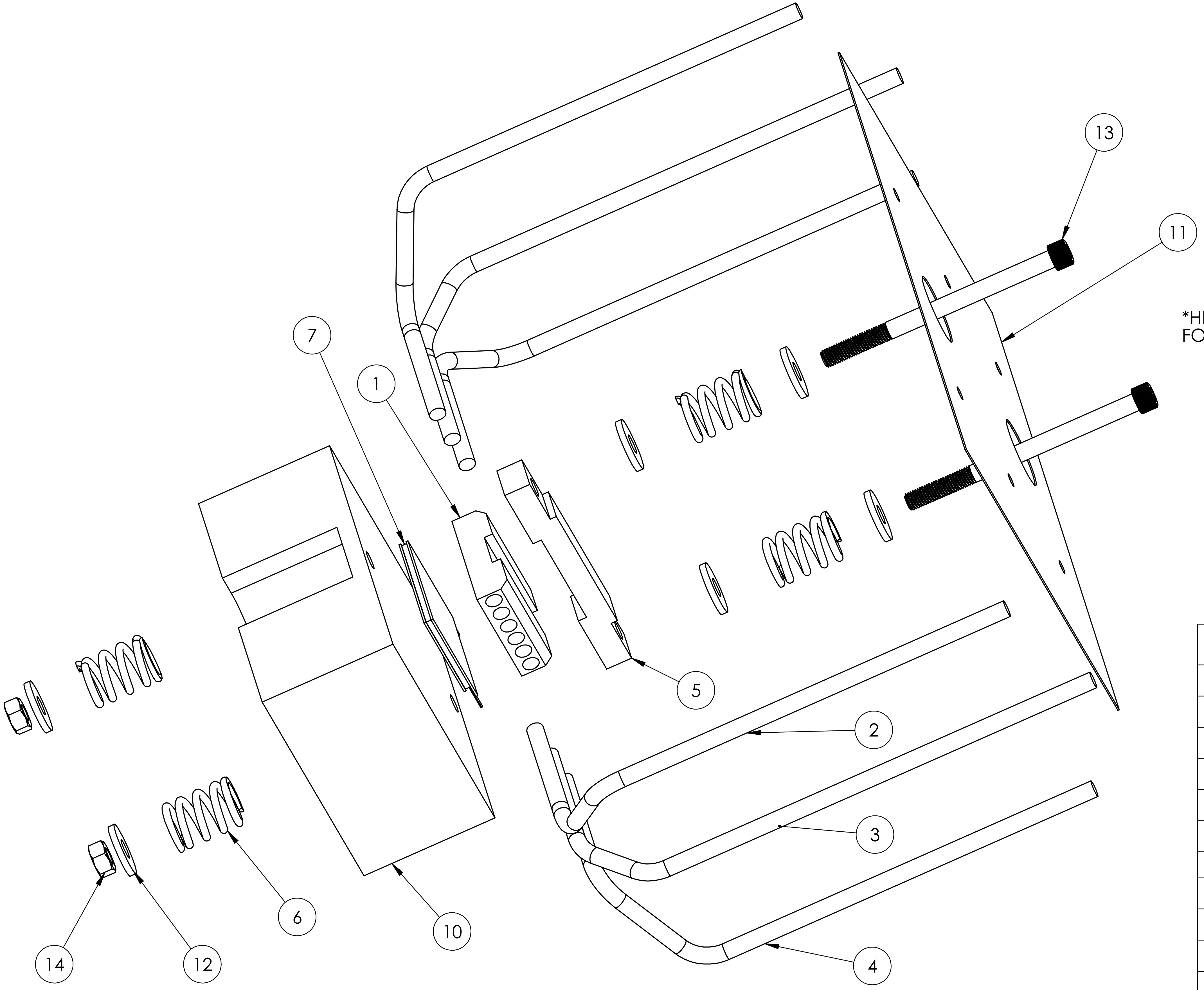
3. Slide Het Pipe C into the fifth hole on the copper base plate on both sides. Fill any empty space with thermal paste.
4. Insert set screws into the 12 top holes using a drill.
5. Insert the thermocouples in the slot on the test stand base and cover any exposed area with thermal paste.
6. Place the TEG in between the copper base with heat pipes and set screws inserted and the test stand base.
7. Place the cross bar in the slot on the pipe base.
8. Using the bolt, secure a washer, then spring, then another washer between the crossbar and the head of the bolt.
9. In the 1.75" depth holes on the test stand base, insert a spring, then washer, then nut (in order from the top of the heat sink to the bottom of the heat sink)
10. Torque the bolt using a wrench until the TEG has 100 psi across it.
11. Repeat Steps 8-11 for the other bolt on the other side of the crossbar.
12. Using the fin spacing jig, solder the fins at all 6 joints.
    a. First step is to clean the heat pipe using acetone
    b. Step 2 is to prep the heat pipe by using the provided paste.
    c. One member is holding the soldering rod and placing it in the right spot. Another member is using the torch to heat the heat pipe and fins. Other two members watch the other joints for movement and are on standby in case.
13. Wait for the heat sink to cool before testing.

Appendix E - Relevant Manufacturing Drawings



ITEM NO.	PART NUMBER	DESCRIPTION	McMaster PN	McMaster Stock PN	QTY.
1	1101	6 Pipe Base		8964K42	1
2	1102	Heat Pipe A		3874N23	2
3	1103	Heat Pipe B		3874N23	2
4	1104	Heat Pipe C		3874N23	2
5	1202	Crossbar		8892K59	1
6	1203	Spring	9657K487		4
7	1207	TEG			1
10	1201	Test Stand Base		6620K312	1
11	1105	Heat Fin		88835K42	16
12	1205	Washer	91525A416		6
13	1204	Bolt	92196A342		2
14	1206	Nut	90499A805		2

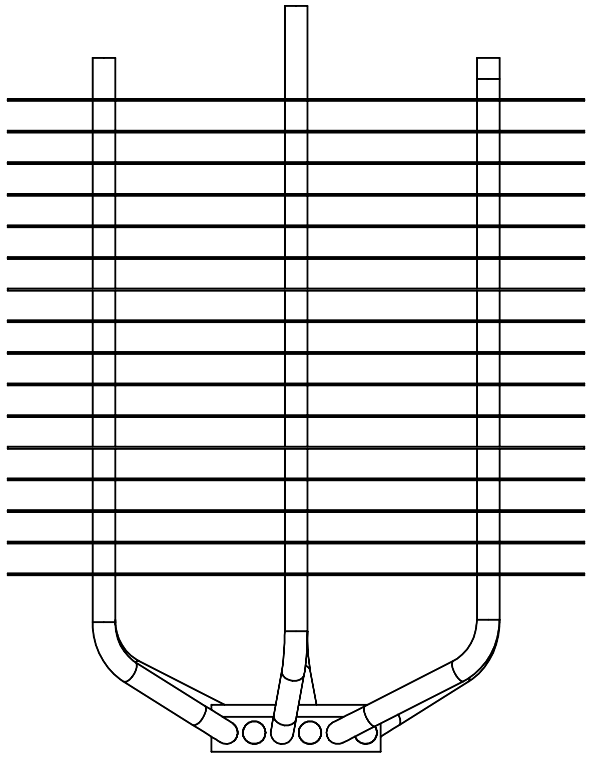
Cal Poly Mechanical Engineering
TEAM F16
SENIOR PROJECT
1000
TOP ASSEMBLY
1/25/22
Drwn. By: KADIN FELDIS
Drwn. By: PEYTON NIENABER

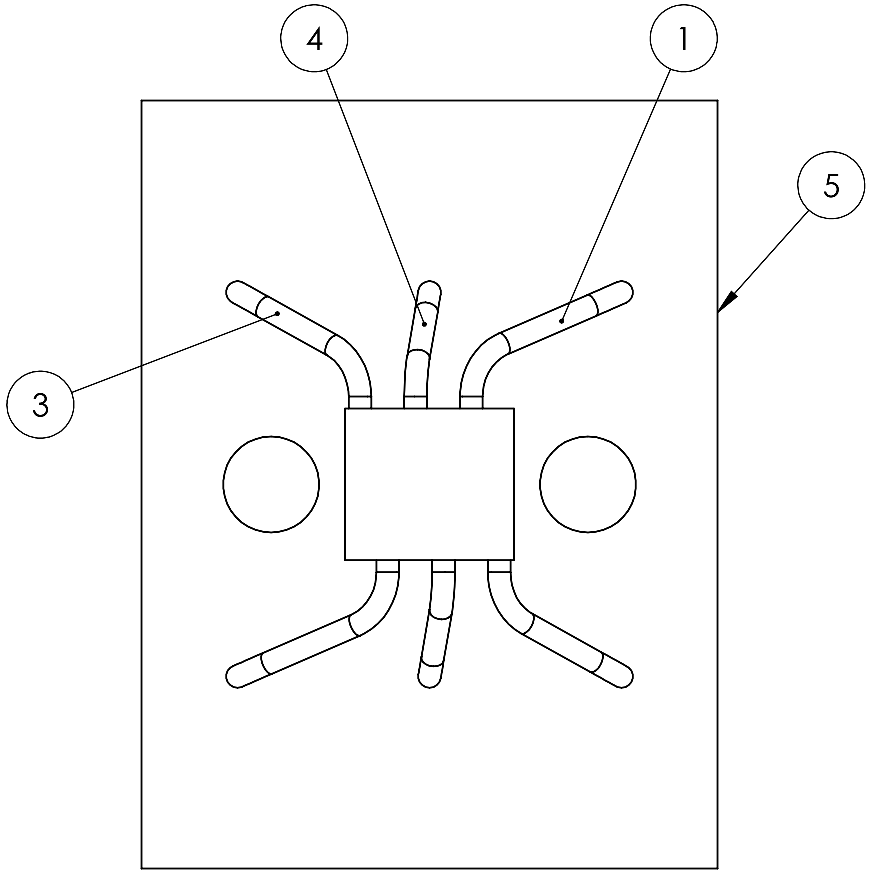


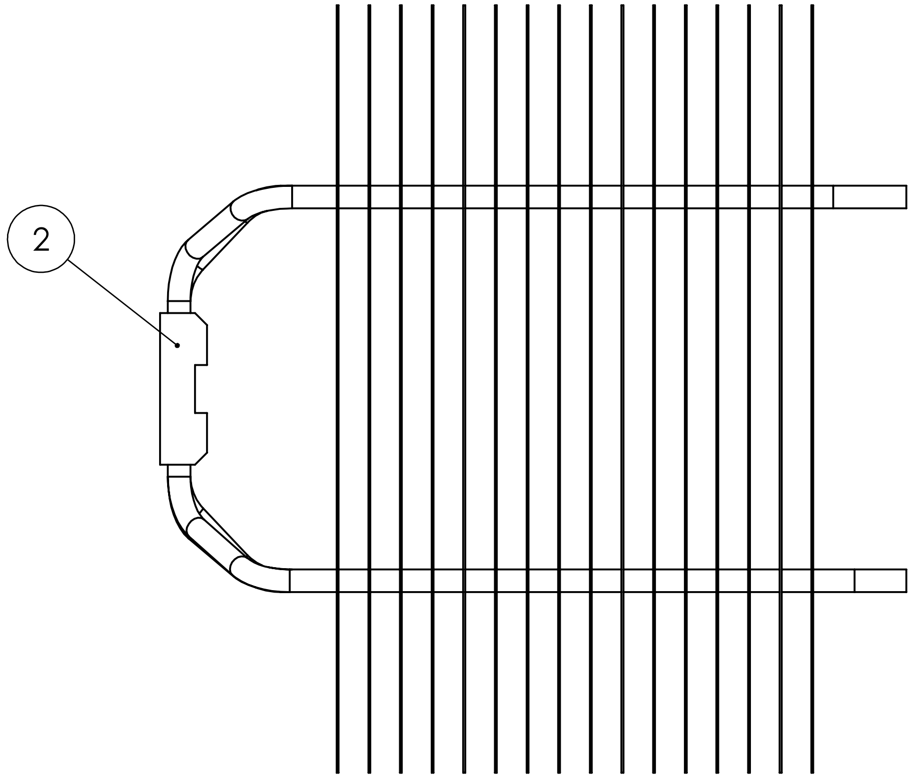
*HEAT FIN ARRAY EXCLUDED FOR CLARITY

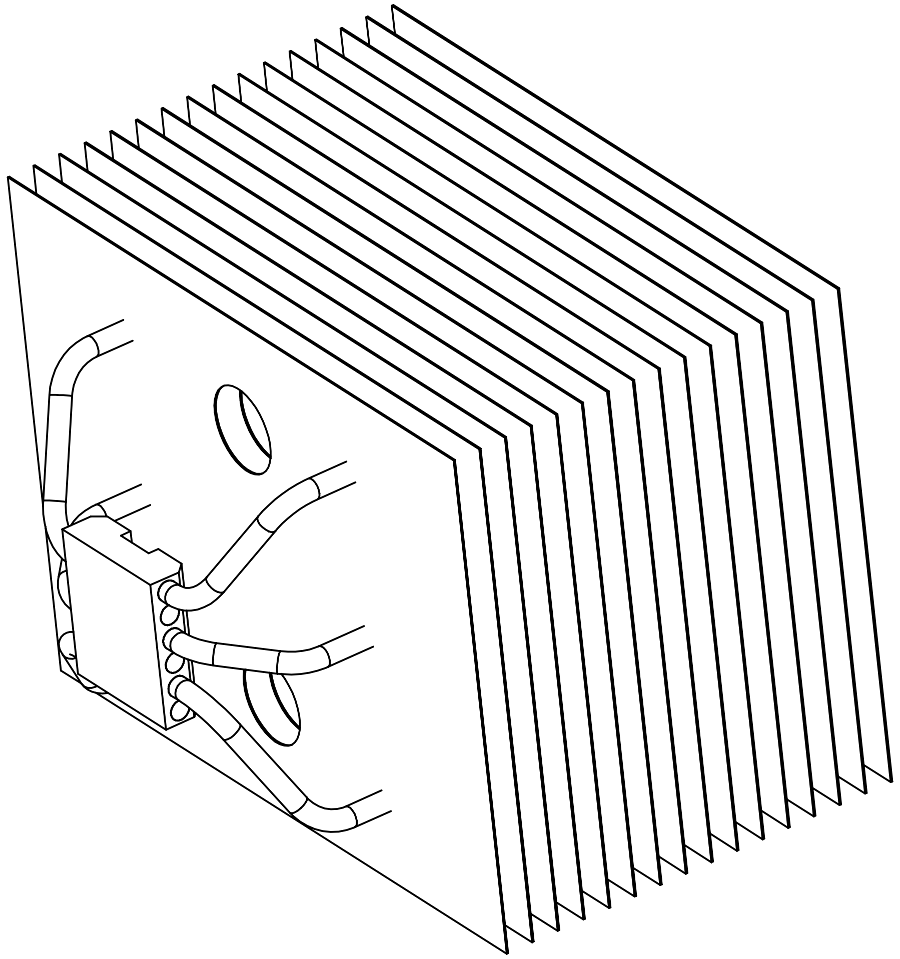
ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	1101	6 Pipe Base	1
2	1102	Heat Pipe A	2
3	1103	Heat Pipe B	2
4	1104	Heat Pipe C	2
5	1202	Crossbar	1
6	1203	Spring	4
7	1207	TEG	1
10	1201	Test Stand Base	1
11	1105	Heat Fin	1
12	1205	Washer	6
13	1204	Bolt	2
14	1206	Nut	2

Cal Poly Mechanical Engineering TEAM F16	SENIOR PROJECT		ASSEMBLY EXPLODED VIEW		Drwn. By: KADIN FELDIS
	1000E		1/26/22		Chkd. By: PEYTON NIENABER



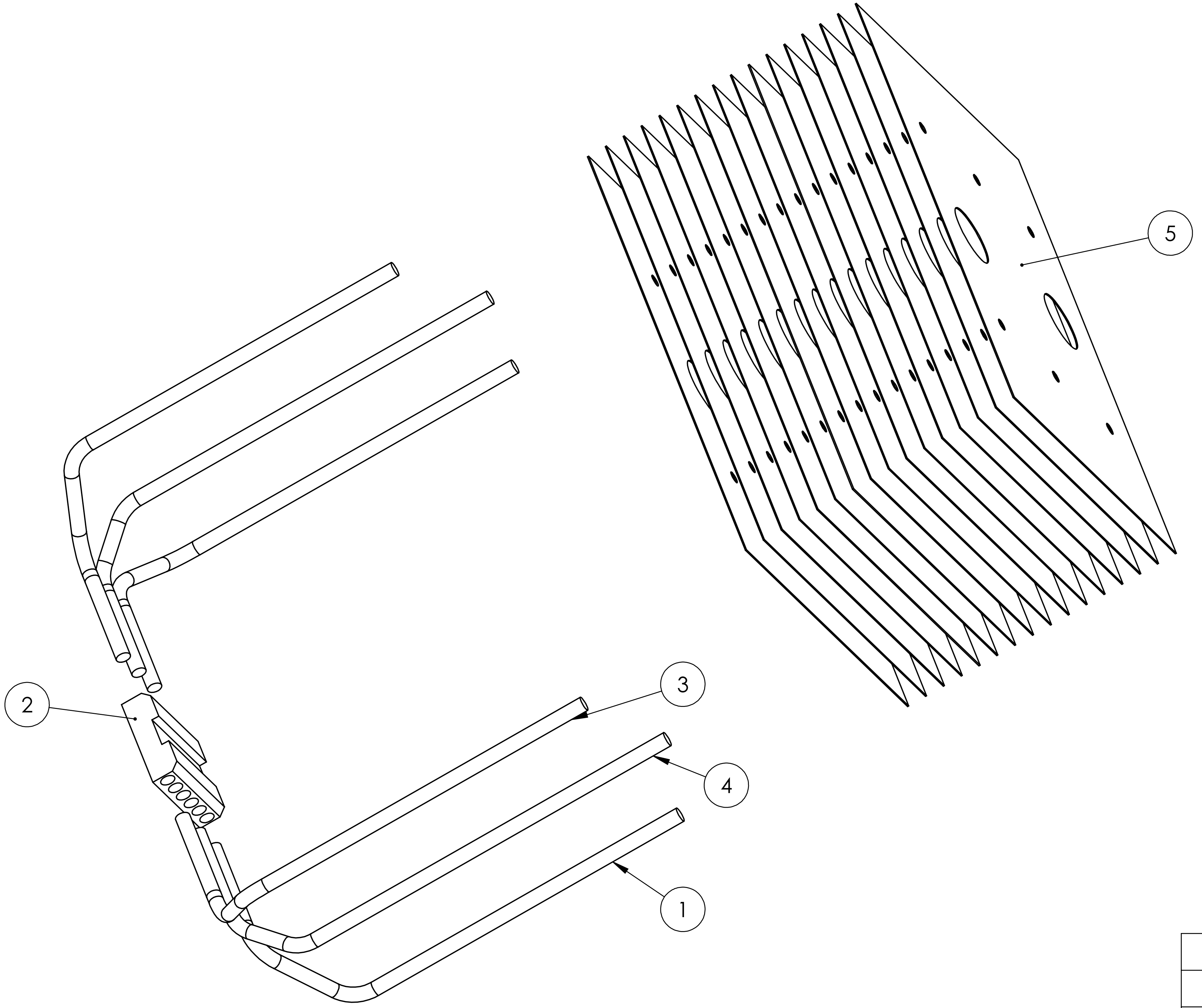






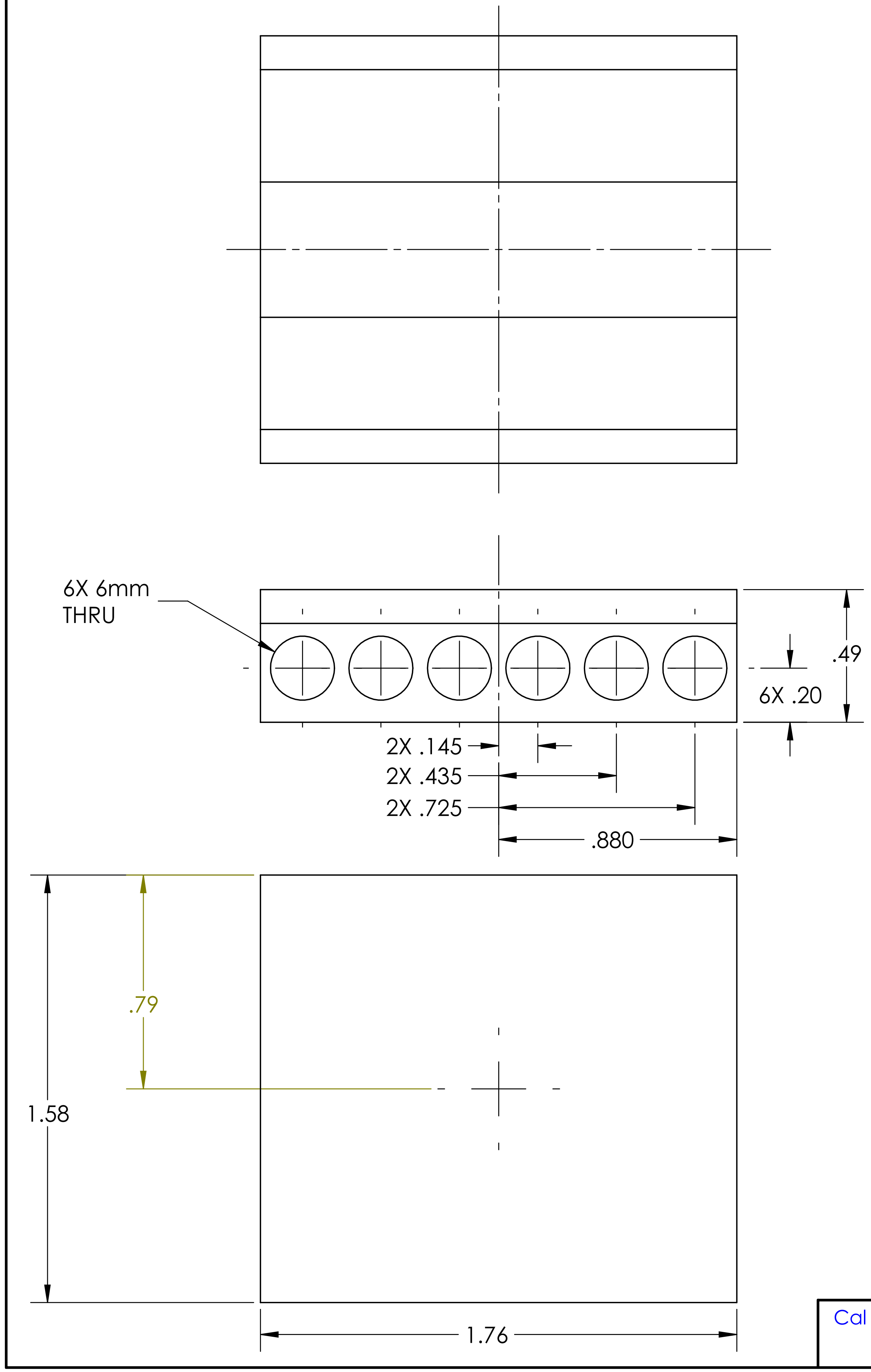
ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	1104	Heat Pipe C	2
2	1101	6 Pipe Base	1
3	1102	Heat Pipe A	2
4	1103	Heat Pipe B	2
5	1105	Heat Fin	16

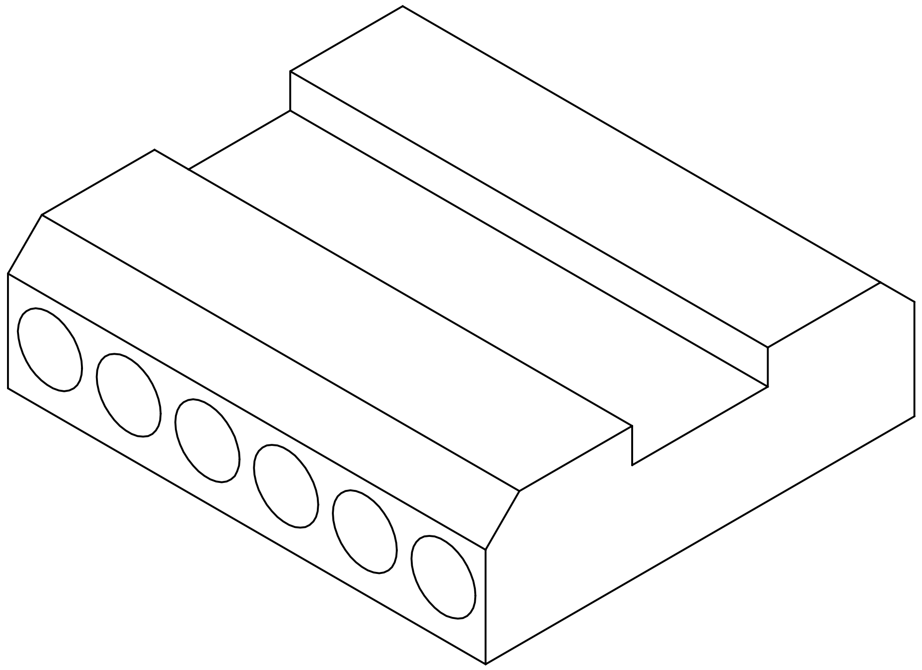
Cal Poly Mechanical Engineering TEAM F16	SENIOR PROJECT		HEAT SINK		Drwn. By: KADIN FELDIS
	1100		1/26/22		Chkd. By: PEYTON NIENABER

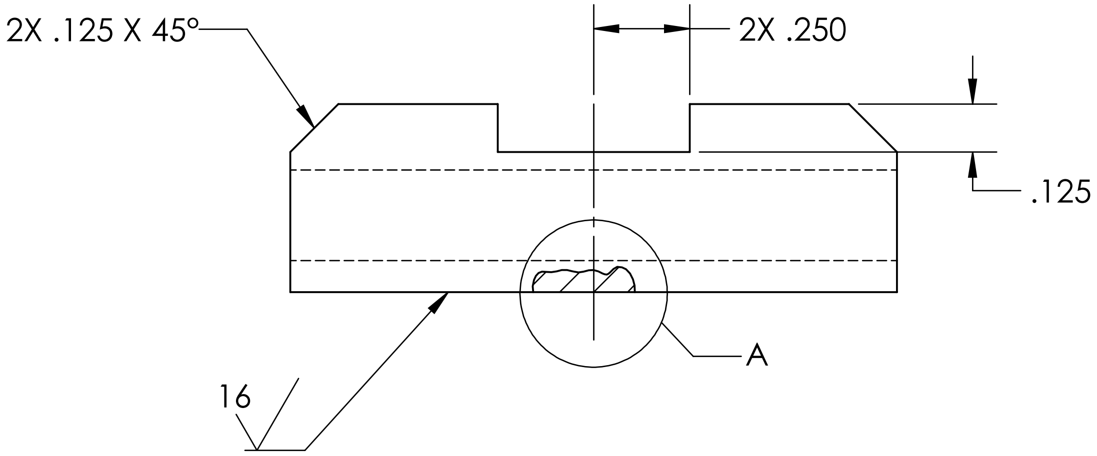


ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	1104	Heat Pipe C	2
2	1101	6 Pipe Base	1
3	1102	Heat Pipe A	2
4	1103	Heat Pipe B	2
5	1105	Heat Fin	16

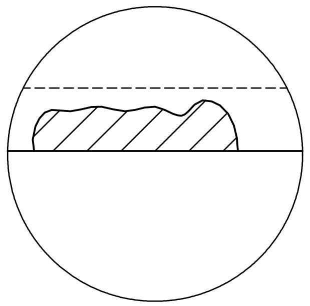
Cal Poly Mechanical Engineering TEAM F16	SENIOR PROJECT		HEAT SINK EXPLODED VIEW	Drwn. By: KADIN FELDIS
	1100E		1/27/22	Chkd. By: PEYTON NIENABER







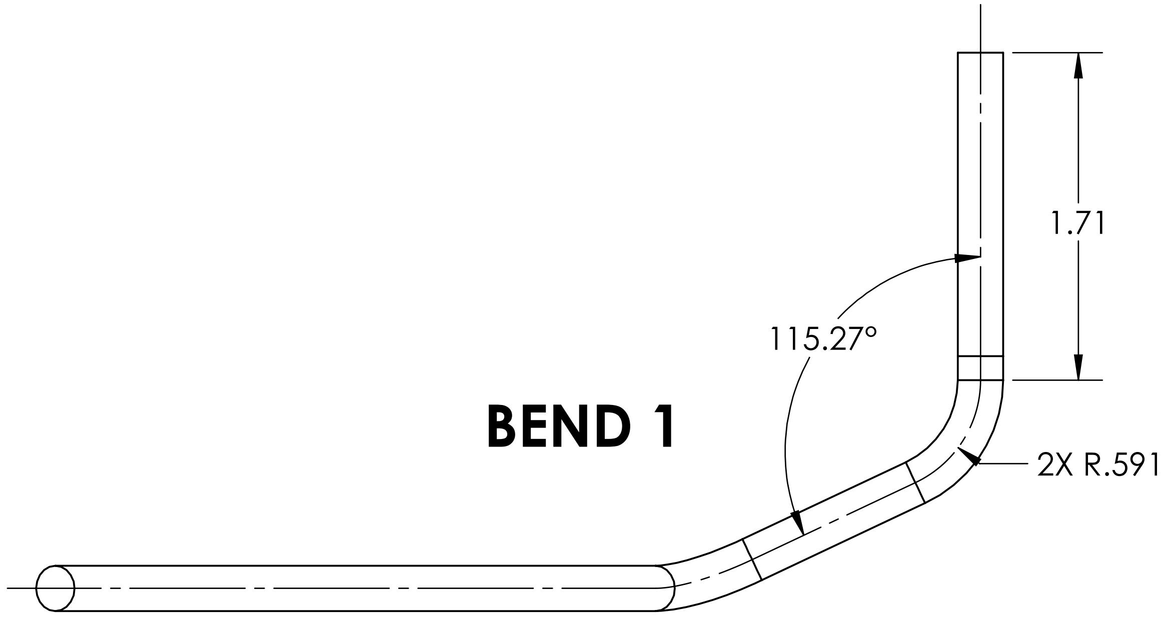
NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMENSIONS IN INCHES
2. TOLERANCES
   X.XX = ±.005
   X.XXX = ±0.002
   ANGLES = ±1 °
3. INSIDE TOOL RADIUS .01 MAX
4. BREAK SHARP EDGES .01 MAX
5. 32 √ FAO
6. CHECK HEAT PIPE FIT
7. CHECK TAPPED HOLES W/ THREAD GAUGE
8. THIS IS A MINIMALLY DIMENSIONED DRAWING PLEASE REFERENCE CAD FOR ANY MISSING DIMENSIONS OR COMPLEX FEATURES



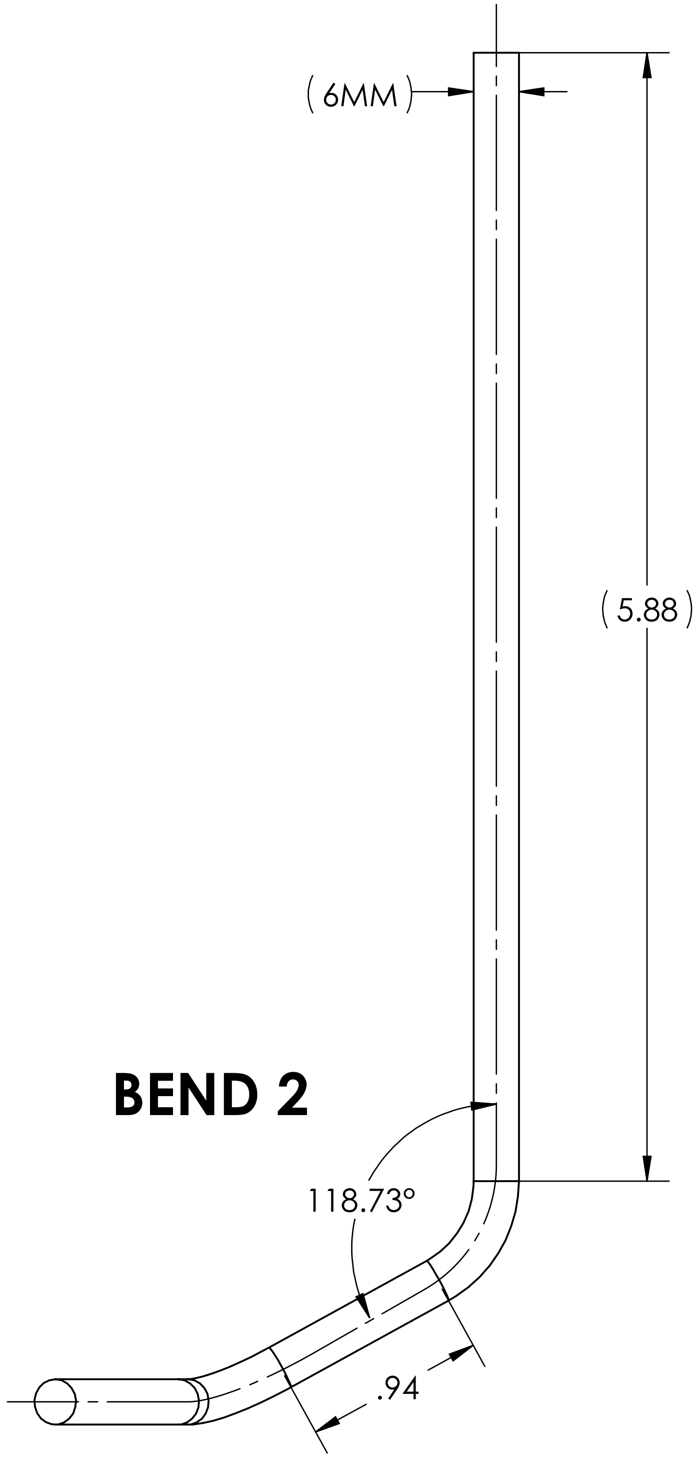
DETAIL A
SCALE 4 : 1

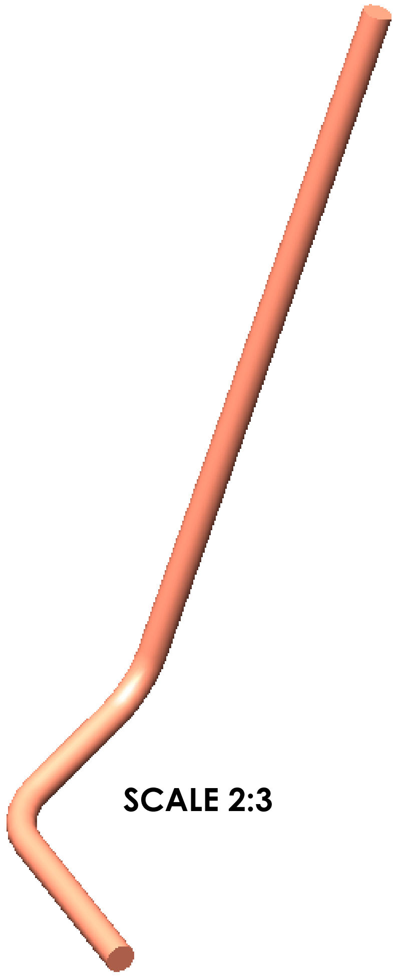
Cal Poly Mechanical Engineering TEAM F16	SENIOR PROJECT		6 Pipe Base		Drwn. By: KADIN FELDIS
	1101		1/25/22		Chkd. By: PEYTON NIENABER

BEND 1



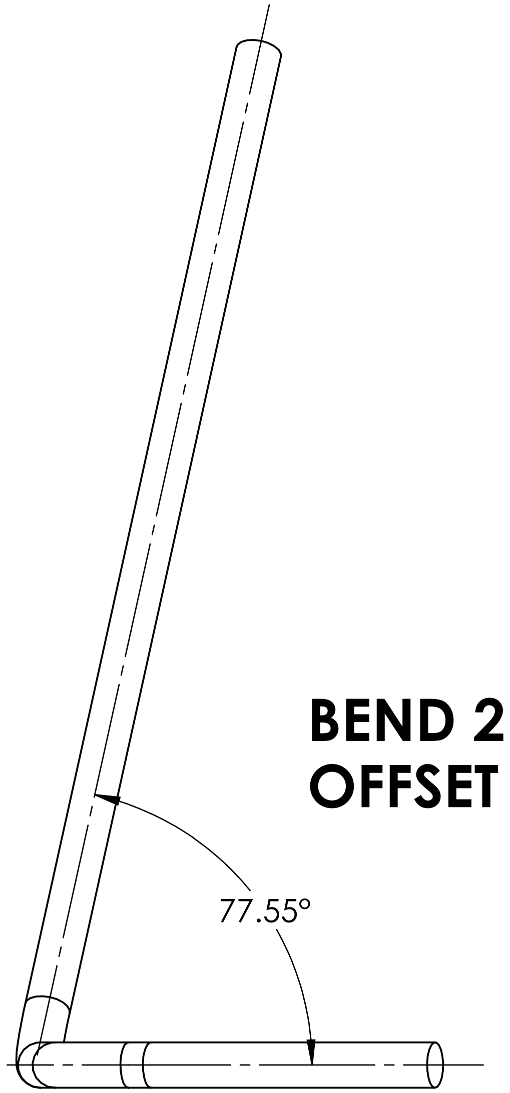
BEND 2





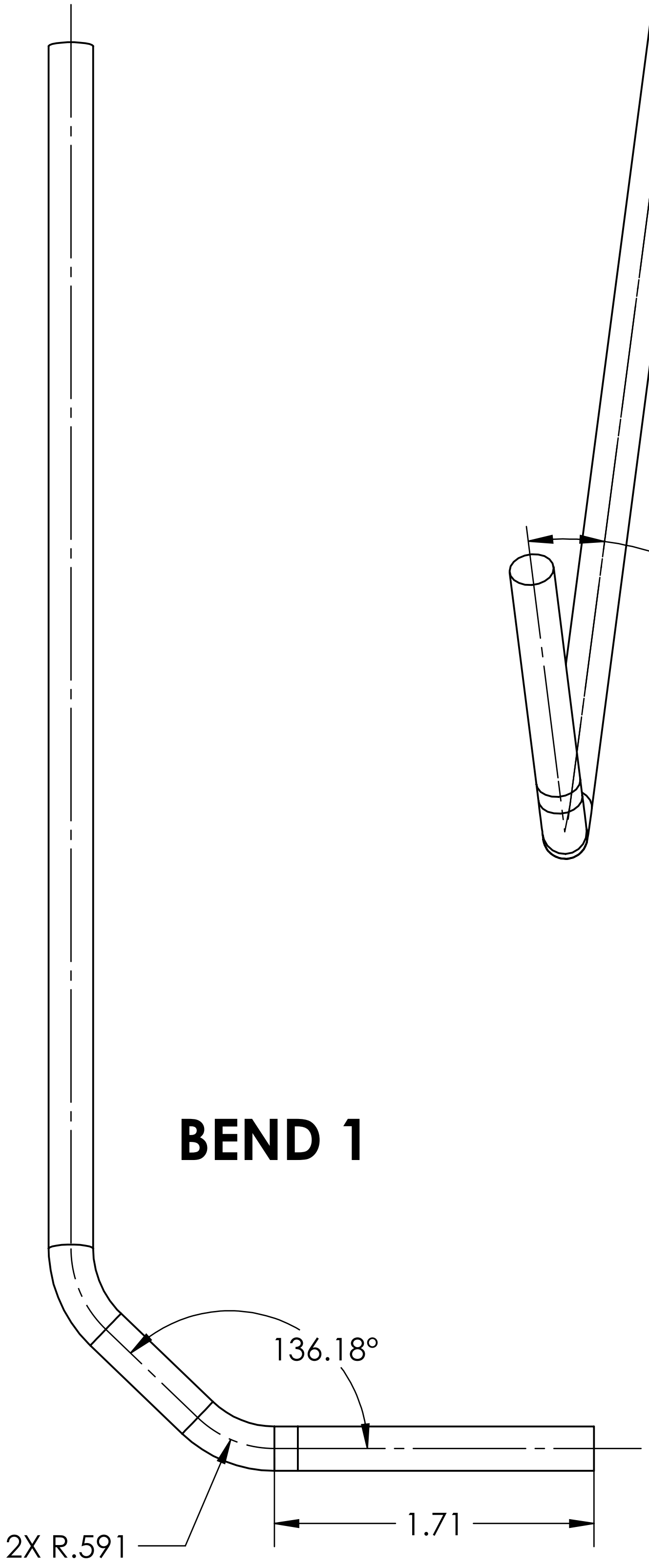
SCALE 2:3

BEND 2
OFFSET ANGLE

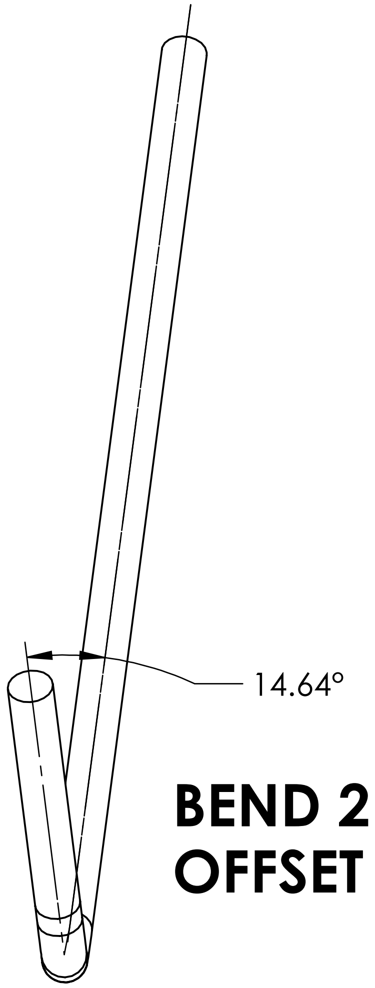


NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMENSIONS IN INCHES
2. TOLERANCES
   X.XX = ±.05
   X.XXX = ±0.002
   ANGLES = ±1.5°
3. INSIDE TOOL RADIUS .01 MAX
4. BREAK SHARP EDGES .01 MAX
5. USE 6MM X 250MM SINTERED WICK HEAT PIPES
6. THIS IS A MINIMALLY DIMENSIONED DRAWING PLEASE REFERENCE CAD FOR ANY MISSING DIMENSIONS OR COMPLEX FEATURES

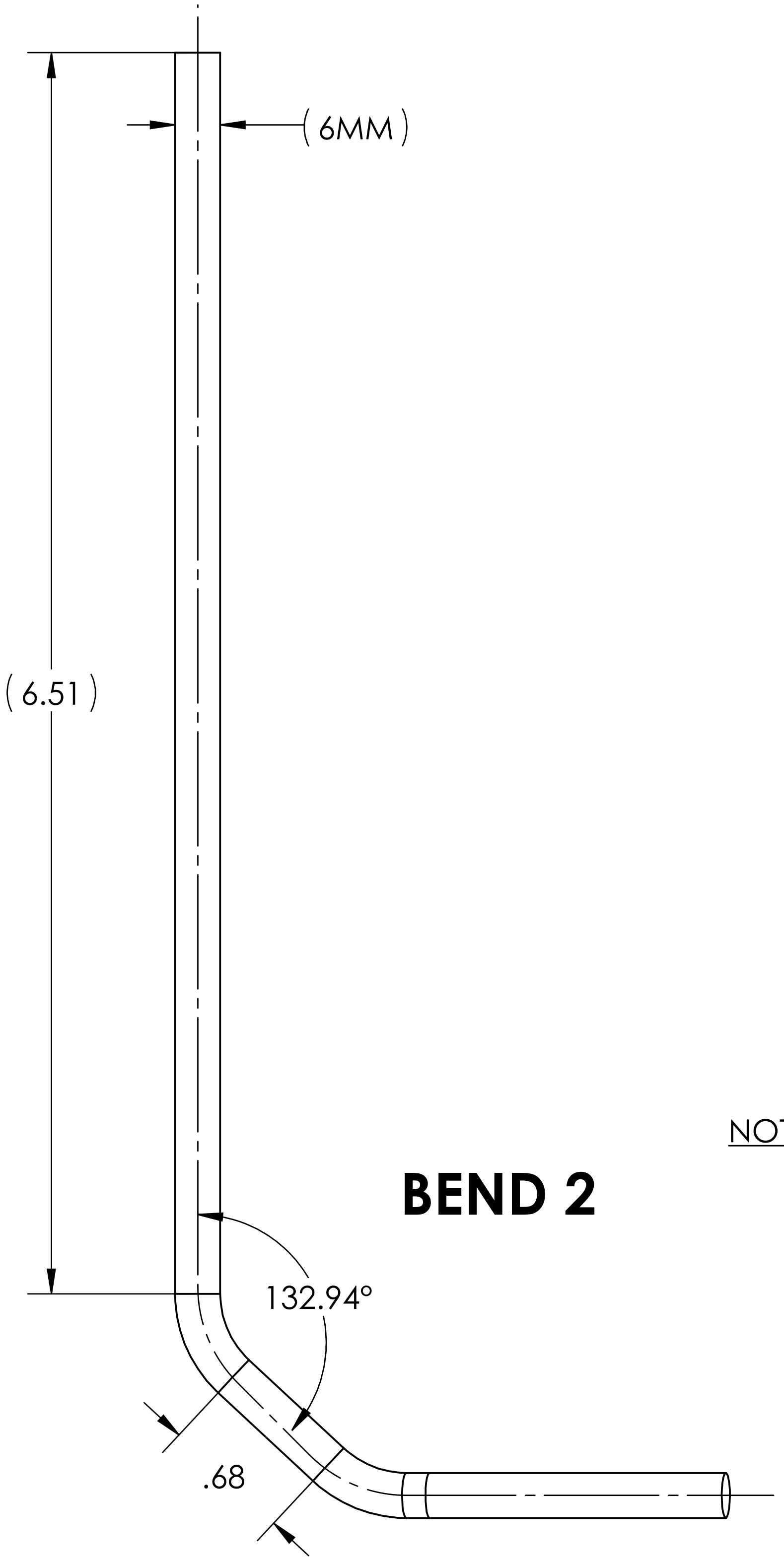
Cal Poly Mechanical Engineering TEAM F16	SENIOR PROJECT		HEAT PIPE A		Drwn. By: KADIN FELDIS
	1102		1/27/22	SCALE: 1:1	Chkd. By: PEYTON NIENABER



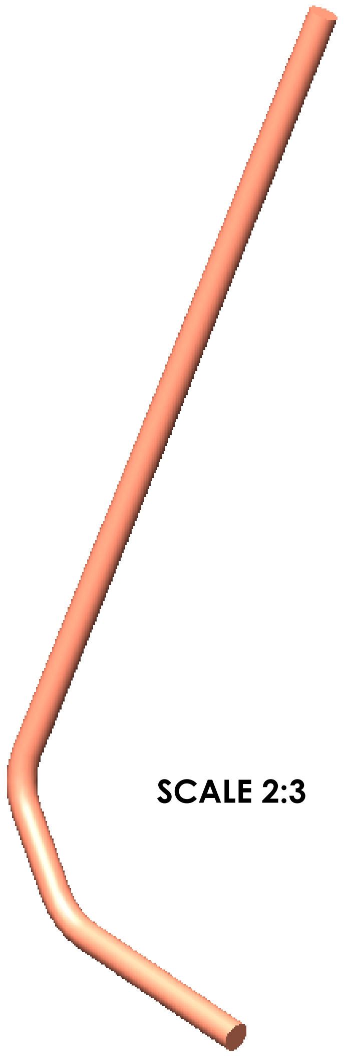
BEND 1



BEND 2
OFFSET ANGLE



BEND 2

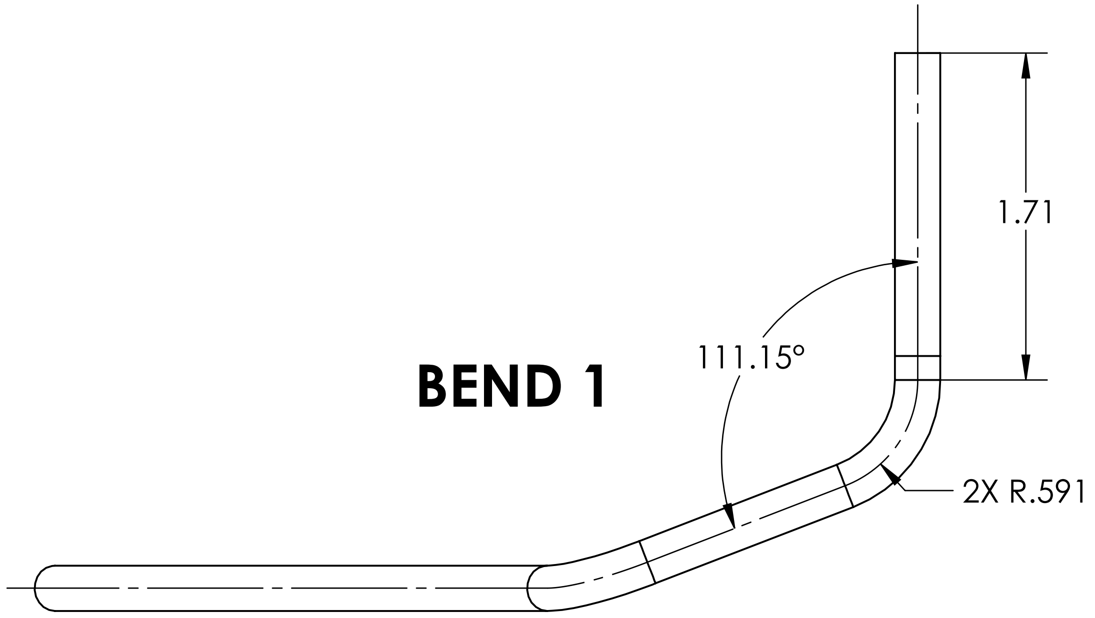


SCALE 2:3

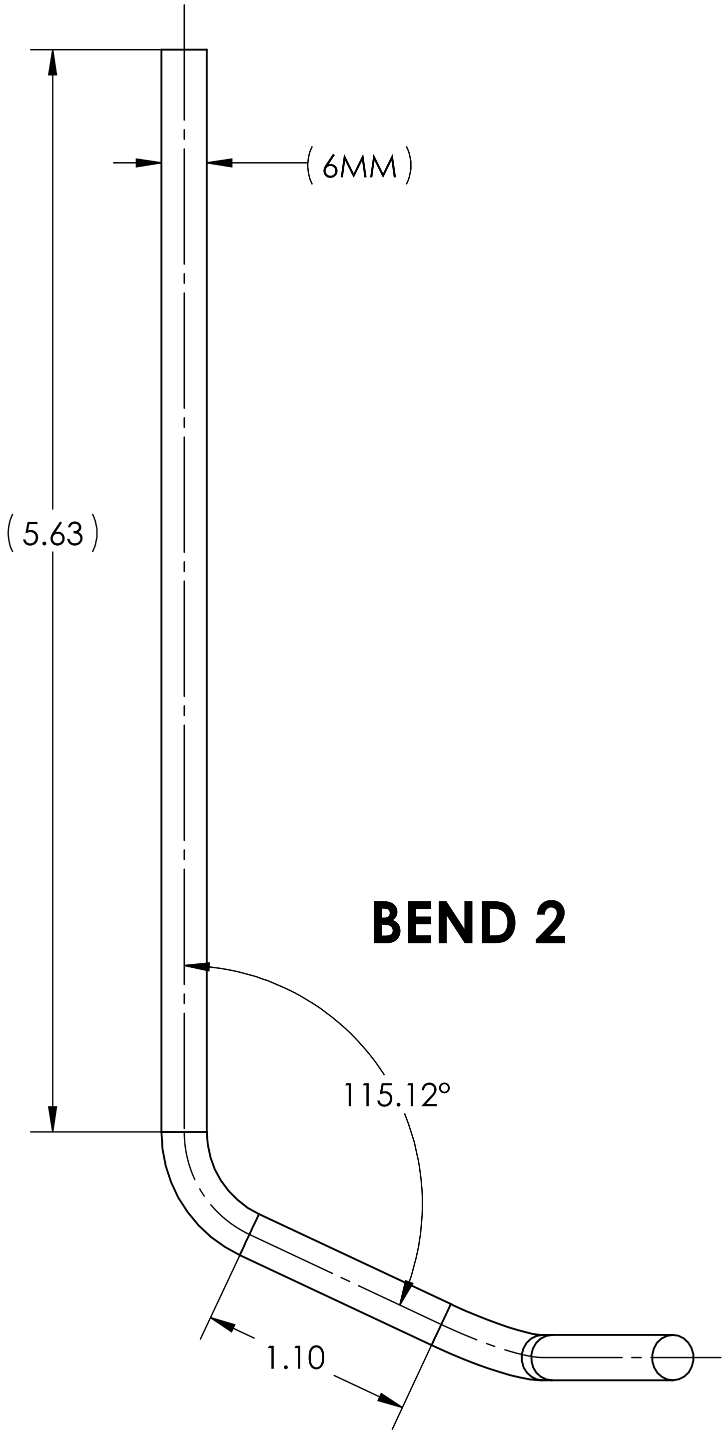
NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMENSIONS IN INCHES
2. TOLERANCES
   X.XX = ±.05
   X.XXX = ±0.002
   ANGLES = ±1.5°
3. INSIDE TOOL RADIUS .01 MAX
4. BREAK SHARP EDGES .01 MAX
5. USE 6MM X 250MM SINTERED WICK HEAT PIPES
6. THIS IS A MINIMALLY DIMENSIONED DRAWING PLEASE REFERENCE CAD FOR ANY MISSING DIMENSIONS OR COMPLEX FEATURES

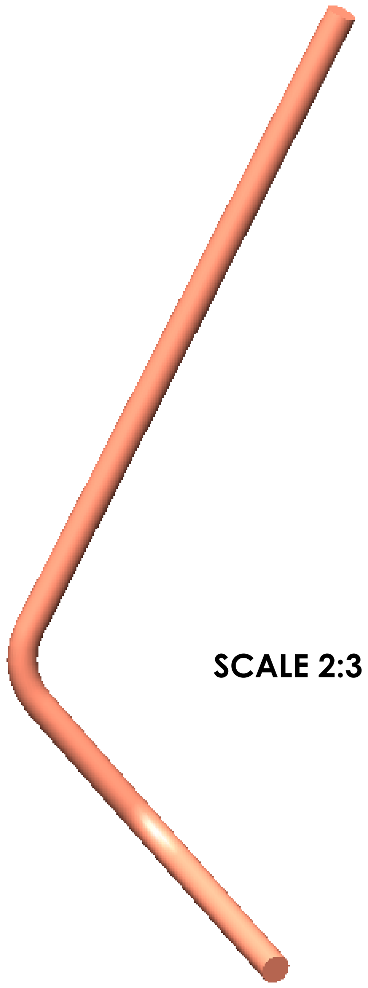
Cal Poly Mechanical Engineering TEAM F16	SENIOR PROJECT		HEAT PIPE B		Drwn. By: KADIN FELDIS
	1103		1/27/22		Chkd. By: PEYTON NIENABER

BEND 1



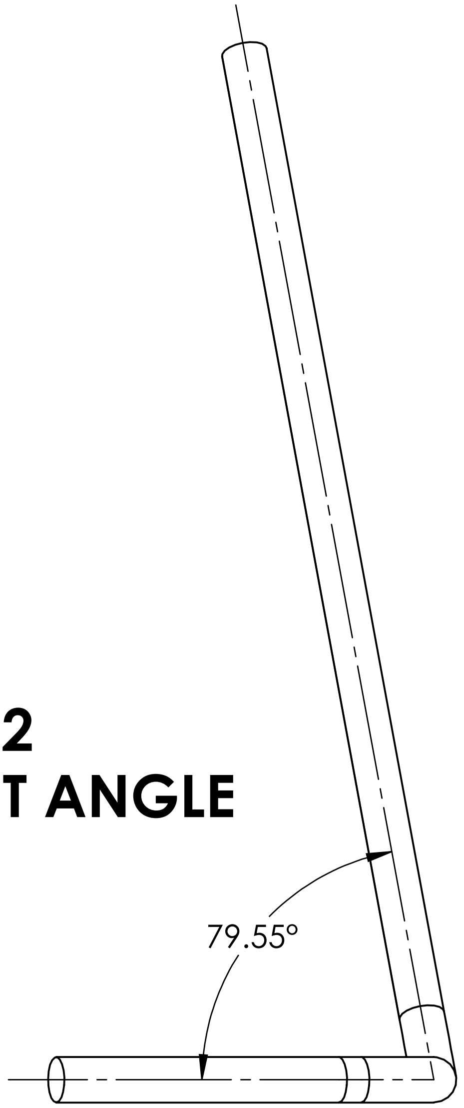
BEND 2





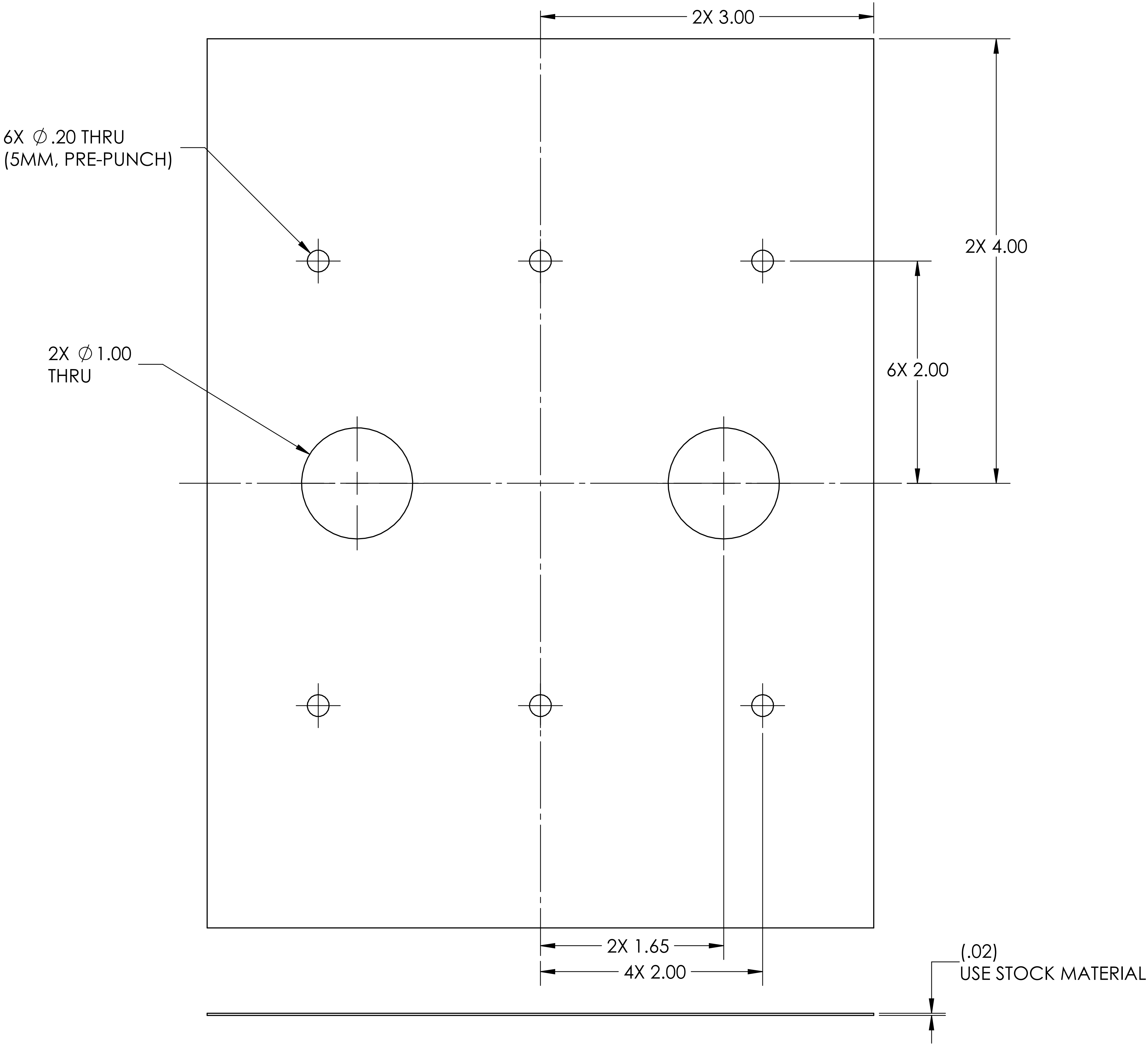
SCALE 2:3

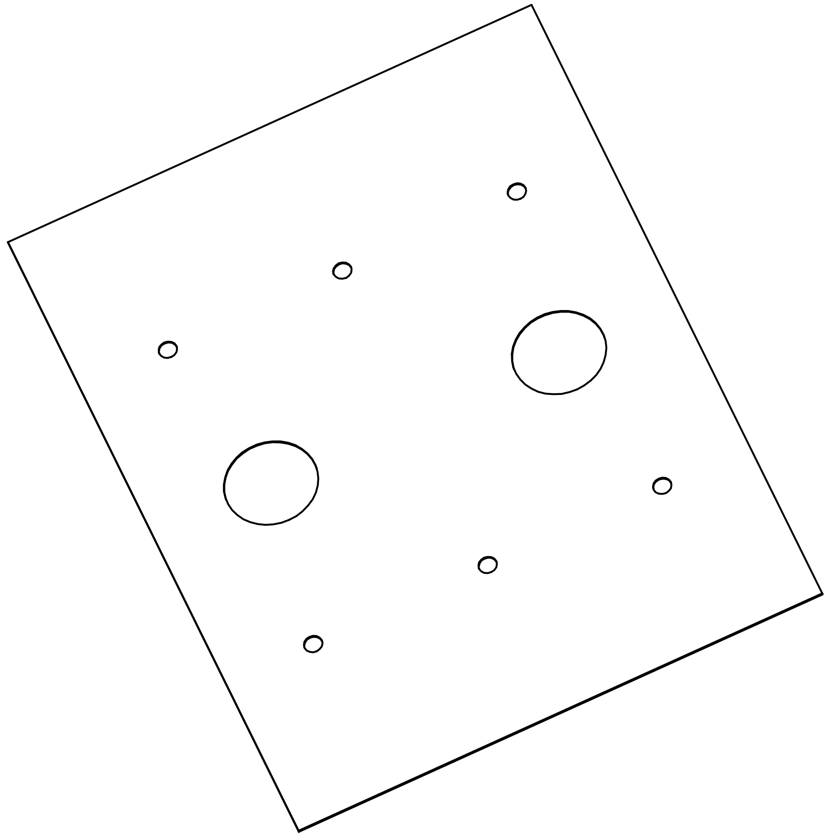
BEND 2
OFFSET ANGLE



NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMENSIONS IN INCHES
2. TOLERANCES
    X.XX = ±.05
    X.XXX = ±0.002
    ANGLES = ±1.5°
3. INSIDE TOOL RADIUS .01 MAX
4. BREAK SHARP EDGES .01 MAX
5. USE 6MM X 250MM SINTERED WICK HEAT PIPES
6. THIS IS A MINIMALLY DIMENSIONED DRAWING
PLEASE REFERENCE CAD FOR ANY MISSING
DIMENSIONS OR COMPLEX FEATURES

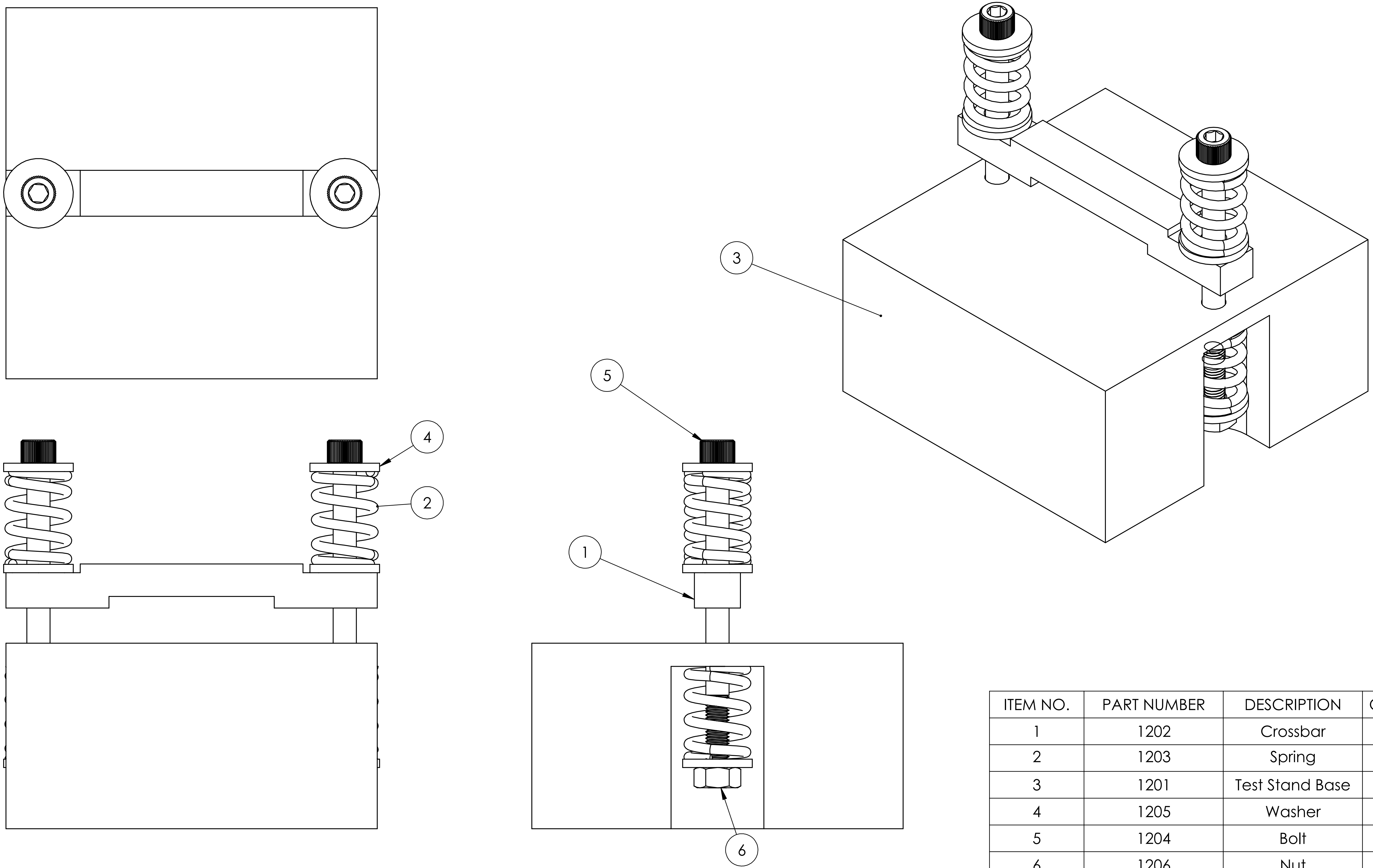
Cal Poly Mechanical Engineering TEAM F16	SENIOR PROJECT		HEAT PIPE C		Drwn. By: KADIN FELDIS
	1104		1/27/22		Chkd. By: PEYTON NIENABER





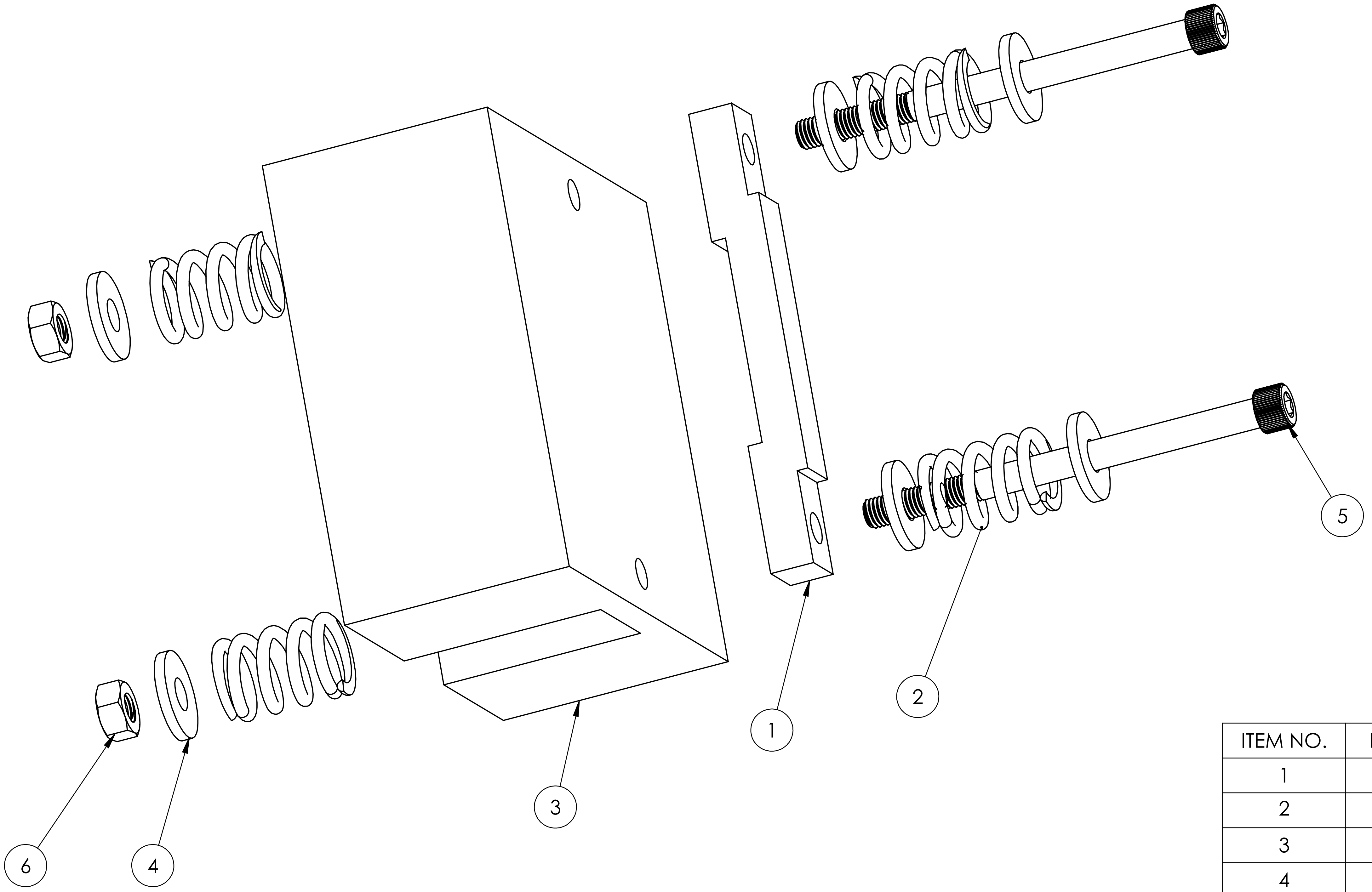
NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMENSIONS IN INCHES
2. TOLERANCES
   X.XX = ±.05
   X.XXX = ±0.002
   ANGLES = ±1.5°
3. INSIDE TOOL RADIUS .01 MAX
4. BREAK SHARP EDGES .01 MAX
5. THIS IS A MINIMALLY DIMENSIONED DRAWING
   PLEASE REFERENCE CAD FOR ANY MISSING
   DIMENSIONS OR COMPLEX FEATURES

Cal Poly Mechanical Engineering TEAM F16	SENIOR PROJECT		HEAT PIPE C		Drwn. By: KADIN FELDIS
	1104		1/27/22		Chkd. By: PEYTON NIENABER



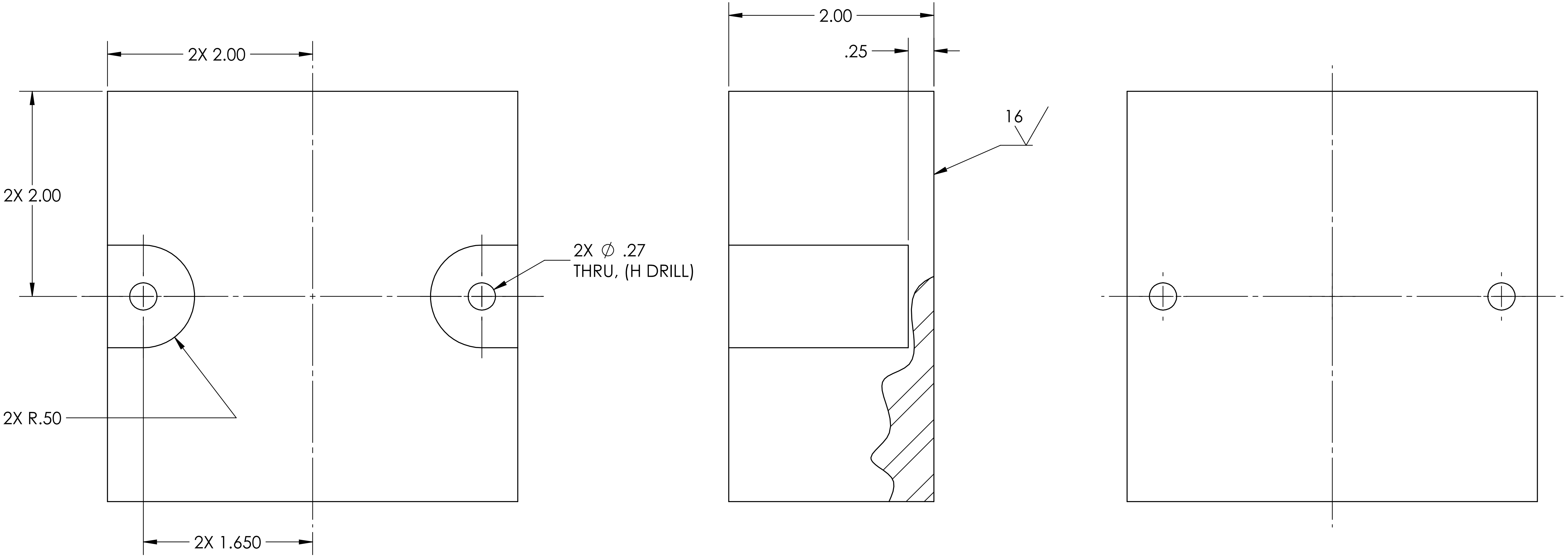
ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	1202	Crossbar	1
2	1203	Spring	4
3	1201	Test Stand Base	1
4	1205	Washer	6
5	1204	Bolt	2
6	1206	Nut	2

Cal Poly Mechanical Engineering
TEAM F16
SENIOR PROJECT
1200
TEST JIG
1/26/22
Drwn. By: KADIN FELDIS
Chkd. By: PEYTON NIENABER



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	1202	Crossbar	1
2	1203	Spring	4
3	1201	Test Stand Base	1
4	1205	Washer	6
5	1204	Bolt	2
6	1206	Nut	2

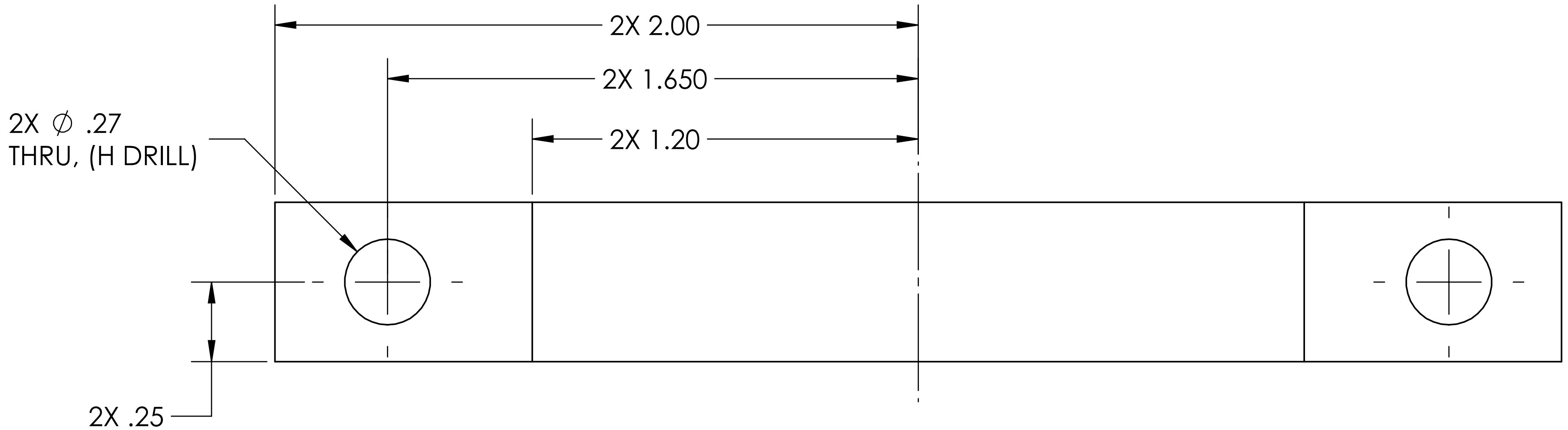
Cal Poly Mechanical Engineering TEAM F16	SENIOR PROJECT		TEST JIG EXPLODED VIEW		Drwn. By: KADIN FELDIS
	1200E		1/26/22		Chkd. By: PEYTON NIENABER

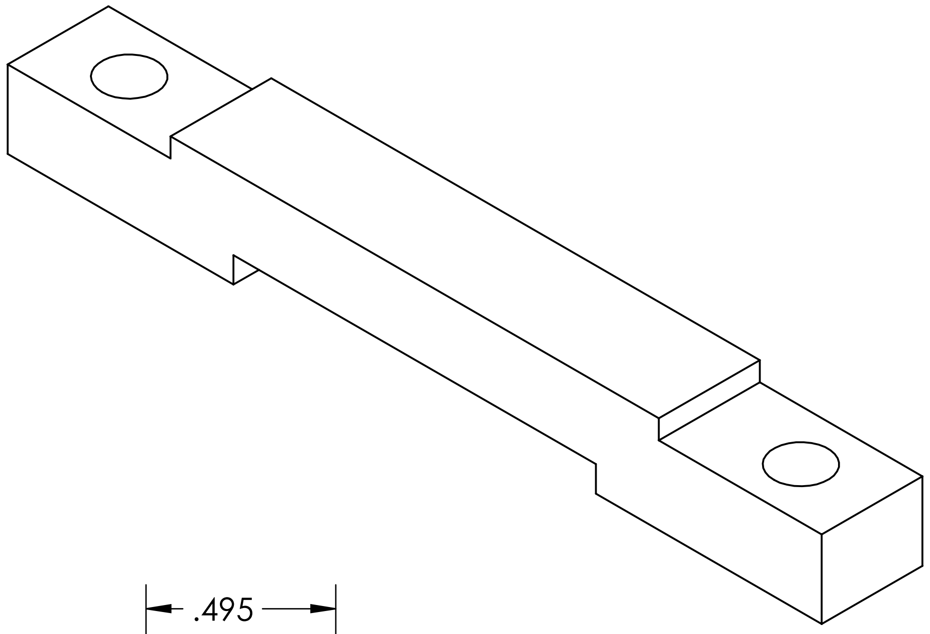


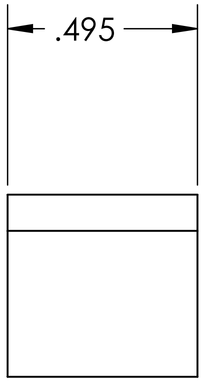
NOTES

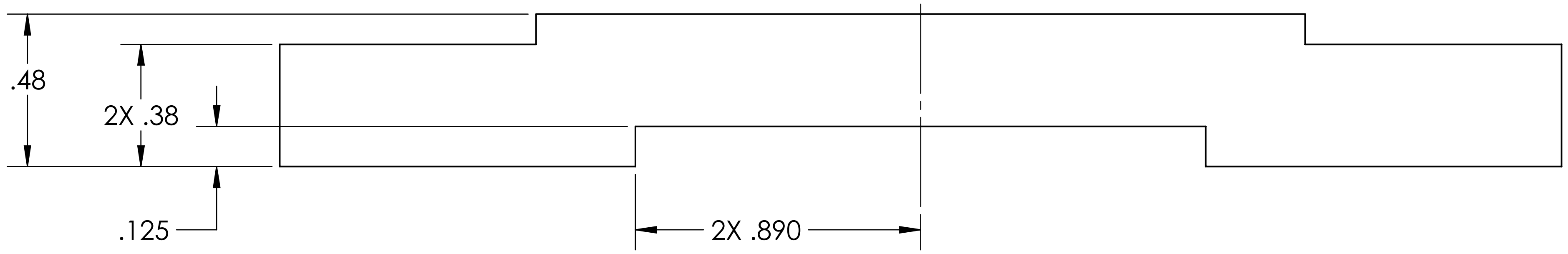
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMENSIONS IN INCHES
2. TOLERANCES
    X.XX = ±.005
    X.XXX = ±0.002
    ANGLES = ±1°
3. INSIDE TOOL RADIUS .01 MAX
4. BREAK SHARP EDGES .01 MAX
5. 32√ FAO
6. CHECK 1/4-28 BOLT CLEARANCE FIT
7. CHECK FIT WITH CROSSBAR
8. THIS IS A MINIMALLY DIMENSIONED DRAWING PLEASE REFERENCE CAD FOR ANY MISSING DIMENSIONS OR COMPLEX FEATURES

Cal Poly Mechanical Engineering TEAM F16	SENIOR PROJECT		TEST STAND BASE		Drwn. By: KADIN FELDIS
	1201		1/25/22		Chkd. By: PEYTON NIENABER



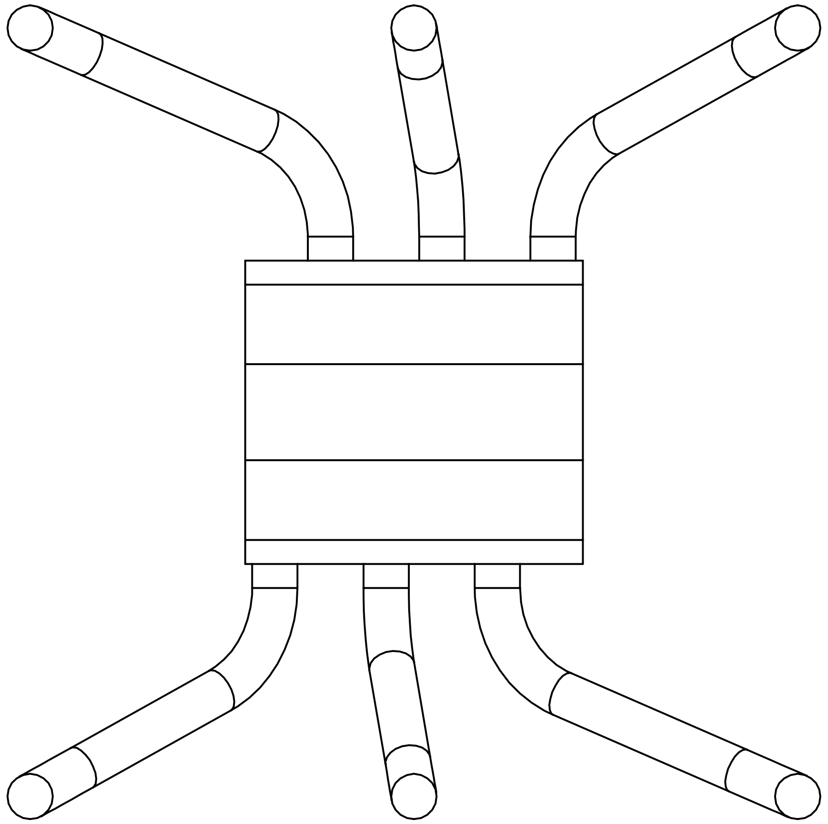






NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMENSIONS IN INCHES
2. TOLERANCES
    X.XX = ±.005
    X.XXX = ±0.002
    ANGLES = ±1°
3. INSIDE TOOL RADIUS .01 MAX
4. BREAK SHARP EDGES .01 MAX
5. 32 √ FAO
6. CHECK 1/4-28 BOLT CLEARANCE FIT
7. CHECK FIT WITH HEATSINK BASE
8. THIS IS A MINIMALLY DIMENSIONED DRAWING
PLEASE REFERENCE CAD FOR ANY MISSING
DIMENSIONS OR COMPLEX FEATURES

Cal Poly Mechanical Engineering TEAM F16	SENIOR PROJECT	CROSSBAR	Drwn. By: KADIN FELDIS
	1202	1/25/22	Chkd. By: PEYTON NIENABER



*HEAT PIPE BEND REFERENCE

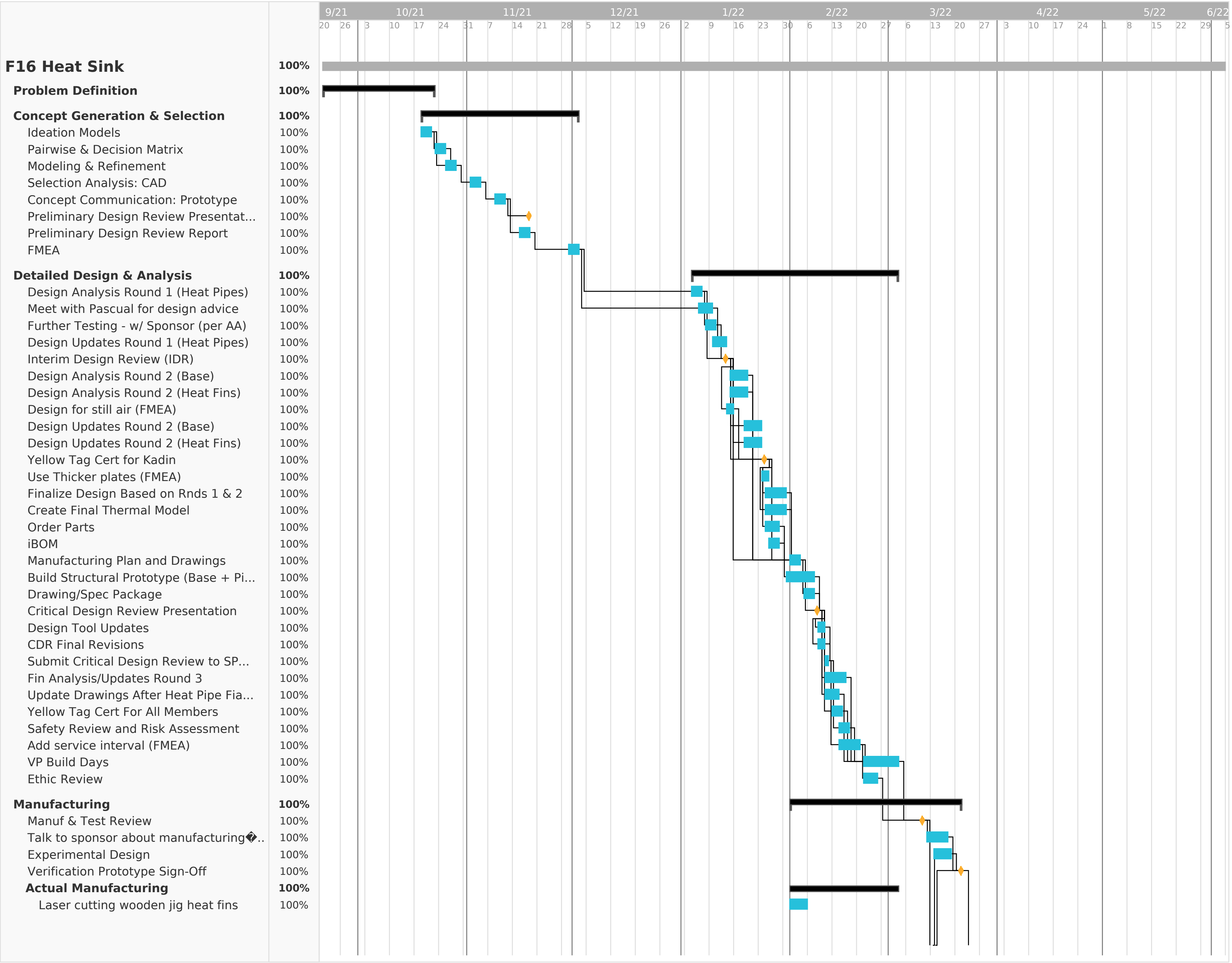
Cal Poly Mechanical Engineering TEAM F16			Title: BEND REF. 1	Drwn. By: KADIN FELDIS
			Scale: 1=1	

Appendix F - Bill of Materials and team Budget

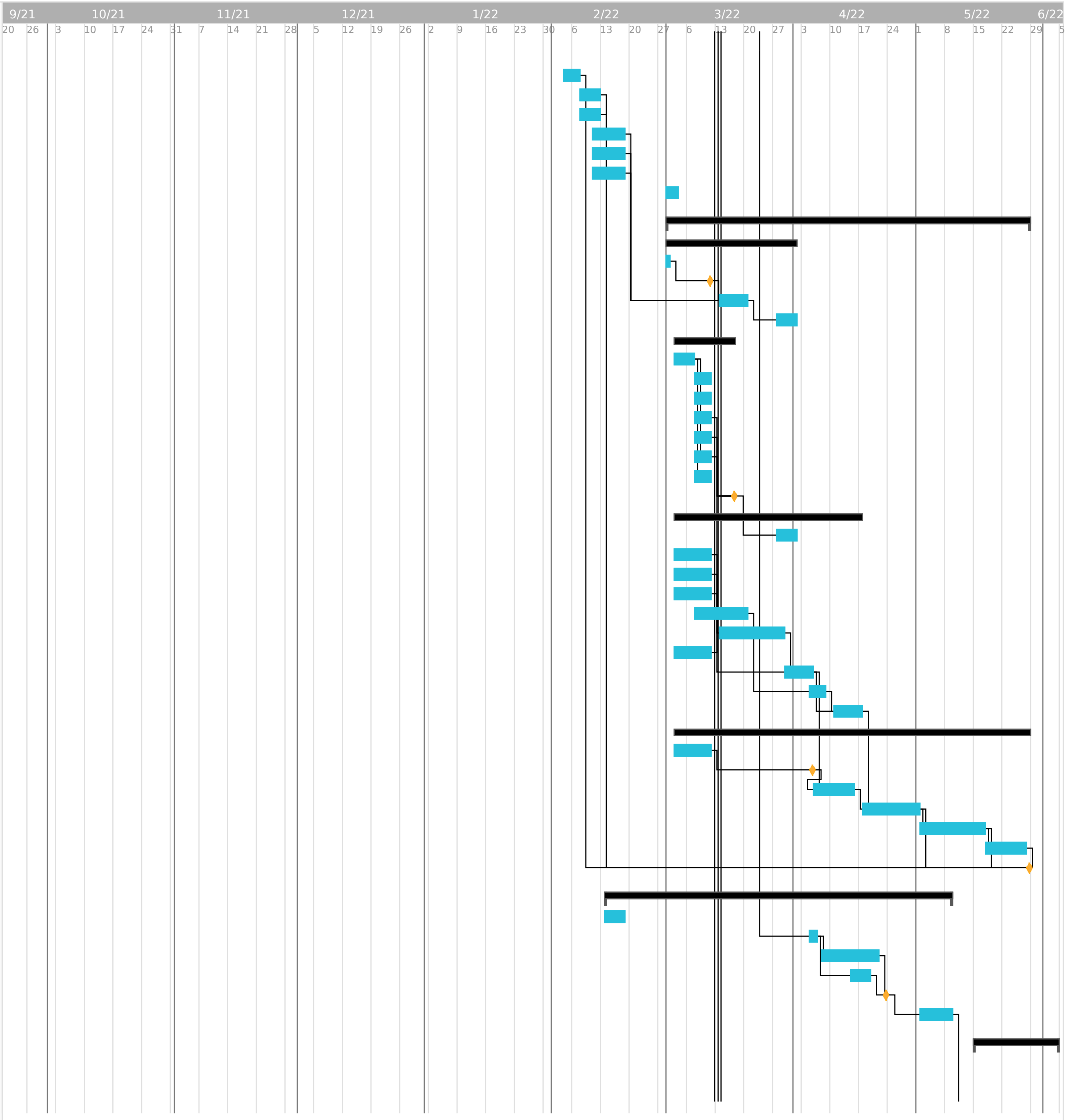
Team F16 BUDGET

Description of Item	Vendor	Vendor Part #	Part #	Material Price	Shipping/Handling/Tax	Procurement	Account Used	Date Purchased	Current Location
Rental Car to LA	Enterprise Car Rentals	N/A	N/A	$ 42.00	$ -	Team Reimbursement	Cal Poly	10/19/2021	N/A
Rental Car Gas	Chevron Gas	N/A	N/A	$ 62.21	$ -	Team Reimbursement	Cal Poly	10/19/2021	N/A
Dual Input Thermometer	Harbor Freight	N/A	N/A	$ 89.92	$ 7.87	Team Reimbursement	Cal Poly	12/9/2021	GTI
Kill-a-Watt Electric Monitor	Harbor Freight	N/A	N/A	$ 25.99	$ 2.27	Team Reimbursement	Cal Poly	12/9/2021	GTI
Single Electric Burner	Miner's Ace Hardware	N/A	N/A	$ 32.99	$ 2.89	Team Reimbursement	Cal Poly	12/9/2021	GTI
Multi Purpose Foil	Home Depot	1541239	N/A	$ 7.88	$ 0.69	Team Reimbursement	Cal Poly	12/9/2021	GTI
Copper Block	McMaster Carr	8964K42	1101	$ 60.02	$ 4.20	ME Pro-Card	Cal Poly	1/24/2022	GTI
16 6mm Heat Pipes	McMaster Carr	3874N23	1102/3/4	$ 125.12	$ 8.76	ME Pro-Card	Cal Poly	1/24/2022	GTI
Aluminum Sheet	McMaster Carr	8973K286	1105	$ 103.82	$ 7.27	Sponsor	GTI	1/27/2022	GTI
Set Screws	McMaster Carr	90669A189	1106	$ 11.57	$ 0.81	Sponsor	GTI	1/27/2022	GTI
Steel Block	McMaster Carr	6620K312	1201	$ 124.86	$ 8.74	Sponsor	GTI	1/27/2022	GTI
Steel Bar	McMaster Carr	8892K59	1202	$ 32.72	$ 2.29	Sponsor	GTI	1/27/2022	GTI
Spring Pack	McMaster Carr	9657K487	1203	$ 8.91	$ 0.62	Sponsor	GTI	1/27/2022	GTI
Bolts	McMaster Carr	92196A342	1204	$ 2.33	$ 0.16	Sponsor	GTI	1/27/2022	GTI
Washer	McMaster Carr	91525A416	1205	$ 10.65	$ 0.75	Sponsor	GTI	1/27/2022	GTI
Nut	McMaster Carr	90499A805	1206	$ 4.70	$ 0.33	Sponsor	GTI	1/27/2022	GTI
Thermal Compound	McMaster Carr	3715N12	N/A	$ 57.89	$ 4.05	Sponsor	GTI	1/27/2022	GTI
6mm Pipe Bender	Swagelok	MS-HTB	6M	$ 213.00	$ 14.91	Sponsor	GTI	2/10/2022	GTI
1 lb. 91%Tin 9%Zinc Solid Wire Solder .031"	H&N Store	N/A	N/A	$ 53.10	$ 3.72	Sponsor	GTI	4/7/2022	Kadin Feldis's Residence
8 fl. oz. Superior No.1261 Aluminum Soldering Flux Viscous Liquid	H&N Store	N/A	N/A	$ 32.50	$ 2.28	Sponsor	GTI	4/7/2022	Kadin Feldis's Residence
Shipping	USPS	N/A	N/A	N/A	$ 89.89	Sponsor	GTI	5/31/2022	GTI
								Total	$ 1,264.67

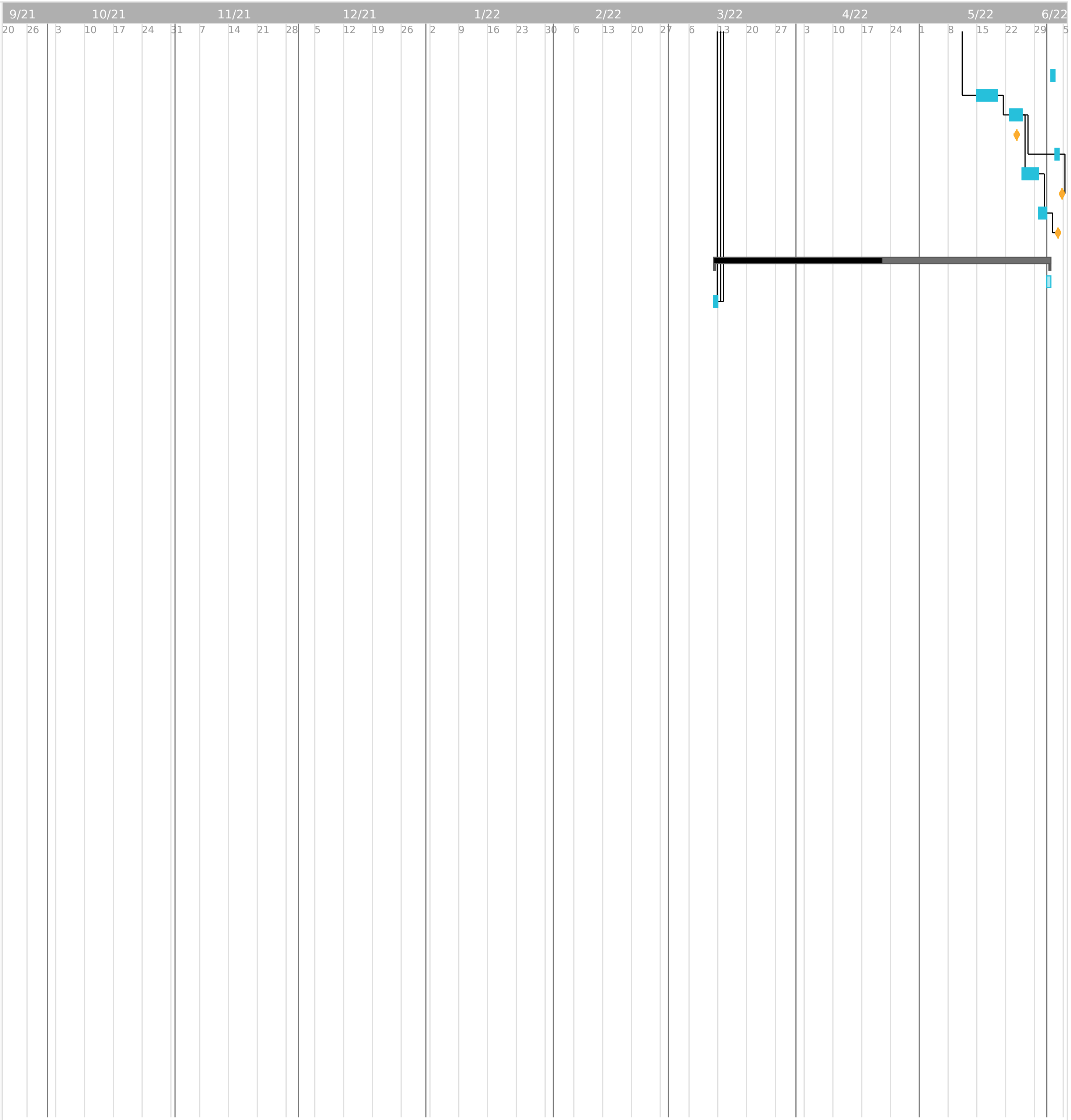
Appendix G - Gantt Chart



Milling the Copper Base	100%
Milling the crossbar	100%
Milling Test Stand Base	100%
Bending Heat Pipe A Prototype	100%
Bending Heat Pipe B Prototype	100%
Bending Heat Pipe C Prototype	100%
Reaching out to Dakota for waterje...	100%
Final Prototype Roadmap	**100%**
Heat Pipes	**100%**
Experimental Heat Pipe Thermal C...	100%
Receive Tube Bender	100%
Bend Heat Pipes	100%
Determine Final Positions of Heat P...	100%
Heat Fin Design	**100%**
Calc Free Convection Coefficient	100%
Finalize Ansys Thermal Sims	100%
Fin Spacing	100%
Fin Quantity	100%
Fin Thickness	100%
External Fin Dimensions	100%
Verify 2000 Series Aluminum	100%
Order Aluminum	100%
Heat Fin Manufacturing	**100%**
Update CAD Heat Fins	100%
Select Water Jet Hole Diameter	100%
Determine Brazing Clearance	100%
Select Punch and Punch Machine	100%
Design Heat Fin Bending Jig	100%
Design Test Tokens	100%
Select Alloy for Heat Fins	100%
Manufacture Test Tokens	100%
Manufacture Heat Fin bending Jig	100%
Manufacture Heat Fins	100%
Final Assembly	**100%**
Select Brazing Rods	100%
Order Brazing Rods	100%
Practice Brazing	100%
Final Assembly Brazing	100%
Final Assembly Brazing 2	100%
Final Assembly, Cleanup	100%
Complete Final Assembly	100%
Testing	**100%**
Structural Prototype Testing	100%
Test Procedures - Late Stage	100%
VP Build - Late Stage	100%
Testing - Late Stage	100%
DVPR Sign-Off	100%
Testing - Final Verification	100%
Project Wrap-up	**100%**
Sign up for a room where we can pre...	100%



Send extra supplies to GTI	100%
Write FDR Report	100%
Create Expo Poster	100%
Sponsor Presentation	100%
Final Design Review (FDR)	100%
Clean out workspaces	100%
EXPO DAY !	100%
Complete Checklist	100%
Submit FDR to Sponsor	100%
Misc	**50%**
Team Bonding - Pad Thai	0%
Senior Exam	100%
Admin	100%
Project	100%
Other	100%
Finalize All Paperwork for LA Trip	100%
Follow Up w/ Sponsor After Meeting i...	100%
Update Gantt Chart	100%
FMEA	100%
Team Bonding - Bike Night	100%
Team Feedback	100%
Team Contract Update 2	100%
Sync w/ Sponsor After Break	100%



Appendix H - Hazards Checklist

PDR Design Hazard Checklist **Project F16 & Heat Sink**

Y	N	
X		1. Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?
	X	2. Can any part of the design undergo high accelerations/decelerations?
	X	3. Will the system have any large moving masses or large forces?
	X	4. Will the system produce a projectile?
X		5. Would it be possible for the system to fall under gravity creating injury?
X		6. Will a user be exposed to overhanging weights as part of the design?
X		7. Will the system have any sharp edges?
	X	8. Will any part of the electrical systems not be grounded?
	X	9. Will there be any large batteries or electrical voltage in the system above 40 V?
X		10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
	X	11. Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?
	X	12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
X		13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
	X	14. Can the system generate high levels of noise?
X		15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc?
	X	16. Is it possible for the system to be used in an unsafe manner?
X		17. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

For any "Y" responses, on the reverse side add:
(1) a complete description of the hazard,
(2) the corrective action(s) you plan to take to protect the user, and
(3) a date by which the planned actions will be completed.

Description of Hazard	Planned Corrective Action	Planned Date	Actual Date
Forming sheet metal presents pinching hazards (1)	Sanding edges and wearing gloves when working with it.	April 2022	April 26 2022
Heatsink mount can fall (5)	Protective measures beneath the heatsink (towel and a strong table) as well as all members wearing closed toe shoes when working on it.	April 2022	April 26 2022
Potential dropping of heat sink (6)	All members must wear closed toed shoes when working on the prototype	April 2022	March-April 2022
Potential for sharp edges (7)	Handle with care and sand the edges	April 2022	March-April 2022
Electrical potential with TEG (10)	Insulation and proper grounding. Keep water away from the system.	April 2022	March 2022-end of project
Thermal paste could be toxic to humans (13)	Wearing a mask and protective gear when handling it.	March 2022	March 29 2022
Extreme conditions subjected to the system (15)	When testing in these conditions, provide proper PPE.	May 2022	May 3 2022
Potential for burns when welding/brazing operations (17)	Consult with experts, wear proper PPE, and find appropriate supervisors.	May 2022	April 26 2022

Appendix I - Design Verification Plan

DVP&R - Design Verification Plan (Team F16)

Project: Cal Poly Design Team F16, GTI MMTEG Sponsor: Gas Technology Institute (rep Abdelallah Ahmed) Edit Date: 3/8/2022

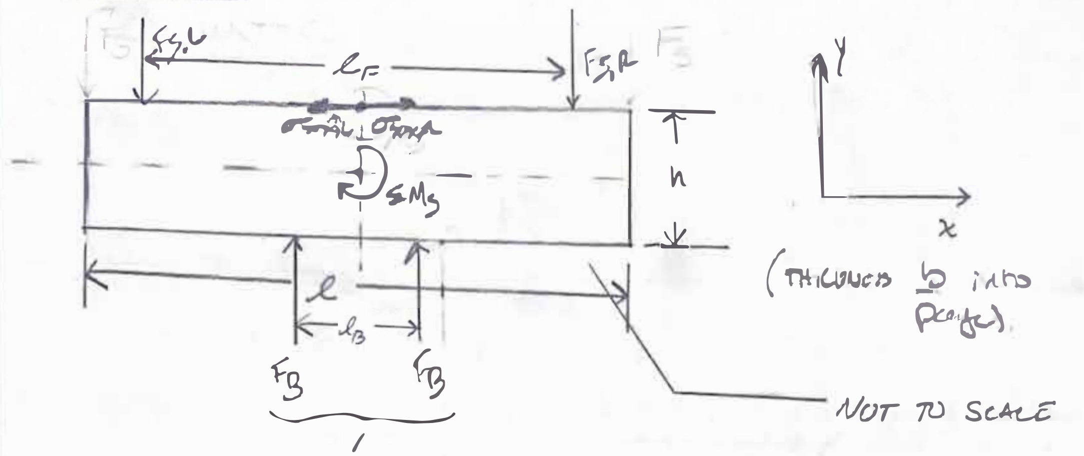
TEST PLAN | TEST RESULTS

Test #	Specification	Test Description	Measurements	Acceptance Criteria	Required Facilities/Equipment	Parts Needed	Responsibility	TIMING		Numerical Results	Notes on Testing
								Start date	Finish date		
1	Thermocouple Thermal Conductivity Check	- Test is meant to determine the thermal conductivity of the heat pipes. Obtain all supplies. 2. Plug in hot plate and turn it on to halfway on the dial. 3. Insert one 0.004 inch thermocouple in between the test jig and the hot side of the TEG. Secure with Kapton tape if necessary. 4. Insert other 0.004 inch thermocouple between the cold side of the TEG and the bottom face of the copper base. Secure with Kapton tape if necessary. 5. Create a plot that will create graphs of the temperature for both thermocouples in real time. 6. Record the thermocouple measurements every minute until steady state is reached. (Visible flattening of the recorded measurements) 7. Record 20 measurements at steady state. 8. Allow all test materials to cool down to a temperature of 85° Fahrenheit and return all supplies.	1) Thermocouples will be placed along the vertical part of the heat pipe.	The thermal conductivity of the heat pipes is near 1000 W/m-K	Hot plate, four type K thermocouples, thermocouple readers, PPE, test base, copper base, clamping fixture, crossbar, single heat pipeand Kapton tape.	Full Design Verification prototype except with only one heat pipe instead of all. (see relevant BoM)	Entire Team	3/1/2022	3/2/2022	Final thermal conductivity value for the heat pipe of 1307 W/m-K at steady state.	It was windy on the day of testing which led to possibly higher convection.
2	TEG temperature difference (outdoor "sunlit" conditions)	-Attach test fixture ("design verification prototype") to 1000 [W] duty cycle-modulated hot plate via mounting defined in CAD geometry -Turn on hot plate and allow steel block to reach steady state temperature (dependent on ambient conditions -record initial temperatures on "hot" and "cold" side of TEG, as well as ambient -Allow system to reach steady state... when measurements plateau (changes between 1s time increments drop below 5% of nominal -plot response -repeat this process twice and average results -Will serve as nominal / "control" performance baseline against which other more dynamic condition tests can be evaluated -Max allowable test time: 90 minutes -Conduct in "typical" sunlight blue skies day. record ambient conditions via photo and measurement of ambient temperature, etc. Reference tabulated values of solar radiation versus atmospheric conditions to evaluate performance	1) Thermocouple probe inserted into steel base to approximate the "HOT" side of TEG temperature 2) Thermocouple probe inserted into slot in copper base to approximate TEG "cold side" temperature	Steady state "Cold side" temperature of TEG < 100 degC for 55 [W] heat input from block. Some linear extrapolation may be necessary based on the steady state that the system finds	-Design Verification prototype -Hot plate or burner capable of consistent 1000 [W] output over duty cycle modulation -Acess to power for said hot plate -Two thermocouples to measure hot and cold side temperatures of TEG, respectively. -Outdoor setting that testing can be reliably conducted without disturbance -Minimal wind and sunny conditions with minimal clouds	Full Design Verification prototype. (see relevant BoM)	Entire Team	5/12/2022	5/12/2022	The ambient conditions was 21 deg C with minimal wind but slight gusts. After reaching steady state in 72 minutes, we determined the cold side of the TEG to be 77 deg C and the hot side to be 147 deg C. We determind the heat flux into the TEG to be 75 W. After post processing, we determined that this test hit spec.	Slight gusts which led to higher convection but attempts to block worked well.
3	TEG temperature difference (outdoor "overnight" conditions)	-Repeat test as in #2. -Conduct outdoors, at night, with no effects of solar radiation. Ambient temperature in the range of 30-45 degrees fahrenheit preferable.	See test #2	See test #2	-See test #2 -Outdoor setting that testing can be reliably conducted without disturbance -Minimal wind and clear skies nighttime conditions	Full Design Verification prototype. (see relevant BoM)	Entire Team	5/11/2022	5/11/2022	The ambient conditions was 15 deg C with minimal wind but slight gusts. After reaching steady state in 72 minutes, we determined the cold side of the TEG to be 50 deg C and the hot side to be 87 deg C. We determind the heat flux into the TEG to be approximately 50 W. After post processing, we determined that this test hit spec.	Slight gusts led to higher convection. The temperature varied as the test commenced which led to a variable ambient temperature but the decrease in wind counteracted it.

Appendix J - Hand-Calculations for Loading on Crossbar

CP TEAM F16 | VERIFICATION PROTOTYPE | HAND CALCS | 1

SCHEMATIC - MOUNTING BRACKET



MODELED AS POINT RXN'S DUE TO SMALL E OF MATERIAL.

ANALYSIS

⇒ GREATEST AREA OF CONCERN IS THE TOP SIDE OF THE MOUNTING BRACKET, AT THE CENTER OF THE BEAM. THE COMBINED BENDING MOMENTS FROM BOTH MOUNTING BOLT ASSEMBLIES COULD RESULT IN EXCESS NORMAL STRESS. REACTION FORCES FROM THE BASE OVER WHICH THE BRACKET IS CANTILEVERED WILL HELP IN REDUCING THIS MOMENT, BUT ANALYSIS IS STILL NECESSARY:

$$\overset{\curvearrowleft +}{M_{S,R}} = (F_B)(\ell_B/2) - F_S(\ell_f/2) \qquad \overset{\curvearrowleft +}{M_{S,L}}$$

$$-(F_B)(-\ell_B/2) + F_S(\ell_f/2)$$

$$\Sigma F_y = 2F_B - 2F_S$$ (ASSUMED SYMMETRIC)

$$\therefore F_B = F_S \checkmark$$

⇒ ANALYZE FOR NORMAL STRESS DUE TO BENDING

→

(...)

$$\sigma_{bendy} = \pm \frac{M_z (h/2)}{I_{xx}}$$ → NEUTRAL AXIS AT CENTER OF BEAM.

$$I_{xx} = \frac{(b)(h)^3}{12}$$

⇒ EVALUATE σ_{bend} FROM **BOTH** $F_{S,L}$ AND $F_{S,R}$.

- THEY WILL ACT OPPOSITE AT SAME POINT (AT TOP OF BEAM)

⇒ SAMPLE CALCULATION FOR:

- $l_F = 3.5$ [in]
- $F_{S,LR} = 140$ [lbf]
- $b = 0.445$ [in]
- $h = 0.375$ [in]
- $\sigma_y = 65$ [Kpsi]

} - POTENTIAL BAR TO PURCHASE

$l_B = 1.76$ [in]

→ $F_{BR} = F_S$
$= 140$ [lbf]

$$M_{S,R} = (140)\left(\frac{1.76}{2}\right)^{[lbf\cdot in]} - (140)\left(\frac{3.5}{2}\right) \; [lbf \cdot in]$$

$= -121.8$ [lbf-in]

$= -M_{S,R}$ (SYMMETRY)

EVALUATE NORMAL STRESS →

$$\sigma_{bending} = \frac{(-121.8)\ [lbf\text{-}in]\left(\frac{0.375}{2}\right)[in]}{\left(\frac{(0.445)(0.375)^3\ [in^4]}{12}\right)}$$

$$= 10,498.6\ [lbf/in^2]$$

$$\therefore \Sigma\sigma_{bend} = 2\left(\overset{10,498.6\ [lbf/in^2]}{\sigma_{bending}}\right)$$

$$= 20997.17\ [psi]$$

$$\therefore \sigma_{bend} = 20.99\ [Kpsi]$$

$$\therefore FS)_{bend} = \frac{85\ [\cancel{kpsi}]}{20.99\ [\cancel{kpsi}]}$$

$$\boxed{\therefore FS)_{BEND} = 4.05\ [-]}$$

→ SUFFICIENT CONSIDERING THERMAL LOADING, FATIGUE FROM CYCLES, AND NOTCHES IN ENDS.

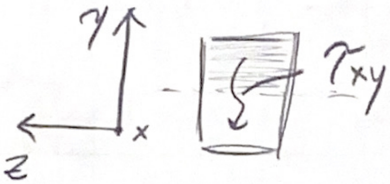
⇒ BY MOHR'S CIRCLE, ASSUMING ISOTROPIC / LINEAR BEHAVIOR OF MATERIAL, $\tau_y = \frac{\sigma_y}{2}$

$$= 42.5\ [kpsi]$$

MAX SHEAR IS 140 [lbf] BETWEEN THE F_S AND F_B...

↳ EVALUATE SHEAR STRESS →

$$\tau_{xy,max} = \frac{QV}{Ib} \rightarrow \frac{3V}{2A}$$



$$\tau_{xy,max} = \frac{(3)(140)\ [lbf]}{2\ (0.445)(0.375)\ [in^2]}$$

$$= 1131.3\ [lbf/in^2]$$

$$\therefore FS)_{SHEAR} = \frac{42.5\ [kpsi]}{1.13\ [kpsi]}$$

$\leftarrow \tau_y$

$\leftarrow \tau_{xy,max}$

$$\boxed{FS)_{SHEAR} = 39.8\ [-].}$$

$\rightarrow$ PLENTY SUFFICIENT.

Appendix K - Failure Modes and Effects Analysis

F16 - FMEA

												Action Results				
System / Function	Potential Failure Mode	Potential Effects of the Failure Mode	Severity	Potential Causes of the Failure Mode	Current Preventitive Activities	Occurence	Current Detection Activities	Detection	RPN	Recommended Action(s)	Responsibility & Target Completion Date	Actions Taken	Sensitivity	Occurrence	Detection	RPN
Maintain cold side temperature	Thermal performance degredation	Decreased heat sink performance	4	Lack of wind	Designing for passive convection	10	Thermal tests in varying conditions	2	80	Design for still air condtions. Assume worst case scenario	Peyton N. 1/20/22	ANSYS® heat transfer coefficients corresponded to natural convection	4	4	2	32
		Not enough energy produced	8	Insufficient number of fins	Fin density tradeoff study	2	Thermal analysis in Ansys	2	32	Finalize the Ansys sims.	Kadin F. 3/20/21	ANSYS® trade study	7	3	2	42
Scalable Design	Difficult to manufacture on assembly line	GTI cannot meeting quantity quota	5	Assembly lines cannot efficiently produce product	Design CAD features can be milled, extruded, and stamped	5	Evaluate designs using past manufacturing experience	4	100	Talk with sponsor and professors about design for manufacturing	Alec S. 3/17/22	Talked to Prof. Pascual, Emberley, and Eric Pulse	5	3	3	45
Minimize Cost	Expensive	Prohibitive cost to GTI MMTEG system	6	Excessively expensive components selected	Simplify design iterations where possible	6	Check component costs on McMaster / Grainger etc	2	72	Checked for the least expensive procurement option	Peyton N. 3/15/22	Looked on McMaster Carr and talked to Eric Pulse about other options	3	3	2	18
Easy Instalation	Hazardous instalation	Injures worker	9	a) Sharp fins b) Cause burns	a) Include deburing and sanding in work instructions b) Round potentially sharp corners c) Heat dependent coating providing visual que	3	a) Visual Inspection. b) Caution warnings	3	81	Add deburing to manufacturing process, use thicker plates	Jack W. 1/25/22	Plate thickness matches that of existing design, which had no issues with worker related injuries	9	2	2	36

Appendix L - Test Procedures

Kadin Feldis

Verification Test Procedure

Test:
Full Sun Project Verification Test

Purpose:
This test will provide a go/no go verdict on the final design of our heat sink. The test will indicate whether we have met our performance requirements or not. In either case, the test should also accurately quantify cooling performance.

Scope:
This test will evaluate the heat sink, test stand, and thermoelectric unit performance.

Equipment:

- Test Jig
- Heat sink
- Thermoelectric
- Thin type K thermocouples
- Thermal paste
- Thermocouple reader
- Multimeter
- Hot plate

Hazards:

- High temperatures

PPE Requirements:

- n/a

Facility:

- Table (preferably outside or in a ventilated lab)

Procedure:

1) Assemble test jig, teg, and heat sink
    a. Ensure that all thermal contact surfaces have thermal paste
    b. Place thermocouples on hot and cold side of the teg
        i. Make sure teg is in the correct orientation
2) Bring clamping pressure up to about 100psi w/ springs as indicators
3) Plug in hot plate and place it on a table in direct sunlight
    a. Be sure that no one touches hot plate
4) Place heat sink / test jig assembly on the hot plate
    a. Be sure that no one touches metal components of the assembly after this stage
5) Collect temperature and teg voltage data every minute until steady state has been achieved
    a. Ensure that steady state has a heat input of approximately 50W

6) Collect steady state data for 15 minutes (15 data points)
7) Power off the hot plate and wait for the system to cool
8) Disassemble and put away test equipment.

Results:

Test Pass Criteria:

- Transient and steady stand temperatures and voltages collected
- Representative heat input, of 50W, achieved

Heat Sink Pass Criteria:

- Maintains 100C cold side temperature for a heat input of 50W or greater

Test Date:

Spring quarter. Exact date TBD & will be based on prototype completion date.

Test Results:

Results of test here.

Performed By:

Senior project group F16.

TEST NAME: Overcast Ambient Conditions Steady State

PURPOSE: Determine heat sink performance without the effects of solar radiation.

SCOPE: This test aims to measure the hot and cold side temperatures of the TEG to evaluate system performance.

EQUIPMENT: Heatsink, crossbar, mounting hardwear (washers, springs, bolts), TEG, Testing base, hot plate, two thin thermocouples, two "normal" thermocouples, hot plate, stopwatch

HAZARDS: Burn hazard from hot plate, steel testing base and heatsink

PPE REQUIREMENTS: Oven mitts in case of moving the apparatus during testing.

FACILITY: Any outdoor setting with access to electrical outlets during an overcast day (Jack's house or Engineering 13 courtyard)

PROCEDURE:

1) Using the heatsink test apparatus (heatsink, testing base, crossbar, mounting bolts, washers and springs, TEG), attach four thermocouples to apparatus
    - Thin thermocouples should be sandwiched between TEG and test base (Hot side temp) and TEG and copper base (cold side temp).
    - Attach remaining two thermocouples to center of bottom and top fins.
2) Next, place apparatus on hot plate in outdoor setting during overcast day.
3) Set hot plate to 1/3 power, and allow to reach steady state (Approximately 45 minutes).
4) Record all four temperature readings from thermocouples every minute for 20 minutes, plot in real time to confirm apparatus is at steady state before terminating data collection
5) After setting apparatus up, remain at least 2 feet from all metal surfaces to avoid burn hazard.
6) To terminate the test, turn hot plate off, and using oven mitts, remove heatsink apparatus from hot plate and set on concrete to speed cooling.
7) Allow to cool for 45 minutes, and check temperature is below 40 degrees Celsius with already attached thermocouples before handing without oven mitts.

RESULTS: 20 to 40 data points, Pass criteria: Cold side of TEG is less than 100 Celcius

TEST DATE: TBD based off of heat sink manufacturing

TEST RESULTS: TBD

PERFORMED BY: Peyton, Jack, Alec, Kadin

Test Procedure – F16 MMTEG Heatsink #3

Alec Savoye (SOLO Procedure)

Test Name: Full test jig subjected to "Sunny Day" conditions with fouled (dirty) heatfins

Purpose: Evaluate the performance of the heatsink in "typical" sunny conditions for the American Southwest, in addition to fouling typical of several months / years of usage in a dusty environment. This dusty condition will be referred to as "fouling" in future team documentation.

Scope: Maintaining sufficient cold side temperature on TEG to sustain sufficient electrical output for heat input from combustion chamber. Verifying if this will be possible when fouled and then placed in sunny outdoor conditions.

Equipment:

- Heatsink
  - Heatpipes (current configuration)
  - Heatfins (current configuration)
  - Copper base (current configuration)
- Test assembly
  - Crossbar
  - Spring / bolt / washer / nut assembly (for compression, one on each side)
  - Steel base (current configuration)
- Thermocouples
  - 0.0045" diameter units X2 + reader (we will need a way to soldering their terminals to the current reader's input ports…)
    - Thermal paste might be required to attach these (TBD)
  - Standard size for measurement of surface temperatures
    - Tape might be necessary to fix these (TBD)
  - Thermocouple readers (for TYPE K, x2)
- Hot plate (used for prior experiments)
  - Extension cord might be required to power …. Require sufficient gauge to run up to 15 amps 30 feet.
- Some dirt from an outdoor region that shares similar material properties to that which will be encountered in the environment these MMTEG units will be installed
- Compressed air for application of dust onto heatfins

Hazards:

- Burning from touching the test assembly or from radiant heat around the components at operating temperature. (The hot plate is 1300 Watts!)

PPE Requirements:

- Masks for potential burning of tape fumes getting ingested somehow
- Gloves (standard cloth type) to prevent burning of hands when manipulating test apparatus.

Facility: This test will be conducted outdoors somewhere that is sufficiently representative of a “desert” or arid climate on a sunny day. Power will be required from either a high-power inverter off of a car or an outlet with an extension cord.

Procedure: (List number steps of how to run the test, can include sketches and/or pictures):

1) Place dust on a flat surface in a pile about 4 inches high and 4 inches in diameter. This is non-critical dimensioning and should just be a ballpark estimate.

2) Sufficiently mask testing components of heatsink from potential dust settling (this includes test base and crossbar).

3) Place heatsink behind the pile of dust and spray compressed air onto the dust. The objective is to land the streams of dust parallel to the faces of the plates, thereby simulating the settling of dust overtime in events like duststorms or clouds of dust churned up by passing vehicles, maintenance crews, etc. Sufficient coating should be at least a few thousands of an inch (clearly visible).

4) Install heatsink / test jig apparatus (already installed onto test jig at this point) onto center of hot plate. Make sure this is placed in a way that is not unstable.

5) Install TCs on top and bottom of TEG to facilitate temperature measurement. Plug into readers and turn on in an easily viewable place for observation.

6) Record initial data point with no heat input. This will serve as a bit of control to consider effects of ambient conditions.

7) Ensure that no stray wind is affecting the apparatus. Shield as necessary.

8) Turn on hot plate to half power (50% duty cycle) and allow it to run like this until temperatures from measurements have stabilized.

9) Measure at least 15 steady-state data points (every minute) of both temperatures (both sides of TEG)… STEADY STATE for system is defined as a variation in read-out of temperatures of less than 5% over the course of 1 minute, for 3 minutes total.

Results: Pass Criteria, Fail Criteria, Number of samples to test

- 15 samples total
- Pass: 100 degC temperature on “cold side” of TEG (that which makes contact with the heatsink)
- No extraneous behavior that would lead to doubts about component reliability overtime considering the fouling condition that the apparatus will be facing.

Test Date(s): TBD based on simulation results timeline and manufacturing progress.

Test Results:

- Temperature differential maintained at steady state, averaged between the 15 trials.
- Optional transient performance characteristics, though this period is expected to represent little of the operational time seen by the heatsinks in actual application.

Performed By:

- Team F16
- Abdelallah Ahmed of GTI has expressed interest in participating, either virtually or in person, to see our process in more detail and provide live input based on his own experience in small component thermal testing.

Test Name: Heat Sink Performance in night time conditions.

Purpose: The purpose of this test is to see how the heat sink performs on a windless evening. This is to simulate the same conditions that the heat sink would experience in the desert where the evenings get very cold.

Scope: The scope of this test the thermal measurements on the cold and hot sides of the TEG and compare the results to the desired ones given from our sponsor. (100 deg C temperature difference at 50 W input power)

Equipment: In order to complete this test, we will need the hot plate, completed test base, copper base, clamping fixture, crossbar, two thermometers, two thermocouples type K with diameter of 0.004 inches, and Kapton tape. All materials will be provided by the team except the Kapton tape and 0.004 inch thermocouples that were provided by Dr. Hans Mayer.

Hazards: In this test, we will come into contact with a hot plate, at a max temperature of 500 K, that could burn the user. The base will heat up the rest of the apparatus too so there is a potential for burns if touched. The base also has sharp corners which users need to be careful around since they could cut themselves. Additionally, working with a thermometer, multimeter, and hot plate could result in electrical burns, fires, and sparks if used near water. Lastly, the hot plate could burn some of the coating which would result in the release of toxic chemicals.

PPE Requirements: All members must wear safety glasses in the testing area, and all members must wear a face mask when the hot plate is on to avoid breathing in the fumes. Additionally, the member touching the hot plate will wear gloves. Lastly, to avoid any cuts from the sharp corners, all members need to be weary of where they are in relation to the test apparatus and remind members to be safe.

Facility: We plan to do this test in Cal Poly Building 13 courtyard since an outdoor space is safer in case of a fire and there is some protection from the wind. The backup plan if there are no spaces available, is to perform the experiment on Jack Waeschle’s deck.

Procedure:

1. Obtain all supplies.
2. Plug in hot plate and turn it on to halfway on the dial.
3. Insert one 0.004 inch thermocouple in between the test jig and the hot side of the TEG. Secure with Kapton tape if necessary.
4. Insert other 0.004 inch thermocouple between the cold side of the TEG and the bottom face of the copper base. Secure with Kapton tape if necessary.
5. Create a plot that will create graphs of the temperature for both thermocouples in real time.
6. Record the thermocouple measurements every minute until steady state is reached. (Visible flattening of the recorded measurements)
7. Record 20 measurements at steady state.
8. Allow all test materials to cool down to a temperature of 85° Fahrenheit and return all supplies.

Trial Number	Time	Bottom TEG Temperature	Top TEG Temperature
[-]	[min]	[K]	[K]

Results:

Pass Criteria: The heat sink allows for the TEG to have a 100 deg C delta Temperature for a 50W power input.

Fail Criteria: The heat sink does not allow for the TEG to have a 100 deg C delta Temperature for a 50W power input.

Number of samples to test: Total 60 readings for each thermocouple.

Test Date: April 27th

Test Results: Not Completed Yet

Performed By: Peyton, Kadin, Alec, Jack

Appendix M - Experimental Raw Data

EXPERIMENTAL TESTING

Test Title: “Best Case”

Ambient: 54 F, Night time, still air (no solar radiation)

Duration: 100 minutes

Date: 5 / 10 / 2022

t	Reader #1		TEG dT	Reader #2		dTC1.2 / dt
[m]	TC1	TC2		TC1	TC2	
	[K]	[K]	[K]	[K]	[K]	[K / min]
1	291.4	292.3		290.3	287.3	
2	292.2	293.7	1.5	293.5	286.8	1.4
3	293.1	295.3	2.2	294.5	286.6	1.6
4	294.9	297.9	3	294.7	286.8	2.6
5	296.8	300.8	4	295.5	286.7	2.9
6	298.4	303.4	5	295.2	286.8	2.6
7	300.1	306	5.9	295.3	287.3	2.6
8	301.8	308.6	6.8	296.4	287.3	2.6
9	303.5	311.3	7.8	296.2	287.3	2.7
10	304.5	313.3	8.8	294.6	287.1	2
11	305.3	314.9	9.6	295.5	287.6	1.6
12	307.5	317.2	9.7	297.1	289.8	2.3
13	308.6	319.1	10.5	297.3	289.1	1.9
14	308.4	320.1	11.7	296.8	288.8	1
15	308.7	321	12.3	296.2	288.1	0.9
16	309.5	322.3	12.8	297.7	288.2	1.3
17	310	323.6	13.6	296.5	288.5	1.3
18	310.6	324.5	13.9	297.6	288.1	0.9
19	310.9	325.9	15	297.1	288.2	1.4
20	311.5	326.7	15.2	296.9	288.1	0.8
21	312.3	328	15.7	295.9	287.8	1.3
22	312.8	328.8	16	297.6	288.3	0.8
23	313.1	329.8	16.7	297.9	288.76	1
24	313.9	331.1	17.2	297.9	288.3	1.3
25	314.4	331.7	17.3	297.2	288.2	0.6
26	315	332.6	17.6	299.1	288.7	0.9
27	315.5	333.6	18.1	297.6	288.6	1
28	315.9	334.2	18.3	297.2	288.3	0.6
29	316	334.9	18.9	298.2	288.5	0.7
30	316.2	335.2	19	297.5	288.5	0.3
31	316.1	336.3	20.2	297	288.2	1.1
32	316.6	336.9	20.3	298.9	288.8	0.6
33	316.5	337.2	20.7	297.1	288.1	0.3

34	317.4	338	20.6	298.8	288.6	0.8
35	317.2	338.5	21.3	298.1	288.3	0.5
36	316.9	338.7	21.8	296.6	287.4	0.2
37	316.8	339	22.2	296.1	287.4	0.3
38	317.4	339.6	22.2	295.5	287.2	0.6
39	317.4	340.1	22.7	296.6	287.5	0.5
40	317.6	340.6	23	297.4	287.3	0.5
41	318.1	341.2	23.1	298	287.8	0.6
42	318.1	341.4	23.3	298.8	288.1	0.2
43	318.7	342	23.3	297.6	287.8	0.6
44	319.1	342.7	23.6	299.2	288.6	0.7
45	319.7	343.3	23.6	297.2	287.8	0.6
46	320.1	343.8	23.7	299.9	288.5	0.5
47	320.2	344.3	24.1	298.3	288.8	0.5
48	320.6	345.1	24.5	297.1	288.2	0.8
49	320.2	345.2	25	296.8	287.9	0.1
50	319.8	344.8	25	297.5	287.7	-0.4
51	319.9	345	25.1	297	287.9	0.2
52	320.2	345.3	25.1	298.6	288.2	0.3
53	320.2	345.5	25.3	297.4	287.5	0.2
54	320.9	346	25.1	298.8	288.5	0.5
55	321	346.3	25.3	298	288.3	0.3
56	321.5	346.7	25.2	299.3	289.1	0.4
57	321.2	346.8	25.6	297.8	287.8	0.1
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61	321.6	347.7	26.1	297.6	288	0
62	322.1	348.5	26.4	297.6	287.9	0.8
63	322.3	349.2	26.9	298.3	288.6	0.7
64	321.3	349.3	28	295.7	287.3	0.1
65	320.9	349.5	28.6	295.5	287.1	0.2
66	321	349.8	28.8	296.4	287.1	0.3
67	321.3	350.2	28.9	298.2	287.3	0.4
68	321.6	350.5	28.9	297.5	287.3	0.3
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76	322.5	352.1	29.6	297.6	287.7	0.4
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79	322.7	352.5	29.8	298.5	287.8	0
80	323.1	352.8	29.7	297.8	287.9	0.3
81	322.3	352.7	30.4	297.8	287.5	-0.1
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83	321.7	352.9	31.2	295.8	286.8	0.2
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87	323.1	354.1	31	299.6	288.4	0.9
88	323	354.4	31.4	298.8	287.4	0.3
89	322.7	354.7	32	296.5	287	0.3
90	322.7	354.9	32.2	297.1	287.2	0.2
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92	322.3	355.2	32.9	297.1	287.4	0.2
93	323	355.5	32.5	297	287.6	0.3
94	323.2	355.8	32.6	299.9	288.8	0.3
95	323.3	356.1	32.8	298.8	288.1	0.3
96	324	356.8	32.8	298.7	287.8	0.7
97	324.2	357.1	32.9	300.7	289.5	0.3
98	324.2	357.2	33	298.5	287.8	0.1
99	324.2	357.5	33.3	298	287.6	0.3
100	324	357.6	33.6	298.1	288	0.1

Test Title: “Worst Case”

Ambient: 72 F, Day time, still air (moderate solar radiation)

Duration: 100 minutes

Date: 5 / 11 / 2022

t	Reader #1		TEG dT	Reader #2		dTC1.2 / dt
[m]	TC1	TC2		TC1	TC2	
	[K]	[K]	[K]	[K]	[K]	[K / min]
1	292.2	293.7	1.5	293.5	286.8	1.4
2	293.1	295.3	2.2	294.5	286.6	1.6
3	294.9	297.9	3	294.7	286.8	2.6
4	296.8	300.8	4	295.5	286.7	2.9
5	298.4	303.4	5	295.2	286.8	2.6
6	300.1	306	5.9	295.3	287.3	2.6
7	301.8	308.6	6.8	296.4	287.3	2.6
8	303.5	311.3	7.8	296.2	287.3	2.7
9	304.5	313.3	8.8	294.6	287.1	2
10	305.3	314.9	9.6	295.5	287.6	1.6
11	307.5	317.2	9.7	297.1	289.8	2.3
12	308.6	319.1	10.5	297.3	289.1	1.9
13	308.4	320.1	11.7	296.8	288.8	1
14	308.7	321	12.3	296.2	288.1	0.9
15	309.5	322.3	12.8	297.7	288.2	1.3
16	310	323.6	13.6	296.5	288.5	1.3
17	310.6	324.5	13.9	297.6	288.1	0.9
18	310.9	325.9	15	297.1	288.2	1.4
19	311.5	326.7	15.2	296.9	288.1	0.8
20	312.3	328	15.7	295.9	287.8	1.3
21	312.8	328.8	16	297.6	288.3	0.8
22	313.1	329.8	16.7	297.9	288.76	1
23	313.9	331.1	17.2	297.9	288.3	1.3
24	314.4	331.7	17.3	297.2	288.2	0.6
25	315	332.6	17.6	299.1	288.7	0.9
26	315.5	333.6	18.1	297.6	288.6	1
27	315.9	334.2	18.3	297.2	288.3	0.6
28	316	334.9	18.9	298.2	288.5	0.7
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32	316.5	337.2	20.7	297.1	288.1	0.3
33	317.4	338	20.6	298.8	288.6	0.8
34	317.2	338.5	21.3	298.1	288.3	0.5
35	316.9	338.7	21.8	296.6	287.4	0.2
36	316.8	339	22.2	296.1	287.4	0.3

37	317.4	339.6	22.2	295.5	287.2	0.6
38	317.4	340.1	22.7	296.6	287.5	0.5
39	317.6	340.6	23	297.4	287.3	0.5
40	318.1	341.2	23.1	298	287.8	0.6
41	318.1	341.4	23.3	298.8	288.1	0.2
42	318.7	342	23.3	297.6	287.8	0.6
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54	321	346.3	25.3	298	288.3	0.3
55	321.5	346.7	25.2	299.3	289.1	0.4
56	321.2	346.8	25.6	297.8	287.8	0.1
57	321.8	347.3	25.5	298.6	288.1	0.5
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61	322.1	348.5	26.4	297.6	287.9	0.8
62	322.3	349.2	26.9	298.3	288.6	0.7
63	321.3	349.3	28	295.7	287.3	0.1
64	320.9	349.5	28.6	295.5	287.1	0.2
65	321	349.8	28.8	296.4	287.1	0.3
66	321.3	350.2	28.9	298.2	287.3	0.4
67	321.6	350.5	28.9	297.5	287.3	0.3
68	321.1	350.7	29.6	296.2	287.1	0.2
69	321.3	350.7	29.4	298.5	288.1	0
70	321.6	351.2	29.6	297.3	287.1	0.5
71	321.5	351.4	29.9	296.7	287.1	0.2
72	321.6	351.5	29.9	298.1	287.4	0.1
73	322.1	351.7	29.6	299.3	287.9	0.2
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75	322.5	352.1	29.6	297.6	287.7	0.4
76	323.1	352.6	29.5	298.6	287.9	0.5
77	322.6	352.5	29.9	297.6	287.7	-0.1
78	322.7	352.5	29.8	298.5	287.8	0
79	323.1	352.8	29.7	297.8	287.9	0.3
80	322.3	352.7	30.4	297.8	287.5	-0.1
81	321.9	352.7	30.8	297.1	287.4	0

82	321.7	352.9	31.2	295.8	286.8	0.2
83	321.5	352.8	31.3	296.5	286.6	-0.1
84	321.5	353	31.5	296.6	286.9	0.2
85	322.1	353.2	31.1	299	287.8	0.2
86	323.1	354.1	31	299.6	288.4	0.9
87	323	354.4	31.4	298.8	287.4	0.3
88	322.7	354.7	32	296.5	287	0.3
89	322.7	354.9	32.2	297.1	287.2	0.2
90	322.2	355	32.8	296.4	286.6	0.1
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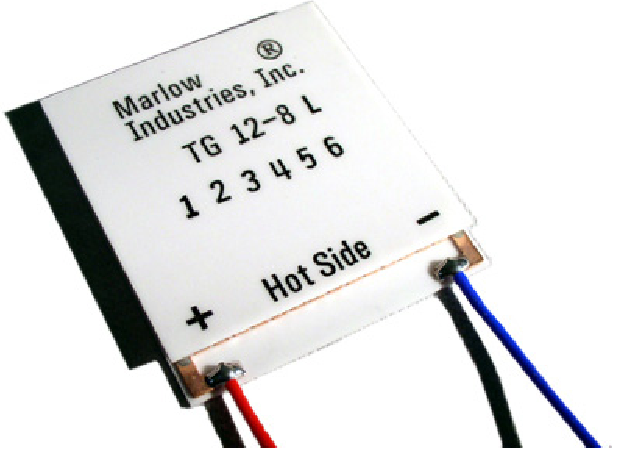
92	323	355.5	32.5	297	287.6	0.3
93	323.2	355.8	32.6	299.9	288.8	0.3
94	323.3	356.1	32.8	298.8	288.1	0.3
95	324	356.8	32.8	298.7	287.8	0.7
96	324.2	357.1	32.9	300.7	289.5	0.3
97	324.2	357.2	33	298.5	287.8	0.1
98	324.2	357.5	33.3	298	287.6	0.3
99	324	357.6	33.6	298.1	288	0.1
100	324.4	357.7	33.3	299.1	287.9	

Technical Data Sheet for TG12-8

Single-Stage Thermoelectric Generator



NOMINAL PERFORMANCE IN NITROGEN

Cold Side Temperature (°C)	27±2
AC Resistance (ohms):	1.36 – 1.69
Device ZT	0.73

PRODUCT FEATURES

- RoHS EU Compliant
- Rated operating temperature of 200°C.
- Ceramic Material: Aluminum Oxide
- Porch configuration for high strength leadwire connection.
- Superior nickel diffusion barriers on elements.
- High strength for rugged environment.
- RTV sealing option available.
- Lapped option available for multiple module applications.

ORDERING OPTIONS

Model Number	**Description**
TG12-8-01	Leadwires
TG12-8-01L	Leadwires, Lapped
TG12-8-01S	Leadwires, Sealed
TG12-8-01LS	Leadwires, Lapped, Sealed
TG12-8-01G	Leadwires, Graphite Pads
TG12-8-01LG	Leadwires, Lapped, Graphite Pads
TG12-8-01SG	Leadwires, Sealed, Graphite Pads
TG12-8-01LSG	Leadwires, Lapped, Sealed, Graphite Pads

OPERATION CAUTIONS

For maximum reliability, continuous operation below 200°C (cold side and hot side) is recommended. Intermittent operation up to 230°C on the hot side of the TG is permissible.

INSTALLATION

Recommended mounting methods: Clamp with uniform pressure to a flat surface with thermal interface material. Recommended 1.4 MPa (200 psi) with thermal grease or flexible graphite pads. For additional information, please contact an applications engineer.

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MI Form 005-0691 Rev. 5

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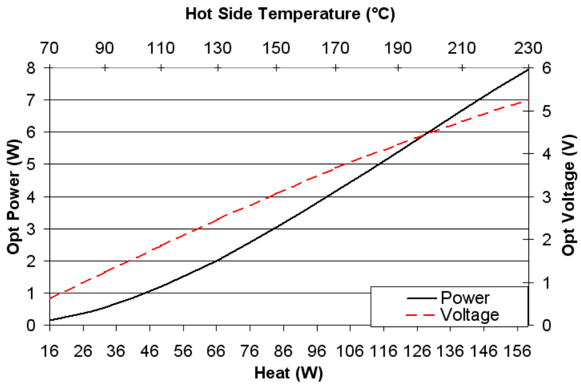
TYPICAL PERFORMANCE CURVES

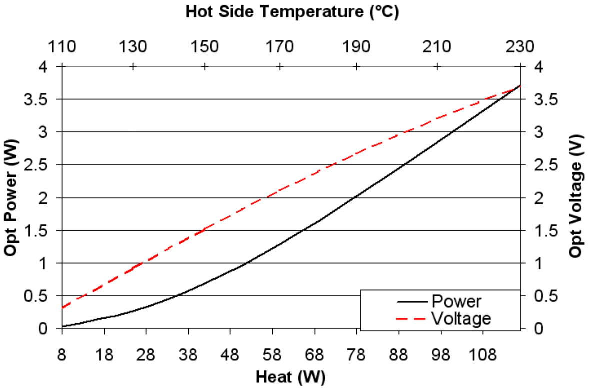
POWER GENERATION PERFORMANCE CURVES

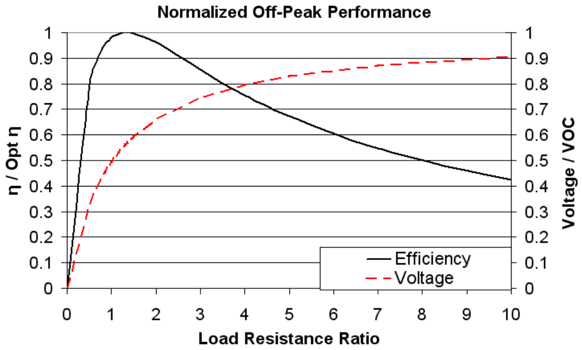
ENVIRONMENT: ONE ATMOSPHERE DRY NITROGEN

Cold Side Temperature 50°C



Cold Side Temperature 100°C

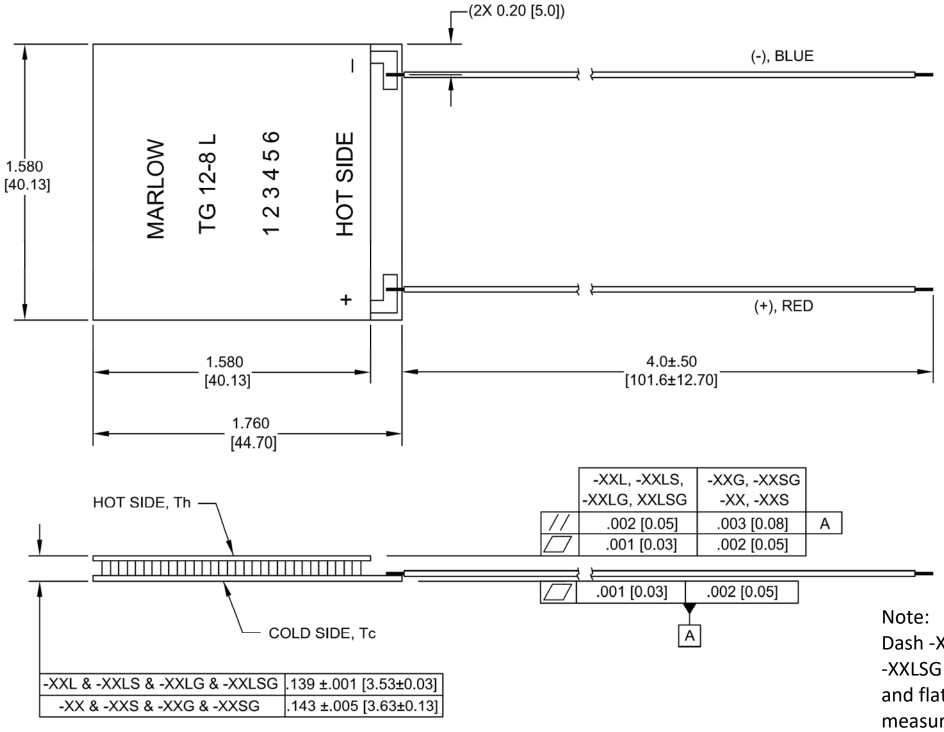




Hot Side Temperature (°C)	230	170	110
Cold Side Temperature (°C)	50	50	50
Optimum Efficiency, η (%)	4.97	4.08	2.39
Optimum Power (W)	7.95	4.17	1.19
Optimum Voltage (V)	5.25	3.65	1.86
Load Resistance for Opt η (Ω)	3.46	3.20	2.90
Open Circuit Voltage, VOC (V)	9.43	6.48	3.27
Closed Circuit Current (A)	3.38	2.60	1.48
Thermal Resistance (°C/W)	1.13	1.17	1.20

For performance information in a vacuum or with cold side temperatures other than 50°C or 100°C, contact one of our Applications Engineers at 877-627-5691.

MECHANICAL CHARACTERISTICS



All units are in inches. All units in [ ] are in millimeters.

Note:
Dash -XXG, -XXLG, -XXSG, -XXLSG: Height, parallelism, and flatness dimensions are measured before adding graphite pads.

For customer support or general questions please contact a local office or visit our website at www.marlow.com.
Marlow reserves the right to make product changes without notice.

Appendix O - User Manual

User Manual

MMTEG Heatsink Design

Sponsor: Gas Technology Institute

Sponsor Contact: Abdellah Ahmed
aahmed@gti.energy

Project Members: *Team F16*

Alec Savoye
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Kadin Feldis
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Peyton Nienaber
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Mechanical Engineering Department
California Polytechnic State University
San Luis Obispo
February 10th, 2022

Installation

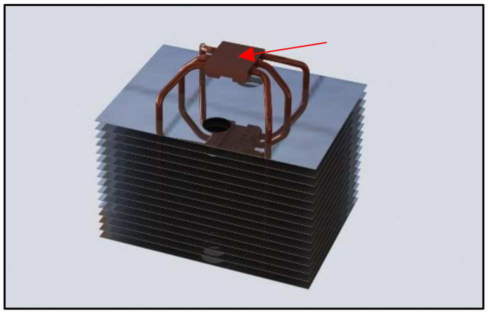
Ensure that you have all of the following materials:

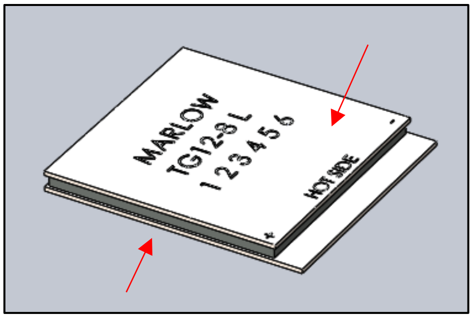
- 1x Heat Sink
- 1x Cross Bar
- 2x 1/4-20 Installation Bolts
- 2x ¼-20 Washers
- 1x Tube of Thermal Paste
- 1x TEG (may be attached to the subsystem already)

Gather the following tools:

- Extended Reach Allen Wrench
- Combination Wrench

Step 1: Clean thermal contact surfaces



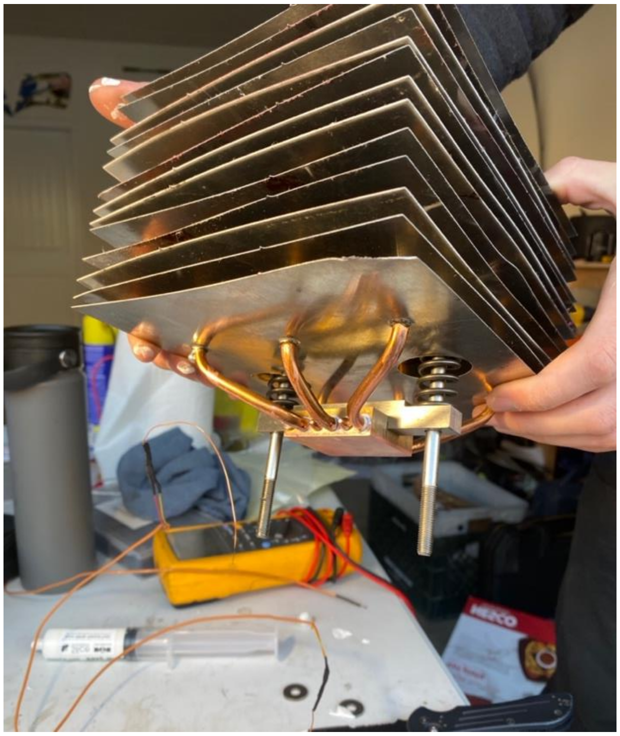


Wipe down all thermal contact surfaces with acetone and a lint free cloth. Thermal contact surfaces include the TEG facing side of the heat sink base, both sides of the TEG, and the outside of the combustion chamber.

Step 2: Apply thermal paste to thermal contact surfaces

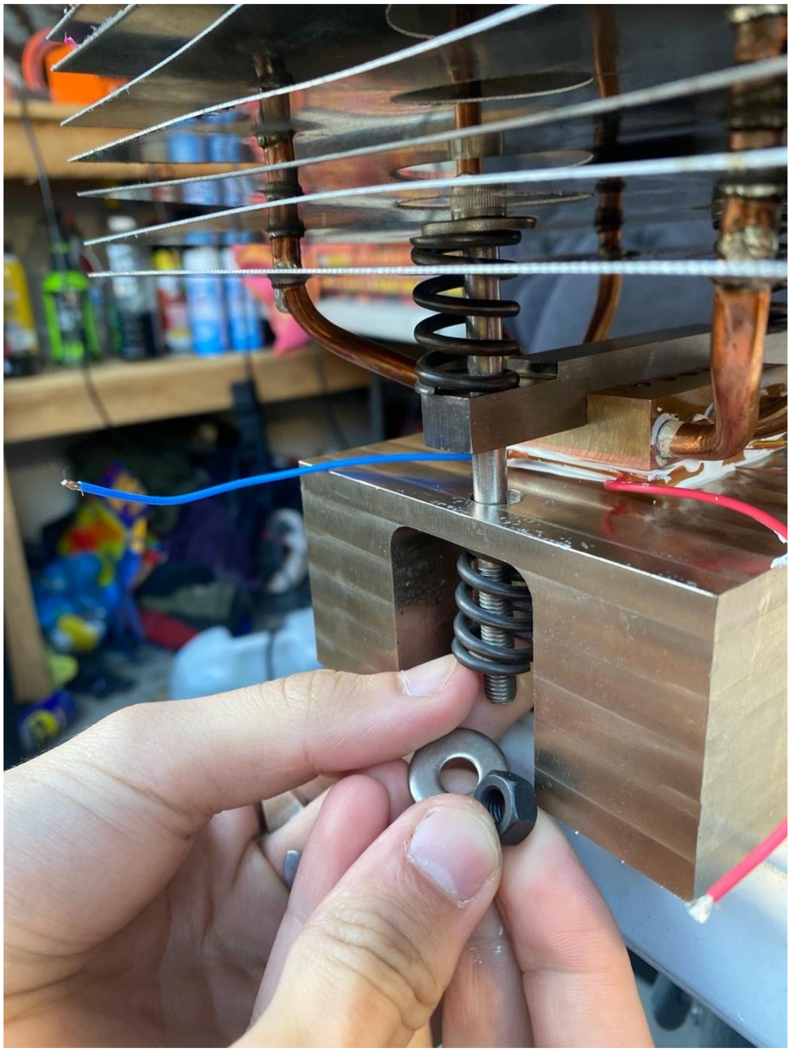
Apply thermal paste to the thermal contact surfaces from step 1.

Step 3: Place cross bar over heat sink base



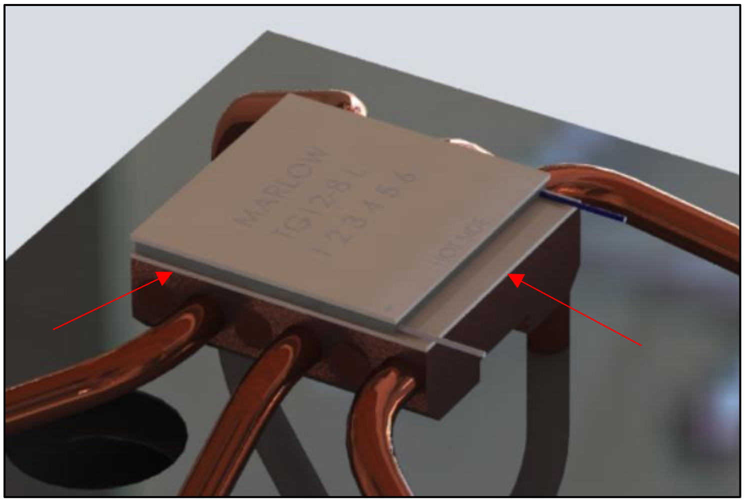
Fit the cross bar into the slot on top of the heat sink base.

Step 4: Install heatsink



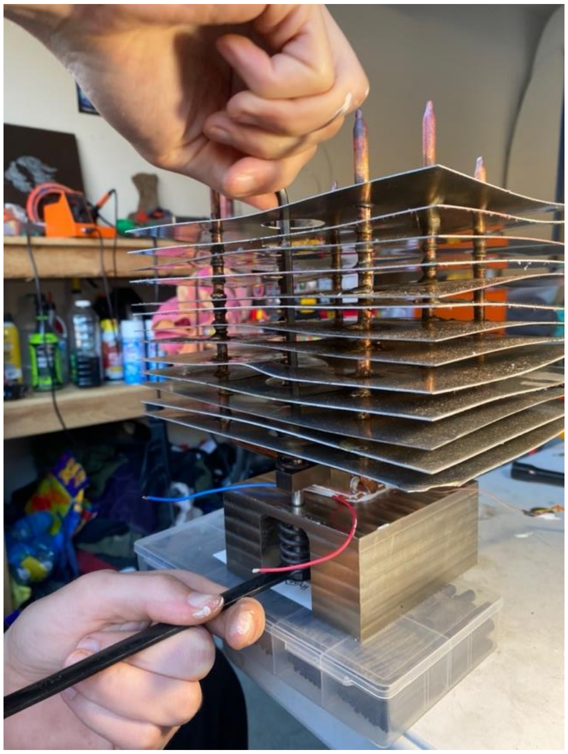
Align the heatsink as seen in the image above and slide bolts into place. Thread bolts into nuts and tighten to finger tight.

Step 5: Verify Orientation



Ensure that the heat sink base covers the entire outside face of the TEG and that the TEG and heat sink base sit flush against one another. Ensure that the inside face of the TEG is sitting flush on the combustion chamber surface and not overhanging into open air.

Step 6: Torque to spec



Torque bolts until the compression springs are fully compressed (coil layers are touching). Make sure that you stop tightening the bolts as soon as the springs are fully compressed as this will ensure the needed 100 [PSI] clamping pressure for the TEG unit.

Step 7: Observe initial transient period

After a new installation observe the initial transient period of the heat sink in operation. Ensure that the TEG unit begins producing a current and charging batteries. Watch for any burning of nearby material and make sure that there are no burning smells.

Maintenance/Troubleshooting

As dirt and dust accumulate on the heat sink fins thermal performance will degrade. Spray the system with compressed air to clean dust, leaves, dead bugs, and other contaminants off of the thermal dissipative surfaces. No other regular maintenance should be necessary. Bent fins can be manually bent back to near parallel by hand or with pliers. If damage is beyond repair or if heat pipes are leaking the unit should be replaced. If unit is not operating correctly insure wires of TEG are still connected and heatsink unit is clean and intact.

Removal

Repeat install steps in reverse order. Back out both screws 1-2 turns in alternating order for the first half of spring travel, and then 3-4 turns in alternating order until completely disassembled. Inspect crossbar for signs of fatigue or deformation. Inspect copper base for any significant deflection. If any of these effects is observed, contact your provider for assistance.

Important safety concerns:

With implementation of any system, it is paramount that the correct PPE and safety measures are taken into account. For our system, the main concerns are the increased temperature felt by the system, the sharp edges of the fins, and the inherent risk that comes with a system that involved electrical components, as well as the toxic nature of some of the components. To start, the technician needs to use a thermocouple along with a thermocouple reader to determine the temperature of the base before touching any part of the heatsink. This ensures that the technician does not get burnt. Additionally, the technician needs to be conscious of touching the When using the thermal paste, the technician must be wearing gloves and safety glasses.